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A dense seismological profile through the Western Carpathians – new data for understanding Earth's structure, geodynamic evolution and seismicity

Tanishka Soni[1], Christian Schiffer[2], Stanisław Mazur[1], Mateusz Mikołajczak[1], Jozef Müller[3,4], Tomáš Potočný[5,6], Jakub Bazarnik[7], Andreas Hoffmann[3], Bálint Süle[8], Ulrich Wegler[3], Lucia Fojtíková[9], Jarosław Majka[2,5]

(1) Institute of Geological Sciences, Polish Academy of Sciences, Kraków, Poland
(2) Department of Earth Sciences, Uppsala University, Uppsala, Sweden
(3) Institute of Geosciences, Friedrich Schiller University Jena, Jena, Germany
(4) Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany
(5) Faculty of Geology, Geophysics and Environmental Protection, AGH University of Krakow, Kraków, Poland
(6) Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University Bratislava, Bratislava, Slovakia
(7) Polish Geological Institute – National Research Institute, Carpathian Branch, Kraków, Poland
(8) HUN-REN Institute of Earth Physics and Space Science, Kövesligethy Radó Seismological Observatory, Budapest, Hungary
(9) Earth Science Institute, Slovak Academy of Sciences, Bratislava, Slovakia

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Abstract

The tectonic evolution of the Western Carpathians remains a widely debated and polarizing topic. Serving as a crucial link between the Eastern Alps and the Eastern Carpathians, this segment of the orogenic belt formed through the closure of the Alpine Tethys Ocean and subsequent regional shortening. Despite over 150 years of geological investigation and well-documented surface geology, the deep structure of the Western Carpathians continues to be the subject of competing hypotheses. To address these uncertainties, a passive seismic experiment has been initiated across the Western Carpathians, funded by the National Science Centre (Poland) and conducted under the framework of the AdriaArray initiative. Seismic station deployment began in May 2023, with data acquisition planned to continue through 2026. The resulting dataset will benefit a wide range of research focused on local seismicity and the seismic imaging of the crust and upper mantle. The primary objective of the project is to perform Receiver Function analysis to image the lithospheric structure beneath the Western Carpathians. Techniques such as Common Conversion Point (CCP) stacking and Receiver Function inversion will be employed to derive key information about the crust-mantle boundary and lithospheric architecture along the profile. This contribution presents preliminary CCP stacks and a corresponding interpretation of Moho depth. Upon completion of the data collection, further Receiver Function analyses using the full dataset will be carried out, alongside potential field studies. Combined with existing geological data these results aim to inform the development of a comprehensive model for the tectonic evolution of the Western Carpathians.

Keywords: Passive Seismic Experiment; Western Carpathians; Tectonics; Receiver Functions

1. Introduction

Large scale passive seismic experiments can be instrumental in understanding regional geodynamics (Burdick et al., 2014; Hetényi et al., 2018; Schmandt and Humphreys, 2010). The AdriaArray is a multi-national initiative to study the fate and dynamics of the Adriatic plate, and the regions it affects (Kolínský et al., 2025). The AdriaArray consists of a large backbone network, as well as several local experiments, totaling more than 435 temporary broadband stations (periods >30 s). One of the local experiments, which is presented in this contribution, forms a dense profile (station spacing of ~10-15 km) of 18 stations from southern Poland (7 stations), across Slovakia (9 stations) and into northern Hungary (2 stations) crossing the Western Carpathians (Fig. 1, part of network Z6, Schlömer et al., 2022) and complementing 9 already existing permanent and temporary stations along this transect in order to decipher the complex Western Carpathian structure and tectonic history using seismological methods with unprecedented station coverage.

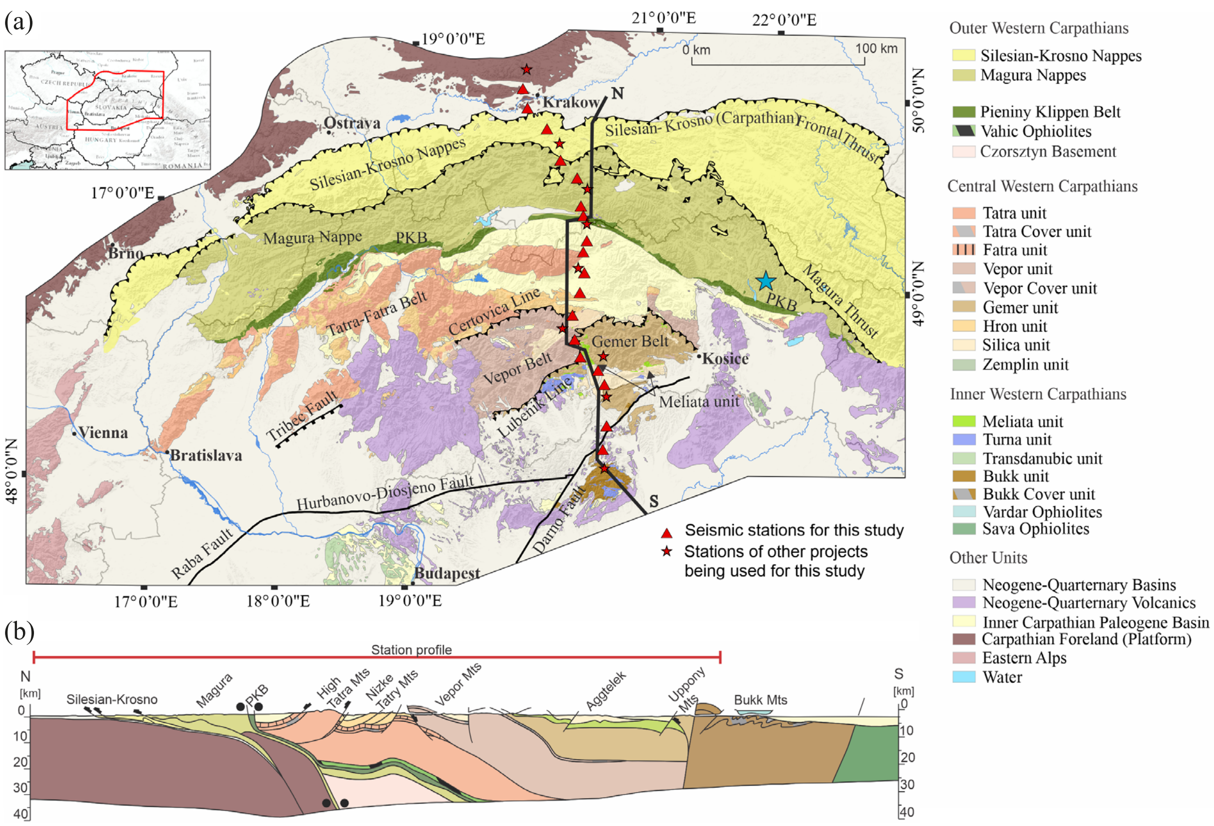

Figure 1. (a) Geological Map of the study area compiled using the data from www.geology.sk. Blue Star marks the 2023-10-09 M5.0 East Slovakia earthquake. (b) Cross-section along the solid black line in subplot (a), based on Schmid et al., 2008.

The Western Carpathians (Fig. 1) are part of the larger Alpine-Himalayan Orogen and have formed due to the collision of the African plate with the European plate. The Neo-Tethys and Alpine-Tethys Oceans that opened between Eurasia and Africa closed subsequently due to later convergence of the two plates, determining the tectonic history of the region (Handy et al., 2015; Plašienka et al., 1997; Schmid et al., 2008, 2020; Ustaszewski et al., 2008). The closure of Alpine-Tethys is thought to be represented in one of the sutures in the Western Carpathians and has a controversial geodynamic history (Golonka et al., 2015, 2019; Marzec et al., 2020; Nemčok, 1980; Oszczypko, 2004; Plašienka et al., 1997, 2012). However, the suture, represented by the Pieniny Klippen Belt (PKB) on the surface, does not reveal the typical characteristics of a suture (Plašienka et al., 1997, 2012). The geology of the frontal fold and thrust belt of the Western Carpathians along with the PKB has been variously interpreted (Oszczypko, 2004; Plašienka et al., 1997). These models propose a number of Briançonnais-like islands in the Alpine-Tethys branch of the Western Carpathians, dividing it into at least two oceanic basins: Magura to the north and Vahic to the south of these hypothesized islands or ridges. This so called Czorsztyn ridge, like other proposed ridges in the region, such as the Silesian ridge, are supposed to have been subducted and remain entrained somewhere beneath the upper plate (Birkenmajer, 1986; Mišík, 1994; Plašienka, 2018; Schmid et al., 2008, 2020) (Fig. 1).

