



# The Pannonian-Carpathian-Alpine seismic experiment (PACASE): network description and implementation

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## Abstract

The Pannonian-Carpathian-Alpine Seismic Experiment (PACASE) is a collaborative project based on a large, passive seismic network comprising 214 temporary stations. Among the primary aims are the imaging of the Earth's crustal, lithospheric and upper mantle structure, including joint inversions; monitoring and mapping of seismic activity; and interpretation of the data from seismotectonic and geodynamic perspectives. The base of the cooperation is a high-quality, broadband seismic network covering the very centre of Europe: the Eastern Alpine and Western Carpathian Mountain ranges, the Bohemian Massif, and the sedimentary Molasse and Pannonian Basins. In this overview, we focus on the implementation and achieved field goals of PACASE, such as seismic station configuration, general network organization, data availability and access to the dataset. With selected seismological examples, we demonstrate the good usability of the records of earthquake detection, and a first publication attests to the structural imaging capability of the PACASE data. We assess the background noise level at various stations and its variations in time and space. Our aim is to collect all practical information relevant to serve as a long-term reference for the PACASE.

**Keywords** Large seismic network · Data quality analysis · Seismic noise level · Central Europe · Cooperation

## 1 Introduction and overview of PACASE

Seismic networks represent the primary passive tool to investigate lithosphere structure and seismotectonic activity of a region. As a function of an array design - including the amount, spatial density, geometry, and sensitivity of stations, deployment duration, and

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Marek Grad deceased before publication of this work was completed.

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method-specific plans to use the acquired data - seismic networks enable very rich and diverse imaging of subsurface velocity heterogeneities and discontinuities. While the benefits of array seismology were demonstrated over 50 years ago (e.g. Keen et al. 1965; Anglin 1971; Bungum et al. 1971), the number of large-aperture, high-density temporary arrays is still small because of the huge logistical and coordination effort needed to operate them. Several regional temporary arrays were realized in Europe during the last three decades and targeted specific tectonic features, e.g. the Trans-European Suture Zone (TOR, Gregersen et al. 2002; PASSEQ, Wilde-Piórko et al. 2008), the Archean-Proterozoic units/domains in northern Europe (SVEKALAPKO, Hjelt et al. 1996; LAPNET, Kozlovskaya et al. 2006), or mantle plumes (French Massif Central, Granet et al. 1995; Eifel, Ritter et al. 2001; BOHEMA, Plomerová et al. 2003). A succinct overview of large-scale networks and arrays is given in Hetényi et al. (2018a).

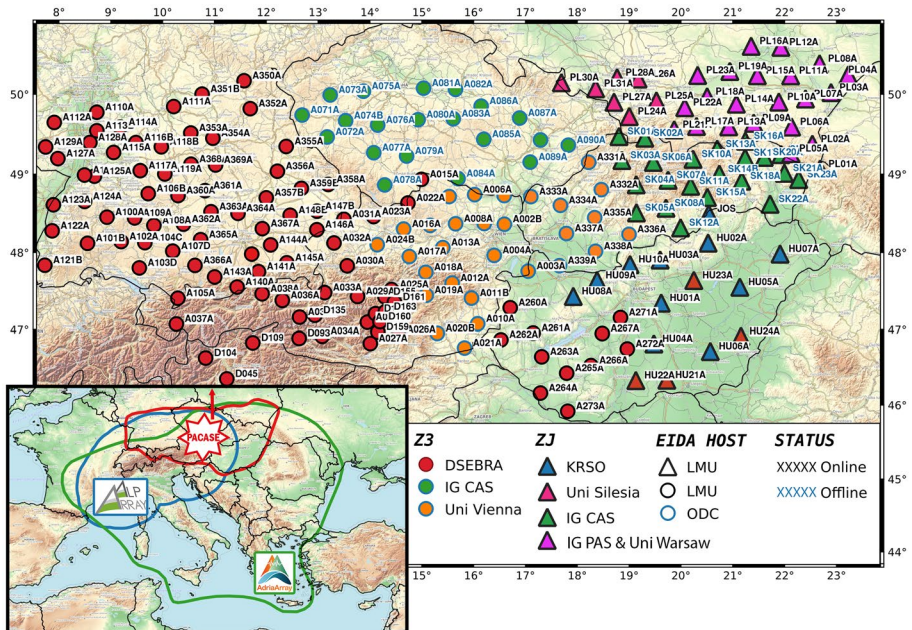
One of the recent broadband seismic arrays, the largest one as to the extent and amount of stations, was the AlpArray Seismic Network (AASN), which was deployed in the frame of the AlpArray program (Hetényi et al. 2018a). The overall goal of AlpArray was to advance our understanding of orogenesis and its relationship to mantle dynamics, plate reorganizations, surface processes and seismic hazard in the Alps-Apennines-Carpathians-Dinarides orogenic system. Its central observation array, the AASN, was the result of a very large collaborative effort across the Alpine region and 4.5 years of practical and logistical planning. As a result, the AASN has deployed over 600 broadband seismometers in a hexagonal compact coverage pattern with no point farther than 30 km away from a station over the entire greater Alpine area. This target-oriented deployment has acquired a dataset which has led to about 100 publications so far mostly associated with the 50 PhD theses related to the AlpArray program. The preparation and the subsequent operation of AlpArray have already boosted the development of national networks: during the 2011-2016 incubation time, the number of stations of openly available, permanent, national network stations increased by 50% in the same area. Moreover, following the official end date of the AASN, numerous sites have been converted to permanent, or at least semi-permanent (long-term temporary) sites, thus creating the decade of one of the fastest rates of increase in network coverage.

Beyond the AASN, the AlpArray program has set the stage for further seismological experiments in the region, called Complementary Experiments. Among these are the Eastern Alpine Seismic Investigation (EASI; Hetényi et al. 2018b), the Central Adriatic Seismic Experiment (CASE; Molinari et al. 2018), SWATH-D (Heit et al. 2021), StressTransfer (Mader and Ritter 2021) and IvreaArray (Scarponi et al. 2021), which have operated with their own seismic network codes, partly, but mostly during the AASN. The official operation time of the AASN started in January 2016 and ended on 31 March 2019. While a 3-year data access embargo was in place before the data became public via the EIDA nodes, numerous AASN stations remained in place and continued operation until further institutional and cooperative plans crystallized. These efforts culminated in launching AdriaArray ([https://orfeus.readthedocs.io/en/latest/adria\\_array\\_main.html](https://orfeus.readthedocs.io/en/latest/adria_array_main.html)) in practice in 2022 to cover the broader Adria plate region. Considering the expected transition period and the likely eastward migration of collaborative European array seismology efforts, it was natural to gather all interested participants in the Pannonian-Carpathian-Alpine Seismic Experiment, dubbed PACASE.

The PACASE has built on the existing momentum and success of AlpArray both in cooperation and seismic network development, however, it includes both new partners and new seismological sites, east of the AlpArray Seismic Network area. 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 (Fig. 1; embedded map). Scientifically, the interests revolve mostly around seismological methods for Earth's imaging (body waves, surface waves, ambient noise) and seismicity (including seismotectonics and the recent stress field), with an important interest in joint inversions (within seismology, and between seismology and potential field methods) as well. Most planned studies aim at addressing geodynamic questions of the region, the evolution of which is shaped by the inherited and ongoing interactions of basins, orogens, and (former) microplates (e.g. Schmid et al. 2020), leading to significant changes in Moho depth marked by geophysical anomalies (e.g. Kalmár et al. 2021). All research projects are planned to be carried out by the cooperation of two or more participating institutions.

