Structure and geodynamics of the Eastern Alps – Pannonian Basin transition using AlpArray Seismic Network data

Final report of the NRDI research project K141860 (former K124241)

1. Research goals and objectives

The Alpine orogen is the most studied and yet the most complex currently active mountain belt on Earth. Through centuries of geological and decades of geophysical investigations, the scientific community is still unable to provide a comprehensive three-dimensional (3D) structural image of this geodynamic system composed of several plates and platelets deforming in a diffuse pattern. The international AlpArray project (http://www.alparray.ethz.ch) was dedicated to finally shed light on the spatial structure and the temporal evolution of this densely inhabited European orogen with the help of a high-end seismological network as well as associated geological and geophysical investigations.

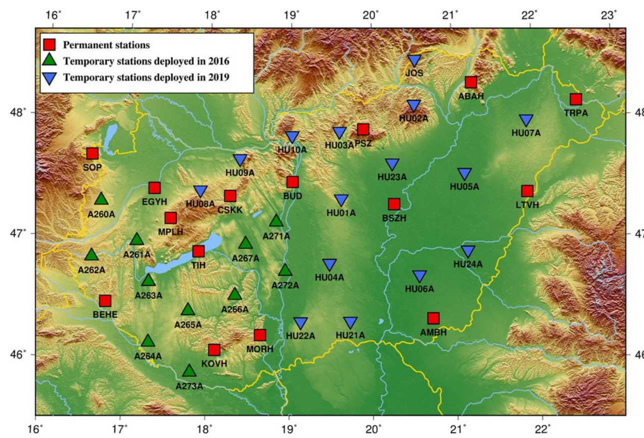
The tectonic evolution of the Pannonian Basin in an Alpine context has been intensively studied (e.g. Horváth 1993; Gerner *et al.* 1999; Bada *et al.* 1999, 2007; Fodor *et al.* 1998, 1999, 2005; Horváth *et al.* 2015 and references therein). However, as the investigations were mostly driven by field geology and geophysical studies for exploration purposes, the amount of information decreases rapidly with depth, and the connection to deep-crustal and mantle processes is comparatively scarce.

Therefore, the original aim of the research project was to investigate the lithospheric structure and present-day geodynamics beneath the Eastern Alps and the western part of the Pannonian Basin using seismological data and methods. We used data already recorded by permanent digital seismic stations as well as data collected by the aforementioned AlpArray Seismic Network to which we actively contributed.

2. Source of data: seismic network

AlpArray was a European collaborative project to study the structure and dynamics of the wider Alpine region. In the framework of the project, 36 institutions from 11 countries have deployed an unprecedentedly large and dense seismic network covering the whole Alpine area. The network consisted of 352 permanent and 276 temporary broadband seismological stations with a hexagonal compact spacing so that no point was left farther than about 30 km from a site (Hetényi *et al.* 2018). Officially, the data collection started on 1 January 2016 and ended on 1 April 2019, although many sites continued operating beyond that date.

The MTA CSFK Geodetic and Geophysical Institute (GGI) – presently the Institute of Earth Physics and Space Science (EPSS) –, as a core member of the AlpArray, contributed to the AlpArray Seismic Network (AASN) with 15 permanent and 11 temporary stations located in the western part of Hungary, covering the transition zone between the Eastern Alps and the Pannonian Basin. Additionally, three stations were operated jointly with the Swiss-AlpArray SINERGIA program (Gráczer *et al.* 2018).



Permanent and temporary seismic stations operating in Hungary since 2019.

Although in April 2019 the operation of the AASN was officially finished, all our stations continued to operate in the field. A cooperation was established between the GGI and the German Seismological Broadband Array (DSEBRA) consortium. While GGI moved its temporary stations to the eastern part of the country, the former AlpArray sites were equipped by DSEBRA. DSEBRA provided the equipment for 15 stations in Hungary including 11 former AlpArray stations in the western and four new stations in the eastern part of the country. As a result, since 2019, 41 broadband seismological stations (15 permanent and 26 temporal) have been operating in Hungary (Süle *et al.* 2020). The Pannonian Basin has never been covered by such a dense and equally distributed seismic network. This also means that a new era has begun both in monitoring the local seismicity and in seismological imaging of the region.

With the above-described seismic network, we also participate in an AlpArray Complementary Experiment called PACASE (**Pa**nnonian-**C**arpathian-**A**lpine **S**eismic **E**xperiment). Other partners in this international cooperation are institutes in Austria, Slovakia, Poland, Germany, the Czech Republic and Switzerland. The aim of this international project is to create a detailed structural and geodynamic model of the Pannonian Basin and its surroundings. The AASN data is already open to the public, the PACASE data will be open in 2025.

3. Results

3.1 Tomographic reconstruction of volumetric velocity images

In the pre-AlpArray era, only a few tomographic models were available from the crust of the Pannonian Basin (e.g. Wéber 2002; Szanyi *et al.* 2013; Ren *et al.* 2012, 2013). The sparse and non-homogeneous station geometry greatly affected the resolution of these models. Some regional models also included the Pannonian region. However, it was mainly situated at the edge of the investigated areas, so the achieved reliability was too crude to yield detailed conclusions on the velocity distribution beneath the basin (e.g. Ren *et al.* 2012, 2013; El-Sharkawy *et al.* 2020). Our research group has published several seismic tomography studies using the latest imaging methods over the years.

3.1.1 Local travel-time tomography

Seismic travel-time tomography has become one of the most frequently and effectively applied methods in seismology at local, regional and global scales. Knowing the velocity field of a particular region is extremely important in seismological research. It is an indispensable input for hypocenter determinations and can be used to reveal the location of discontinuities (Moho, lithosphere-asthenosphere boundary [LAB], etc.) and horizontal velocity anomalies, which contribute significantly to understanding the tectonics of a region.

Timkó *et al.* (2019) used joint local and teleseismic travel-time tomography to image the crust and upper mantle of the Pannonian region. For the 3D P-wave velocity structure, over 32,000 phase picks have been derived from the International Seismological Centre (ISC) and the local Hungarian National Seismological Bulletins. Although this P-wave model was an excellent baseline for further tomographic models, this study has not used time picks from temporary stations. A database of reliable phase picks of the seismic events are essential for travel-time-based tomographic methods and very often, the earthquake catalog of a given country is years behind the date and only contains the picks for permanent stations. Another problem with the seismic catalogs is the non-homogeneity of the arrival time estimations, so manual waveform pick selection is needed. At the beginning of 2020, two researchers left our institute, so picking a sufficiently large travel-time database was impossible. Nevertheless, we seek working on this topic in the future.

3.1.2 Local ambient noise tomography

Szanyi *et al.* (2021) published a new S-wave velocity model for the transition zone between the Eastern Alps and the Pannonian Basin. In this study, we used ambient noise-based surface-wave tomography. This approach can provide higher resolution images, especially for the crust. With this method, the empirical Green's function can be estimated between two seismological stations, which contain all the necessary information to describe the wave-dispersion properties of the volume. We processed the data from all available broadband seismic stations from permanent and temporary networks (AASN; Carpathian Basin Project [CBP]; South Carpathian Project [SCP]). The achieved horizontal resolution is 0.2° in the upper crust and 0.3°–0.5° in the lower crust, significantly better than any other model could achieve in the research area. This upper crustal shear velocity model revealed low velocities in the sedimentary depocenters and high velocities below the surrounding mountains. However, at greater depths (24–29 km), high shear velocities beneath the basins suggest crustal thinning accompanied by mantle updoming. A deep low-velocity anomaly was mapped beneath the Vienna basin, which we argue is caused by either sediment transfer to the lower crust, ductile deformation suggested by seismic anisotropy or the presence of fluids.