This project will image the sub-surface beneath the north-south profile of the Western Carpathians in order to understand the lithospheric structure and get new perspectives on the existence of the Czorsztyn ridge using Receiver Functions (RFs). These will then be interpreted with the best knowledge of the geology of the Western Carpathians, adjoining regions and regions with similar geodynamic history (for example the Eastern Alps). With the help of this analysis, after the completion of the experiment, a new evolutionary model will be proposed. Therefore, this experiment will contribute to the understanding of the Western Carpathians from a new perspective. Furthermore, the project provides a rich seismological dataset to serve as a valuable resource for many other analyses in the region, as it will be open to the entire community, after a two-year running embargo, during which the data is accessible to the AdriaArray consortium only.

2. Geological Formation

The Western Carpathians stretch across Poland, Slovakia and parts of Czechia, Hungary and Austria (Fig. 1). The formation of the Western Carpathians is closely linked to the closure of the Tethys Ocean and the subsequent collision of the European continent with small continental fragments and volcanic islands as early arrivals of the approaching Adriatic plate. The Carpathians began to form as the Tethys Ocean started to close during the Late Jurassic. The subduction of oceanic crust led to the accretion of sedimentary rocks, which later became incorporated into the Carpathians (Handy et al., 2015; Plašienka et al., 1997; Schmid et al., 2008, 2020; Ustaszewski et al., 2008). The Carpathians are part of the Alps-Carpathian-Pannonian (AlCaPa) unit derived from the Adriatic plate.

During the Late Cretaceous, the intense compressional forces in the Western Carpathians, leading to the development of faults and the stacking of nappes, caused significant shortening and thickening of the crust (Plašienka, 2018; Schmid et al., 2008). During the Paleogene and early Neogene, further shortening resulted in the formation of the mountain belt as a result of AlCaPa being thrust over the European plate (Oszczypko, 2004; Plašienka et al., 1997). The tectonic regime of the now distinct geological unit of the Western Carpathians shifted again during the Middle to Late Miocene, when the subducting European plate beneath the Carpathians began to roll back. This caused extension and volcanism within the advancing upper plate of the orogen leading to the formation of some of the other units mentioned in Fig. 1 (Handy et al., 2015; Plašienka et al., 1997; Schmid et al., 2008, 2020).

The Western Carpathians are geologically complex, comprising several distinct units, and can be divided into three parts: Outer Western Carpathians (OWC), Central Western Carpathians (CWC) and Inner Western Carpathians (IWC) (Plašienka et al., 1997). The boundaries between these parts are marked by two sutures: the Meliata suture zone and the PKB (Plašienka et al., 1997) (Fig. 1). The OWC comprise a fold and thrust belt, involving mostly Cretaceous to Paleogene sedimentary rocks. The Silesian-Krosno nappes (Fig. 1) represent remnants of the European passive margin succession, that have been folded and thrust over the North European Platform (Plašienka et al., 1997; Schmid et al., 2008), while the Magura nappe may represent the fill of an oceanic basin (Magura Ocean). Moving south, the Carpathians include the CWC and IWC, which consist of older, crystalline basement formed during the late Paleozoic Variscan orogeny, and associated mostly Mesozoic sedimentary cover (Hók et al., 2019; Plašienka, 2018; Plašienka et al., 1997; Schmid et al., 2008). The CWC include Tatra, Vepor and Gemer basement nappes together with the Fatric, Hronic and Silicic cover nappes, while the Transdanubian, Bükk and Zemplin units constitute the IWC (Hók et al., 2019; Plašienka et al., 1997) (Fig. 1).

The Meliata zone and the PKB (Fig. 1), are the Neo-Tethys and the Alpine-Tethys sutures, respectively (Oszczypko, 2004; Plašienka et al., 1997, 2012). The Meliata suture, represented by the rocks of Meliata unit (Fig. 1), is older and comprises typical components like an ophiolite suite, accretionary wedge and low-temperature high-pressure metamorphic rocks (Hók et al., 2019; Plašienka et al., 1997). The PKB suture is distinct in its composition, consisting rocks of mainly shallow marine facies and minor slope and deep-sea facies (Hók et al., 2019; Plašienka et al., 1997; Schmidt et al., 2008). These sediments are believed to be deposited on a continental sliver known as the Czorsztyn Ridge that divided the Alpine-Tethys Ocean into two smaller oceanic basins, the northern Magura and southern Vahic oceans (Birkenmajer, 1986; Mišík, 1994; Plašienka et al., 1997). The ridge is now thought to be deeply buried beneath the crust of the CWC along with the Vahic oceanic crust (Plašienka et al., 1997; Schmid et al., 2008, 2020) (Fig. 1).

3. Project Description

3.1 Polish Research Council Project

The Carpathian project "Closure of the Alpine Tethys Ocean recorded in the Pieniny Klippen Belt of the Western Carpathians" was awarded to Jarosław Majka by the Polish National Science Centre (no. 2021/43/B/ST10/02312). The AGH University of Krakow is the leader of the consortium, in which the Institute of Geological Sciences of the Polish Academy of Sciences also participates. International collaborators are: (1) the Department of Earth Sciences, Uppsala University; (2) Institute of Geosciences, Friedrich Schiller University Jena; (3) Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University Bratislava; (4) HUN-REN Institute of Earth Physics and Space Science; (5) Earth Science Institute, Slovak Academy of Sciences and (6) Swedish Natural History Museum. The project roadmap includes six interconnected tasks that should resolve the main research questions addressed in this study. These tasks are: (1) a passive seismic experiment; (2) a potential field study; (3) a provenance study; (4) geochronology and characterization of high-pressure minerals and rocks; (5) documentation and dating of deformation within the Tatric unit and (6) data integration and tectonic model development. Although the extensive knowledge of PKB is based on over a century of research and detailed mapping and structural studies, current interpretations lack modern geochronological and geophysical data. Our project will build upon the above mentioned detailed regional knowledge and serve the community with an extensive, state-of-the-art geochronological and geophysical database. Therefore, the main results of this project should: (1) contribute to a better understanding of the deep structure of the Carpathians; (2) provide geochronological data on the age of subduction and closure of the Alpine Tethys and the origin of the Western Carpathian sedimentary successions; (3) present a new evolutionary model for the closure of the Alpine Tethys in the Carpathian region, with consequences for other related mountain belts; (4) establish new constraints on solving the problem of the origin of PKB; and (5) create the foundations for an important change in the understanding of the Western Carpathians.

The project includes a N-S oriented passive seismological profile through the Western Carpathians, reaching from the Carpathian foreland near Kraków into the northern limit of the Pannonian basin in order to cover the full extent of the Western Carpathians at this location. We assembled equipment for 18 seismic stations, which, together with permanent stations of the Polish (PL) and Slovak National Seismic Networks (SK), as well as temporary stations of the PACASE project (Schlömer et al., 2024), form a dense seismological profile comprising 27 stations with ~10-15 km station spacing (Fig. 1).

3.2 Development of collaborations

The project was initially designed to run as an independent, stand-alone project and different potential sources for lending seismological equipment were assessed. Various project participants were already connected to AdriaArray, as well as collaborating with the Friedrich Schiller University Jena, and the fact that the project falls in the general scope and sphere of AdriaArray, a collaboration between the three partners was established. This collaboration is building on obvious synergies, such as sharing of data, equipment and logistics. The Friedrich Schiller University Jena supports this project with equipment for 6 seismic stations, logistics, technical support and staff. The equipment for the remaining 12 stations was lent from the Geophysical Instrument Pool Potsdam (GIPP) at GFZ Potsdam through a larger lending agreement of a total of 25 stations for various AdriaArray sub-projects through the AdriaArray leadership. The group then contacted the local seismological networks in Slovakia (Slovak Academy of Sciences) and Hungary (HUN-REN Institute of Earth Physics and Space Science) for collaboration and logistical support. Data from the Western Carpathian stations have already been included in the routine seismic service of the Earth Sciences Institute of the Slovak Academy of Sciences.

3.3 Equipment – access, training and preparation

The 12 seismic units provided by GIPP, each consisting of sensors, digitizers/data loggers, modems, transport and storage boxes, as well as the required cables, were prepared by GIPP-staff, who also organized a training day, in which 5 project members participated. The training day involved a presentation providing information about the instruments and fieldwork, followed by some hands-on training to install, configure and run the seismometers, digitizers and routers. After the training, the 12 instruments were taken to Kraków. The sensors are Nanometrics Trillium Compact 120s, connected to Earth Data EDR-210 digitizers and Teltonika RUT 955 routers. Cables, two mobile network antennas, one GPS antenna, charger and various fuses and circuits were part of the GIPP setup. SIM cards and batteries were organized in Uppsala and Kraków, respectively, after which the stations were assembled and tested in Kraków. The firmware of the router and digitizer can be accessed via a LAN cable connected to the router. The firmware was configured to send data online to the Applied Geophysics group at the Friedrich Schiller University Jena. The box containing the station houses the digitizer, router and the battery, while antennas and sensor are located outside the box. All instruments were run for a day in the lab to monitor data transfer and detect any problems that might emerge during continuous operation. This reduced the possibility of unforeseen issues in the station while in the field and also increased the speed at which the deployment took place later. All SSD disks were checked and emptied in case required.