Organisational questions related to the PACASE were discussed during the first months of 2019. 13 institutions from seven countries (Institute of Geophysics of the Czech Academy of Sciences, Prague (IG CAS); Kövesligethy Radó Seismological Observatory (KRSO of EPSS), Budapest; Polish Academy of Sciences, Warsaw (PAS); University of



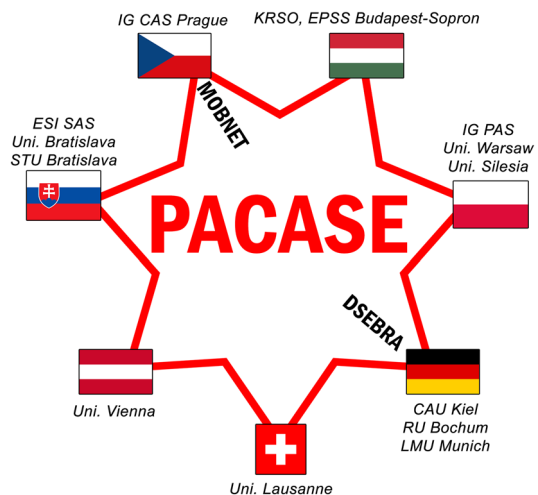
**Fig. 1** Station network map of PACASE: The circles indicate stations with the AlpArray network code Z3 while the triangles mark stations with the PACASE network code ZJ. Black-rimmed circles and triangles mark the stations hosted by LMU (Ludwig-Maximilians-Universität in Munich), while the blue-rimmed stations are hosted by ODC (ORFEUS Data Center). Black station codes mark online stations and blue station codes mark offline stations. Red stations belong to DSEBRA (Deutsches Seismologisches Breitband Array), orange stations are operated by University of Vienna, green stations are operated by the Institute of Geophysics of the Czech Academy of Sciences (IG CAS), blue stations are operated by the Kövesligethy Radó Seismological Observatory (KRSO of EPSS) in Budapest, purple stations are operated by the Institute of Geophysics, Polish Academy of Sciences (owned by IG PAS & Uni Warsaw) and magenta stations are operated by the Institute of Earth Sciences (University of Silesia in Katowice). The embedded map shows the areas of the preceding AlpArray Seismic Network (2016–2019; blue contour), the PACASE network (2019–2022; red contour) discussed in this paper and the subsequent AdriaArray network (2022–2026; green contour)

Warsaw (UW); University of Silesia, Katowice (US); Christian-Albrechts-Universität zu Kiel (CAU); Ruhr University Bochum (RUB); Ludwig-Maximilians-Universität in Munich (LMU); University of Lausanne (UNIL); University of Vienna (UV); Earth Science Institute of the Slovak Academy of Sciences (ESI SAS); Comenius University Bratislava (CUB); Slovak University of Technology in Bratislava (STU); Fig. 2) signed the final Memorandum of Collaboration (MoC) on 13 July 2019. By agreement, the PACASE was adopted as a new AlpArray Complementary Experiment. The initial field operation time was planned to be two years, nevertheless with the COVID-19-related restrictions both the preparation of AdriaArray and the cooperation in the PACASE were hindered. This has inherently led to an extension of the project by one year, and the inability to receive the purely project-specific cooperation short-term funding through the Visegrad Fund scheme. As of today, the official operation time of the PACASE has ended at the end of 2022 and continued seismological sites and/or instruments have naturally evolved to become part of AdriaArray.

## 2 Station distribution and network operators

13 institutions from seven Central European countries (Figs. 1 and 2) combined their mobile pools to create a dense (station spacing: ~30 km) PACASE seismological network. It comprises a total of 214 temporary stations, which cover the Eastern Alps in Germany and Austria, the Bohemian Massif in the Czech Republic, the Pannonian Basin in Hungary and the Carpathians in Poland and Slovakia (Fig. 1). With the end of the AASN in 2019, 146 former AASN stations in Southern Germany, Eastern Austria, Czech Republic, Western Hungary, and Western Slovakia remained in place, retained their station codes (AXXXX) and network code (Z3), but were transferred to the PACASE network. 68 new mobile seismological stations were installed in Poland, Eastern Slovakia, and Eastern Hungary. They were assigned to the PACASE network code ZJ. In contrast to former AASN stations, these station codes start with a two-letter country code followed by a two-digit number. According to the usage adopted at the time of AASN, all station codes (Z3 and ZJ) ended with a version letter (A, B, C or D) indicating small location changes during

**Fig. 2** Participating institutes of the PACASE, grouped by country, with the text in bold naming the respective mobile seismometer pools



their runtime. Figure 1 shows all PACASE stations with their station codes and network affiliation.

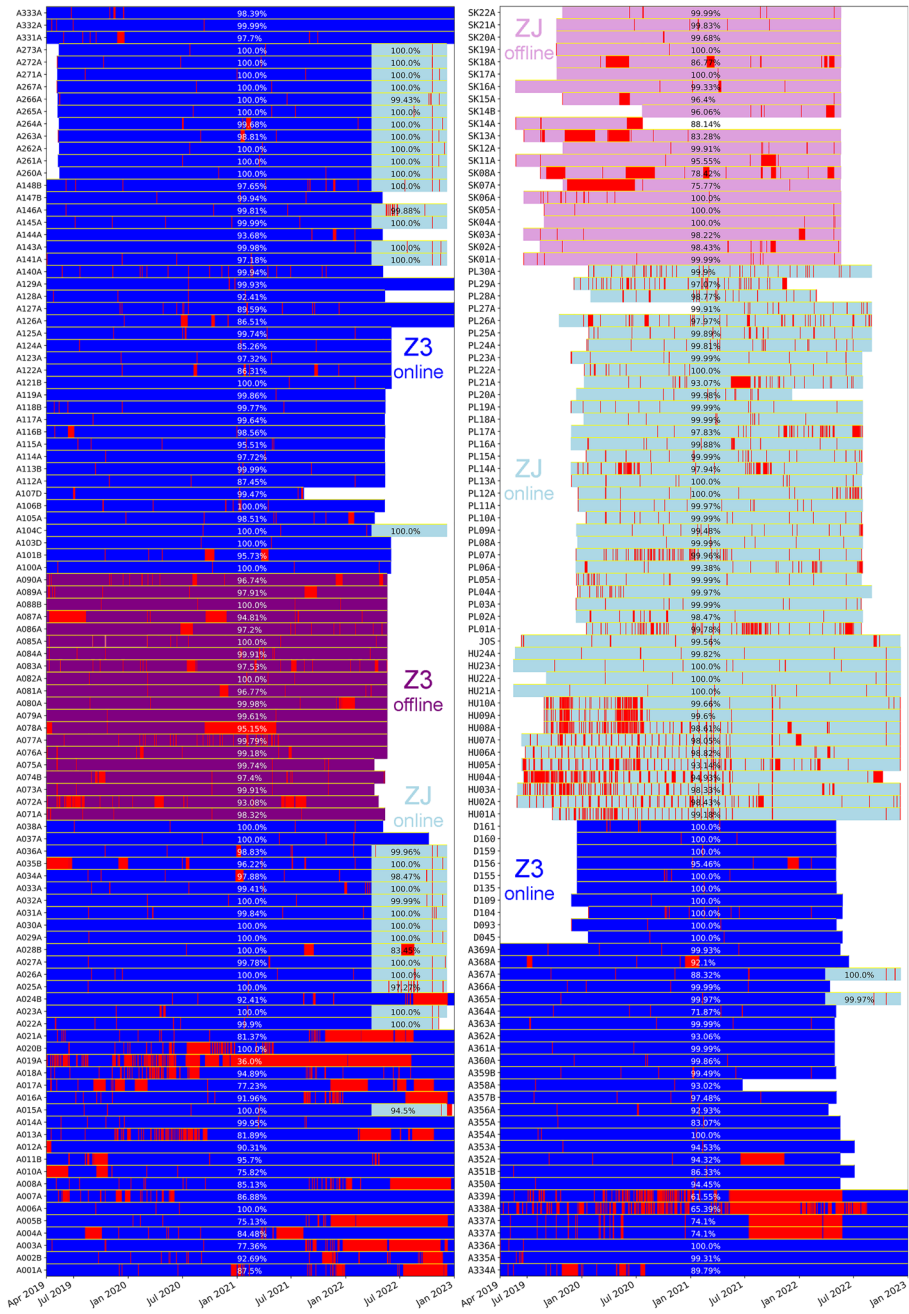
Seismological instruments in Germany, North and Central Austria (Z3.AXXXX) and mainly in Eastern Hungary (Z3.AXXXX and ZJ.HU2XA) belong to the German Seismological Broadband Array (DSEBRA; Schlömer et al. 2022; Fig. 1; red stations) operated by the DSEBRA consortium (CAU, RUB, LMU) and maintained by LMU. Stations in the Czech Republic (Z3.AXXXX) and Central and Eastern Slovakia (ZJ.SKXXX) belong to MOBNET (Mobile Network) operated by IG CAS (Fig. 1; green stations). The seismological stations in Eastern Hungary (ZJ.HU0X and ZJ.JOS) are operated by the KRSO of EPSS (Fig. 1; blue stations). UV operates stations in Eastern Austria and Western Slovakia (Z3.AXXXX, Fig. 1, orange stations). IG CAS and the UW provide stations in Southeastern Poland (ZJ.PLXXX, Fig. 1; purple stations), while the US operates seismological stations in Southwestern Poland (ZJ.PLXXX, Fig. 1; magenta stations). A list of all PACASE stations with their locations, equipment and runtime can be found in the supplemental material for this article.