3.1.3 Joint surface-wave tomographic inversion of ambient noise and earthquake data on a regional scale

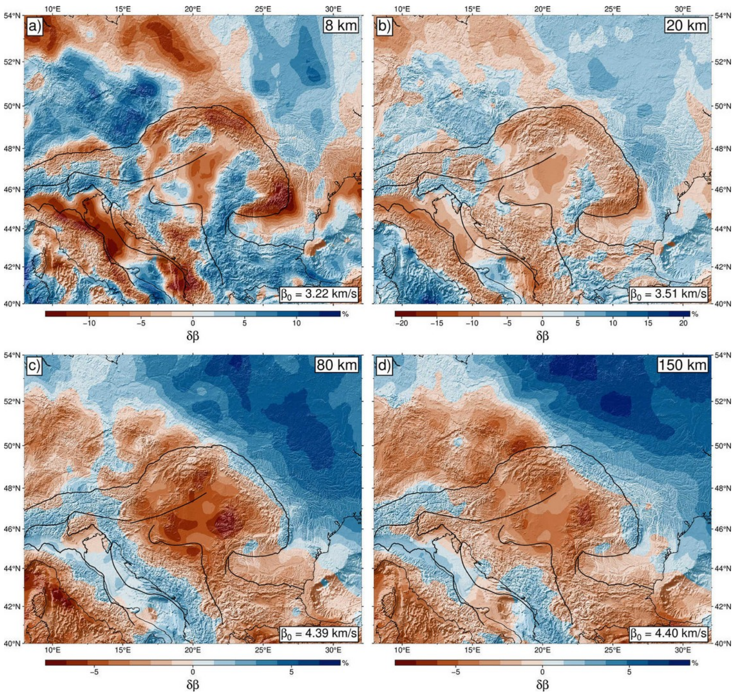
Classical earthquake-based surface wave tomographic imaging is fundamental in the geodynamic interpretation of a region. It is ideally suited to investigate the shear-wave velocity structure of the mantle lithosphere and the asthenosphere. Regional surface-wave studies recently reached the lateral resolution of about 200 km or even below 100 km in regions of dense station coverage (e.g. El-Sharkawy *et al.* 2020). The ideal approach is the joint inversion of surface wave dispersion measurements from both ambient noise and earthquake data because it provides high resolution for the crustal and the subcrustal structure as well.

To better understand the tectonic character and evolution of the Carpathian-Pannonian Region (CPR), a high-resolution model of the crust, the mantle lithosphere, and the asthenosphere is essential. The region's crustal structures are well documented by, e.g., classical active seismic, receiver functions, and ambient noise surface wave studies, but consistent imaging of the entire lithosphere remains a challenge.

Within the framework of the AlpArray project, and in strong international collaboration with the seismological research group of the University of Kiel, Timkó *et al.* (2022) present a new high-resolution 3D shear wave velocity model of the crust, mantle lithosphere, and asthenosphere for the broader CPR based on the joint tomographic inversion of ambient noise and earthquake data. For the 3D shear wave velocity structure estimation, we collected continuous waveform data from 1254 broadband seismic stations from the greater Pannonian region for ambient noise cross-correlation measurements. This dataset consists of waveforms from all the broadband seismological stations within the 9-degree radius of the Pannonian region from the time period between 2006 and 2018. Ambient noise phase velocity dispersion curves were calculated using the noise cross-correlation functions in the period range from 5 to 200 s. Following Soomro *et al.* (2016), a strict quality control workflow was applied to eliminate the inaccurate measurements, and around 165,000 dispersion measurements were kept. Finally, the ambient noise dataset was combined with existing phase velocity measurements from earthquake data in the period range of 8-300 s (El-Sharkawy *et al.* 2020).

At lower periods (< 50 s) and shorter inter-station distances, there is a well-documented systematic discrepancy between the dispersion measurements collected by the two methods (Kästle *et al.* 2016; Magrini *et al.* 2022). The phase-velocity curves measured by the noise-based method tend to be slower than the dispersion curves extracted by the classical earthquake-based method. The study presents a new methodological approach to eliminate this bias. The authors defined a correction term by comparing the phase velocity curves from the station pairs from both data sets (Timkó *et al.* 2022).

The resulting tomographic images reveal significant variations in lithospheric thickness and properties related to deep earth processes in the region. Although a detailed analysis will take place in the near future, some preliminary conclusions were presented at the last AlpArray meeting.



Horizontal S-wave velocity sections at four different depths in the wide Carpathian-Pannonian Region (Timkó et al. 2022).

At shallow depths, there are strong negative velocity anomalies of the deep sedimentary basins such as the Great Hungarian Plain, the Danube, Drava, the Miocene Molasse and Polish basins. Our model agrees with the Deep Seismic Sounding results of the earlier tomographic models published in the literature (Ren *et al.* 2013; Schippkus *et al.* 2018; Szanyi *et al.* 2021).

At greater depths, the features of the Moho topography and the associated updoming of the asthenosphere below the Pannonian region are clearly imaged. Northeast to the Trans-European Suture Zone, the thick cratonic lithosphere of the European Craton is indicated by high shear wave velocities. Thanks to the joint dataset and high station density, it is also remarkable that, in addition to the Pannonian region, the Alpine, the Dinaric and the East-Carpathian slabs are also resolved in great detail (Timkó *et al.* 2022). A remarkable feature is the steep negative anomaly beneath the north-western segment of the Carpathians and the adjacent Bohemian Massif. Its plate tectonic significance should be investigated in the near future.

The results of the joint inversion based on the ambient noise and earthquake-based dispersion curves contribute significantly to a better understanding of the recent geology and geodynamics of the Pannonian Basin.

3.2 Receiver function analysis for discontinuity mapping and anisotropy

Receiver function (RF) analysis is one of the most appropriate seismological methods for mapping sharp velocity discontinuities beneath a seismic station. We collected 454,089 three-component broadband waveforms from 3,098 teleseismic events at 221 stations in the CPR. To process such a large amount of data, we developed an automatic pre-processing and three independent quality control procedures (Kalmár *et al.* 2019, 2021).

