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AdriaArray experiment on the territory of Bulgaria

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Abstract

We describe stations of the AdriaArray Seismic Network deployed on the territory of Bulgaria. The network consists of 50 stations, 25 of which are permanent stations of the Bulgarian National Seismic Network NOTSSI. Another 25 temporarily deployed stations belong to MOBNET (Institute of Geophysics) and DanSeis (Aarhus University) pools. The temporary stations of MOBNET began their operation in June 2022, and the DanSeis pool's temporary stations in August and September 2022. For each of the stations, we document the site geology, station location, instrumental equipment, as well as data transmission, preprocessing and availability, which exceeds 95% at some stations. Noise at the stations stays between the limits of the New Low and New High Noise models. As an example of planned data exploiting, we present the P-to-S receiver functions for station BG11A in the Strandzha unit (southeast of Bulgaria) and respective Moho depth estimates from the P delay times, H-κ stacking and from the 1D v_S velocity-depth modeling at the station site.

Keywords: MOBNET pool; DanSeis pool; Temporary stations; Permanent seismic stations; Network performance

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1. Introduction

The AdriaArray initiative is a comprehensive international project (Kolínský et al., 2025a) that has established a dense network of seismic stations to investigate the complex tectonic structure, seismicity, and geodynamics of the Adriatic region and adjacent areas across central, eastern and southeastern Europe. The research is built on earlier seismic projects, particularly the AlpArray (Hetényi et al., 2018a) and its complementary experiment PACASE (Schlömer et al., 2024), which advanced understanding of lithospheric deformation, plate boundary dynamics, and seismic hazard in the broader area of the Alps. The AdriaArray focuses on integrating geodynamic analysis, seismicity studies, and high-resolution imaging to unravel complex tectonic interactions and refine models of crustal and mantle processes across southeastern Europe.

The primary goals of the AdriaArray (AdA) experiment include mapping the tectonic boundaries between the Adriatic microplate, and Eurasian and African plates to reveal complex plate interactions, and to investigate the long-term evolution of the lithosphere subductions. Furthermore, the project aims to better understand fault behavior and tectonic stress distribution to improve seismic hazard assessment. For that and to improve monitoring of the seismic activity, the seismic network coverage in southeastern Europe has been enhanced by the dense deployment of temporary seismic stations.

Several seismic and geophysical studies have focused on the deep structure and geodynamic evolution of the Bulgarian territory and its surroundings. For example, Babuška et al. (1987) used teleseismic P-wave residuals and 3-D inversion techniques to characterize the uppermost mantle beneath Bulgaria, and revealed contrasting lithospheric blocks, exhibiting anisotropic features possibly associated with remnants of paleosubduction zones. Spassov et al. (1988) and Shanov et al. (1992) proposed the presence of paleosubduction features beneath the Rhodope Massif based on seismic refraction and gravity data. The tectonic processes shaping the Stara Planina range were examined by Roy et al. (1996), who suggested that the uplift of the range results from flexural bending linked to Pliocene-Quaternary extension rather than from earlier compressional phases alone. Marchev et al. (2004) used geochemical, isotopic (Sr-Nd-Pb), and petrographic analyses to characterize the basaltic magmatism in the Eastern Rhodopes and its tectonic setting. Further insights into the regional lithospheric structure are provided by magnetic anomaly analyses, as demonstrated by Abramova and Filippov (2019), who identified fault-related magnetic features that correlate with known tectonic boundaries within the Rhodope Massif. Also, receiver function studies provided basic information on the crust thickness in the region (Georgieva and Nikolova, 2013; Georgieva, 2015; Vinnik et al., 2021).

In this paper, we describe locations and equipment of stations on the territory of Bulgaria, included in the AdriaArray Seismic Network (Kolínský et al., 2025a), and present examples of the first results from receiver functions.

2. Tectonic setting

The tectonic architecture of Bulgaria is diverse (Fig. 1), ranging from the stable European lithosphere in the north to Mesozoic and Cenozoic orogens in the south. Tectonic reconstructions have fundamentally changed over the past 40 years. The high-metamorphic and plutonic basement that had been interpreted as Precambrian in age is now identified as being shaped during Variscan, Mesozoic, or even Cenozoic orogenic processes. Figure 1 (modified from Kounov et al., 2015; Kounov and Gerdjikov, 2020) illustrates the major tectonic units in Bulgaria and the adjacent area to the south in Greece and Turkey. The northern part of Bulgaria, i.e., the Moesian platform north of the Balkan mountains, belongs to stable Europe. It is characterized by a few kilometers thick pile of little deformed Cenozoic and Mesozoic sedimentary rocks, which unconformably overlay Paleozoic successions (e.g., Dabovski et al., 2002). Units to the south experienced Variscan deformation, magmatism, metamorphism, and an early Alpine orogenic event in middle and upper Jurassic times. This Jurassic event was associated with broadly north-directed thrusts, which are recorded in all units south of the Moesian platform except for the lower units in the Rhodopes, which underwent intense Cenozoic overprint (e.g., Okay et al., 2001; Dabovski et al., 2002; Vangelov et al., 2013; Bonev et al., 2015). Except for the Balkan mountains, this event usually involves the pre-Mesozoic basement and is associated with varying degrees of metamorphism. The Balkan mountains also experienced a younger Alpine deformation event. Cenozoic north-directed thrusting in the Balkan mountains includes a high-metamorphic Variscan basement in the western part, but is only thin-skinned in the east (Vangelov et al., 2013). The Sredna Gora and the Strandzha units consist of a Variscan high-metamorphic basement with late Variscan intrusions covered by Mesozoic series. The Sredna Gora unit and the northern Strandzha unit are characterized by intense Late Cretaceous arc-magmatic activity and the coeval formation of thick volcano-clastic series (Kounov and Gerdjikov, 2020). This event postdates Jurassic nappe stacking and relates to the northward subduction of oceanic lithosphere of the Vardar ocean. Most of the Rhodope metamorphic complex is a part of the Dinaric-Hellenic orogen. It consists of low- and high-grade metamorphic rocks affected by syn-metamorphic southwest-directed thrusting (e.g., Ricou et al., 1998). The age of major orogeny in the lower units of the Rhodope metamorphic complex is highly controversial with propositions ranging from Jurassic to Eocene (e.g., Krenn et al., 2010; Froitzheim et al., 2014). The Sredna Gora unit, the

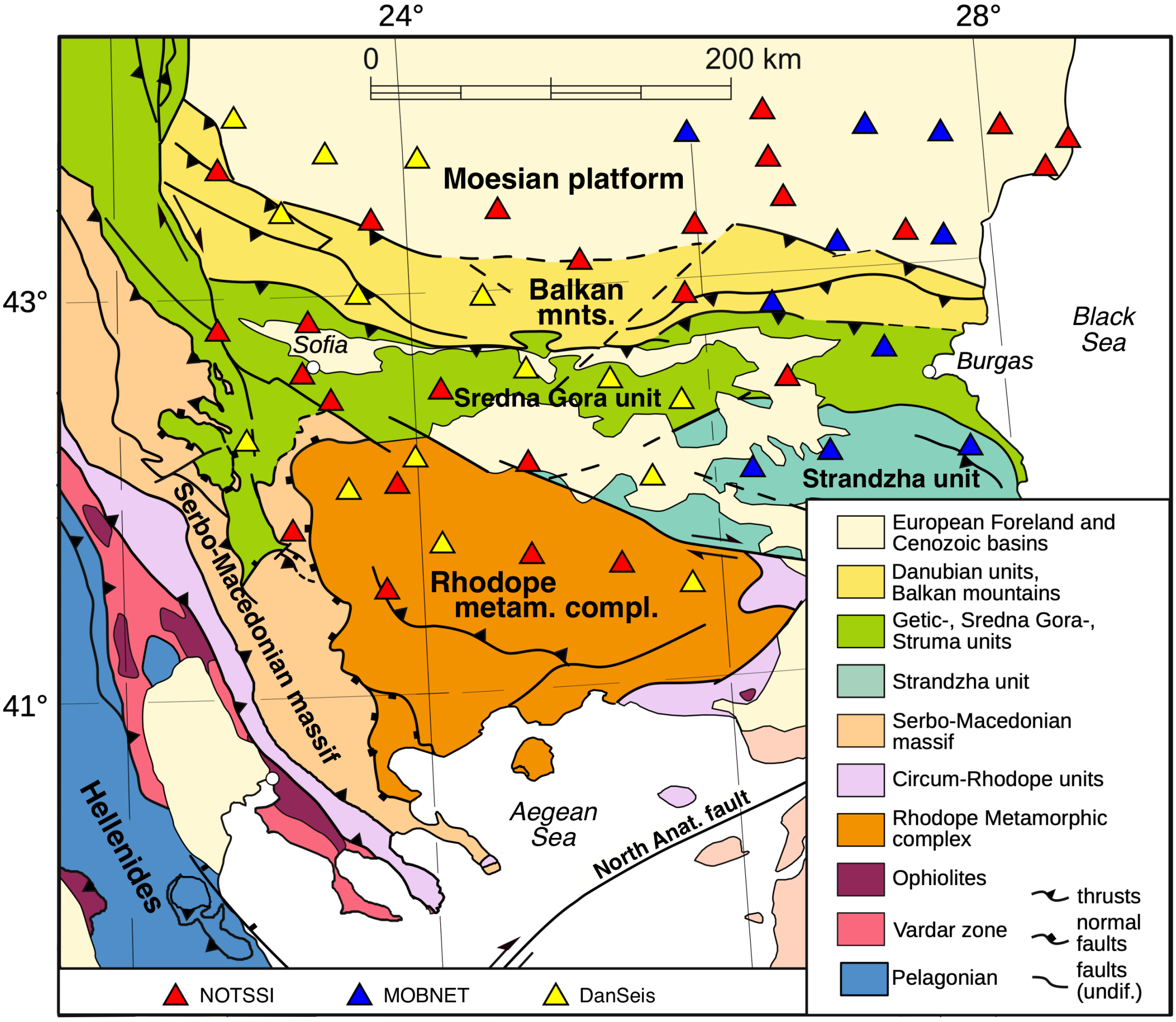

Figure 1. Tectonic map of territory of Bulgaria and surroundings (after Kounov et al., 2015; Kounov and Gerdjikov, 2020) along with both permanent stations of the Bulgarian National Seismic Network (NOTSSI) and temporary seismic stations of the MOBNET and DanSeis pools.