### 3 Data access and data availability

Within the three-year runtime of the PACASE, we collected 7.1 TB of broadband data with continuous operation and a sampling rate of 100 Hz. Figure 3 shows the data availability, network affiliation and time gaps of all PACASE stations. Every missing data sample is indicated by a red line. A series of short gaps can produce a thick red bar in the figure. Here, the percentage value shown for each station and rounded to two decimal places gives information about the real data availability available from the respective EIDA node. The data availability averaged over the various stations is 96%, with a median value of 99.5%. The data of the PACASE network are accessible from the EIDA portal (<http://eida.gfz-potsdam.de/webdc3/>) or directly available at the two hosting EIDA nodes LMU (<https://erde.geophysik.uni-muenchen.de>; Fig. 1; ZJ and Z3; black framed stations) and ORFEUS Data Center (ODC: <https://www.orfeus-eu.org>; Fig. 1; Z3; blue framed stations). With the end of the AlpArray Seismic Network embargo in April 2022, Z3 data are freely accessible to everyone. Data with the network code ZJ is subjected to the PACASE embargo time (MoC) and therefore only available to members of the PACASE group until July 2025. Afterwards, the data will be released to the public. Data and metadata can be accessed via Federation of Digital Seismograph Networks (FDSN) web services with smart clients (e.g. `fdsnws_fetch`, `wget`) or with the ObsPy routing client (Megies et al. 2011). The restricted access for the ZJ data is managed by an access control list archived at LMU. Examples of data requests (open and restricted) can be found in Schlömer et al. (2022).

With the launch of AdriaArray, 60 DSEBRA Z3 stations were dismantled in spring 2022 to be prepared for deployment in the southeastern part of the AdriaArray region. In autumn 2022, RUB installed 42 stations in Greece and in North Macedonia in spring 2023 (network codes: 1Y, HA, MK). LMU installed 19 stations in Albania, Montenegro, and Kosovo in spring 2023 (network code Z6). 38 DSEBRA Z3 stations in Germany, Austria and Hungary will remain at their current locations. To protect the data, the stations were initially transferred to the ZJ network and subjected to the PACASE embargo in April 2022 and then subjected to the AdriaArray network (network code at LMU: Z6; stations kept their station codes) in December 2023. Similarly, five stations in the western part of the Bohemian Massif of Z3 were dismantled and along with other instruments transferred to





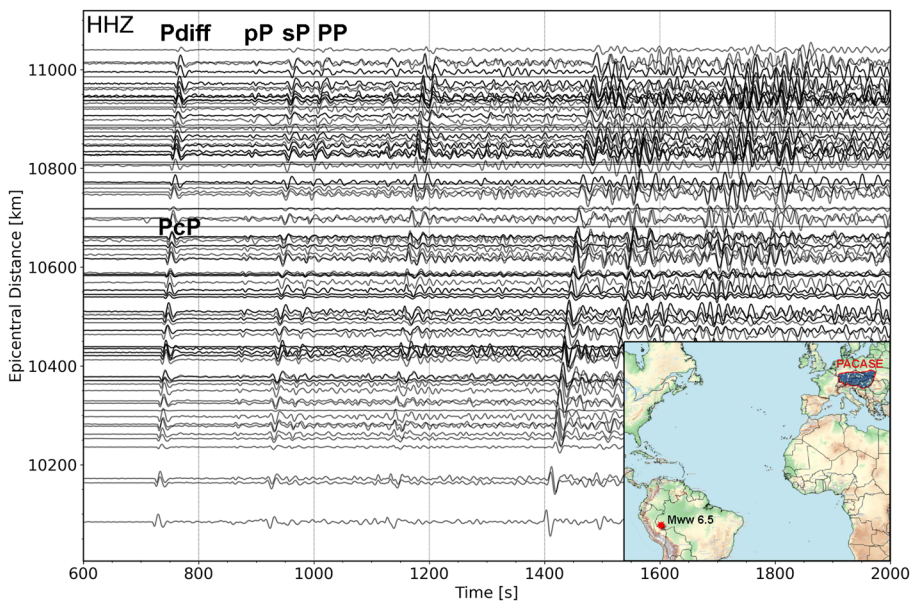
**Fig. 3** Data availability of all PACASE stations. A gap of more than 90 s is indicated by a red line. A series of short gaps can produce a thick red bar in the figure. Here, the percentage value, rounded to two decimal places, gives information about the real data availability of a station. Online Z3 and ZJ stations are coloured in blue and light blue, respectively. Offline Z3 and ZJ stations are coloured in purple and pink

AdriaArray to form its component in Romania and Bulgaria (altogether 18 units of the MOBNET). The PACASE ZJ stations in the Czech Republic, Hungary and Slovakia were transferred to the AdriaArray network in 2023 (AdriaArray network code at LMU: Z6), remained at their location and kept the station code. Stations in Poland were also transferred to AdriaArray and archived at the NIEP EIDA node. Consequently, the data are subjected to a two-year rolling embargo and accessible only to members of the AdriaArray group. The restricted access to the embargoed data is managed by the EIDA Authentication System (EAS: <https://geofon.gfz-potsdam.de/eas/EIDAAuthenticationService.pdf>) and is only available for members of the AdriaArray group.