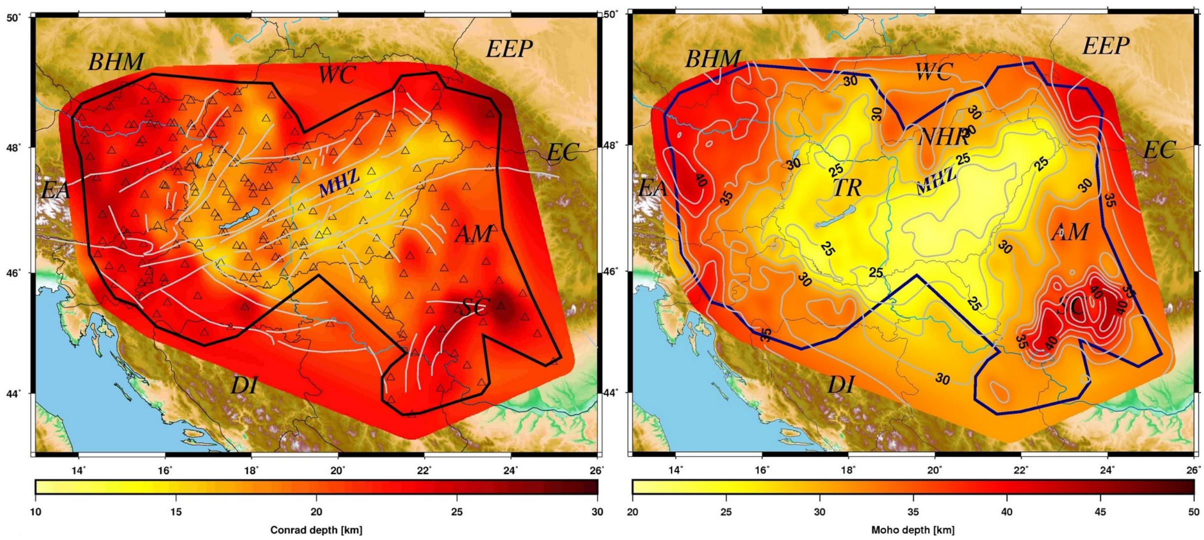
The most crucial step is the deconvolution of the ZNE components after the quality controls. In our forerunner article (Kalmár *et al.* 2018), we performed the deconvolution of the waveforms in the frequency domain (Ammon *et al.* 1990). Subsequently, for more stable and better defined discontinuity mapping, we calculated the radial and tangential RFs using the iterative time-domain deconvolution method (Ligorría and Ammon 1999) in this project (Kalmár *et al.* 2019, 2021).

With the full RF dataset in hand, we then employed three imaging techniques. First, we applied the station-wise H-K grid search algorithm (Zhu and Kanamori 2000) and the Common Conversion Point migration (Zhu 2000) to image the topography of the Moho, which resulted in a first-order approximation of the crustal structure (Kalmár *et al.* 2019).

Then, we focused on the 3D S-wave velocity structure of the area in more detail, which we determined by the Neighbourhood Algorithm inversion method (Sambridge 1999a,b) at each station, with back-azimuthal sub-division of the data into bundles of similar Ps delay times. These 1D, non-linear inversions provided the depth of the discontinuities, shear-wave velocities and Vp/Vs ratios of each layer locally, together with uncertainty estimates based on Kernel Density Estimation (Kalmár *et al.* 2021).

We then developed an interpolation method called **N**atural **N**eighbor **C**one **I**nterpolation (NNCI) to obtain the 3D crustal structure from the local inversion results. This interpolation method can handle data gaps between stations, in back-azimuthal coverage, as well as dipping discontinuities (Kalmár *et al.* 2021).

We mapped the thickness of the primary intracrustal layers and determined their S-wave velocity properties and Vp/Vs ratios (Kalmár *et al.* 2021). The Conrad depth, upper crust, and lower crust thickness maps are the first such maps for the Pannonian Basin region and will provide reliable constraints for geodynamical numeric modeling studies. We propose that the Conrad discontinuity is a change in velocity gradient between the upper and lower crust, rather than a large velocity jump at the lower-upper crust boundary. The obtained sedimentary layer thickness and Moho depth maps show a good correlation with previous ones, and are locally richer in detail than previous maps. Our Moho depth map reveals variations across the investigated area: the crust-mantle boundary is at 20–26 km beneath the sedimentary basins, while it is situated deeper below the Apuseni Mountains, Transdanubian and North Hungarian Ranges (28–33 km), and it is the deepest beneath the Eastern Alps and the Southern Carpathians (40–45 km). Overall, the dense seismic network with large amounts of quality-controlled data processed here allowed us to infer a 3D structural and shear-wave velocity model of the research area, which is valuable new information for any region.



Maps showing the depth of the Conrad (left) and Moho (right) discontinuities beneath the Carpathian-Pannonian Region. The thick line encircles the well-resolved area (Kalmár et al. 2021).

We also estimated the dip of the Moho from the Pannonian Basin to the neighbouring orogens, as well as locally some seismic velocity anisotropy values from the tangential RFs. Additional investigations are required, but these preliminary results are good starting points that help to understand the crustal thinning from the orogens to the back-arc basin.

Furthermore, we actively participated in the work of the AlpArray Receiver Function Working Group (Michailos *et al.* 2022). In this paper, we set up a homogeneous processing scheme to compute RFs using the time-domain iterative deconvolution method and apply consistent quality control to yield 107,633 high-quality RFs. We present a new Moho depth map for the broader European Alpine region, based on RFs and time-to-depth migration calculations of seismic waveform data from more than 600 broadband seismic stations.

Dániel Kalmár has obtained his PhD degree summa cum laude (Kalmár 2021) based on the above-mentioned articles.

3.3 Mantle anisotropy

Our research group has also used SKS splitting measurements to investigate the anisotropic features of the Carpathian-Pannonian system. Information on seismic anisotropy in the Earth's mantle can be obtained from shear-wave splitting analysis, which allows us to distinguish between single or multi-layered anisotropy. The delay time between the fast and slow polarized waves can indicate the thickness. It is also possible to study mantle peridotites where seismic properties can be inferred from lattice preferred orientation of deformed minerals. Previous shear-wave splitting studies have analyzed the recordings of the CBP, SCP and most of the permanent stations in the Pannonian Basin (Qorbani *et al.* 2016; Petrescu *et al.* 2020). The AlpArray project has provided an opportunity to significantly increase the number of splitting measurements. At the same time, the newly available misorientation data of the stations allowed us to account for them when measuring the shear-wave splitting parameters.

In the paper of Liptai *et al.* (2022), shear-wave splitting data and seismic properties of upper mantle xenoliths were jointly evaluated in the western part of the CPR to investigate the nature, depth extent and regional differences of mantle anisotropy. Based on our results, anisotropy differs in the northern and central-southern parts of the studied area. We also compared the results with seismic properties reported from mantle xenoliths to characterize the anisotropic layer's depth, thickness, and regional differences. The shear-wave splitting results, along with previous observations in the CPR, reveal a significant role of the asthenosphere in contributing to mantle anisotropy and deep seismic anomalies and surface topography. As a response to the tectonic inversion, the asthenosphere is vertically (or sub-vertically) foliated and forced to escape perpendicular to the NE-SW compression. This asthenospheric flow could explain anomalous features such as offset of Moho and LAB topographies in the NW and SE margins of the CPR (the Vienna Basin and Southeastern Carpathians, respectively).

3.4 Earthquake focal mechanisms and crustal stress field

In areas of low-to-moderate seismicity, such as the Eastern Alps and Pannonian Basin, small-magnitude local earthquakes provide the only key to determine fault parameters of small-scale tectonic structures. The focal mechanisms of small ($M < 4$) earthquakes can be used to infer the structure and kinematics of faults at depth and to constrain the crustal stress field in which the earthquakes occur. It is therefore important to determine the mechanisms of small events as accurately as possible.

Reliably estimating the mechanisms for small events is, however, quite challenging. A common scenario is that neither the available polarity data alone nor the well-predictable near-station seismograms alone are sufficient to obtain reliable focal mechanism solutions for weak events (Wéber 2006, 2009, 2016a,b; Wéber and Süle 2014).