Strandzha unit, and especially the Rhodope metamorphic complex were affected by post-Early-Eocene extension and basin formation (e.g., Burchfiel et al., 2000; Georgiev et al., 2010). In the Rhodopes, extension was also associated with intense Paleogene magmatism (Marchev et al., 2004). The Serbo-Macedonian massif in the southwesternmost part of Bulgaria represents the continuation of the Supragetic units further north in the southern Carpathians. It mainly consists of Variscan metamorphic rocks of Early Paleozoic protoliths (Antic et al., 2016).

Analyses of receiver functions based on data from the Bulgarian National Seismic Network (NOTSSI – National Operational Telemetric System for Seismological Information) have been used to investigate the lithospheric structure, including the mantle transition zone and the lithosphere-asthenosphere boundary (Vinnik et al., 2021), as well as to provide constraints on the crustal structure and variations of the Moho depths (e.g., Georgieva and Nikolova, 2013). The Moho depths vary between 30 and 40 km in Northern Bulgaria and increase from the west to the east in this region. Beneath the Upper Thracian Plain, the crust is about 33 km thick and the Moho deepens to 50 km beneath the Rhodope Massif and Pirin Mountains. The crustal thickness in the Struma valley is estimated at 29 km, and varies between 37 and 40 km in the Srednogorie unit. A 10 km thick sedimentary layer was identified beneath stations in Northern Bulgaria (PVL, MPE, SZH). The v_P/v_S ratio in Northern Bulgaria varies between 1.80 and 1.90, and decreases toward the south and southwest. The ratio attains values between 1.76 and 1.85 in the Upper Thracian Plain, and between 1.72 and 1.82 in the Rhodope Massif. The western part of the massif is characterized by low v_P/v_S (1.60-1.65).

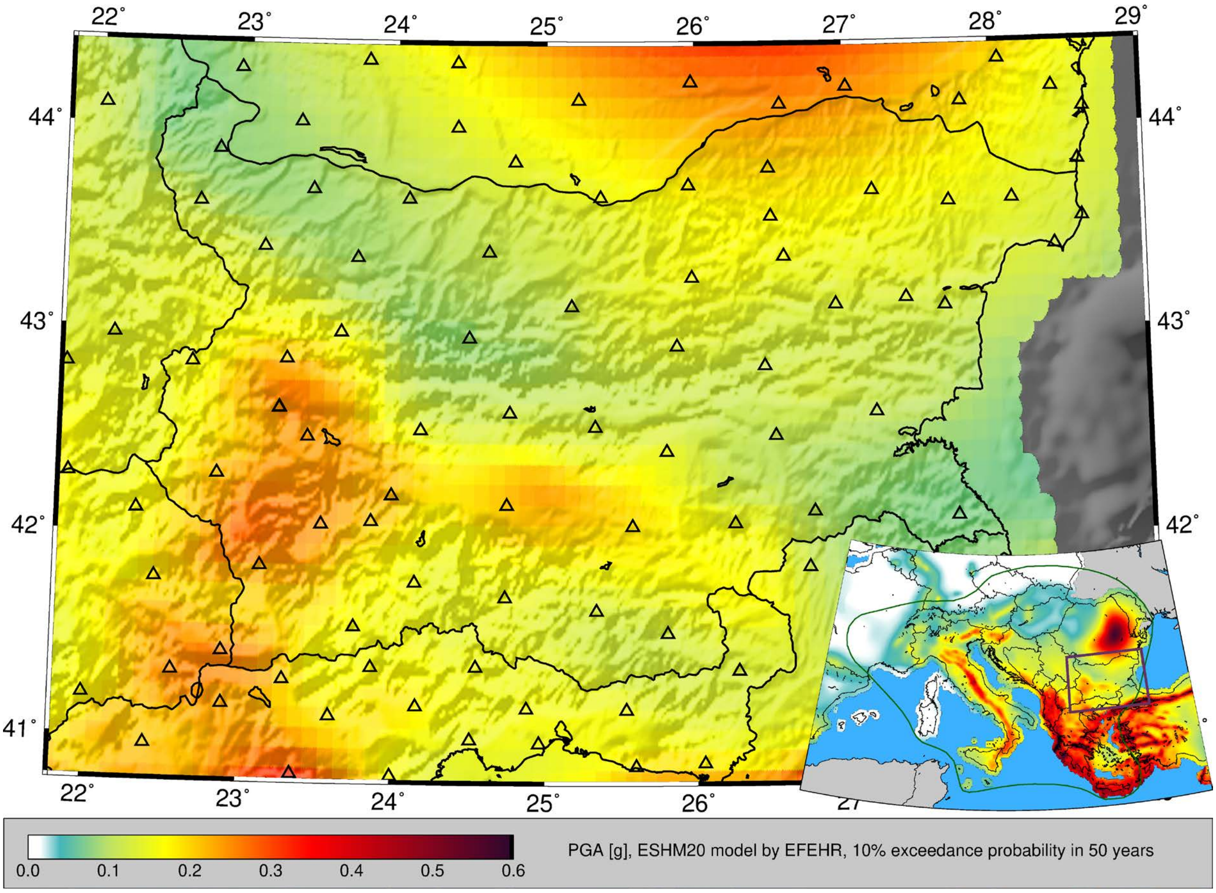

Figure 2. Seismic hazard on the territory of Bulgaria. Map is the extraction from the European Seismic Hazard Model (ESHM20), provided by European Facility for Earthquake Hazard and Risk (Danciu et al., 2021), and complemented by broadband stations in the region.

The territory of Bulgaria belongs to the most seismically active region of Europe, in which seismic hazard plays an important role. The 2020 European Seismic Hazard Model (ESHM20), developed by the European Facilities for Earthquake Hazard and Risk (EFEHR) (Danciu et al., 2021), highlights areas of elevated Peak Ground Acceleration (PGA) on rock-like ground types (Fig. 2). The PGA is determined for a 10% probability of exceedance over a 50-year period, which is equivalent to a mean return period of 475 years. Although the region of Bulgaria belongs to less seismic active parts of the Balkan peninsula (see the inset of Fig. 2), increased seismic hazard affects the southwestern part of the territory. The Vrancea seismic zone is responsible for the increased values of the hazard in the northernmost part of the region.

3. Network description

The AdriaArray Seismic Network on the territory of Bulgaria (Fig. 3) is formed by 1) permanent stations of the Bulgarian National Seismic Network – NOTSSI (Christoskov et al., 2019), 2) the MOBNET pool of temporary stations of the Institute of Geophysics of the Czech Academy of Sciences (IG CAS) (Plomerová, 2025) and 3) the Danish temporary stations pool (DanSeis), provided by the Aarhus University in Denmark. Locations of the temporary stations were selected to fill the gaps between permanent broadband stations to cover the whole territory with broadband sensors with an interstation distance of ~30 km (Fig. 4). In total, the territory is covered by 25 permanent and 25 (10 + 15) temporary stations. The network design will improve the assessment of tectonic stresses, crustal deformation specific to the territory and seismic hazard. Data recorded by the densified network will be used for creating high-resolution images of the Balkan lithosphere and the upper mantle and contribute to studies of subduction processes, lithospheric deformation, and seismic anisotropy.