## 4 Data examples

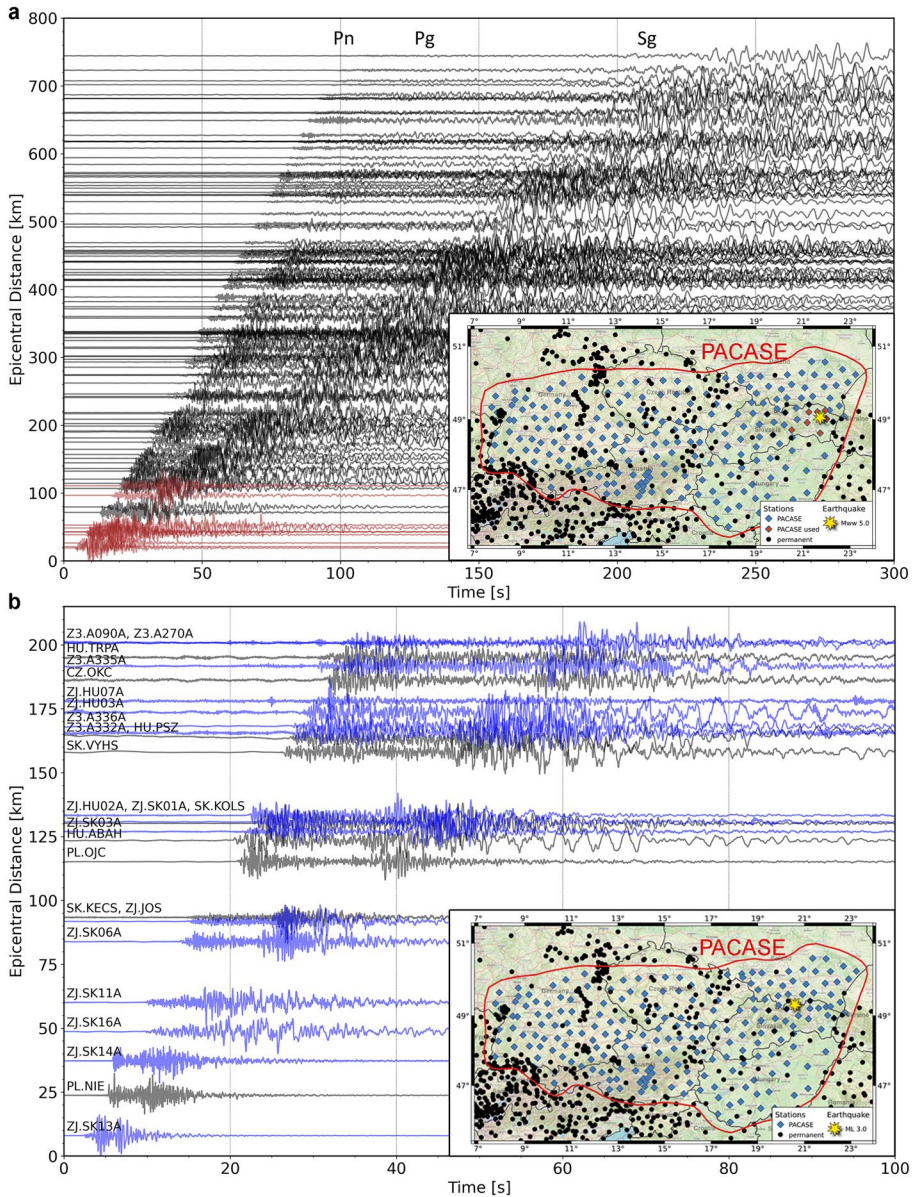
Already during the operation of the PACASE network, several events illustrated the sensitivity and recording capability of the seismic array. As an example of teleseismic events, Fig. 4 shows the filtered (bandpass with corner frequencies of 0.01 and 0.08 Hz) vertical waveforms of a teleseismic earthquake in Peru (8 June 2022;  $M_{\text{w}}=6.5$ ). Such kind of earthquakes are used for structural studies of the Earth by using various seismological methods (e.g. body-, surface- and full-waveform tomography, receiver functions and shear-wave splitting).

Especially the MOBNET stations of the PACASE network in Slovakia improved the existing network in that region considerably. A recent strong earthquake of  $M_{\text{w}}=5.0$  (National Earthquake Information Center, NEIC) occurred on 9 October 2023 in



**Fig. 4** Examples of teleseismic waveforms following the 2022-06-08 00:55:46 (UTC)  $M_{\text{w}}=6.5$  Peru earthquake. The waveforms are filtered with a bandpass filter from 0.01 Hz to 0.08 Hz. The time axis is set with respect to the origin time of the earthquake

easternmost Slovakia at 18:23:09 (UTC) (Fig. 5a). It was localized at 49.097°N and 21.781°E (41 km east of Prešov) at a depth of 8.6 km ( $\pm 3.4$  km) by NEIC on basis of



**Fig. 5** **a** Example of raw waveforms following the 2023–10–09 18:23:09 (UTC) M<sub>w</sub>=5.0 easternmost Slovakia earthquake. The inset map shows the location of the earthquake as well as the PACASE (blue) and permanent (black) stations. The PACASE waveforms and stations in the map, which are used for improved localization are coloured in red. **b** Raw waveforms of selected PACASE (blue) and permanent (black) stations with a distance smaller than 200 km to the 2019–07–13 12:07:46 (UTC) M<sub>I</sub>=3.0 earthquake east of the High Tatras in Slovakia. The inset map shows the location of the earthquake as well as the PACASE and permanent stations



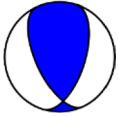

world-wide permanent stations and a radial Earth velocity model. The densely spaced MOBNET stations of the PACASE/AdriaArray network in close vicinity to the epicentre (Fig. 5a; marked in red) provided data for an improved determination (Lucia Fojtíková, ESI SAS) of epicentre, depth, and focal mechanism by using a local velocity model compiled from the CEL06 and CEL11 active seismic experiments (Janik et al. 2011). Table 1 compares the different results of the localizations and focal mechanisms. The locations of the event epicentre do not change much (6.4 km) but incorporating the PACASE stations surrounding closely the epicentre improved the depth estimation to 7.3 km ( $\pm 2$  km) and resulted in a different focal mechanism. Two similarly strong events occurred in this region at the end of the 18th century. A weaker event with  $M_b=4.3$  shook the region on 20 May 2003 (20:13:40 (UTC); 48.879°N, 22.160°E; depth=10 km). Much weaker events are more frequent in the broader surroundings in the inner band of the Carpathians.

With the help of the MOBNET stations in Slovakia, it was possible to precise the localization of a weak event east of the High Tatras in Slovakia (2019-07-13 12:07:46 (UTC); 49.3159°N, 20.5898°E; depth=16.9 km,  $M_l=3.0$ ; International Seismological Centre 2019). Figure 5b shows the vertical waveforms of selected PACASE (blue waveforms) and permanent stations (black waveforms) at a close distance (<200 km) to the epicentre. The improved detection is an important contribution to the local earthquake catalogue due to the rareness of earthquakes in this region. All these examples demonstrate that the PACASE data are suitable for any type of earthquake analysis and all other seismological techniques (e.g., tomography, ambient noise, receiver functions). Especially in regions of high or very weak seismicity, the PACASE stations improve the earthquake analysis capabilities by densifying the coverage hitherto available through the permanent networks.

## 5 Data quality

All individual mobile pool operators were responsible for the data quality and availability of their stations. Besides the maintenance of the stations, they were responsible for the update and correctness of metadata, they had to fill data gaps of online stations and had to arrange the transfer to the European Integrated Data Archive (EIDA, Strollo et al. 2021) in

**Table 1** Comparison of localizations and focal mechanisms of the  $M_{ww}=5.0$  Slovakia earthquake (2023-10-09 18:23:09 (UTC)) calculated by the National Earthquake Information Center (NEIC) and by Lucia Fojtíková (ESI SAS)

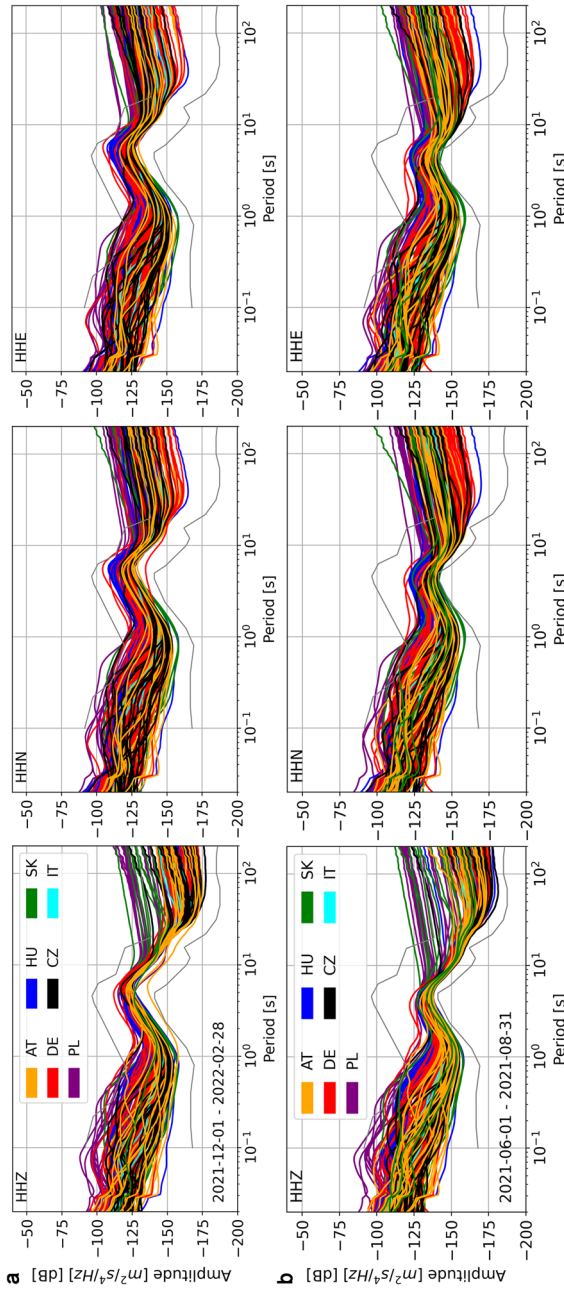
Method:	Longitude:	Latitude:	Depth:	Magnitude:	Focal mechanism:			
					Strike:	Dip:	Rake:	
NEIC	21.781°E	49.097°N	8.6 km $\pm$ 3.4 km	$M_{ww}=5.0$		18°	48°	122°
Regional (+PACASE)	21.7173°E $\pm 0.751$ km	49.0575°N $\pm 0.856$ km	7.32 km $\pm 2.02$ km	$M_l=4.9$		18.7°	32.9°	75.2°