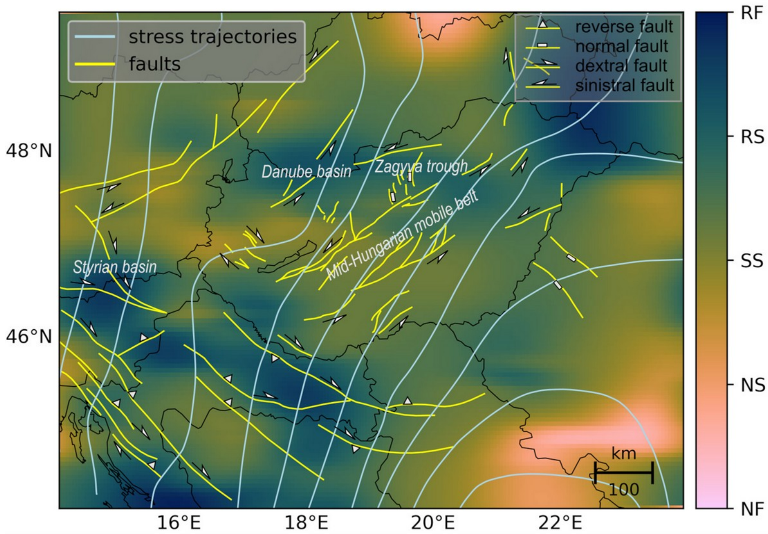
To handle this situation, in this project we have developed a new method that jointly inverts waveforms and polarity data following a probabilistic approach (Wéber 2018). The procedure called Joint Waveform and Polarity (JOWAPO) inversion maps the posterior probability density of the model parameters and estimates the maximum likelihood double-couple (DC) focal mechanism, the optimal source depth and the scalar seismic moment of the investigated event. The uncertainties of the solution are described by confidence regions. We have validated the method on earthquakes for which well-determined focal mechanisms are available. For more details, the reader is referred to Wéber (2018).

Using the newly developed JOWAPO method and the improved version of the previously developed Monte Carlo Moment Tensor (MCMT) inversion procedure (Wéber 2006, 2009, 2016a), we have compiled a new database of high-quality earthquake focal mechanism solutions in the central part of the Pannonian Basin. For this purpose, we primarily used waveform data from the Hungarian National Seismological Network (HNSN) and the temporary AASN (Gráczer *et al.* 2018; Hetényi *et al.* 2018). For larger events and events close to the national border, seismological data from neighboring countries were also utilized. When the amount and quality of the waveform data made it possible, we estimated the full moment tensor using the MCMT method, otherwise we calculated the DC focal mechanism applying the JOWAPO inversion. Altogether, we have calculated 50 high-quality focal mechanism solutions for seismic events in Hungary and near the borders of the country (e.g. Wéber *et al.* 2020).

For the latest information from regions further away from the Hungarian national border, i.e. from the peripheral regions of the Pannonian Basin, we have also retrieved the highest quality waveform inversion solutions recently published by international seismological organizations. In this way, we were able to add 32 additional focal mechanisms to our database, with moment magnitudes ranging from 3.5 to 6.4.

The new focal mechanism solutions in Hungary (50 events), as well as those collected from international agencies (32 events), well complement the World Stress Map (WSM16) database (Heidbach *et al.* 2016), which contains earthquake data up to 2016. The integration of the datasets provides 214 focal mechanism solutions, which is a very good basis for investigating the crustal stress field in the region.

In addition to the new and compiled focal mechanism solutions, we also collected stress indicators from borehole breakout analysis, overcoring measurements and geologic fault-slip data from the WSM16 database. Together with the earthquake data, the compilation yielded 368 horizontal stress (SH) observations that were interpolated to a regular grid to produce stress orientation and relative stress magnitude maps (Békési *et al.* 2022). The interpolated maximum SH orientations are generally marked by low uncertainties (mostly between 10° – 30°), indicating that the interpolated results can be considered reliable for the majority of the study area. Inferred SH directions show a good fit with previous studies, confirming earlier findings that the Pannonian Basin is under compression and transpression, controlled by the combination of its intracontinental position with the N-NE directed motion of the Adriatic microplate. The new tectonic regime map highlights several new features, such as the complete absence of extension in the entire Pannonian Basin. The determined stress regimes and trajectories calculated from interpolated SH directions generally agree well with the orientation and kinematics of neotectonic structures in the Pannonian region and reveal several new details. Additionally, measured and interpolated SH directions and faulting styles can provide boundary conditions for geomechanical studies, serving as valuable input for geo-energy applications (Békési *et al.* 2022).



Map of the revealed tectonic regimes and stress trajectories (light blue lines) with active fault structures (yellow lines) (Békési et al. 2022).

3.5 Earthquake location and seismicity

Accurate earthquake hypocenter parameters are a prerequisite for a better understanding of the neotectonic activity in the Pannonian Basin and for facilitating seismic hazard studies. We relocated the seismicity of the Pannonian Basin recorded in the digital instrumental period between 1996 and 2021 using the state-of-the-art iLoc location algorithm (Bondár and Storchak 2011) to obtain more accurate locations. Prior to the relocations, we downloaded additional phase and hypocenter data from the ISC Bulletin (http://www.isc.ac.uk) for events that occurred in the coordinate rectangle (45°N, 15°E – 49°N, 24°E). These data were associated with the events in the Hungarian National Seismological Bulletin (HNSB), so the bulletin contains all associated phases from local to teleseismic distances. Thanks to the temporary AASN (Hetényi *et al.* 2018), from 1 January 2016 the Pannonian Basin has an outstanding station coverage, which greatly contributes to the relocations and the identification of ground truth (GT) events.

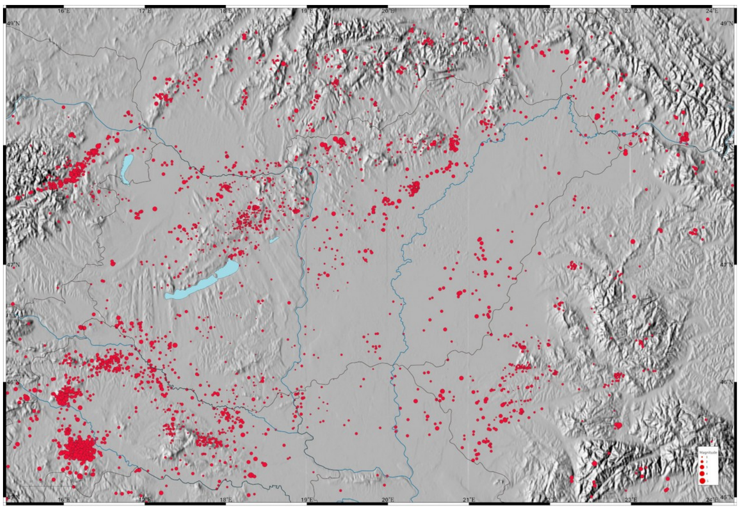
In the case of complex tectonic structures, 1D velocity models can cause systematic travel-time prediction errors over certain ray paths, which may result in location bias. Ground truth (Bondár *et al.* 2004; Bondár and McLaughlin 2009b) information, defined as events known with 5 km or better location accuracy at a high, 95%

confidence level, is necessary to evaluate and test the location performance of the various velocity models. We relocated 324 GT events using the global 1D ak135 (Kennett *et al.* 1995) travel time tables, two local 1D velocity models (Mónus 1995; Gráczer and Wéber 2012) and the 3D RSTT (Myers *et al.* 2010) velocity model. RSTT provides 90% location coverage, that is, the 90% confidence error ellipse contains the true location 90% of the time. For the local velocity models, however, the location coverage is only between 70-90%. Hence, we chose RSTT to relocate the entire seismicity of the Pannonian Basin (Bondár *et al.* 2018).