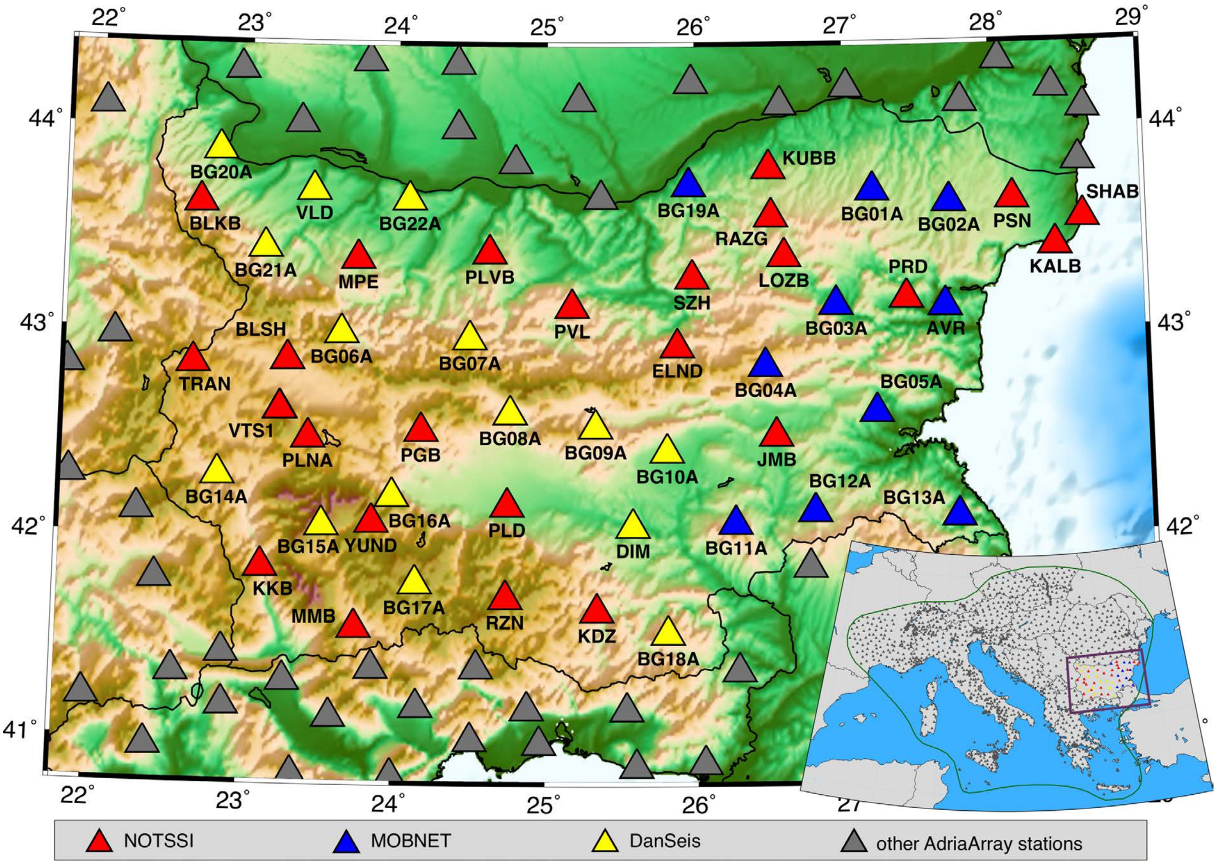

Figure 3. Map of the broadband seismic stations of the AdriaArray Seismic Network on the territory of Bulgaria. Red triangles denote Bulgarian permanent broadband stations, blue and yellow triangles represent the Czech and Danish temporary stations, respectively. The inset map shows the distribution of stations across the entire AdA experiment.

During the site scouting process, the main priority was creating a dense network by combining the Bulgarian permanent and AdA temporary seismic stations. At the same time, several important factors, such as ambient noise, power supply, site accessibility, environmental conditions, maintenance requirements, communication capabilities, and security, were evaluated. Two or three potential localities (more than 70 in total) were selected according to the cadastral database of Bulgaria for each of the 25 suggested sites for temporary stations. The locations were carefully assessed for the vicinity of noise sources such as roads, railways, industrial areas, and others. Meteorological conditions such as temperature, humidity, and precipitation were also reviewed to minimize their effects on the stations. Seismic stations Dimitrovgrad (DIM), Vulchedrum (VLD), and Avren (AVR) of the NOTSSI, originally equipped only with short-period seismometers, were upgraded by installation of the broadband instruments.

Telecommunication providers were consulted to confirm the availability of cellular or on-land communication services significant for real-time data transmission. To secure the stations, each site was evaluated for risk of vandalism, theft, and natural threats such as wildlife or flooding. The station conditions were discussed with the municipal mayors, who also provided us with access to the basements of the city hall buildings and the possibility to deploy the stations.

Since the three individual parts of the AdA network in Bulgaria have different settings, equipment, and methods of operation, they are described separately in the following text. Nevertheless, the data from all stations are stored in one EIDA node – NIEP, with the Y8 network code for temporary stations and BS network code for permanent stations.

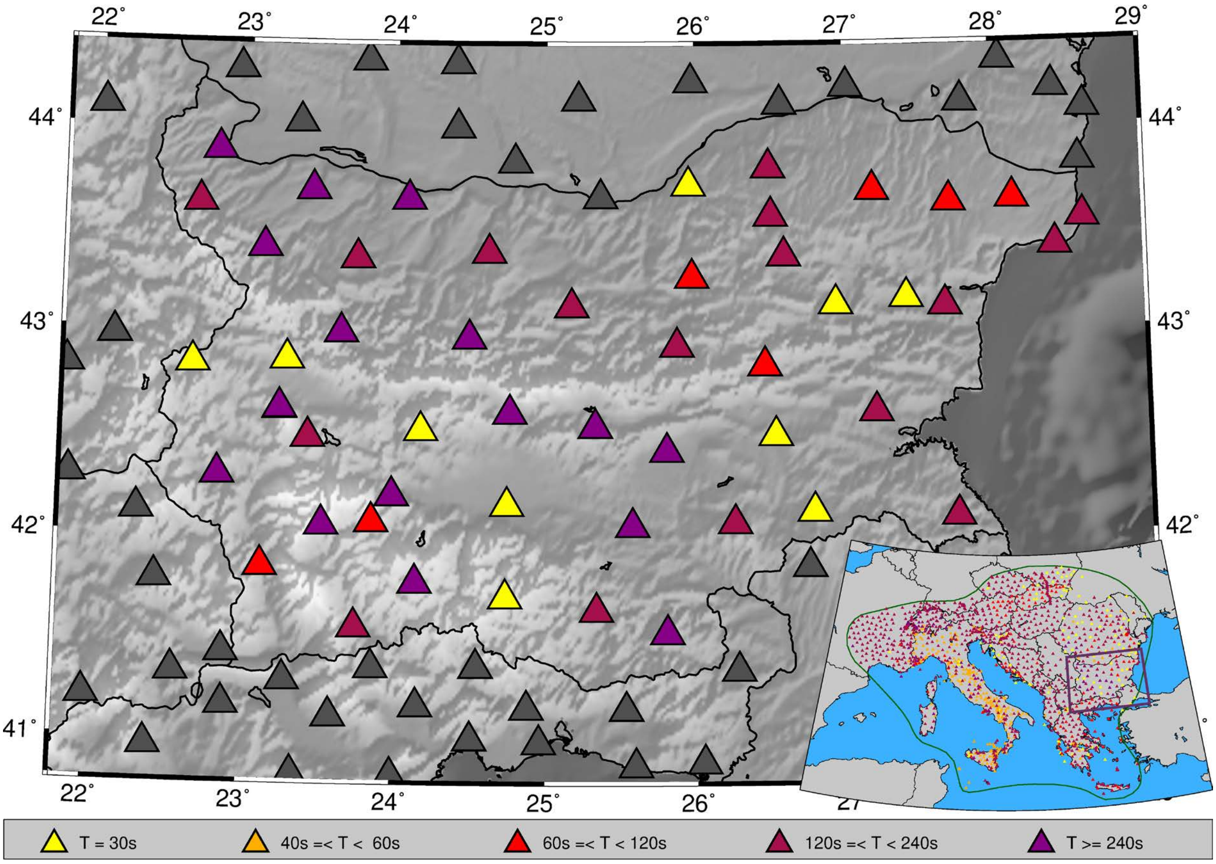

Figure 4. Distribution of seismic stations on the territory of Bulgaria, colored according to the corner periods T of seismometres. The inset map shows the distribution of stations across the entire AdA experiment.

3.1 Bulgarian permanent seismic network

The Bulgarian National Seismic Network was established in 1980 with the main goal of monitoring seismicity within the territory of Bulgaria and the surrounding regions. Data is transmitted from the stations to the Seismic Data Center (SDC). The SDC is a part of the National Institute of Geophysics, Geodesy and Geography (NIGGG)) of the Bulgarian Academy of Sciences, formerly called Geophysical Institute (until 2010). The network enables rapid data processing, as data is transferred in real time to the SDC and handled using automatic and interactive processing software. The hypocenter information of the earthquakes on the territory of Bulgaria and the Balkan Peninsula is published on the NIGGG website. Daily bulletins and periodic catalogs of the registered seismic events are also prepared. If an earthquake is felt on the territory of Bulgaria, the state civil protection authorities are immediately notified according to an approved protocol.

Currently, NOTSSI consists of 42 seismic stations, 25 stations are equipped with broadband three-component seismometers (Fig. 3). Ten of them are equipped in addition with accelerometers. Eight stations are equipped with accelerometers only, and the remaining eight stations with three-component short-period seismometers. A vertical short-period seismometer is installed in a borehole at a depth of over 200 m at the VLD seismic station.

Within the NOTSSI, two local seismic networks operate in the vicinity of the Kozloduy Nuclear Power Plant and the salt deposit located near the town of Provadia to monitor seismic activity. Each network consists of the central broadband station and two peripheral short-period stations in case of the MPE station (Kozloduy network) and five short-period stations in case of the PRD station (Provadia network) (see Fig. 3).

The recent development of methodologies for seismic risk analysis and the new seismic hazard assessment in Bulgaria (see Fig. 2) improve preparedness and risk mitigation strategies. This involves evaluating seismic data archived in the Bulgarian Data Center to form a comprehensive understanding of potential hazards and risks associated with earthquakes.