near-real-time for online stations and with up to 3 months delay for offline stations. Since the PACASE network was fully equipped with broadband seismometers (Table 1 in the supplemental material), high-level data quality could be achieved. Detailed data quality studies for the participating mobile pools were performed by Schlömer et al. (2022) for the DSEBRA stations, by Vecsey et al. (2017) for MOBNET, by Gráczner et al. (2018) for the Hungarian network including temporary stations, and by Fuchs et al. (2016) for the Eastern Austrian and Western Slovakian network.

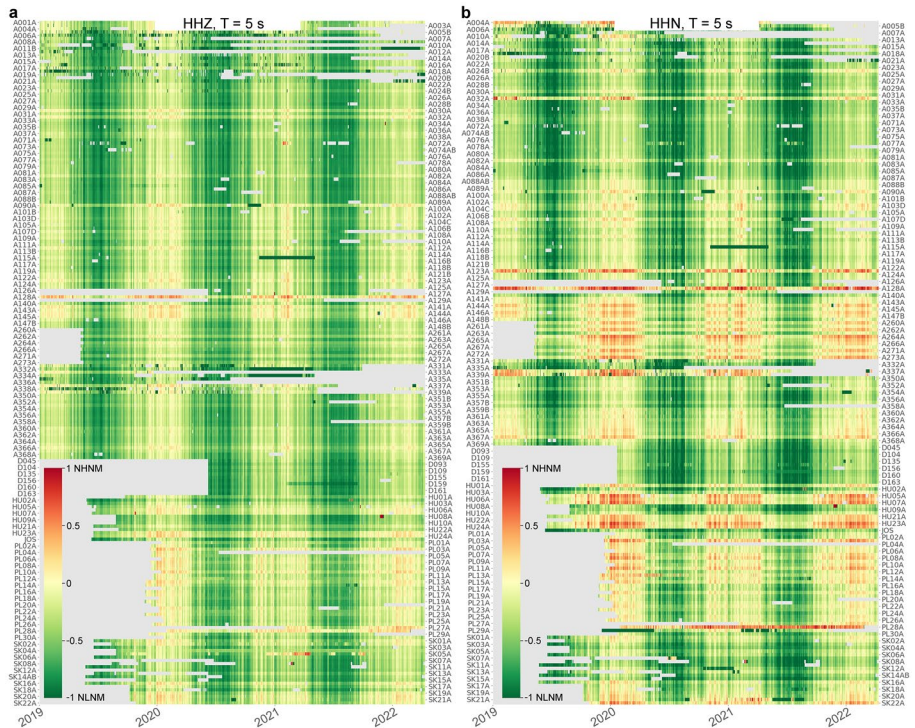
To give an overview of the data quality of the PACASE network, we present seismic noise analyses in the frequency domain but also in the time domain. Figures 6, 7, 8, 9 show the probabilistic power spectral densities (PPSDs created with the ObsPy toolbox, Krischer et al. 2015, following the procedure of McNamara and Buland 2004) in different ways, while Figs. 8 and 10 show results from statistical noise analyses.

Figure 6 shows the median curves of the PPSDs, calculated for all PACASE stations for all three channels during a winter period (Fig. 6a; 2021-12-01 to 2022-02-28) and a summer period (Fig. 6b; 2021-06-01 to 2021-08-31). The colours of the individual PPSDs indicate the country of installation. All stations are below the new high-noise model (NHNM; Peterson 1993) for the vertical component and also for the horizontal components during summertime in a period range of 1-8 s, which is the frequency range for teleseismic body waves and ambient noise tomography. Two stations located in Germany and Poland lie on or slightly above the NHNM for periods longer than 7 s for the horizontal components during wintertime (Fig. 6a; HHN and HHE; red and purple). While Polish and Slovak stations mainly exceed the NHNM for periods longer than 18 s for the vertical component (Figs. 6a and b; HHZ; purple and green), German, Hungarian and Czech Republic stations exceed the NHNM for periods longer than 18 s for the horizontal components as well (Figs. 6a and b; HHN and HHE; red, blue and black). The low performance of several stations (especially in Poland, Slovakia, and Germany) below periods of 1 s can be attributed to anthropogenic noise like roads, villages, industries, or wind power, which cannot be avoided at predefined locations constrained by the overall network geometry. For example, some Polish stations (PL26A, PL28A and PL29A) are located close to the Upper Silesian Metropolitan Area with heavy industry, highways, railways and many medium to large cities, which caused the high noise level. In contrast to that, almost all Austrian stations (Figs. 6a and b; orange) have a low noise level, reflecting an installation in sparsely populated areas in the Alpine mountains. The low performance at periods greater than 10 s of many stations and especially detected on the horizontal components can be attributed to instrument noise and tilt caused by changes like temperature or pressure fluctuations due to insufficient insulation. Recommendations for seismometer shielding, defined in the Technical Strategy cannot be fully implemented by many mobile pool operators due to low budgets for temporary installations. A comparison between the median curves of the PPSDs for a summer and a winter period reveals a lower noise level during the summertime, mainly in the microseismic range (1-10 s). The higher noise during the winter months can be related to storms and wind in oceans, generating swell at the coastlines.

While Fig. 6 shows the median curves of the PPSDs in time windows of three months, Fig. 7 shows the temporal behaviour of the PPSDs during the whole runtime of the PACASE (2019-01-01 to 2022-04-12) for the vertical and north component at the period of 5 s. Here, the PPSD values are normalized between the NHNM (-141.2 dB) and NLNM (-97.7 dB), and the corresponding relative value for the period of interest for each day is plotted. Green colours indicate values close to the NLNM, while red colours indicate values close to the NHNM. At the considered microseismic period, the seasonal variation between summer (green) and wintertime (yellow to red) can be clearly