The application of the iLoc location algorithm with the RSTT velocity model has been implemented in the routine observatory practice at the Kövesligethy Radó Seismological Observatory of the EPSS.

We performed single-linkage hierarchical cluster analysis on the entire seismicity of the Pannonian Basin and successfully applied the Dynamic Tree Cut algorithm (Langfelder *et al.* 2008) to identify 84 event clusters that would be suitable for multiple-event location (Czecze and Bondár 2019). In order to prepare for the double-difference multiple event location analysis of the event clusters, we performed waveform cross-correlation on the filtered vertical, radial, and transverse components of the seismograms and obtained P- and S- differential times on every station between all event pairs. We also performed manual quality control to remove noise correlations from the database. With the waveform cross-correlation, a significant amount of good-quality differential time data has been obtained. The double-difference algorithm (Waldhauser and Ellsworth 2000) is a relative event location method. It combines the differential times and the differences between the arrival times of each phase in the bulletin data by minimizing the double difference for each pair of events, specifying the vector difference between hypocenters. In the relocation process, we used the iLoc (RSTT) locations as initial locations. HypoDD (Waldhauser 2001) employs a 1D velocity model, so we chose a local velocity model (Gráczer and Wéber 2012). We relocated the largest event clusters in the Pannonian Basin (Czecze and Bondár 2019; Wéber *et al.* 2020). The hypoDD relocations focus the initial locations into smaller clusters and provide improved solutions for events determined even with unfavorable station geometry. Combining the differential times from waveform cross-correlation with absolute travel time significantly contributes to the accuracy of the final solutions.

Based on estimates, some 50-60% of the events in the studied area are found to be anthropogenic that may be misclassified as earthquakes in the HNSB. We performed a second hierarchical cluster analysis using the correlation coefficients as a distance metric to re-identify mine blasts in the earthquake clusters. The correlation matrices were rearranged by the nearest-neighbor order obtained from the single-linkage cluster analysis. Anthropogenic events had considerably more acceptable correlations than natural events. With this method, we identified hundreds of explosions labeled as earthquakes, thus the geological interpretation is more reliable (Czecze and Bondár 2019).



Seismicity in the Pannonian Basin between 1996 - 2021

As a result of this work, the HNSB has been revised, the catalog is consistent and provides more accurate hypocenters for further studies. Our methodology opens a way for a systematic analysis of event clusters in the HNSB and helps to discriminate earthquakes and explosions and thus allows for a more reliable determination of the natural seismicity of the Pannonian Basin.

3.6 A homogeneous pan-Alpine gravity database

The AlpArray Gravity Research Group, as part of the AlpArray program, focuses on the compilation of a homogeneous surface-based gravity data set across the Alpine area. In 2017, 10 European countries in the Alpine realm, including our research group, agreed to contribute with gravity data for a new compilation of the Alpine gravity field. Gravity field investigations promote the interdisciplinary examination of the Alpine orogeny.

The new Alpine gravity data set (Zahorec *et al.* 2021) is the first of its kind in the sense that it is homogeneous regarding the input data sets, applied mathematical methods and corrections, as well as reference frames (positioning and gravity) over the entire Alpine area. The new Alpine gravity field covers an area of 2-23 °E and 41-51°N, the target resolution for each country is 1 point every 4 km^2. The Hungarian gravity data set for the collaboration consists of ~25,000 raw gravity data. We calculated the Bouguer anomaly in ellipsoidal approximations, mass correction densities used are 2670 kg/m^3 for landmasses, 1030 kg/m^3 for water masses above, and -1640 kg/m^3 below the ellipsoid. High-resolution national digital elevation models with spacing of 30 m were utilized for near-zone correction, while the global elevation model MERIT was applied for distant zone effects.

A first interpretation of the new map shows that the resolution of the gravity anomalies is suited for various studies from small to regional to continental scales, as well as for joint inversion with other (e.g. seismic) datasets.

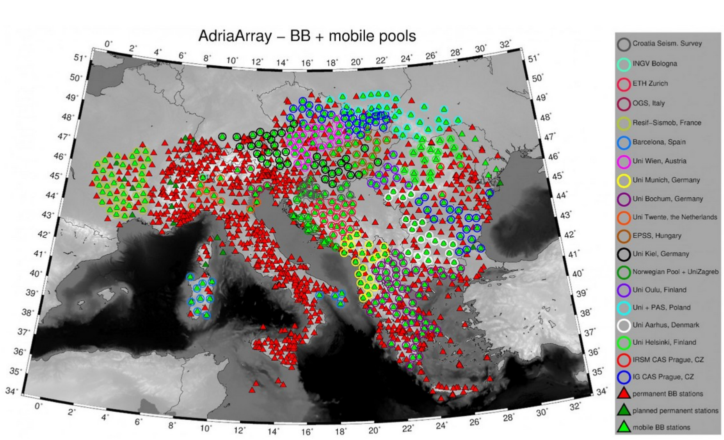
4. Options for future research

The new research results summarized in the previous section shed light on many aspects of the structure and present-day geodynamics of the Pannonian region. However at the same time, a number of questions remain open or have newly opened. Indeed, there are many opportunities to continue and expand our research.

A new, high-resolution 3D P-wave velocity model of the crust and uppermost mantle for the wider CPR should be constructed using travel-time tomographic inversion of arrival time data from all available permanent and temporary seismic stations.

In the crust and upper mantle, anisotropy is caused by aligned cracks or lattice-preferred orientations of minerals (e.g., olivine), which reflects the stress/strain status in the Earth. Thus, knowledge of anisotropy could provide important information for understanding the structure and geodynamics in the Earth. Therefore, the anisotropy in the CPR needs to be mapped in great detail using different approaches and across spatial scales. The classical SKS splitting analysis should be carried out for a much larger area than in this project. We can also apply Pn tomography, which can reveal the distribution of both the P-wave velocity and anisotropy in the uppermost mantle. Assuming an anisotropic Earth, ambient noise tomography could estimate the 3D anisotropic S-wave velocity model for both the crust and upper mantle with good vertical resolution (in this project we inverted for isotropic velocities). To explore anisotropy in the crust, we may also use receiver function analysis, providing very good vertical and reasonably good horizontal resolution.

The joint inversion of the new homogeneous pan-Alpine gravity dataset and the 3D P- and S-wave velocity models would also help to build a new structural model of the region.



The Carpathian-Pannonian Region is fully covered by the dense AdriaArray Network. Contributions of the different participating institutes are also indicated.

For these planned studies, we have or will have the necessary data, because the 15 permanent stations and all of the 26 temporary stations in Hungary will continue to operate for at least the next 2 years under the AdriaArray program, which was launched in 2022. The AdriaArray program is a new European initiative built on the successful AlpArray project. The large-scale seismic network of the AdriaArray will cover the entire Adriatic plate in south-eastern Europe and will seek answers to fundamental questions related to plate geodynamics and deformation. Given the fact that the entire CPR is more densely covered by this network than ever before, there is a good opportunity to continue our research in strong multinational cooperation and at a high international level.

References

The 18 publications marked with an asterisk have been published in the framework of this project.

Ammon CJ, Randall GE, Zandt G (1990) On the nonuniqueness of receiver function inversions, *J. Geophys. Res.* **95**, 15,303–15,318.