The six units provided by the Friedrich Schiller University Jena included the same Trillium Compact 120s sensors with the flat response from 120s to 100 Hz, Nanometrics Centaur digitizers/data loggers, and Teltonika RUT 955 routers. Parameter configuration of all six units was identical.

All units were set up to record at 100 samples per second.

3.4 Site Scouting

Scouting for suitable deployment sites was performed by three teams, one for each country of deployment: Poland, Slovakia and Hungary. For obvious reasons, such as language, different customs and policies, local team members organized scouting in their respective countries. The teams were briefed in terms of number and ideal location of the stations in each respective country. For obvious reasons, the following guidelines were used to identify potential station locations: (i) to place stations as close as possible to the ideal locations along a straight profile with equal distancing, (ii) to avoid noise sources; primarily roads, industries and crowded areas, (iii) to ensure a safe and secure place with a stable power supply, and (iv) to place stations in locations with sufficient mobile network and GPS reception. These requirements usually resulted in municipal/ community buildings, schools or graveyards in small villages. However, sometimes compromises had to be made. The final sites selected based on these attributes are listed in Table 1.

3.4.1 Poland

Following the requirements listed above, the optimal locations in Poland were six village-level primary schools, and one private residential building (Table 1). The seismometers are located in basements, below ground level on a more consolidated base (usually on a concrete foundation), maximizing the station coupling to consolidated bedrock and reducing noise.

The disadvantage of deploying seismometers in schools is the regular noise during the school's opening hours. However, the stations were usually placed in quiet areas or abandoned rooms of the schools. Additionally, schools are usually empty during holidays and weekends, which gives about 180 ‘quiet’ days a year. Some schools are very small and sometimes partially abandoned.

Before the installation of the seismic stations, preliminary talks were held with the school authorities, consisting of a presentation of the equipment and the research program. Moreover, the good reception and willingness to help by the management of the participating schools is worth mentioning.

3.4.2 Slovakia

The majority of the 18 installed stations are located in Slovakia, encompassing nine stations distributed between the Polish border in the north and the Hungarian border in the south. The locations of the stations include the basements of primary schools, currently unoccupied buildings of the municipalities, funeral homes, a small fire station and the research facility of the Slovak Hydrometeorological Institute, typically in small villages with very little activity.

The placement of the seismometers within the various buildings has been subjected to rigorous examination, with consideration given to the requirements listed above.

Following the selection of the most appropriate villages that fulfill the geographical requirements, the mayors were contacted and asked for collaboration and the placement of a seismometer on the property of the municipality. Following a favorable response, a request was made to explore potential installation sites, describing our needs and requirements.

Following the identification of potential sites, each of these were visited and inspected. The sites were finally chosen in nine municipalities in Slovakia, after evaluating a number of options and based on our preliminary inspection visit.

3.4.3 Hungary

The two southernmost stations of the profile were installed in Hungary. They are located between a pair of stations deployed in 2019 in the frame of the PACASE project (Schlömer et al., 2024). The scouting started by searching potential sites on the map around the preliminary location points. In general, the geological conditions in Hungary are not ideal for installing seismological stations, since a large part of the country is covered by thick sediments. However, the hilly northernmost region of Hungary, where the stations were installed, has slightly better conditions than most of the remaining areas. Although hard rock cannot be found at the surface, the sediments are locally thin, and the seismic noise level is expected to be sufficiently low at a reasonable distance from human noise sources.

We contacted the municipalities of three villages in the vicinity of the preliminary points. With the help of the municipalities, we identified possible sites (unused or rarely used buildings, cellars, etc.) on the outskirts of the settlements, far from roads with heavy traffic, as well as considering the other usual requirements and factors listed above.

After careful consideration, funeral homes were chosen for both stations. The graveyards are located at the edge of the settlements, at 100-200 m distance from residential houses. Human activity producing higher seismic noise rarely occurs nearby. Sensors were placed on concrete and tiled floors.

3.5 Network Deployment

The network was installed in May 2023 after the stations were prepared and the locations identified. The field base was located close to the city of Poprad, in Slovakia, approximately in the centre of the profile. The equipment was moved to the field base from Kraków and Jena, respectively. From the field base, the equipment was distributed during daily campaigns in two teams of three to four members. All stations were installed within one week. This efficiency was achieved due to extensive site scouting, as well as preparation and thorough testing of the equipment prior to installation.

At each location, the sensor was aligned to the north as measured using a Quadrans fiber-optic gyrocompass that was provided by the Czech Academy of Sciences. The station was then assembled, by connecting sensor, digitizer/data logger, antennas, GPS receiver and the electricity supply. The antennas and the GPS receiver were positioned to have the best signal possible and to still be protected from the weather. Then, the digitizer and router were checked for the state of health, mobile network, GPS signal and data from the sensor. Throughout the fieldwork, one of the team members located in Jena continuously checked and monitored the online data flow of the newly installed stations. A warning sign with the contact information of relevant team members in the local language and English was applied to the main box that housed most of the equipment. An example of the station design and the equipment used is shown in Fig. 2. The procedure, location and installation were documented in an online spread-sheet and photos were taken. Every evening during the field work, the online data stream was checked for any problems or visible signs of extreme noise. In some cases, the stations stopped working after a few hours and therefore required revisits during the fieldwork. In most cases of any observed problems, these could be easily solved, e.g., by restarting of the equipment, or replacing of antennas. For example, at one location in Poland, there was a problem with the power supply, which was fixed during the field campaign. In other cases, the placement of the antennas had to be changed. In another case, the fuses of the host building blew, which required a rewiring of the station to a different power outlet. It was important to solve these simple problems during the fieldwork in order to ensure a steady data flow and minimize problems with data flow and long driving hours at later stages.

Still, some stations showed persistent problems in the first months after deployment. These stations either stopped working entirely or had poor internet connection. In a few cases, this was due to malfunction of the equipment. These stations were visited and fixed until, after a few months, all stations were stable and recorded continuously.