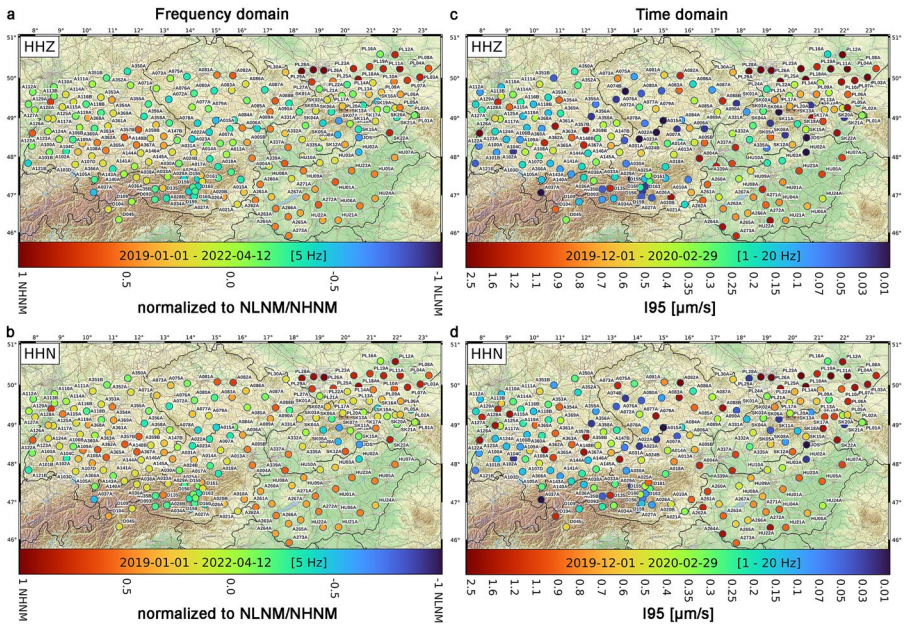
**Fig. 6** Median curves of probabilistic power spectral densities (PPSDs) of all PAC/ASE stations for each channel (HHZ, HHN, HHE) and colour-coded by country. The grey lines mark the Peterson New High/Low Noise Model (Peterson 1993). **a** Median curves of PPSDs calculated during a winter period from 2021-12-01 to 2022-02-28. **b** Median curves of PPSDs calculated during a summer period from 2021-06-01 to 2021-08-31



**Fig. 7** Temporal behaviour of the PPSDs during the PACASE runtime (2019-01-01 to 2022-04-12). The amplitudes are normalized between the Peterson New High Noise Model (NHNM = -141.2 dB, Peterson 1993) and the Peterson New Low Noise Model (NLNM = -97.7 dB) for a period of 5 s **a** for the vertical and **b** for the north component

identified. Stations with values very close to the NHNM during wintertime (red) are located in western (A12XX) and southeastern Germany (A14XX), Poland (PLXXX), Slovakia (>SK16A) and a few in Hungary (e.g. HU05A, HU06A, HU07A, HU23A, HU24A; Fig. 6a). While the PPSD values of the Polish and of the Slovakia stations are close to the NHNM during wintertime in 2020 and 2022 (Fig. 6a; red), the values are closer to the average (yellow to orange) during wintertime 2021, corresponding to lower wind speeds in the area that year. A comparison between the PPSD values of the vertical component with the north component shows that especially stations in Hungary (HUXXX and A2XXX), southeastern Poland ( $\leq$  PL15A), southeastern Germany (A14XX), stations close to the Danube in Germany (A36XX) and a few single stations in Austria (e.g. A004A, A032A) and Slovakia (e.g. A337A, A339A and >SK19A) have much higher noise levels on the north component than on the vertical component. This increased noise level on the horizontal component at a period of 5 s reflects the location of these stations being in sedimentary basins. Gráczner et al. (2018) discussed the differences in the average noise characteristics between the vertical and horizontal components of Hungarian stations located on hard rock or in sedimentary basins. The authors identified a noise difference of more than 10 dB between the horizontal and vertical components of a station located in the basin compared to the difference smaller than 5 dB of stations located on hard rock in a period range of 1 to 10 s.



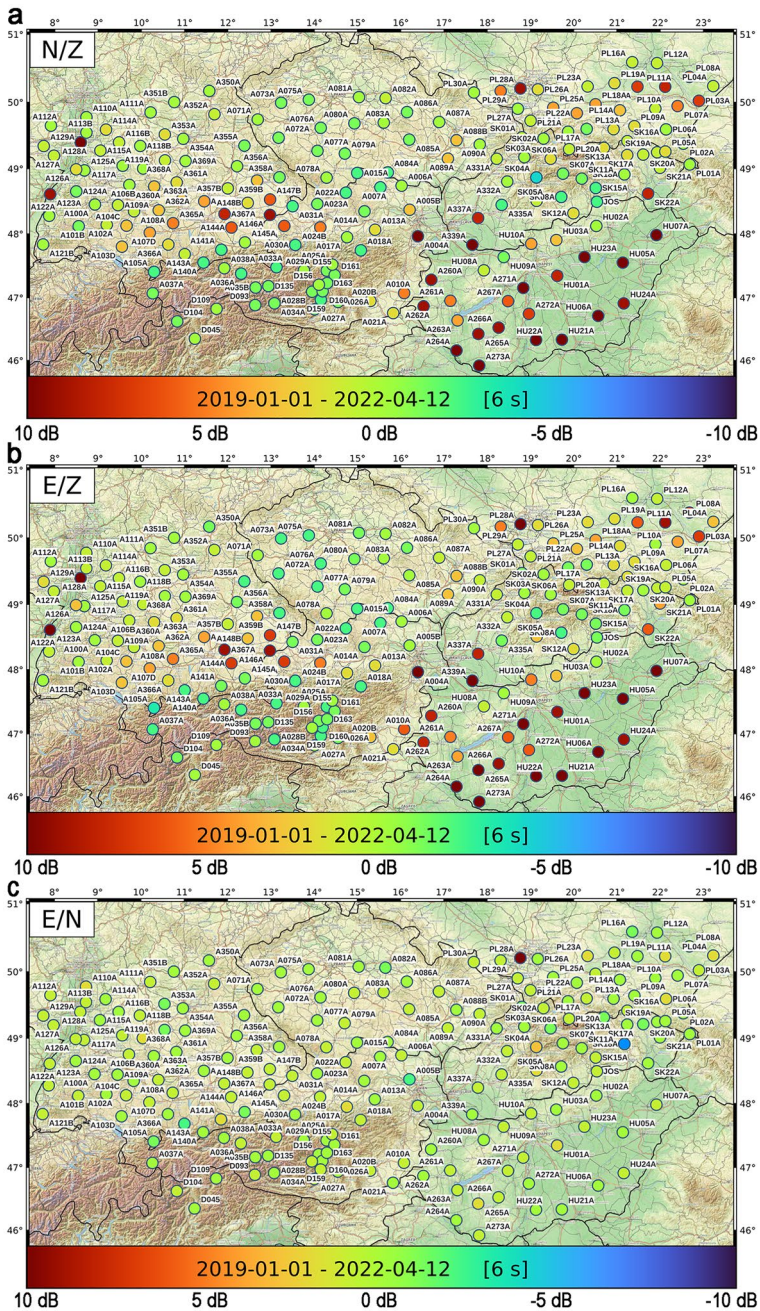


**Fig. 8** **a** Normalized (NHNM = -96.7 dB, NLNM = -166.7 dB) PPSD values averaged for the whole runtime of PACASE (2019-01-01 to 2022-04-12) at a period of 0.2 s for the vertical component and **b** for the north component. **c** 195 amplitudes calculated in a time span between 2019-12-01 and 2020-02-29 with a sliding window of 1 h, averaged for time steps of 30 min and filtered in a frequency range from 1 to 20 Hz for the vertical component and **d** for the north component