Bada G, Horváth F, Fejes I, Gerner P (1999) Review of the present day geodynamics of the Pannonian basin: progress and problems, *J. Geodynamics* **27**, 501-527.

Bada G, Horváth F, Dövényi P, Szafián P, Windhoffer G, Cloetingh S (2007) Present-day stress field and tectonic inversion in the Pannonian basin, *Global and Planetary Change* **58**, 165-180.

*Békési E, Porkoláb K, Wesztergom V, Wéber Z (2022) Updated stress dataset of the Circum-Pannonian region: implications for regional tectonics and geo-energy applications, *Tectonophysics* (submitted: tecto16013, 2022.10.04)

Bondár I, McLaughlin K (2009a) Seismic location bias and uncertainty in the presence of correlated and non-Gaussian travel-time errors, *Bull. Seism. Soc. Am.* **99**, 172-193.

Bondár I, McLaughlin K (2009b) A new ground truth data set for seismic studies, *Seism. Res. Let.* **80**, 465-472.

*Bondár I, Mónus P, Czanik C, Kiszely M, Gráczer Z, Wéber Z, the AlpArrayWorking Group (2018) Relocation of seismicity in the Pannonian Basin using a global 3D velocity model, *Seismol Res Lett.* **89**, 2284–2293.

Bondár I, Myers SC, Engdahl ER, Bergman EA (2004) Epicenter accuracy based on seismic network criteria, *Geophys. J. Int.*, **156** 483-496.

Bondár I, Storchak D (2011) Improved location procedures at the International Seismological Centre, *Geophys. J. Int.* **186**, 1220-1244.

*Czecze B, Bondár I. (2019) Hierarchical cluster analysis and multiple event relocation of seismic event clusters in Hungary between 2000 and 2016, *J Seismol* **23**, 1313–1326.

El-Sharkawy A, Meier T, Lebedev S, Behrmann JH, Hamada M, Cristiano L, Weidle C, Köhn D (2020) The slab puzzle of the Alpine-Mediterranean region: Insights from a new, high-resolution, shear wave velocity model of the upper mantle. *Geochemistry, Geophysics, Geosystems*, **21**, e2020GC008993.

Fodor L, Bada G, Csillag G, Horváth E, Ruszkiczay-Rüdiger Zs, Palotás K, Síkhegyi F, Timár G, Cloetingh S, Horváth F (2005) An outline of neotectonic structures and morphotectonics of the western and central Pannonian basin, *Tectonophysics* **410**, 15-41.

Fodor L, Csontos L, Bada G, Györfi I, Benkovics L (1999) Tertiary tectonic evolution of the Pannonian basin system and neighbouring orogens: a new synthesis of paleostress data. *In*: Durand B, Jolivet L, Horváth F, Séranne M (eds): The Mediterranean Basins: Tertiary extension within the Alpine Orogen. *Geological Society, London, Special Publications* **156**, 295-334.

Fodor L, Jelen B, Márton E, Skaberne D, Čar J, Vrabec M (1998) Miocene-Pliocene tectonic evolution of the Slovenian Periadriatic Line and surrounding area – implication for Alpine-Carpathian extrusion models, *Tectonics* **17**, 690-709.

Gerner P, Bada G, Dövényi P, Cloething S, Oncescu M, Müller B (1999) State of recent stress in the Pannonian Basin: data and models. – *In*: Durand B, Jolivet L, Horváth F, Séranne M. (Editors): The Mediterranean Basins: Tertiary extension within the Alpine Orogen. Geological Society Special Publications 156: 269–294.

*Gráczer Z, Szanyi G, Bondár I, Czanik C, Czifra T, Győri E, Hetényi G, Kovács I, Molinari I, Süle B, Szűcs E, Wesztergom V, Wéber Z, AlpArray Working Group (2018) AlpArray in Hungary: temporary and permanent seismological networks in the transition zone between the Eastern Alps and the Pannonian basin, *Acta Geodaetica et Geophysica,* **53**, 221-245.

Gráczer Z, Wéber Z (2012) One-dimensional P-wave velocity model for the territory of Hungary from local earthquake data, *Acta Geod. Geophys. Hun.* **47**, 344–357.

Heidbach O, Rajabi M, Reiter K, Ziegler M. (2016) World stress map database release 2016, GFZ Data Services, v. 10.

*Hetényi G, Molinari I, Clinton J, Bokelmann G, Bondár I, Crawford WC, Dessa J-X, Doubre C, Friederich W, Fuchs F, Giardini D, Gráczer Z, Handy MR, Herak M, Jia Y, Kissling E, Kopp H, Korn M, Margheriti L, Meier T, Mucciarelli M, Paul A, Pesaresi D, Piromallo C, Plenefisch T, Plomerová J, Ritter J, Rümpker G, Šipka V, Spallarossa D, Thomas C, Tilmann F, Wassermann J, Weber M, Wéber Z, Wesztergom V, Živčić M, AlpArray Seismic Network Team, AlpArray OBS Cruise Crew, AlpArray Working Group (2018) The AlpArray Seismic Network: A large-scale European experiment to image the Alpine orogen, *Surveys in Geophysics,* **39**, 1009-1033.

Horváth F (1993) Towards a mechanical model for the formation of the Pannonian basin, *Tectonophysics* **225**, 333-358.

Horváth F, Musitz B, Balázs A, Végh A, Uhrin A, Nádor A, Koroknai B, Pap N, Tóth T, Wórum G (2015) Evolution of the Pannonian basin and its geothermal resources, *Geothermics* **53**, 328-352.

*Kalmár D (2021) Crustal structure determination in the wider region of the Pannonian Basin from P receiver function analysis, PhD Thesis, Eötvös Loránd University, Budapest

*Kalmár D, Hetényi G, Bondár I (2019) Moho depth analysis of the eastern Pannonian Basin and the Southern Carpathians from receiver functions, *Journal of Seismology,* **23**, 967–982.

*Kalmár D, Hetényi G, Bondár I, Balázs A, AlpArray Working Group (2021) Crustal thinning from orogen to back-arc basin: the structure of the Pannonian Basin region revealed by P-to-S converted seismic waves, *J. Geophys. Res.,* **126**, Paper: e2020JB021309

*Kalmár D, Süle B, Bondár I, Alparray Working Group (2018) Preliminary Moho depth determination from receiver function analysis using AlpArray stations in Hungary, *Acta Geod. Geophys,* **53**, 309–321.

Kästle ED, Soomro R, Weemstra C, Boschi L, Meier T (2016) Two-receiver measurements of phase velocity: cross-validation of ambient-noise and earthquake-based observations, *Geophys. J. Int.*, **207**, 1493-1512.

Kennett BLN, Engdahl ER, Buland R (1995) Constraints on seismic velocities in the earth from traveltimes, *Geophys. J. Int.* **122**, 108–124.

Langfelder P, Zhang B, Horvath S (2008) Defining clusters from a hierarchical cluster tree: the Dynamic Tree Cut Package for R, *Bioinformatics* 2008 **24**,719–720.

Ligorria J, Ammon CJ (1999) Iterative deconvolution and receiver-function estimation, *Bull. Seism. Soc. Am.* **89**, 1395–1400.

*Liptai N, Gráczer Z, Szanyi G, Cloetingh SA, Süle B, Aradi LE, Falus G, Bokelmann G, Timkó M, Tímár G, Szabó C, Kovács IJ, AlpArray Working Group (2022) Seismic anisotropy in the mantle of a tectonically inverted extensional basin: A shear-wave splitting and mantle xenolith study on the western Carpathian-Pannonian region. *Tectonophysics*, 229643.