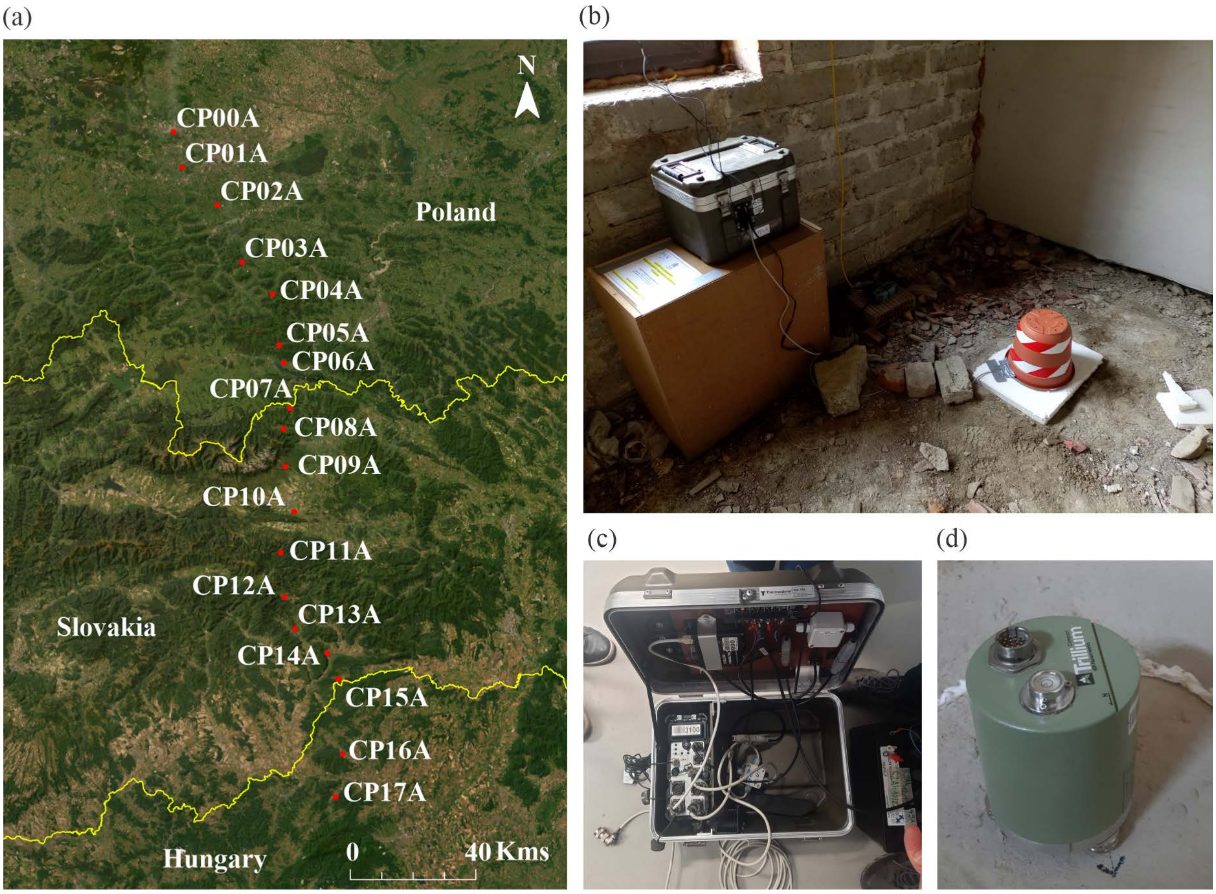

Figure 2. (a) Locations of the stations deployed in the passive seismic experiment. (b) Photo of a station after deployment. The sensor is under the red pot lying on concrete, built to ensure a solid base. (c) Major parts of the station: digitizer (in this case an EDR-210), router and battery. (d) Sensor oriented to the north marked on the floor.

3.6 Data Acquisition, maintenance and quality

The recorded data is stored on local SSD or SD cards and also transmitted in real time via the mobile phone network. The data transmission is done via VPN network of the provider 'wherever SIM' to a dedicated SeisComP system in Jena. This system is based on SeisComP version 5.3.0 and runs on a Fujitsu PC with Ubuntu Linux 22.04 operating system. The data received is stored in an SDS structure and is finally transferred to an external seedlink server where it is further transferred to the EIDA node hosted by the Ludwig Maximilian University of Munich. The data is stored there as a part of the Z6 network (Schlömer et al., 2022). Via the Ubuntu Linux system, we can also remotely access the web interface of the Teltonika routers and the digitizers to check the state-of-health and to solve problems remotely. Via the router, the stations equipped with EDR-210 digitizers can be remotely power cycled. This is not possible at the stations equipped with the Centaur digitizer.

Physical maintenance of the stations is done regularly once a year or as required. During visits, the local data copies on SD/SSD cards are copied and emptied. During the course of the experiment, some of the stations showed problems of various nature. If the problems could not be solved remotely, the stations were visited by a team member, as soon as possible. In some cases, the problems persisted and required multiple visits. Several stations were affected by local weather conditions, such as storms, lightning and flooding, like in summer of 2023 in the village Silica (CP15A) and the village Koceľovce (CP13A). This led to malfunctioning equipment, due to flooded basements or overvoltage. In this case, the faulty parts were replaced and the station was moved to another location in a neighboring building.

The station availability between 1 June 2023 and 26 November 2024 is listed in Table 1 and also shown in Fig. 3. The best working stations have worked throughout the entire acquisition period with a data recovery of 100%. The station with the most problems has only recorded 72.88% of the installation period, although such gaps may still be filled later with the locally stored data. The average data availability has been 94.01 %.

Table 1. Basic information about each station deployed in this project.

Station name	Network	Location	Latitude	Longitude	Description of installation	Digitiser	Sensor	HHZ data availibility (%)
CP00A	Z6	Zabierzów, PL	50.1167	19.7699	Basement of private house	EarthData EDR-210 Recorder	Trillium compact	82.06
CP01A	Z6	Tyniec, PL	50.0162	19.8105	Basement of public school	EarthData EDR-210 Recorder	Trillium compact	95.83
CP02A	Z6	Siepraw, PL	49.9093	19.9698	Basement of public school	EarthData EDR-210 Recorder	Trillium compact	100.00
CP03A	Z6	Węglówka, PL	49.7469	20.0818	Basement of public school	EarthData EDR-210 Recorder	Trillium compact	91.90
CP04A	Z6	Półrzeczki, PL	49.6558	20.2179	Basement of public school	EarthData EDR-210 Recorder	Trillium compact	72.88
CP05A	Z6	Ochotnica Górna, PL	49.5126	20.2481	Basement of public school	EarthData EDR-210 Recorder	Trillium compact	80.34
CP06A	Z6	Maniowy, PL	49.4611	20.2689	Basement of public school	EarthData EDR-210 Recorder	Trillium compact	95.35
CP07A	Z6	Veľká Franková, SK	49.3358	20.297	Basement of public school	EarthData EDR-210 Recorder	Trillium compact	100.00
CP08A	Z6	Ždiar, SK	49.2716	20.2717	Basement of a municipal building	Nanometrics Centaur digitizers	Trillium compact	98.42
CP09A	Z6	Tatranská Lomnica, SK	49.1637	20.2821	Basement of public school	EarthData EDR-210 Recorder	Trillium compact	99.42

Station name	Network	Location	Latitude	Longitude	Description of installation	Digitiser	Sensor	HHZ data availibility (%)
CP10A	Z6	Gánovce, SK	49.0345	20.322	Basement of Slovakian Hydrometeorological Institute	Nanometrics Centaur digitizers	Trillium compact	100.00
CP11A	Z6	Vernár, SK	48.9167	20.2652	Abandoned School	EarthData EDR-210 Recorder	Trillium compact	100.00
CP12A	Z6	Rejdová, SK	48.7901	20.2836	Basement of a Hostel	Nanometrics Centaur digitizers	Trillium compact	99.95
CP13A	Z6	Koceľovce, SK	48.7117	20.3406	Chapel on graveyard	EarthData EDR-210 Recorder	Trillium compact	86.19
CP14A	Z6	Kružná, SK	48.6363	20.4674	Chapel on graveyard	EarthData EDR-210 Recorder	Trillium compact	99.87
CP15A	Z6	Silica, SK	48.5567	20.5208	Fire Station	Nanometrics Centaur digitizers	Trillium compact	97.15
CP16A	Z6	Dövény, HU	48.3421	20.5399	Chapel on graveyard	Nanometrics Centaur digitizers	Trillium compact	97.29
CP17A	Z6	Bánhorváti, HU	48.2191	20.511	Chapel on graveyard	Nanometrics Centaur digitizers	Trillium compact	95.58

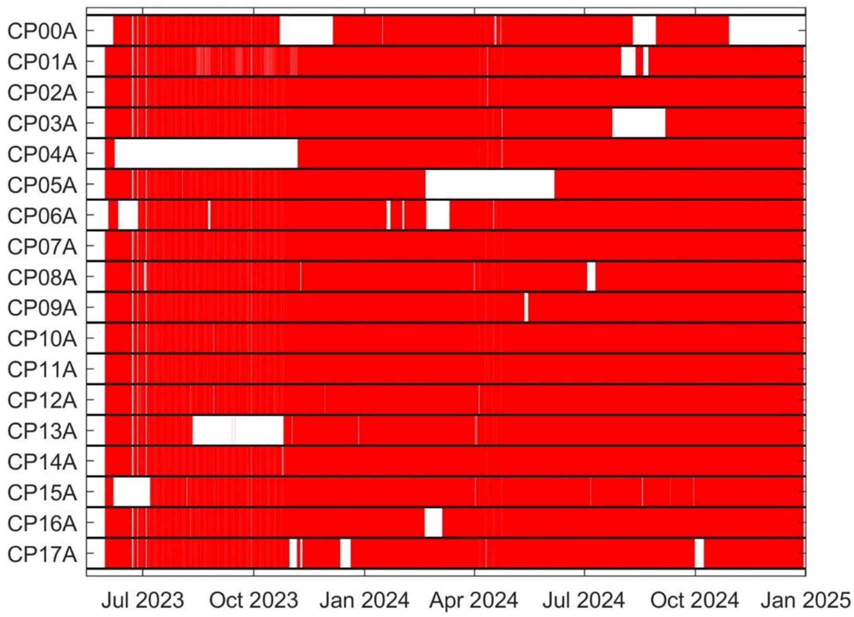

Figure 3. Plot showing data availability for the Western Carpathian network on the EIDA node LMU Munich from 1st of May, 2023 to 30th of December, 2024. Red areas show available data, white areas show data gaps.