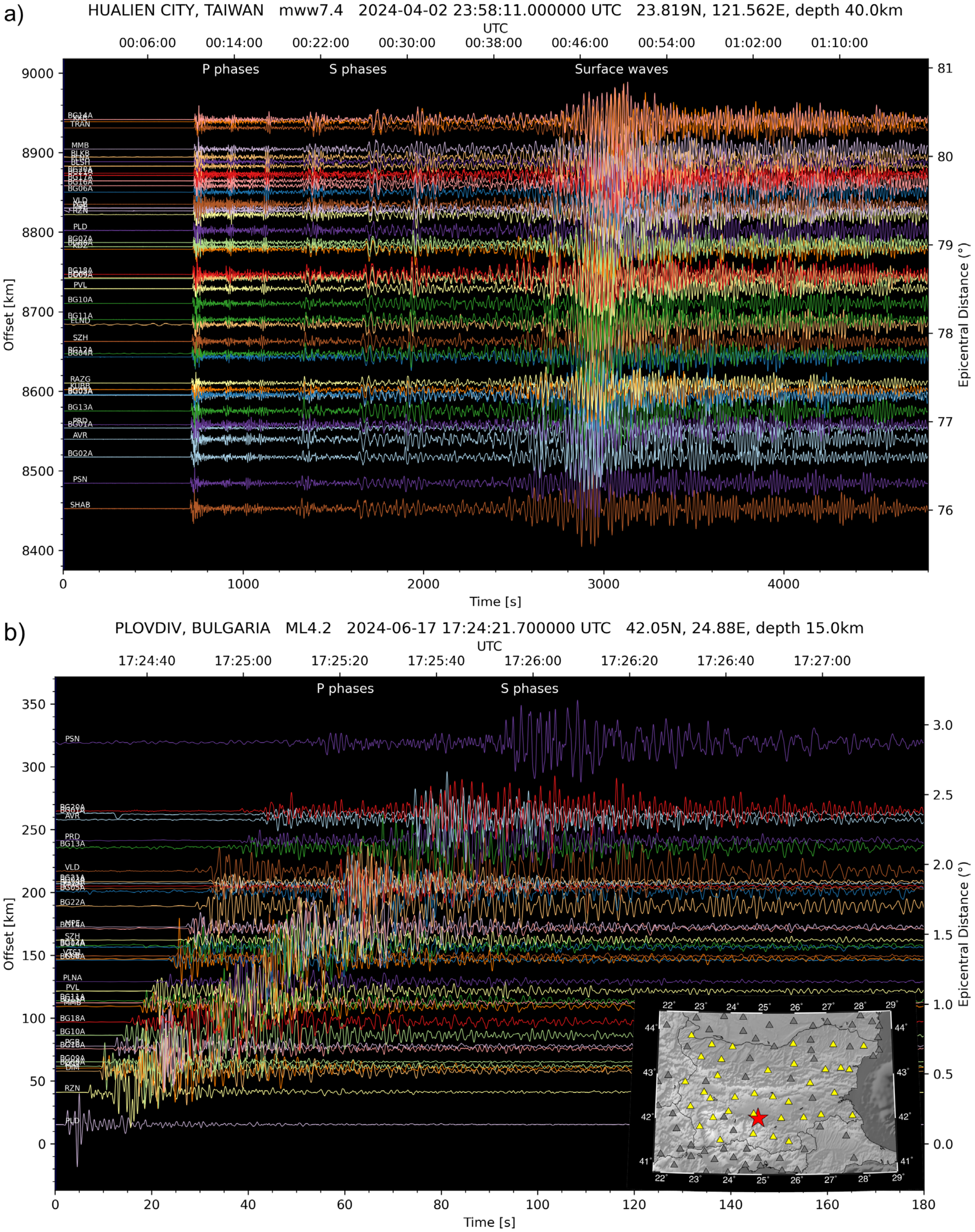

Figure 5. Examples of the AdA seismograms of two events recorded on the territory of Bulgaria: (a) the teleseismic event: Hualien City, Taiwan, Mw 7.4, 2024-04-02; (b) the local event: Plovdiv, Bulgaria, ML 4.2, 2024-06-17; the inset map shows the event epicenter and the AdA stations (yellow – stations with seismograms shown, grey – other stations). Recordings are normalized on traces maxima.

3.2 Czech temporary stations

The IG CAS participates in the AdA project with 52 broadband stations belonging to the MOBNET pool (Plomerová, 2025). The stations are deployed in the Czech Republic and Slovakia (Vecsey et al., 2025), Romania (Borleanu et al., 2025) and Bulgaria. Stations in the Czech Republic and Slovakia operated in the previous AlpArray and PACASE experiments, respectively. During 2022, the networks were partly reconfigured and the stations were incorporated into the AdriaArray Seismic Network. The stations in Bulgaria and Romania were deployed throughout June 6-17, 2022, during the first of the campaigns deploying the AdA network.

The MOBNET pool in Bulgaria consists of 10 broadband stations. The stations cover the eastern part of Bulgaria from the Romanian to the Turkish border. The stations are located in the cellars of the municipality buildings (Fig. 6), except for station AVR (Fig. 7), situated in the adit in the garden of the Astronomical Observatory in Avren.

Figure 6. An example of station installation in municipality building: station BG03A at Suha Reka.

Figure 7. Installation of the broadband seismometer and data acquisition system GAIA at station AVR in the Astronomical Observatory in Avren.

3.2.1 Station design

Each station consists of a broadband sensor of different types (Table 1), a data acquisition system GAIA, modems for sending SMS reporting the state-of-health of the stations, for telemetric data transmission and for remote control, as well as antennas, battery, and charger. All stations are connected to the power grid. The three modems guarantee remote access to the stations in case of emergency needs. Online data is transferred by a SeedLink to the IG CAS and, after station name adjustments, to the EIDA node in Romania – NIEP.

The sensors were thermally insulated with styrofoam boxes during the installation. In May 2023, we extended the thermal insulation with an additional layer (Fig. 8). At each station, except for BG05A, an insulating sleeve made of 25 mm thick mineral wool with an outer cover of durable layered aluminum laminate was added under the styrofoam box. At the BG05A station, we used a fleece hat instead of an insulating sleeve (Fig. 8c). Later, in October 2023, we replaced the styrofoam box with another layer of insulating sleeve at station BG01A, and we reverted to insulating only with a styrofoam box due to the increased noise at station BG04A.

Figure 8. Examples of thermal isolations of the sensors: (a) insulating sleeve from mineral wool and durable layered aluminium laminate; (b) insulating sleeve with the styrofoam box; (c) fleece cover; (d) final cover.

The Czech team maintains and collects off-line recorded data twice a year – once for all stations and the second time for those that need an on-site technical intervention that is impossible to do remotely. During the standard maintenance, the seismometer pendulums are centered, the sensor leveling is checked, the sensor and digitizer are calibrated, and the sensor orientation is remeasured by the gyrocompass. Moreover, all cables, antennas, and insulation of the seismometers are checked. In addition, the Bulgarian team helped to solve problems in several cases.

Off-line data collected during the maintenance missions are checked in IG CAS for their quality, possible time errors, or gain imperfections, and corrected (for more details, see Vecsey et al., 2017; Kolínský et al., 2025b). The possible gaps in off-line data from SD cards are filled with online data originally transmitted from the stations. Then, with about one year delay, the complete data set, corrected and cleaned in the IG CAS, replaces the online data originally sent to the EIDA node. With this procedure, we meet, on one hand, immediate access to the data and, on the other hand, provide complete sets of high-quality data.

3.2.2 Site description

AVR is located on the Moesian (Danube) platform, specifically within the Shumen-Provadia platform (Zagorchev, 2009). This platform represents a stable tectonic unit covered by Mesozoic and Tertiary calcareous sediments (Yanev et al., 2005). Asch (2005) defines the area with marine molasse deposits of Eocene to Oligocene ages, composed mainly of clay, marl, and tuff formations, with coal-bearing sequences present. The station itself is positioned in the adit, within the garden of the Astronomical Observatory in Avren, along with the short-period sensor of the permanent AVR station. The sensor is installed on a concrete block separated from the surrounding floor (Fig. 7).

BG01A is placed on the Moesian platform in the region of the Ludogorie-Dobrudzha platform (Zagorchev, 2009). The area is characterized by Early Cretaceous deposits consisting primarily of limestones, marlstones, and sandstones (Asch, 2005). The station is located in the semi-basement of the Skala municipality building, 1 m below ground level. The place has a clay floor with stone paving. The sensor stands on one of the stone tiles.

BG02A is situated in the same region as BG01A at the Ludogorie-Dobrudzha platform (Zagorchev, 2009). The location is characterized by marine molasse deposits from the Miocene, consisting of conglomerates, sandstones, marls, and limestones (Asch, 2005). The station is placed in the basement of a large municipality building in Smolnitsa, approximately 1.5 m below the terrain, and the sensor stands on the concrete floor.

BG03A is located in the area of the Ludogorie-Dobrudzha platform (Zagorchev, 2009). The area is composed of Early Cretaceous sedimentary cover rocks such as limestones, marlstones, and sandstones (Asch, 2005). The seismometer is placed on the concrete floor in the basement of the Suha Reka municipality building, 1 m below the ground level, while the rest of the equipment is located on the floor above (Fig. 6).

BG04A is situated in the Kotels highlands area within the thrust belt of the eastern Balkan mountains (Zagorchev, 2009). The complex area consists of sedimentary rocks (sandstones, limestones, marlstones) ranging from Triassic to Middle Jurassic age, as well as Cretaceous flysch-like and Paleogene clastic sedimentary rocks (Asch, 2005; Vangelov et al., 2013). The village of Jeravna has been declared a national architectural reserve since 1964. The station is placed in the municipality building, in the semi-basement on a slope with a clay floor. The seismometer stands on the concrete tile.