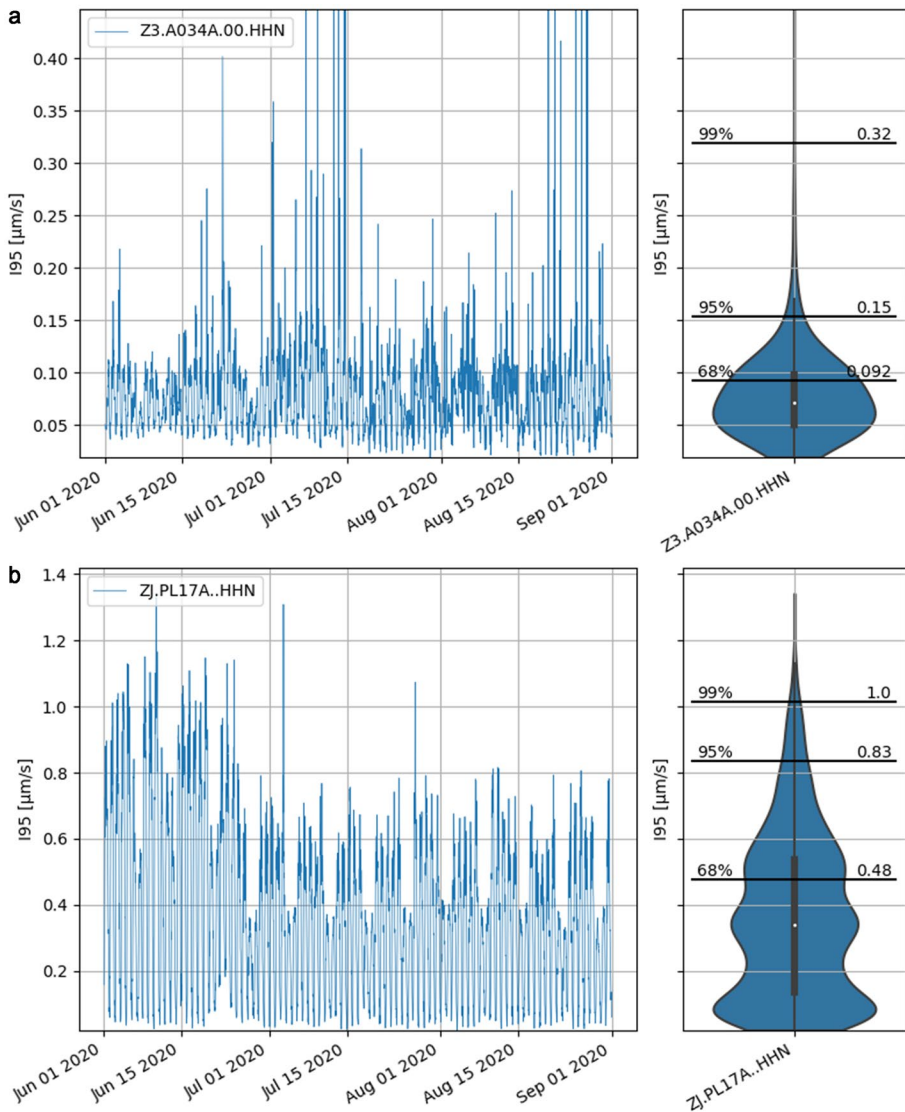
Figures 8a and 8b show the averaged PPSD values for  $T=0.2$  s and normalized to  $NHNM=-96.7$  dB and  $NLNM=-166.7$  dB for the whole runtime of PACASE on a map.

Here, we can also clearly identify the noise difference between the stations located in basins ( $>0.3$  NHHM; orange to red) and on hard rock ( $<0$  NLNM; green to blue), corresponding to the proposed noise difference of  $\sim 20$  dB at the shown period of 0.2 s by Grácz et al. (2018). Stations close to the NHNM (orange to red) are located in the Pannonian Basin in Hungary, the Molasse Basin in southeastern Germany (northern foreland of the Alps), the Vienna Basin (eastern Austria and western Slovakia) and in the northern foreland of the Carpathians in Poland (Fig. 8a). The significant high noise at the northern Polish stations at this period (already shown in Fig. 6) is probably a summation of anthropogenic noise and a location in a basin. Noise values close to the NHNM at some stations in Germany (e.g. A108A, A362A, A357B, A123A and A128A) could be related to a river basin (Danube River Basin and Upper Rhine Graben) but it is more likely that the vicinity to large cities and industries located at the main waterways caused the noise. In contrast to the PPSD amplitudes at a period of 5 s (Fig. 7), no remarkable noise differences between the vertical (Fig. 8a) and the north components (Fig. 8b) are visible. This corresponds to the insignificant noise differences between the vertical and horizontal components at a period of 0.2 s proposed by Grácz et al. 2018.

Horizontal-to-vertical spectra ratios (HVSZR) of PPSDs are the most popular approach to assess the dominant frequency of a site (e.g. Bahavar et al. 2020). Here, we use the method of the PPSD ratios in the range of the microseism at 6 s to map again the sediments



**Fig. 9** Microseism PPSD ratios at a period of 6 s. The colour indicates the difference (in dB) from a median value, which is calculated to be **a** N/Z = -0.11 dB, **b** E/Z = -0.47 dB and **c** E/N = -0.32 dB



**Fig. 10** I95 curves calculated in a time span between 2020-06-01 to 2020-08-31, with a sliding window of 1 h and a shifted step of 30 min, in a frequency range from 1 to 20 Hz, for the north component. **a** Line (left side) and violin plot (right side) of station A034A located on a meadow of a forest farmer in Austria. **b** Line and violin plot of station PL17A located at the foot of a hill near a road in Poland

(e.g. Díaz et al. 2023) and detect outliers. Figure 9 shows the PPSD ratios of all components. The colours indicate deviations from a median value, which is calculated to be  $N/Z = -0.11$  dB;  $E/Z = -0.47$  dB and  $E/N = -0.32$  dB. Reddish colours indicate higher noise than the median, while bluish colours represent lower noise. A green colour indicates a value close to the median value. As discussed in the description of Fig. 7, the ratios of the vertical component (Fig. 9a,  $N/Z$ ; Fig. 9b,  $E/Z$ ) allow the detections of sites located



on sediments due to the consequential higher microseism noise values on the horizontal components at this period. The PPSD ratios of the horizontal components (E/N) allow the detection of outliers. Here, we identified SK18A and PL28A (Fig. 9c). SK18A had a wrong gain on the north component in the metadata, which was subsequently corrected. PL28A had extremely high noise with different magnitudes on each component. As a consequence, the station was dismantled and the location is no longer used.

While PPSDs are calculated in the frequency domain, we also perform statistical noise analyses in the time domain (Figs. 8c, 8d and 10). This is advantageous to get velocities (m/s) in comparison to the calculation of PPSDs (dB). The velocities can directly be used as trigger thresholds for detection filters, to identify relevant or critical velocities, e.g. for signal-to-noise ratio analyses or to show the temporal variations within a distinct time span. Here, we show the I95 (Interval 95%) amplitude values, which represent the threshold, where in the case of a zero mean Gaussian distribution, 95% of all measurements in a chosen time window fall below. 95% of data values represent the two times standard deviation ( $2\sigma$ ) of a measurement. A detailed explanation of the I95 calculation can be found in Schlömer et al. (2022). Figures 8c and 8d show the I95 amplitudes calculated in a time span between 2019-12-01 and 2020-02-29 with a sliding window of 1 h, averaged for time steps of 30 min and filtered in a frequency range from 1 to 20 Hz for the vertical (Fig. 8c) and for the north component (Fig. 8d) of each individual PACASE station in a map. By a visual comparison, it becomes evident that results obtained from calculations in the frequency domain (Figs. 8a and 8b; 2019-01-01 to 2022-04-12; 5 Hz) and time domain (Figs. 8c and 8d; 2019-12-01 to 2020-02-29, 1-20 Hz) are very similar. Stations located in the basins have I95 values higher than  $0.6 \mu\text{m/s}$ , with significant high values ( $> 2 \mu\text{m/s}$ ) at most of the northern Polish stations. Similar to the PPSD values shown in Figs. 8a and 8b, no remarkable differences between the vertical and horizontal components are visible. Contrasts are clearer between the I95 values in the time domain compared to values in the frequency domain due to the different shown time ranges. The PPSD values in Figs. 8a and 8b are averaged over the whole runtime of PACASE, while the I95 values in the time domain are averaged over one winter period. Therefore, remarkable I95 values ( $> 0.7 \mu\text{m/s}$ ) in an otherwise quiet environment (e.g. A003A, D135 or A073A; Figs. 8c and 8d), indicate time-dependent noise variations.