3.6.1 Data examples

A relatively major earthquake of M5.0 hit eastern Slovakia on 2023-10-9. The epicenter was in north-east Slovakia as shown in Fig. 1. The intensity reached 8 on the EMS –98 scale in the epicenter. The signal was recorded by all stations from this experiment, except for stations CP04A and CP13A, which were not operational at that time (Fig. 4), and data were used to refine location and focal mechanism. The data for this local event shows clear P-arrivals at all recording stations, with clear site-specific variation in the waveforms. Visually, the noise level appears to be larger at the two northernmost stations (CP00A, CP01A), which is expected due to the location of the stations in the suburbs of Kraków. A smaller earthquake of M3.0 hit eastern Slovakia on 2024-22-2 only ~10 km away from the previous M5.0 event. Fifteen out of 18 stations from this experiment were operational at the time of the event (Fig. 5). However, the three northernmost stations (CP00A, CP01A and CP02A) clearly illustrate the higher noise levels at these sites, as no clear arrivals can be identified. Several relatively large teleseismic earthquakes were also recorded by the stations. An example is shown in Figs. 6 and 7, a M7.0 earthquake in Uqturpan, western China which occurred on 2024-01-22 and was recorded by all the stations in this experiment. The waveforms, especially those of the body waves, are generally very similar at all stations, which is to be expected, as we are using sensors of the same type. The surface waves seem to be more affected by local and path effects, as clear differences are seen between stations in the north, center and south of the profile. Also, for this example, the noise level is higher for the two northernmost stations (CP00A, CP01A) compared to the rest of the stations.

3.6.2 Noise performance

We performed noise analysis by means of Probabilistic Power Spectral Densities (PPSD) using data from the year 2024 of a selected set of stations (CP01A, CP04A, CP10A, CP15A and CP17A) (Fig. 8), which provide a good representation of the various environments and expected noise levels. CP01A is located in Tyniec near Kraków, in a school close to the village centre and is expected to be one of the noisiest stations of this network. CP04A is located in an abandoned room of a very small pre-school in the small village of Półrzeczki, the noise levels of which we expect to be among the smallest. CP10A is an interesting case as it was installed in a deep basement with a thick concrete foundation of the Slovak Hydrometeorological Institute. It appeared that the location had been previously used for seismic recording equipment. We expect excellent coupling at this location; however, the place is an active workplace with other scientific instrumentation and machinery, which may show an effect. CP15A was installed in the small village of Silica, which is located close to the Hungarian border, on a plateau and at the end of a road. The seismometer is installed in an infrequently used room of the local fire brigade, and we expect low noise levels. CP17A is located in the funeral home of the Bánhorváti graveyard, which is at quite some distance from the small village. Although noise from roads and the village should be low, the graveyard does receive visitors and hosts ceremonies. Furthermore, the funeral home is not heated, which may cause thermal fluctuation over the course of a year.

After analysing the PPSD plots (Fig. 8), CP01A appears to be the noisiest station of the selection, as expected. CP10A and CP17A show intermediate noise levels at periods <1 sec. CP04A and CP15A show similar low noise levels throughout the spectrum.

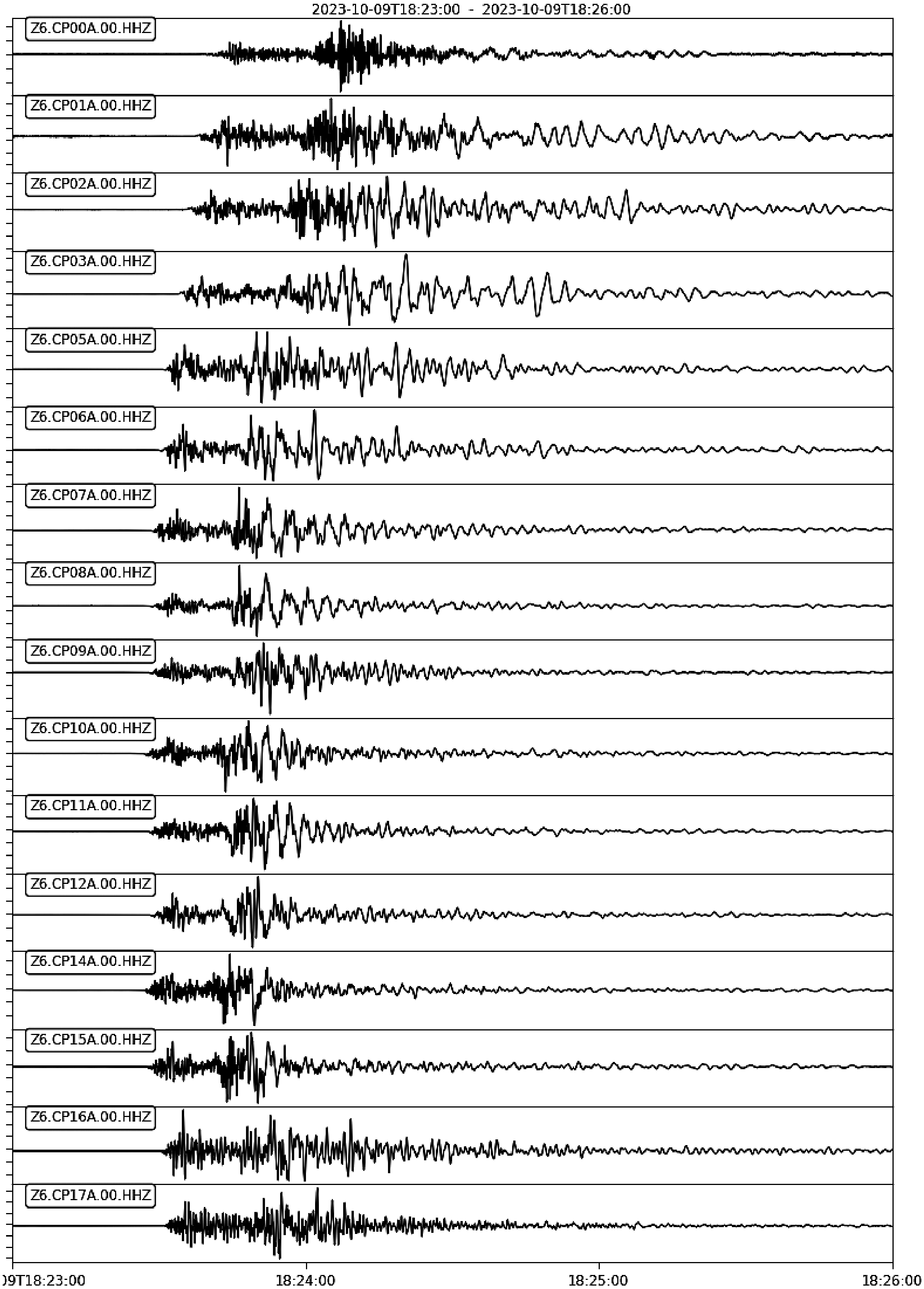

Figure 4. Recording of the 2023-10-9 M5.0 East Slovakia earthquake at 16 of the 18 Western Carpathian stations (CP04A and CP13A were not recording at the time of the event). No frequency filter was applied.