BG05A lies in the Burgas lowland, which tectonically belongs to the eastern part of the Sredna Gora unit. Quaternary alluvial deposits overlay the subsurface Eocene to Oligocene marls and limestones. At greater depths, Late Cretaceous sandstone, tuff group, and volcanic rocks such as andesite and tephrite are present, representing the Mediterranean Late Cretaceous formations (Asch, 2005). The station is placed in the basement of the municipality building in the village of Vinarsko. The sensor stands on the concrete floor.

BG11A is located on the northern flank of the Sakar mountains, which tectonically belong to the broader Strandzha unit. The site is in a major Late Carboniferous to Permian granitic pluton, which intruded into Paleozoic gneisses and schists. A few kilometers to the northeast, the pluton is followed by metasedimentary rocks of Late Paleozoic and Triassic origin, which were affected by the Late Jurassic orogeny (Bonev et al., 2019, 2020). The station is located in the semi-basement of the Hljabovo municipal office on a slope, and the seismometer stands on the concrete floor.

BG12A is in the southeastern Thracian Lowland, in the northern part of the Strandzha unit. The station site lies within Late Cretaceous volcanic and subvolcanic rocks (Bonev et al., 2019; Georgiev et al., 2012). The station is situated in the Mamarchevo municipality building, with the sensor standing on the 6th step to the cellar to avoid flooding of the sensor in case of water penetration into the cellar.

BG13A lies in the Strandzha Nature Park, in the upper part of the Strandzha nappe. This unit contains Paleozoic and Early Mesozoic metamorphic rocks (amphibolites and schists), which are affected by Late Jurassic-Early Cretacous tectonics and subsequent Late Cretaceous magmatism (Bonev et al., 2020). The station is located close to the contact between the Cretaceous volcanic and Triassic metamorphic rocks. It is placed in the basement of the Balgari municipality building with a stone pavement floor; the sensor is positioned on a stone tile below the stairs.

BG19A is situated in the Danubian Plain (Zagorchev, 2009), a region dominated by Quaternary loess and alluvium overlying the stable Moesian platform (Jordanova et al., 2024). The area is characterized by Early Cretaceous deposits, primarily consisting of limestones, marlstones, and sandstones (Asch, 2005). The station is situated in the basement of the municipality building in the village of Bojichen. The sensor stands on the concrete floor.

3.3 Danish temporary stations

Danish Research Council funding has been acquired for a project in order to study the mantle transition zone on the Balkan Peninsula. The project was designed as an independent support of the AdA initiative. Fifteen stations were hired from the Danish seismic instrument pool, DanSeis, for installation in Bulgaria. Additional four stations have been hired for installation in southwest Romania (Borleanu et al., 2025). The instruments were hired for a two-year period initially, but the period was later extended for three years. The stations were assembled, packed, and shipped in August 2022, received by the NIGGG, tested and prepared for deployment. In late August – September, 12 of the 15 DanSeis stations were installed. The remaining three stations started to operate in July – October 2023.

At the beginning, the DanSeis stations operated in an off-line regime. Later, they were equipped with modems and started transmitting data continuously to the NIEP EIDA node. In August 2023, all stations were visited, checked, and maintained. Data recorded in the off-line regime was copied from the SD cards and stored. The off-line data were step-by-step reformatted and uploaded to the NIEP EIDA node to provide data access and to fill data gaps.

3.3.1 Station design

Each unit consists of the Nanometrics Trillium 240 sensor, the Nanometric Centaur digitizer, a Nanometrics insulation hood (a double-walled hard-plastic dome covering the sensor, placed on top of a foam base), and the necessary cables. The digitizers were hung on walls to avoid problems with flooding. We used this setup for installation without any further insulation, as all stations were installed indoors. The GPS was usually installed on an outer wall. Later, a router with high-gain mobile-data network antenna – Mikrotik RBSXTR&R11e-LTE was added for the off-line to online data transmission upgrade.

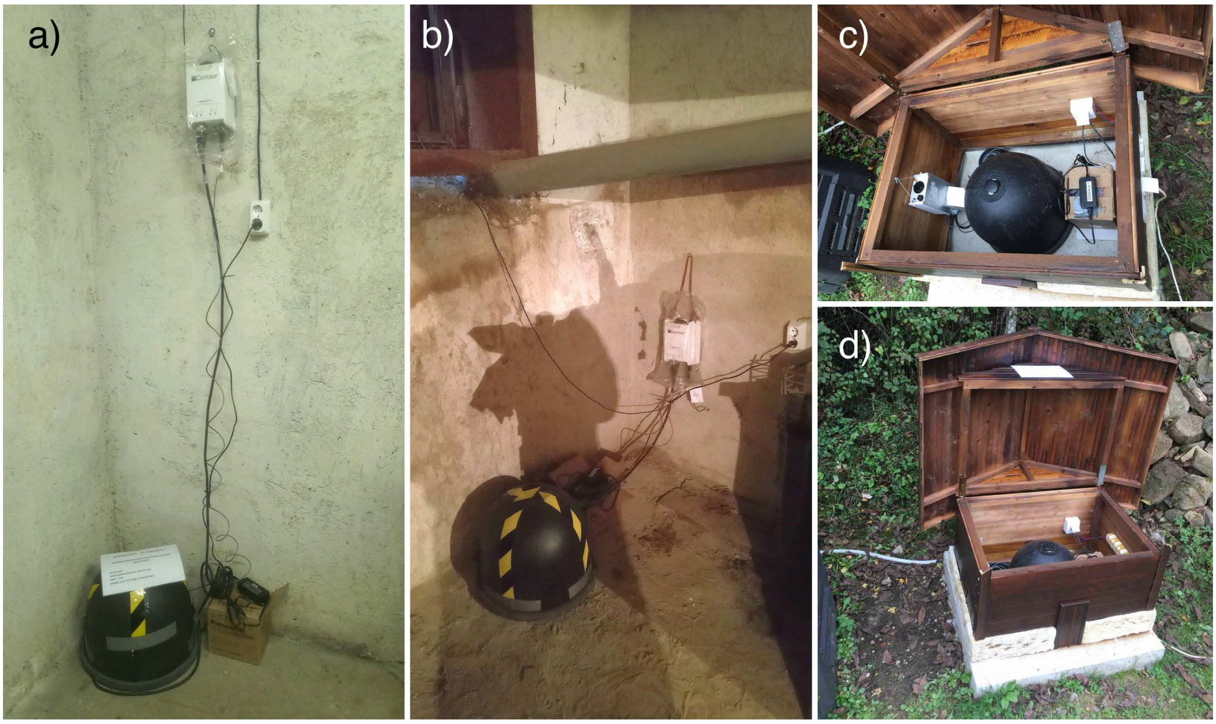

Figure 9. Typical installation of the DanSeis temporary stations: (a) station BG17A at Shiroka Polyana; (b) station BG09A at Srednogorovo. Station BG07A at Goliama Jeliazna (c), placed in a wooden box with a concrete base (d).

3.3.2 Site description

The stations were ideally installed in the basements of abandoned municipality buildings in small villages. However, this was not always the case. In the buildings that are actively used, an abandoned basement room was chosen to minimize any disturbance. In some cases, GPS reception or power supply was challenging and required building infrastructure (laying cables, drilling holes, locating alternative places, etc). Figure 9 shows the typical station installation.

BG06A is located in western Bulgaria and lies within the thick-skinned area of the western part of the Balkan mountains. The region with complex tectonics is composed primarily of Late Paleozoic metamorphic and intrusive rocks, as well as Mesozoic sedimentary rocks. The station site is in the village of Radotina, where thin alluvial deposits rest on top of the Permian Botevgrad granodiorite pluton, which belongs to the Stara Planina granodiorite-granite complex (Georgiev et al., 2024).

BG07A (Figs. 9c, 9d) is located in the Fore-Balkan region, near the boundary between the central Balkan mountains and the Moesian platform, within the north-directed thrust belt in the Mesozoic series. Rock formations in the region

Table 1. List of temporary stations.