Magrini F, Diaferia G, El-Sharkawy A, Cammarano F, van der Meijde M, Meier T, Boschi L (2022) Surface-Wave Tomography of the Central-Western Mediterranean: New Insights Into the Liguro-Provençal and Tyrrhenian Basins. *J. Geophys. Res.*, **127**, e2021JB023267.

*Michailos K, Hetényi G, Scarponi M, Stipčević J, Bianchi I, Bonatto L, Czuba W, Di Bona M, Govoni A, Hannemann K, Janik T, Kalmár D, Kind R, Link F, Lucente FP, Monna S, Montuori C, Mroczek S, Paul A, Piromallo C, Plomerová J, Rewers J, Salimbeni S, Tilmann F, Środa P, Vergne J, the AlpArray, AlpArray-EASI and AlpArray-PACASE Working Groups (2022) Moho depths beneath the European Alps: a homogeneously processed map and receiver functions database, *Earth System Science Data* (submitted: essd-2022-397, 2022.11.18)

Mónus P (1995) Travel time curves and crustal velocity model for the Pannonian basin, *MTA GGKI Technical Rept.*, Hungarian Academy of Sciences, Budapest, Hungary, 12 pp.

Myers SC, Begnaud ML, Ballard S, Pasyanos ME, Phillips WS, Ramirez AL, Antolik MS, Hutchenson KD, Dwyer JJ, Rowe CA, Wagner GS (2010) A crust and upper-mantle model for Eurasia and North Africa for Pn travel-time calculation, *Bull. Seism. Soc. Am.* **100**, 640-656.

Petrescu L, Pondrelli S, Salimbeni S, Faccenda M, AlpArray Working Group (2020) Mantle flow below the central and greater Alpine region: Insights from SKS anisotropy analysis at AlpArray and permanent stations, *Solid Earth*, **11**, 1275-1290.

Qorbani E, Bokelmann G, Kovacs I, Horváth F, Falus G (2016) Deformation in the asthenospheric mantle beneath the Carpathian-Pannonian Region, *J. Geophys. Res.*, **121**, 6644–6657.

Ren Y, Grecu B, Stuart GW, Houseman GA, Hegedűs E, South Carpathian Project Working Group (2013) Crustal structure of the Carpathian–Pannonian region from ambient noise tomography, *Geophys. J. Int.* **195**, 1351-1369.

Ren Y, Stuart GW, Houseman GA, Dando B, Ionescu C, Hegedűs E, Radovanovic S, Shen Y, South Carpathian Project Working Group (2012) Upper mantle structures beneath the Carpathian–Pannonian region: implications for the geodynamics of continental collision. *Earth Planet. Sci. Let.*, **349**, 139-152.

Sambridge M (1999a) Geophysical Inversion with a Neighbourhood Algorithm - I. Searching a parameter space, *Geophys. J. Int.* **138**, 479-494.

Sambridge M (1999b) Geophysical Inversion with a Neighbourhood Algorithm - II. Appraising the ensemble, *Geophys. J. Int.* **138**, 727-746.

Schippkus S, Zigone D, Bokelmann G, AlpArray Working Group (2018) Ambient-noise tomography of the wider Vienna Basin region. *Geophys. J. Int.*, **215**, 102-117.

Soomro RA, Weidle C, Cristiano L, Lebedev S, Meier T, PASSEQ Working Group (2016) Phase velocities of Rayleigh and Love waves in central and northern Europe from automated, broad-band, interstation measurements, *Geophys. J. Int.*, **204**, 517-534.

*Süle B, Bondár I, Czanik C, Gráczer Z, Győri E, Szanyi Gy, Wéber Z, Kovács IJ (2020) How we are sensing every little vibration of our homeland. The development and mission of the Research Centre for Astronomy and Earth Sciences Geodetic and Geophysical Institute Radó Kövesligethy Seismological Observatory from 2013 to the present, *Magyar Tudomány*, **181,** 1202-1215. (*in Hungarian with English abstract*)

Szanyi G, Gráczer Z, Győri E (2013) Ambient seismic noise Rayleigh wave tomography for the Pannonian basin, *Acta Geod. Geophys.* **48**, 209-220.

*Szanyi G, Gráczer Z, Balázs B, Kovács IJ, AlpArray Working Group (2021). The transition zone between the Eastern Alps and the Pannonian basin imaged by ambient noise tomography, *Tectonophysics*, **805**, 228770.

*Timkó M, Kovács I, Wéber Z (2019) 3D P-wave velocity image beneath the Pannonian Basin using traveltime tomography, *Acta Geod. Geophys.*, **54**, 373-386.

*Timkó M, El-Sharkawy A, Wiesenberg L, Fodor L, Wéber Z, Lebedev S, Meier T, the AlpArray Working Group (2022) Crustal and upper mantle 3D Vs structure of the Pannonian Region from joint earthquake and ambient noise Rayleigh wave tomography. *Geophys. J. Int.* (submitted).

Waldhauser F (2001) hypoDD – program to compute double-difference hypocenter locations, *US Geol Surv Open File Report*, 01 113

Waldhauser F, Ellsworth WL (2000) A double-difference earthquake location algorithm: method and application to the northern Hayward fault, California, *Bull Seismol Soc Am* **90**, 1353–1368.

Wéber Z (2002) Imaging Pn velocities beneath the Pannonian basin, *Phys. Earth Planet. Int.,* **129**, 283-300.

Wéber Z (2006) Probabilistic local waveform inversion for moment tensor and hypocentral location, *Geophys. J. Int.* **165**, 607-621.

Wéber Z (2009) Estimating source time function and moment tensor from moment tensor rate functions by constrained L1 norm minimization, *Geophys. J. Int.* **178**, 889-900.

Wéber Z (2016a) Probabilistic waveform inversion for 22 earthquake moment tensors in Hungary: new constraints on the tectonic stress pattern inside the Pannonian basin, *Geophys. J. Int.,* **204**, 236-249.

Wéber Z (2016b) Source parameters for the 2013-2015 earthquake sequence in Nógrád county, Hungary, *J. Seismol.* **20**, 987-999.

*Wéber Z (2018) Probabilistic joint inversion of waveforms and polarity data for double-couple focal mechanisms of local earthquakes, *Geophys. J. Int.,* **213**, 1586-1598.

*Wéber Z, Czecze B, Süle B, Bondár I, AlpArray Working Group (2020) Source analysis of the March 7, 2019 ML=4.0 Somogyszob, Hungary earthquake sequence, *Acta Geod. Geophys,* **55**, 371-387.

Wéber Z, Süle B (2014) Source properties of the 29 January 2011 ML 4.5 Oroszlány (Hungary) mainshock and its aftershocks, *Bull. Seism. Soc. Am.* **104**, 113-127.

*Zahorec P, Papčo J, Pašteka R, Bielik M, Bonvalot S, Braitenberg C, Ebbing J, Gabriel G, Gosar A, Grand A, Götze HJ, Hetényi G, Holzrichter N, Kissling E, Marti U, Meurers B, Mrlina J, Nogová E, Pastorutti A, Salaun C, Scarponi M, Sebera J, Seoane L, Skiba P, Szűcs E, Varga M (2021) The first pan-Alpine surface-gravity database, a modern compilation that crosses frontiers, *Earth Syst. Sci. Data*, **13**, 2165–2209.