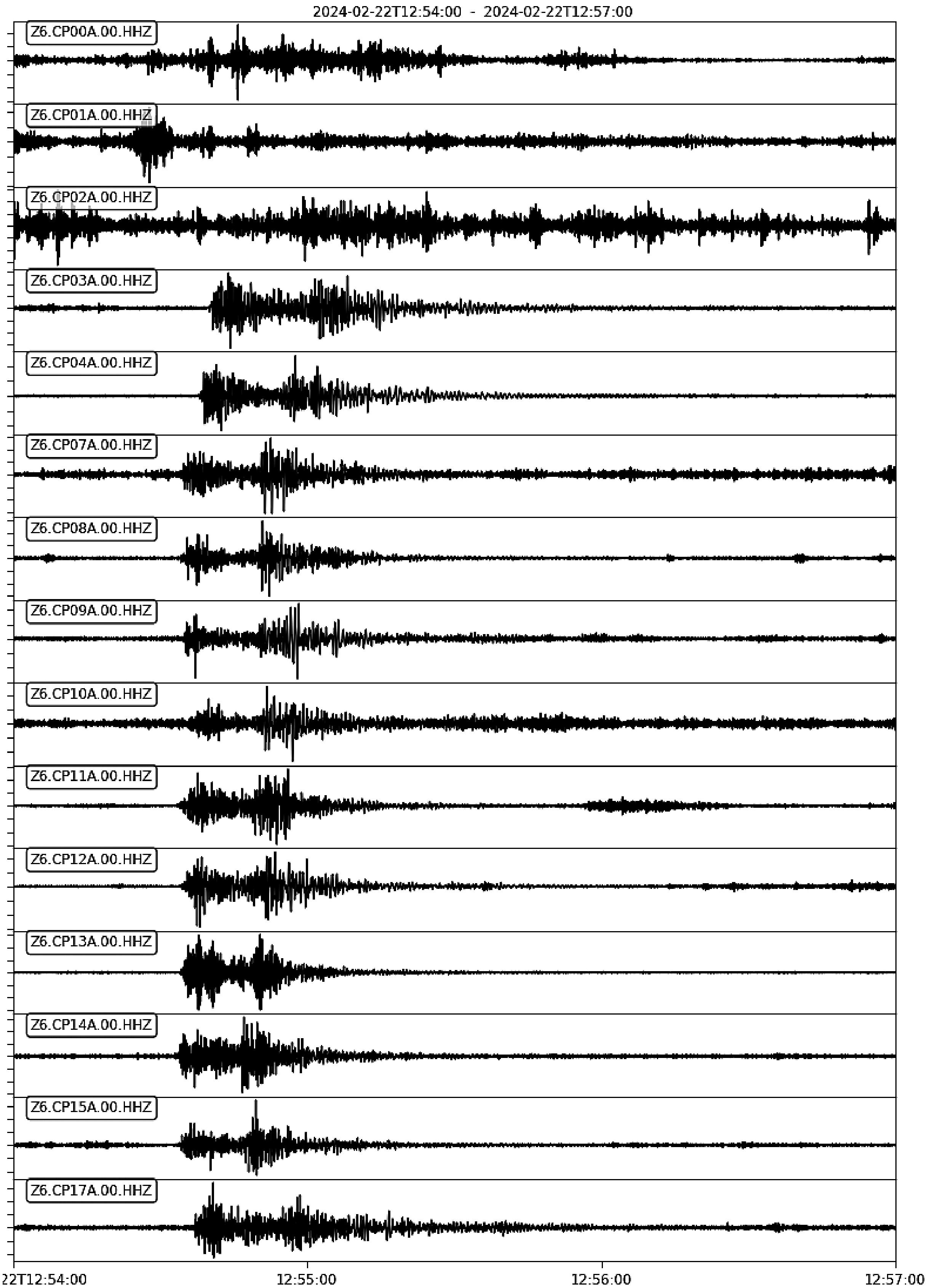

Figure 5. Recording of the 2024-02-22 M3.0 East Slovakia earthquake at 15 of the 18 Western Carpathian stations (CP05A, CP06A and CP16A were not recording at the time of the event). The data were filtered between 1 and 10 Hz.

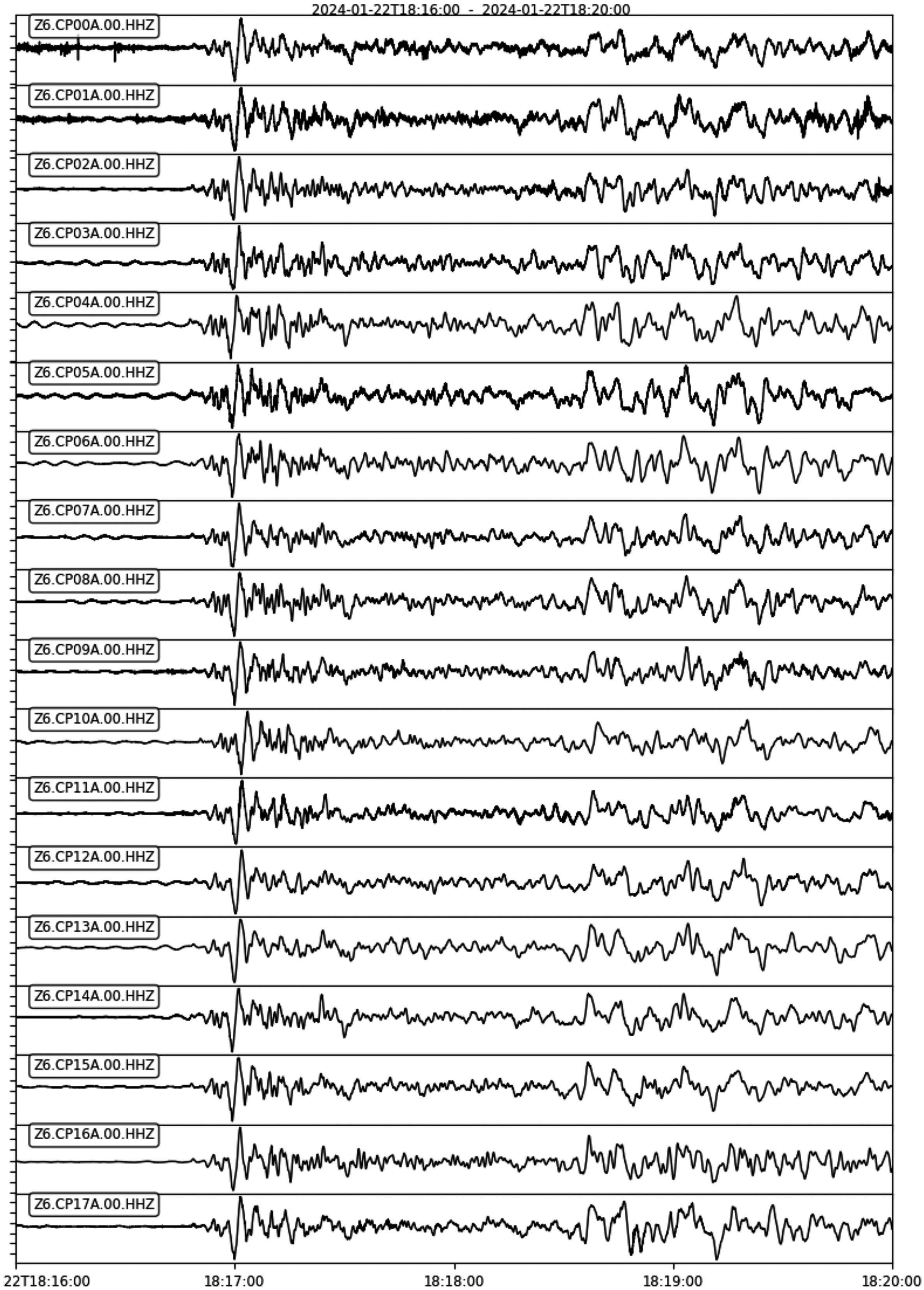

Figure 6. Recording of the first approx. 3 minutes of the 2024-01-22 M7.0 Uqturpan earthquake (western China) at all 18 Western Carpathian stations. No frequency filter was applied.

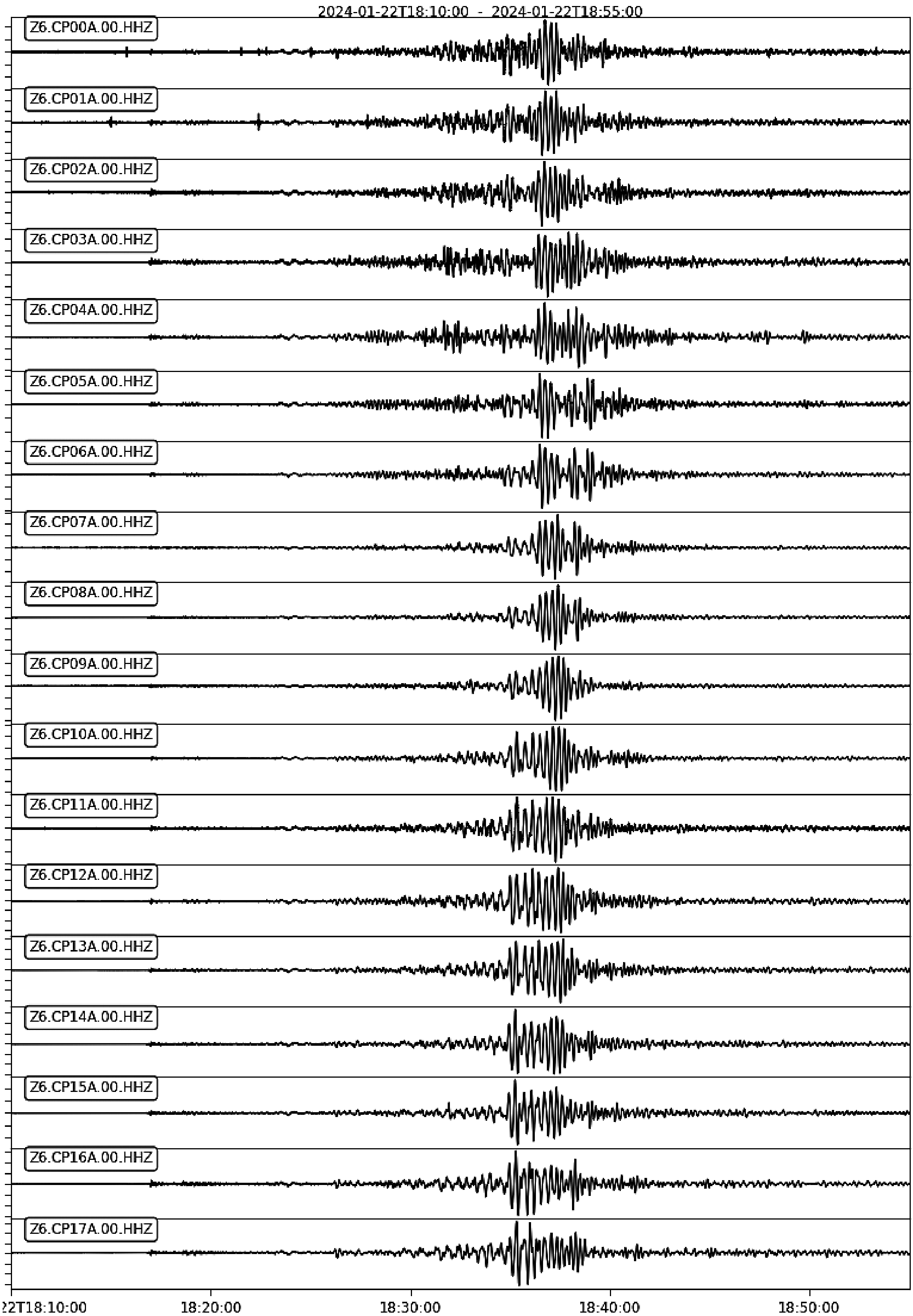

Figure 7. Recording of approx. 40 min from P-wave arrival of the 2024-01-22 M7.0 Uqturpan earthquake (western China) at all 18 Western Carpathian stations. No frequency filter was applied.