Net-work	Station	Location	Deployment	Latitude	Longitude	Sensor	Corner period [s]	Datalogger	Subpool
Y8	AVR	Avren	adit in the garden	43.11949	27.66911	STS-2	120	GAIA 5	MOBNET (CZ)
Y8	BG01A	Skala	basement of municipality bldg.	43.68857	27.19330	CMG-3ESPC	60	GAIA 5	MOBNET (CZ)
Y8	BG02A	Smolnitsa	basement of municipality bldg.	43.62874	27.70896	CMG-3ESPC	60	GAIA 5 GAIA 5+	MOBNET (CZ)
Y8	BG03A	Suha Reka	basement of municipality bldg.	43.13219	26.93805	CMG-3ESPC CMG-3T	30 120	GAIA 5	MOBNET (CZ)
Y8	BG04A	Jeravna	basement of municipality bldg.	42.83369	26.46095	CMG-3ESPC	60	GAIA 5+	MOBNET (CZ)
Y8	BG05A	Vinarsko	basement of municipality bldg.	42.60374	27.19934	STS-2	120	GAIA 5+	MOBNET (CZ)
Y8	BG06A	Radotina	basement of municipality bldg.	42.991448	23.63689	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG07A	Goliama Jeliazna	small wooden house	42.965878	24.492339	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG08A	Dabene	basement of municipality bldg.	42.599033	24.764593	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG09A	Srednogorovo	basement, town hall	42.531642	25.331197	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG10A	Gorno Botevo	basement, town hall	42.413133	25.804958	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG11A	Hljabovo	basement of municipality bldg.	42.06144	26.25492	STS-2	120	GAIA 5+	MOBNET (CZ)
Y8	BG12A	Mamarchevo	basement of municipality bldg.	42.11819	26.78039	CMG-3ESPC	30	GAIA 5+	MOBNET (CZ)
Y8	BG13A	Balgari	basement of municipality bldg.	42.08762	27.72937	STS-2	120	GAIA 5	MOBNET (CZ)
Y8	BG14A	Katrishte	basement, town hall	42.288958	22.831374	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG15A	Semkovo	basement / garage, university seminar centre	42.047733	23.524965	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG16A	Golyamo Belovo	basement, town hall	42.192493	23.988035	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG17A	Shiroka Polyana	basement, forestry department bldg.	41.766003	24.145215	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG18A	Belopoltsi	basement / garage, town hall	41.520753	25.807248	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG19A	Bojichen	basement of municipality bldg.	43.71763	25.95611	CMG-3ESPC	30	GAIA 5	MOBNET (CZ)
Y8	BG20A	Zheglitza	basement of municipality bldg.	43.879918	22.797826	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG21A	Gorno Tzerovene	basement of municipality bldg.	43.405501	23.116078	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	BG22A	Galovo	basement of the unusable school	43.647441	24.080401	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	DIM	Dimitrovgrad	dedicated seismic station bldg.	42.045966	25.577616	Trillium 240	240	Centaur CTR4	DanSeis (DK)
Y8	VLD	Valchedrum	dedicated seismic station bldg.	43.689857	23.435478	Trillium 240	240	Centaur CTR4	DanSeis (DK)

are primarily sedimentary, ranging from Late Jurassic to Early Cretaceous (Cheshitev et al., 1989), i.e., shales and marls, flysch interbedded with sandstones and siltstones (Asch, 2005). The station site is located within Lower Cretaceous limestones and marls.

BG08A is located in the central part of Bulgaria within the Sredna Gora unit. The local geology is defined by the Neogene Karlovo basin, which is part of the east-west sub-Balkan graben system between the central part of the Balkan mountains and the Sredna Gora unit. The station site is in Quaternary sediments, including pebbles, sands, and swamp deposits, which rest on a few hundred meters thick upper Miocene to Pliocene alluvial sediments (Cheshitev et al., 1989; Ivanov et al., 2010).

BG09A (Fig. 9b) is situated in the village of Srednogorovo in central Bulgaria. Tectonically, this area belongs to the Sredna Gora unit, a few kilometers south of the sub-Balkan graben system. The local geology is dominated by vast Late Paleozoic granites and granodiorites with preserved patches of the hosting high-grade metamorphic basement (Asch, 2005; Tzankov et al., 1995).

BG10A is located in Gorno Botevo in southeastern Bulgaria. The area is part of the Thracian Plain within the Sredna Gora unit. The geology is dominated by Neogene and Quaternary alluvial-drift and talus-drift sediments, including clays, sands, gravels, and loess, resulting from fluvial and aeolian processes (Cheshitev et al., 1989).

BG14A is located in the village of Katrishte, in southwestern Bulgaria, within the Struma unit. Upper Eocene to Lower Oligocene sandstones (Nevestino formation) discordantly overlay Middle Triassic limestones, which crop out a few hundred meters to the south. The regional tectonic architecture is complex, shaped by a Mesozoic thrust stack overprinted by Cenozoic normal faulting and basin formation (Kounov et al., 2004).

BG15A lies in southwestern Bulgaria on the southern flank of the Rila massif in the mountain resort Semkovo. Geologically, the station is situated north of the Cenozoic Mesta basin in the western branch of the large composite Rila-West Rhodopes batholith. This batholith is a complex series of Late Cretaceous to Paleogene granitic and granodioritic intrusions (Kamenov et al., 1999). The area around the station consists of biotite-granite, which is probably Cenozoic in age (Peytcheva et al., 2021).

BG16A is situated in Goliamo Belovo northeast of the Rila-West Rhodope batholith. The station site is in metamorphic rocks in a complex tectonic position close to the contact between two nappes of the Rhodope metamorphic complex: the middle and the upper Allochthon, respectively. Both consist of medium- to high-grade gneisses, amphibolites, schists, and other metasediments. The contact between the two units in this region is interpreted as a Late Eocene – Early Oligocene north-directed extensional detachment fault (North Rhodope detachment), south of the Upper Cretaceous right-lateral Maritsa fault zone (Georgiev et al., 2014).

BG17A (Fig. 9a) is located at the western shore of Shiroka Polyana reservoir, situated in the high Rhodopes of southern Bulgaria. The station site lies on up to 1 km-thick Oligocene-aged volcanic rocks, mainly acidic ignimbrites, part of the large Bracigovo-Dospat volcanic complex (Harkovska et al., 1998). The volcanic edifice lies on top of metamorphic rocks of the Middle Allochthon of the Rhodope metamorphic complex, which crop out a few kilometers to the west.

BG18A is located in Belopoltsi in the southeastern part of the Rhodope metamorphic complex. It is situated in high-grade metamorphic rocks: an eclogite-bearing tectonic sliver containing serpentinite, metagabbro and garnet-micaschists, which is interpreted as a metaophiolite (Miladinova et al., 2018). The tectonic position of this sliver is at the top of the Byala-Reka dome, which represents the deepest structural level exposed in the Rhodope metamorphic complex and mainly consists of Late Variscan granitoids that underwent Cenozoic high-grade metamorphism (Peytcheva and von Quadt, 1995).

BG20A is situated in northwestern Bulgaria, in the Danubian Plain, just outside the thrust front of the Balkan mountains. The geology is dominated by sedimentary rocks of Miocene age, primarily marine sediments like limestones, banded claysand sandstones (Cheshitev et al., 1989).

BG21A is situated in Gorno Tserovene in northern Bulgaria in the foothills of the Balkan mountains. The geology of the area is primarily composed of Lower Cretaceous sedimentary rocks of Aptian age, including limestones, sandy limestones, organogenic limestones, and calcareous sandstones (Cheshitev et al., 1989). To the north, the region is bounded by lithology consisting mainly of marbles from the Mramoren formation, dating to the Barremian-Aptian stage.

BG22A is located on the Moesian platform at the Danube River, in a region characterized by eolian sediments deposited during the Quaternary. The lithology consists of loess, sandy loess, and clayey loess (Cheshitev et al., 1989). Tectonically, the area is influenced by normal and strike-slip faults to the northeast of the station.

DIM is located in the Dimitrovgrad Observatory in southern Bulgaria in the Maritsa basin, the plain north of the eastern Rhodopes. The area is dissected by active faults. The geology to the north is characterized by Oligocene deposits including tuffs, tuffites, tuffaceous sandstones, and reef limestones. The area to the south consists of Neogene terrigenous sediments of the Ahmatovo and Elhovo formations of the Upper Thracian graben. They consist of conglomerates, sands, and clays (Cheshitev et al., 1989). The sensor is installed on a concrete block separated from the surrounding floor.

VLD is located in northern Bulgaria, near the Danubian Plain and the southern foothills of the Balkan mountains. The geology of the area mainly consists of Quaternary eolian sediments, such as limestones, sandstones, and claystones, deposited in marine and fluvial environments (Cheshitev et al., 1989). To the east of the station, alluvial sediments are predominant, including pebbles and sands of floodplains and higher terraces, beach terraces and sands, and swamp deposits. The Brusartsi formation, composed of sandy clays from the Pliocene, is present in the region. The sensor is installed on a concrete block separated from the surrounding floor.

4. Array performance and data processing

Analysis of the data availability at NIEP EIDA node for the time period from June 2022 to January 2025 (Fig. 10) shows the high performance of the AdA in Bulgaria. In total, 83.3% of data can be downloaded at the moment: 77.4% for Bulgarian permanent stations, 97.3% for MOBNET temporary stations, and 83.9% for DanSeis temporary stations. More than 90% of data is accessible for 25 stations, out of which 21 provide even more than 95% of data. Altogether, 1.562 TB of data have been uploaded into the EIDA archive from the stations of the AdriaArray Seismic Network on the territory of Bulgaria. Backfilling of the gaps of recorded data in EIDA is an ongoing process, which will improve the data completeness.

Hundred percent completeness in Fig. 10 means that all three components recorded during the day are available. The white color represents data currently not available at the EIDA node. The end of the grey color denotes the start-time of the station.

One of the methods used to monitor station performance, to optimize station deployment, and to understand noise characteristics across diverse spatial-temporal scales, is the Probabilistic Power Spectral Density (PPSD) analysis. The PPSD enables an assessment of noise environments at individual seismic stations in great detail. Figure 11 shows examples of PPSD for selected stations and the variations of seismic noise with periods. Local anthropogenic activities, such as traffic or industrial machinery, dominate at short periods (<1 s). Significant diurnal variations of the short-period noise can split the amplitudes of the spectral density into two branches. Intermediate periods (1-20 s) are primarily influenced by ocean microseisms generated by wave interactions and wave impacts on the seafloor. Environmental factors, such as wind or atmospheric pressure, affect the long-period noise (>20 s), sometimes with noticeable seasonal variations. We use the ObsPy toolbox (Krischer et al., 2015) based on the procedure of McNamara and Buland (2004) and compare individual variations of noise levels with the New High Noise Model (NHNM; Peterson, 1993).