To get information about the daily and weekly noise variation of a station, a line and violin plot visualizes the statistical noise distribution for a time span of three months during the summer (2020-06-01 to 2020-08-31) for the north component of two different PACASE stations (Fig. 10). In addition to a boxplot, a violin plot shows, besides the median (white dot in the black bar) and interquartile ranges (50% data, marked by the vertical black bar), also the full distribution of data (horizontal width). It allows us to recognize multimodal distribution, their positions, and their amplitudes. The horizontal lines mark the quantiles comprising 68%, 95% and 99% data. Figure 10a shows the I95 amplitude values of station A034A Stadlberg, Tirol (Austria) located on a meadow of a forest farmer. The line plot (left side) shows a daily and weekly periodicity with decreasing noise ( $< 0.07 \mu\text{m/s}$  during daytime) at the weekends (e.g. 15 and 16 August 2020) and higher noise ( $> 0.13 \mu\text{m/s}$ ) from Wednesday to Friday, probably corresponding to the working days of the farmer. The violin plot (right side) shows an almost Gaussian distribution with the peak at the median ( $0.07 \mu\text{m/s}$ ) but with many high outliers (2020-07-01 to 2020-07-15 and 2020-08-20 to 2020-08-27) reflected by a high I99/I95 ratio (2.1). Figure 9b shows the I95 amplitudes of station PL17A, located in Szczawa, in the Carpathian Mountains close to a road. Here three modes can be observed in the violin plot. The strongest mode at  $\sim 0.05 \mu\text{m/s}$  can be attributed to the daily periodicity between day and night, while the second mode



at  $\sim 0.37 \mu\text{m/s}$  indicates a clear weekly periodicity (working days - weekends). The weakest mode at  $\sim 0.55 \mu\text{m/s}$  can be related to another weekly periodicity, for example slightly higher noise on Fridays. An offset of  $-0.22 \mu\text{m/s}$  in the amplitudes can be observed after 26 July 2020. This date corresponds to the start of the summer holidays in Poland, indicating less rush-hour traffic during the holidays. By comparing the line plots of the two stations, it can be observed that the I95 amplitudes of A034A are  $\sim 0.03 \mu\text{m/s}$  higher during the night on working days (Fig. 10a) than on weekends compared to station PL17A. Here the amplitudes are  $\sim 0.03 \mu\text{m/s}$  lower during night at working days than on weekends, reflecting the leisure behaviour of the residents.

All discussed examples show that the PACASE community developed many tools and methods to monitor the quality of stations (including anthropogenic activity variations), detect outliers and wrong metadata. These are important tools to ensure continuous high-quality data within the whole runtime of any seismological network project.

## 6 Results and findings from PACASE

### 6.1 Scientific research

As explained in the introduction, the PACASE project lasted longer than initially planned, with a 1-year extension of the data acquisition period, and a longer delay of actual research cooperation and project-based work. Data are currently processed for passive seismic imaging using body, surface wave, and waveform tomography as well as for receiver function studies. At the time of preparing this manuscript, all projects have been initiated, sometimes in connection to similar work using AASN data (e.g. Plomerová et al. 2022), but few have advanced enough to refer to established findings.

The first project that has been completed is the joint effort between PACASE and AlpArray working groups to prepare a homogeneously processed and quality-controlled P-to-S receiver function dataset, which is then migrated in 3D spherical coordinates, and results picked for a Moho map (Michailos et al. 2022). This full receiver function database covers 6 years of data and 708 stations, to which PACASE contributed greatly with about 80 independent sites and 2 years of data. The second publication with a contribution of the PACASE database focuses on the lithosphere-asthenosphere boundary of the broader Pannonian Basin area, exploiting S-to-P converted waves (Kalmár et al. 2023).

In parallel, registered seismological observatories accessed the real-time data over a SeedLink server for monitoring and alerting duties, thus making PACASE a contributor to local and regional catalogues. As shown in Sect. 4, the PACASE stations improved localizations of small earthquakes within the network considerably. Further collaborative work is planned within PACASE on the crust and the lithosphere studies, with a more important focus on joint inversions compared to AlpArray working groups.

### 6.2 Findings relevant for seismic networks

The AASN was the first large European broadband array to this extent (Hetényi et al. 2018a), with a corresponding Technical Strategy adopted by all station operators. Since every participating institute had to request its own funding, procure the material, organize staff, scout the prescribed locations, install, maintain the stations and organize the data transfer, not all requirements (see Technical Strategy of the AASN) could

be fully met with the beginning of the AlpArray Seismic Network in 2016. However, all the logistical and practical experience gained while building the AASN resulted in a well-trained procedure and in-house expertise of mobile pool operators. Some of the learned lessons were on precise north orientation, metadata complexity, and efficient site selection, all while maintaining the network geometry constraints. Hence, with the beginning of PACASE in 2019 almost all problems were fixed, and we started to acquire high-quality data from the beginning.

Mobile array installations can also be used as a platform to test and compare technical equipment. LMU developed a power box for the DSEBRA stations to remotely monitor and control the technical equipment of a station (Paffrath et al. 2023). Problems and failures were recognized in the first year of the AASN, while the power box was developed and tested during the PACASE runtime. Now 80% of all DSEBRA stations are equipped with this box. It reduces many service activities triggered by minor technical issues. This is a big advantage especially for an installation in remote areas.

Several facilities (Guralp host box, Guralp control and calibration unit, STS-2 control and calibration unit, GAIA gain and calibration unit) have been developed for remote control and/or control and calibration of MOBNET stations during AlpArray (Vecsey et al. 2017) and continued to improve during the runtime of PACASE.

All mentioned points lead to a continuous improvement of the arrays' performance, the technical design of the stations, and the expansion of our knowledge of observational practices. Since AdriaArray adopted most of the PACASE stations with their locations and equipment, it creates excellent prerequisites for ongoing good cooperation and high-quality data collection in AdriaArray.

## 7 Conclusions

PACASE represents a major milestone in a series of regional, temporary passive seismic arrays operated by European institutions. It covers at least five major geodynamic units: the Eastern Alps, the Western Carpathians, the Bohemian Massif, the eastern part of the Molasse Basin, and most of the Pannonian Basin, spanning across six countries. A total of 214 stations operated for more than 3 years, deployed in a pattern and spatial density like the AlpArray Seismic Network. The network has collected over 7 TB of data, with an average data availability of 96% and a station-wise median of 99.5%. The data quality is satisfactory, between the low and high noise models with the stations located at sedimentary basins having relatively higher level of seismic noise. The temporal variability in noise levels can be well explained by anthropogenic sources and seasonal variations. Selected data examples demonstrate that the collected data is suitable for both structural imaging as well as seismicity analysis of local, regional and teleseismic events. The scientific cooperation in PACASE includes 13 institutes from seven countries and focuses on the seismological structure, seismic activity, and the geodynamics of the covered region. With two research papers already published, several other collaborative works are underway. Seismic sites and station equipment of the PACASE project have been transferred into the new multi-national AdriaArray project.

## 8 Field teams of the participating institutes

1. DSEBRA field team (Germany and Austria): A. Schlömer, M. Terpoorten, J. Loos (LMU)
2. DSEBRA field team (Hungary; Installation with KRSO field team; Maintenance: KRSO field team): A. Schlömer, J. Loos, S. Keil (LMU); T. Czifra, B. Süle (KRSO Budapest)
3. KRSO field team (Hungary): T. Czifra, B. Süle; KRSO organization (Hungary): Z. Gráczner, I. Kovács, G. Szanyi, Z. Wéber
4. MOBNET field team (Czechia, Slovakia): J. Plomerová, P. Jedlička, J. Kotek, H. Kampfová Exnerová, L. Vecsey (IG CAS), K. Csicsay, M. Bognár (ESI SAS)
5. Uni Vienna field team (Austria, Slovakia): F. Fuchs, P. Kolínský, D. Schützenhofer, C. Esteve, G. Bokelmann, I. Bianchi, S. Schippkus, E. Grafendorfer, Y. Lu, Y. Aiman, R. Kramer, A. Novoselov, G. Hein
6. Polish field team: E. Gaczyński, W. Materkowska, S. Oryński, B. Owoc, J. Rewers, P. Środa, A. Tokarz, D. Wójcik (IG PAS); M. Mendecki, A. Braclawska, D. Nawrocki, P. Romański (Uni Silesia)

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## Declarations

**Conflict of interest** GH is Editor in Chief of the journal, and for this reason has fully withdrawn himself from the manuscript handling and reviewing process. The authors declare to have no other relevant financial or non-financial interests.

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