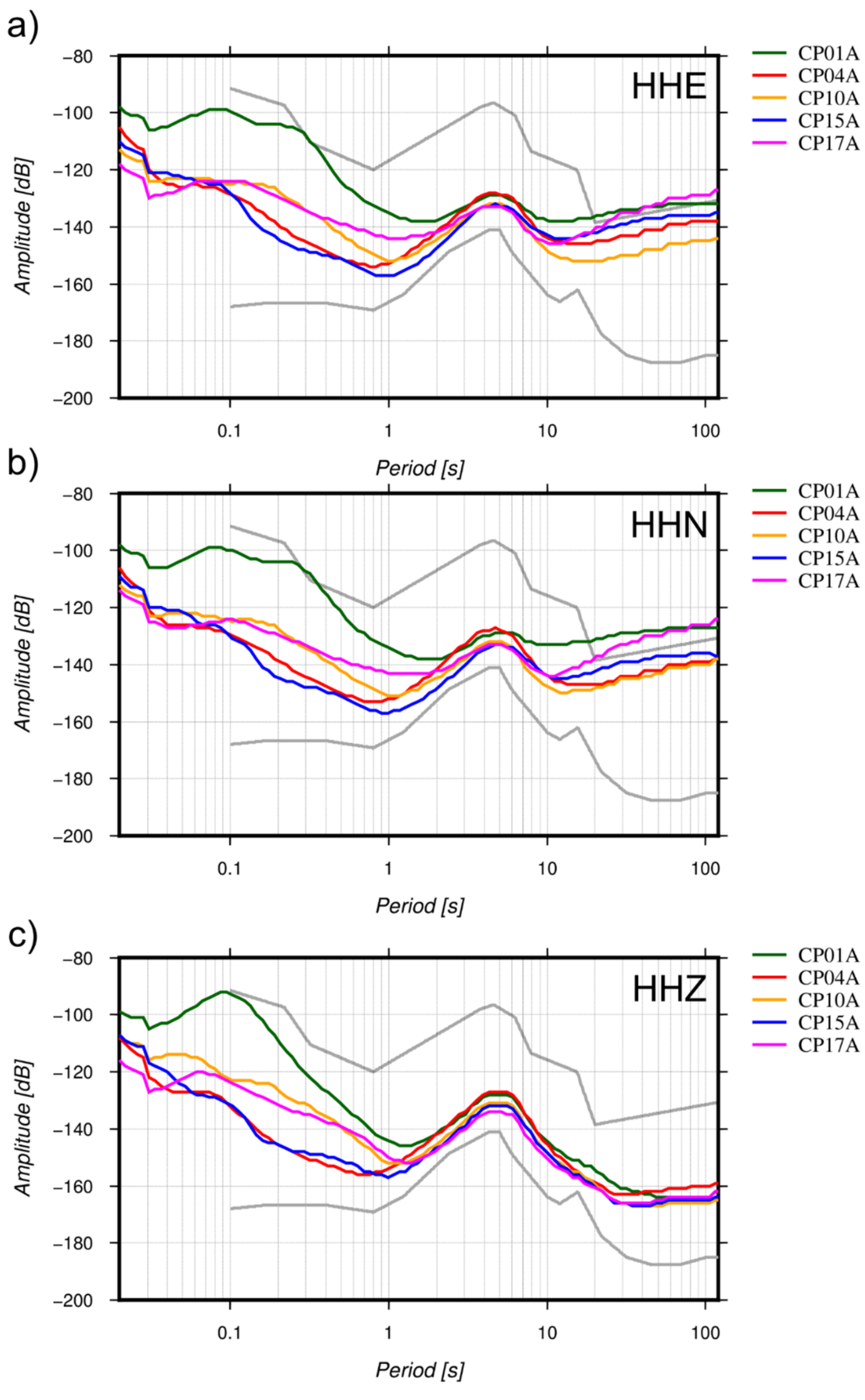

Figure 8. Examples of median curves the Probabilistic Power Spectral Densities (PPSD) using the HHE (a), HHN (b) and HHZ (c) components of the temporary stations CP01A, CP04A, CP10A, CP15A and CP17A from data of year 2024. The full PPSD plots are listed in supplementary material S1. Station CP01A appears to be the noisiest station of the selection, which can be explained by the fact that it is located at one of the largest schools along the profile. CP10A and CP17A show intermediate noise levels at periods <1 sec. CP10A is located in the Slovak Hydrometerological Research Centre in Gánovce, which is quite remote, in a deep basement, but after all, an active working place. CP17A is located on a quite remote graveyard, however, probably on a substantially thick sedimentary package, possibly explaining the slightly elevated noise levels. CP04A and CP15A show similarly low noise levels throughout the spectrum. Both stations are located in very small, remote villages in locations rarely accessed and used.

4. Preliminary Receiver Function processing

One of the main methods to be used in the project is the Receiver Functions (RF) method to image the lithospheric structure in the Western Carpathians. RF imaging is used in this paper mainly as a measure of data quality for RF processing, but also for other teleseismic applications. The RFs were computed from teleseismic waveforms of the 18 stations isolating conversions of the incident P- to S-waves at velocity discontinuities, such as the Moho (Ammon, 1991). This was done by filtering the waveforms between 0.25 and 16 Hz and rotating the vertical, north and east teleseismic components with regard to back azimuth of the arriving P-wave, creating the radial and transverse components (Vinnik, 1977). Waterlevel deconvolution (Ammon, 1991) with waterlevels between 0.01 and 0.1 (depending on noise levels) removed the incoming P-waveform from the converted S-waveform, focusing each conversion as isolated impulses at the specific delay time after the incident waveform. For each station, initially three-component waveform data of ~300-500 events were extracted via GEOFON WebDC3 spanning the time period between June 2023 and June 2024, with epicentral distances from 30° to 95° and magnitudes >5.0. The number of extracted events depended on the recording time of the individual station. This waveform data was used to calculate receiver functions. A semi-automatic selection procedure was applied to the receiver functions. The criteria include parameters such as noise amplitudes (time before –2 sec), the presence of too large amplitudes, as well as large-amplitude low frequency signals, the amplitude at P-wave arrival (time at 0 sec) and the shape of the z-component of the RF. These parameters were adjusted manually to select 50-130 events per station for further analysis with an average of ~90.

Finally, a Common Conversion Point (CCP) migration was applied using 3D raytracing, projecting each RF waveform in time along its teleseismic ray path to the corresponding conversion position (e.g. Schiffer et al., 2021) using a 2.5D velocity model of the region, meaning that a 2D model was expanded to 3D. The 2D crustal Vp model (supplementary material S2) for the ray tracing was derived from a roughly coincident wide-angle seismic profile (Środa et al., 2006) resampled at 20 km laterally and 2.5 km in depth. The Vs was then derived from Vp/Vs ratios taken from Christensen, 1996 for specific lithologies. The density is calculated from Vp depth relationship based on Christensen and Mooney, 1995. We produced CCP images (Fig. 9) of conversions of primary and multiple arrivals, in which the RF amplitudes are distributed over a Gaussian distribution with the corresponding conversion point at its center. The width of the 3D Gaussian distribution corresponds to the vertical and horizontal seismic resolution. Multiple information from different events and stations at every point are averaged and normalized considering the weight of each amplitude. Migrated RF-profiles were finally produced by projecting and averaging the RF amplitude information from the 3D cuboid on vertical sections.