As an example of data processing, we show the sum of the P-to-S Receiver Functions (PRF) (Fig. 12), the Moho depth derived by the Zhu and Kanamori (2000) method, and S-wave velocity-depth variations (Fig. 13) derived by the inversion algorithm of Schiffer et al. (2024) at station BG11A. We calculated the PRFs used for sum and Moho depth estimation by the Zhu and Kanamori method using the time-domain spiking deconvolution implemented as a single-channel predictive deconvolution filter (Kind et al., 1995; Hetényi et al., 2018b). The sum of PRFs (Fig. 12a) is calculated from all available back-azimuths, where the time delays of P-to-S arrivals are migrated to the Moho depth according to the IASP91 velocity model (Hetényi et al., 2018b, for more details). Figure 12b shows the sums of Ps delay times in piercing points at 35 km depth for 30° bins, and Fig. 12c is the H-κ stacking plot by the method of Zhu and Kanamori (2000) of the PRFs for the crust thickness (Moho depth) and the v_P/v_S ratio estimates. An example of a one-dimensional velocity inversion of the stacked PRFs and apparent S-wave velocities is shown in Fig. 13. The PRFs for the inversion were processed using a frequency-domain deconvolution method (i.e. Ammon 1991) with an applied water level of 0.1 before spectral division, as well as a Gaussian filter of 2.5. The apparent S-wave velocities were calculated following the procedure by Svenningsen and Jacobsen (2007). The ratio of the R- over Z-components of the PRFs allows the calculation of the apparent S-wave velocity with a known ray parameter. Apparent S-wave velocities were then calculated at increasing periods. The inversion estimates the Moho as a crust-mantle transition zone at depths between 32 and 35 km. The lower crust of ~18 km thick includes a high-velocity layer, ~6 km thick, with velocities v_S ranging between 4.05 and 4.20 km/s. The upper crust, around 16 km thick, contains a low-velocity layer approximately 2 km thick, which likely represents a fractured

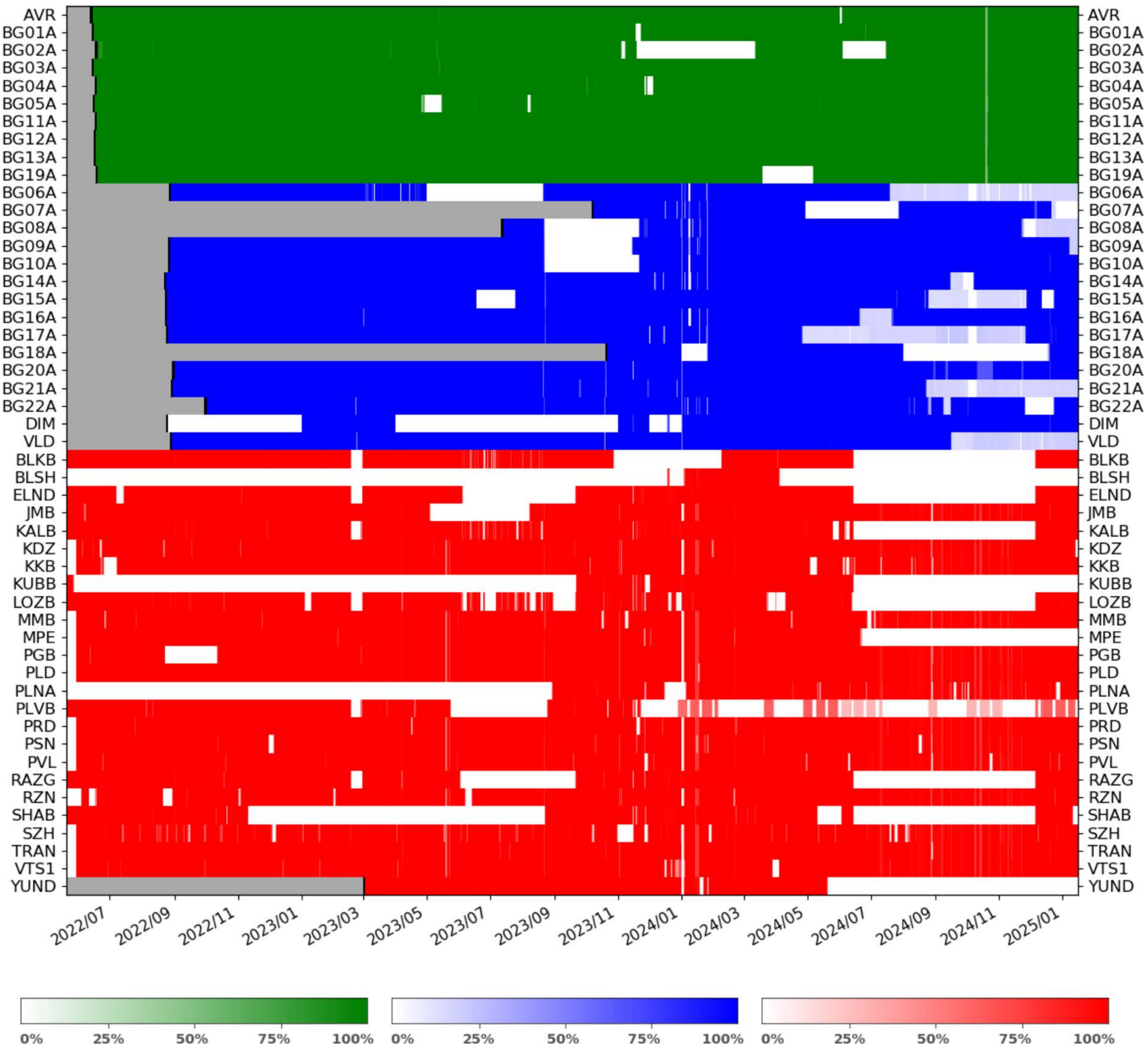

Figure 10. Color-coded daily data availability at the NIEP EIDA node for the MOBNET (green) and DanSeis (blue) temporary stations and permanent stations of the Bulgarian permanent network NOTSSI (red).

top layer of the crystalline basement. Incorporating the data from the AA stations within Bulgaria and surrounding regions into future studies will improve the currently existing model of the crust and upper mantle (Georgieva and Nikolova, 2013; Georgieva, 2015; Vinnik et al., 2021).

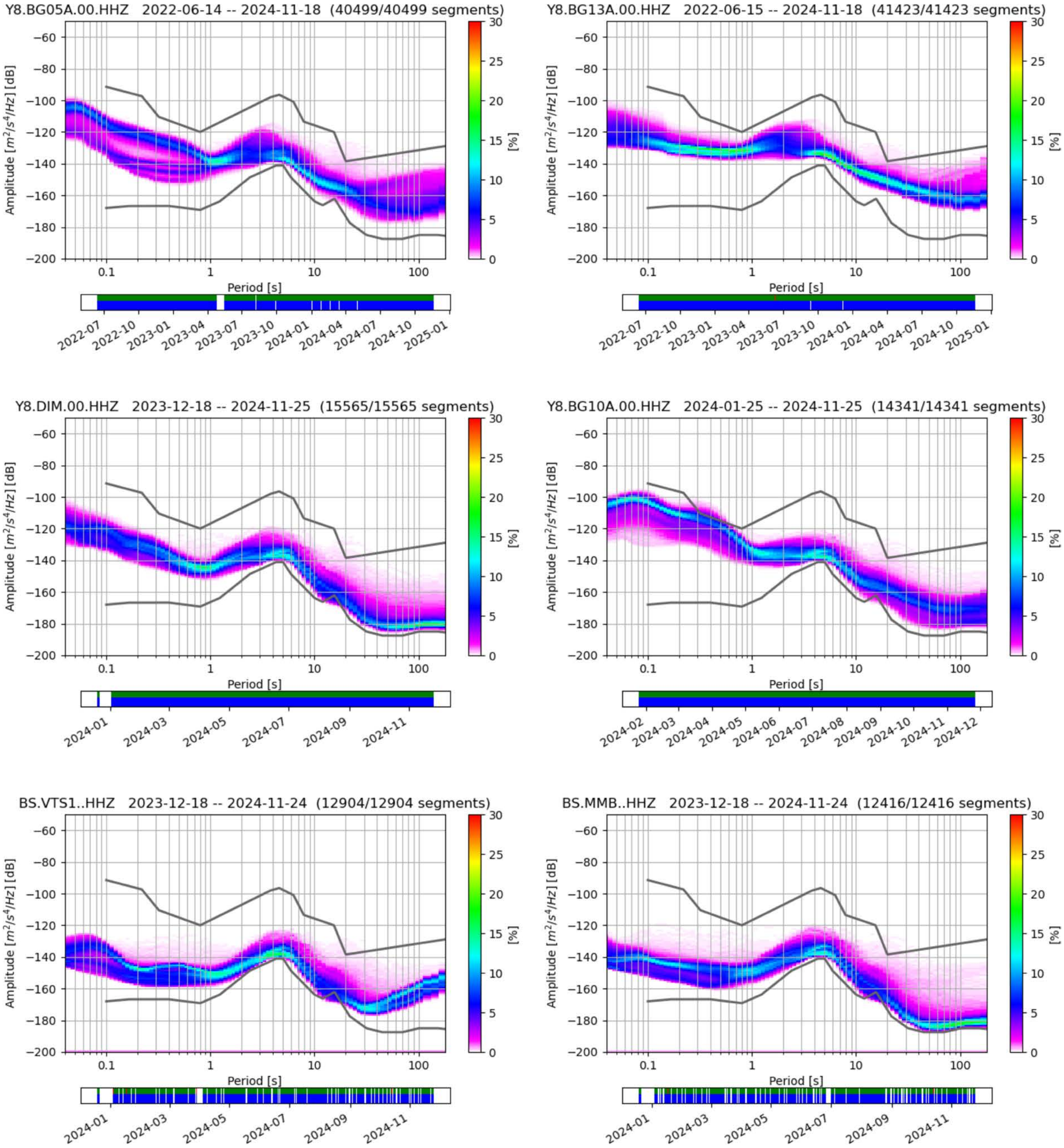

Figure 11. Examples of the probabilistic power spectral densities (PPSD) on the Z components at temporary stations BG05A, BG13A, DIM and BG10A, and at permanent stations VTS1 and MMB. Diurnal variations at short periods of ~<1 s are visible at stations BG05A and VTS1. The grey thick lines mark the upper and lower limits of the New Low and New High Noise Models (NLNM and NHNM; Peterson, 1993).