The profile complements 3 permanent stations (networks PL and SK) and 6 temporary stations in the region (networks ZJ, Z6 and Y8, Hetény et al., 2019; Schlömer et al., 2022; Neagoe, 2022) to form a dense, roughly N-S oriented profile (Fig. 9). However, preliminary results are only reported from one year of data recorded by the 18 stations installed in the scope of this project.

5. Preliminary results

The RF data processing yielded CCP stacks of the Ps and the multiple PpPs and PsPs conversions. Horizontal features are better detected by this method compared to dipping features.

The Ps CCP image (Fig. 9) shows a clear positive-polarity (red) conversion at ~30-35 km depth almost throughout the entire section (unmarked profiles in supplementary material S3). This is associated to the Mohorovičić discontinuity as represented in Fig. 9 by a thick solid black line. The Moho interpretation from the CEL04 profile of Środa et al. (2006) is also included as stippled black line in the CCP images (Fig. 9) for comparison. Clear, coherent and robust conversions are also detected within the crust; however, intra-crustal multiples complicate the picture when interfering with primary conversions. Below the Moho, a gently south-dipping weaker, but astonishingly linear positive feature is observed (thin solid black line in Fig. 9), likely located within the uppermost mantle. The CCP images of the multiple conversions (Fig. 9) also show a strong Moho conversion throughout the profile, consistent with the CCP of the primary conversion. Furthermore, CCP images of multiples can be used to identify uppermost-crustal features.

In both the interpretations of the primary and multiple conversion CCP images, the effect of multiples and wrongly placed primary conversions needs to be carefully taken into account.

After one year of data acquisition, the preliminary CCP images already show that the data are of high quality for the purpose of RF imaging and are able to retrieve the major structures in the area. The striking consistency between the Moho imaged using primary and multiple conversions is one of the strong indications of the data quality.

The similarity of the wide-angle refraction profile by Środa et al. (2006) with that obtained by this preliminary study also demonstrates the robustness of the data. Despite a generally similar Moho depths, the RF (and other future analysis of this dataset) will be complementary and already now reveals different detail compared to the refraction model, for example allowing to interpret the coherency of the Moho conversion, tracing major faults and contacts in the crust, and imaging structure in the uppermost mantle. For example, the preliminary RF CCP images suggest a rather simple contact of the European and AlCaPa crust, rather than the involvement of buried crustal ridges, such as the Czorsztyn Ridge. However, data from a longer recording period, as well as the data of permanent and other temporary stations, will increase the imaging quality even further, and will provide more diagnostic images of the lithosphere in the Western Carpathians.

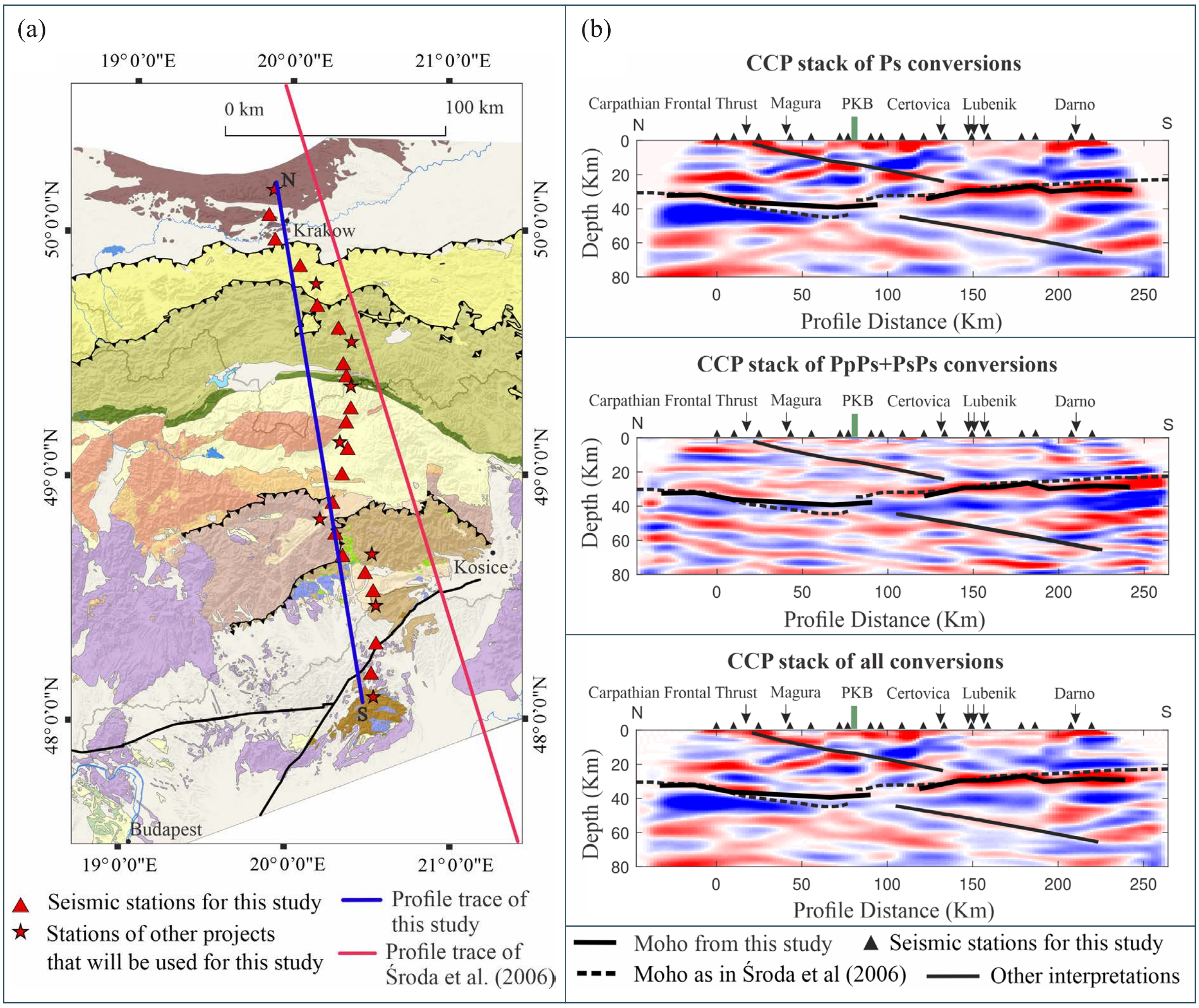

Figure 9. (a) Location of all the stations used for this study along with the profile of the CCP sections. Please refer to Fig. 1 for the legend. (b) CCP images of selected conversions. The Moho conversion is interpreted based on the preliminary CCP stack of all conversions. The northern segment is European Moho while the southern is AlCaPa Moho.

6. Conclusions and Future work

The passive seismic experiment presented in this paper was originally designed to contribute additional data toward resolving the geological inconsistencies in the evolutionary history of the PKB and, by extension, the Western Carpathians. As the experiment progressed – and thanks to the high quality of the data and the retrieved receiver functions – the seismological component has become a central element of the broader multi-disciplinary research effort.

Due to the AdriaArray initiative, we got uncomplicated access to the instruments through GIPP/GFZ, as well as from the Friedrich Schiller University Jena, and we received training to assemble and run the instruments. The colleagues who have joined the project during its implementation played a key role in the handling and transfer of data, organizing the field work and scouting locations. Coming from different scientific backgrounds, the team has been full of varying and important insights. This has been very useful until now and will continue to be in the future of the experiment.

Over the time period of the data acquisition since June of 2023, the data has been constantly monitored, and the stations have been serviced as often as required. This has been done to ensure continuous and high-quality data. From the data availability, PPSDs and RF analysis- it is apparent that the data quality is generally high. There are only a few larger gaps in data at certain stations because of technical problems that have occurred. Despite being installed in public places, the noise levels of the stations are usually low, although two stations (CP00A and CP01A) are clearly above the average, but still acceptable. The noise does not inhibit in any case our main aim, the RF analysis.

As the seismic experiment continues over the next year, more data will help to refine the RF model and uncover finer details about the deep structures that are key to understanding the evolution of the Western Carpathians. Besides updating CCP images, the analysis will be continued with RF inversion. Furthermore, the data is free to use for any complementary data analysis, first within the AdriaArray consortium and later, after the two-year running embargo, through full open access. This experiment has the potential to offer new insights into the complex geology of the Western Carpathians, challenging previous theories and providing a more detailed understanding of the region's tectonic history.

Data availability statement. The data from this project has a rolling embargo which makes the data available within two years of its acquisition (https://orfeus.readthedocs.io/en/latest/adria_array_seismicnetworks.html). Data can be downloaded within the AdriaArray consortium from EIDA.

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***CORRESPONDING AUTHOR: Tanishka SONI**,

Institute of Geological Sciences, Polish Academy of Sciences, Krakow, Poland

e-mail: ndsoni@cyf-kr.edu.pl