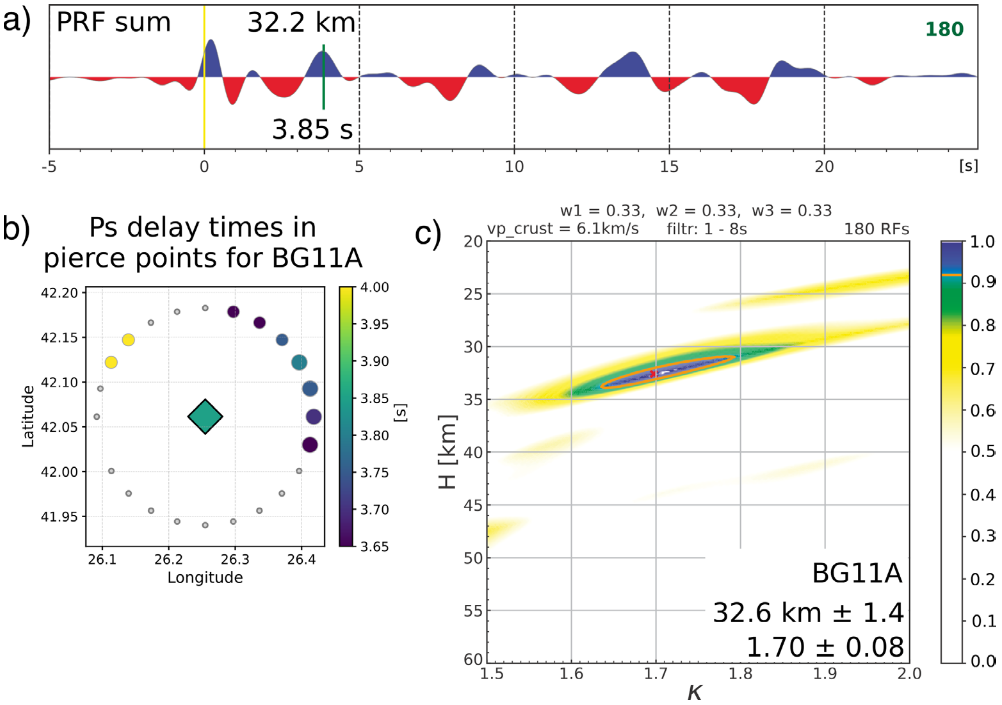

Figure 12. Example of the P Receiver Function (PRF) results at station BG11A: (a) the sum of PRFs over all available back-azimuths, the time delay of P-to-S arrival is migrated to the Moho depth according the IASP91 velocity model; (b) Ps delay times (colored dots) in piercing points at 35 km depth for 30° bins with half-width overlay with minimum 10 PRFs. Diamond represents the delay time from the PRFs sum, grey dots are bins where less than 10 PRFs were available; (c) the H-κ stacking plot by method of Zhu and Kanamori (2000) of the PRFs for the crust thickness and the V_P/V_S ratio estimates.

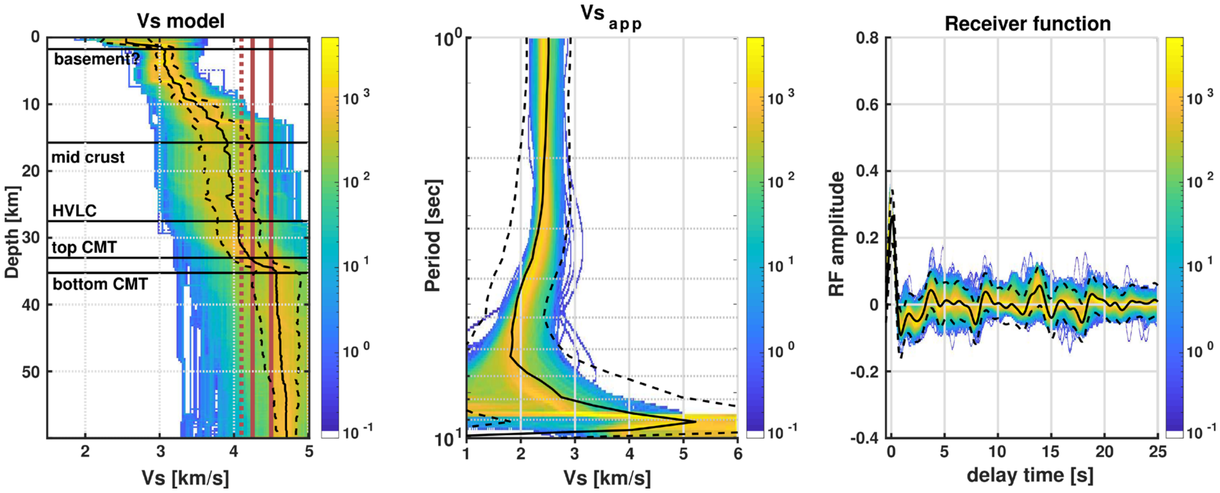

Figure 13. Example of inversion of PRF and apparent S-wave velocity (vSapp) for station BG11A (the same station as in Fig. 12) using the algorithm by Schiffer et al. (2024). The left plot shows the resulting 1D velocity model with interpretation of interfaces (solid black horizontal lines: basement: basement or bottom of uppermost velocity gradient; mid-crust: upper-lower crustal boundary; HVLC: top high velocity lower crust; CMT: crust-mantle transition zone). The colored background shows a density plot of 10 000 model estimations, weighted with their inverse total error. Black solid line shows the mean model. Black stippled lines show the uncertainties. Middle plot shows the observed vSapp (solid black line) and its uncertainties (stippled black line), as well as a weighted density plot of 10 000 forward vSapp corresponding to the 10 000 inverse models. Right panel shows the observed PRF (solid black line) and its uncertainties (stippled black lines), as well as a weighted density plot of 10 000 forward PRFs corresponding to the 10 000 inverse models.

5. Concluding remarks

Twenty five temporary stations of the Czech MOBNET and Danish DanSeis pools complemented the same amount of permanent stations of the Bulgarian National Seismic Network NOTSSI, to cover homogeneously the region as a part of the AdriaArray Seismic Network. In this paper, we describe in detail station sites and document station equipment, as well as data transmission and their storage. Before storing data from the temporary stations at the NIEP EIDA node, their quality is checked and in case of a transmission failure, they are complemented by data recorded off-line. For the period June 2022 – January 2025, data availability at the NIEP node exceeds 80% in general, and even exceeds 95% at some stations.Approximately 1.6 TB have been uploaded for temporary stations on the Bulgarian territory into the EIDA archive, during the first two and half years of the AdA experiment.

The huge amount of high-quality broadband data from the AdA experiment will improve in near future existing models of the crust and upper mantle. Currently existing models are based only on rarely-distributed permanent stations. Thus, the new data will provide, e.g., estimates of Moho depth and crust velocities at regions without any previous information. As an example, we present the shear-wave velocity depth distribution and the Moho depth in the Strandzha unit (southeast of Bulgaria). The estimates are based on the P-to-S receiver functions, and show the Moho as a transitional layer at depths of ~33-35 km. The high-quality data recorded during the AdriaArray passive seismic experiment contribute essentially to foreseen improving our understanding of the deformation of the lithosphere, to identifying tectonic boundaries of the Adriatic, Eurasian and African plates, to unraveling complex tectonic interactions and stress distribution, to investigating the long-term evolution of the lithosphere subductions and to refining models of crustal and mantle processes across south-eastern Europe through high-resolution 3D images, and all of that together to seismic hazard assessment.

Data availability statement. Waveform data obtained from the MOBNET and DanSeis stations included in AdriaArray in Bulgaria are available through ORFEUS EIDA node NIEP. The data from temporary stations (network code Y8) are accessible for the AdriaArray Seismology Group participants. Data from the permanent stations (network code BS) are publicly accessible with no restrictions. Two-year rolling embargo allows the data to be publicly available two years after its acquisition (https://orfeus.readthedocs.io/en/latest/adria_array_seismicnetworks.html). Data from all AdriaArray temporary stations are, however, immediately available for seismological observatories with monitoring and alerting duties within the AdriaArray region.

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