Zhu L (2000) Crustal structure across the San Andreas Fault, southern California from teleseismic converted waves, *Earth Planet. Sci. Let.* **179**, 183–190.

Zhu L, Kanamori, H (2000) Moho depth variation in southern California from teleseismic receiver functions, *J. Geophys. Res.,* **105**, 2969-2980.

Other publications of the project

PhD and BSc theses

Kalmár D (2021) Crustal structure determination in the wider region of the Pannonian Basin from P receiver function analysis, *PhD Thesis,* Eötvös Loránd University, Budapest

Németh K (2022) Mikroszeizmikus háttérzaj-adatok feldolgozása és diszperziós görbék előállítása az Északnyugati-Kárpátok területén, *BSc Thesis,* Eötvös Loránd University, Budapest

Conference papers

Timkó M, El-Sharkawy A, Wiesenberg L, Fodor L, Wéber Z, Lebedev S, Meier T, AlpArray Working Group (2022) 3D Vs model of the broader Pannonian region from the joint inversion of earthquake and ambient noise surface wave tomography, *Proceedings of the Third European Conference on Earthquake Engineering and Seismology,* September 4 - 9 2022, Bucharest, Romania, 4678-4682.

Conference abstracts

Kalmár D, Hetényi G, Balázs A, Bondár I, AlpArray Working Group (2021) Comprehensive receiver function analysis of the Pannonian Basin and its surrounding regions., In: *IAGA-IASPEI 2021 Abstracts*, Paper: IAGA21_2021_ABS_B1107

Kalmár D, Hetényi G, Balázs A, Bondár I, AlpArray Working Group (2021) The crustal structure of the Pannonian Basin and wider region from P-to-S receiver function analysis, In: *37th General Assembly of the European Seismological Commission ESC 2021 - Book of Abstracts,* Paper: ESC2021-S07-081

Kalmár D, Hetényi G, Bondár I (2019) Receiver function analysis of the transition zone between the Pannonian Basin and the Southern Carpathians, *Geophysical Research Abstracts,* **21**, Paper: EGU2019-503

Kalmár D, Hetényi G, Bondár I, AlpArray Working Group (2020) Moho depth determination in the Eastern Alps-Pannonian basin- Carpathian mountains region based on H-K grid search method and CCP migration of receiver functions, *Geophysical Research Abstracts,* **22**, Paper: EGU2020- 3334

Kalmár D, Hetényi Gy, Süle B, Bondár I (2018) Moho depth determination from P receiver function analysis in the Carpathian Basin, *36th General Assembly of the European Seismological Commission,* 2-7 September 2018, Valletta, Malta, Paper: ESC2018-S42-116

Kalmár D, Hetényi G, Süle B, Bondár I, the AlpArray Working Group (2018) Receiver function analysis in the Eastern Alps – Pannonian Basin transition zone, *Geophysical Research Abstracts,* **20**, Paper: EGU2018-464

Michailos K, Scarponi M, Stipčević J, Hetényi G, Hannemann K, Kalmár D, Mroczek S, Paul A, Plomerová J, Tilmann F, Vergne J, AlpArray Working Group (2022) Moho depths beneath the European Alps from receiver functions of the AlpArray Seismic Network, *EGU General Assembly 2022,* Vienna, Austria, 23–27 May 2022, EGU22-8174

Timkó M, El-Sharkawy A, Wiesenberg L, Fodor L, Wéber Z, Lebedev S, Meier T, AlpArray Working Group (2022) Crustal and upper mantle 3D Vs structure of the Pannonian Region from joint earthquake and ambient noise Rayleigh wave tomography, *EGU General Assembly 2022*, Vienna, Austria, 23–27 May 2022, EGU22-7892

Timkó M, Wéber Z (2018) 3D lithospheric structure of the Pannonian Basin from body-wave traveltime tomography, *36th General Assembly of the European Seismological Commission,* 2-7 September 2018, Valletta, Malta, Paper: ESC2018-S8-346

Timkó M, Wéber Z (2018) Lithosphere structure of the Pannonian Basin using seismic traveltime tomography, *Geophysical Research Abstracts,* **20**, Paper: EGU2018-10618

Timkó M, Wiesenberg L, El-Sharkawy A, Wéber Z, Meier T, AlpArray Working Group (2020) Lithospheric structure of the Pannonian Basin using Rayleigh wave ambient noise tomography – preliminary results, *Geophysical Research Abstracts,* **22**, Paper: EGU2020-10726

Timkó M, Wiesenberg L, El-Sharkawy A, Wéber Z, Meier T, AlpArray Working Group (2021) Crustal and upper mantle velocity structure of the Pannonian Region using Rayleigh wave ambient noise tomography, *Geophysical Research Abstracts,* **23**, Paper: EGU21-14525

Wéber Z, Czecze B, Gráczer Z, Süle B, Szanyi Gy, Bondár I, AlpArray Working Group (2020) Comprehensive analysis of the March 7, 2019 Somogyszob, Hungary earthquake cluster, *Geophysical Research Abstracts,* **22**, Paper: EGU2020-18040

Conference presentations

Czecze B, Süle B, Timár G, Bondár I (2018) Dendrogram analysis and multiple event relocation of Hungarian seismic event clusters between 200 and 2016, *36th General Assembly of the European Seismological Commission*, 2-7 September 2018, Valletta, Malta, Paper ESC2018-S42-994

Békési E, Porkoláb K, Broerse T, Wéber Z (2022) Present-day stress field and geodetic strain rate in the Circum-Pannonian region, *6th Annual AlpArray Scientific Meeting,* 12-14 October 2022, Prague, Czech Republic

Bondár I, Wéber Z, Süle B, Timkó M, Kalmár D, Czecze B (2020) Hungarian network, *ORFEUS / AdriaArray / EPOS SP 2020 workshop*, Online, 2-6 November, 2020

Fodor L, Handy M, Le Breton E, Kalmár D, Meier T, Rybár S, Sujan M, Timkó M, Wéber Z (2022) Transition of the Eastern Alps – Western Carpathians – Pannonian Basin – Dinarides, *6th Annual AlpArray Scientific Meeting*, 12-14 October 2022, Prague, Czech Republic

Gráczer Z, Szanyi G, Kovács IJ, AlpArray Working Group (2019) Seismic anisotropy beneath western Hungary, *Second AlpArray Science Meeting* (13-15 November 2019, Frankfurt, Germany)

Kalmár D, Hetényi G, Balázs A, Bondár I, AlpArray Working Group (2021) The Structure of the Pannonian Basin Region Revealed by P-to-S Receiver Function, *AlpArray Scientific Meeting,* 10-12 November 2021 (online)

Kalmár D, Hetényi G, Balázs A, Bondár I, AlpArray Working Group (2022) The crustal structure of the Pannonian Basin region from P receiver function analysis, *6th Annual AlpArray Scientific Meeting*, 12-14 October 2022, Prague, Czech Republic

Kalmár D, Hetényi G, Bondár I, AlpArray Working Group (2019) P receiver function analysis in the Pannonian Basin, *Second AlpArray Science Meeting* (13-15 November 2019, Frankfurt, Germany)

Kalmár D, Hetényi G, Bondár I, AlpArray Working Group (2019) Crustal structure and Moho depth determination in the Eastern Alps and the Pannonian Basin from receiver function analysis, *27th IUGG General Assembly* (8-18 July 2019, Montreal, Canada)

Szanyi G, Gráczer Z, Kovács IJ, AlpArray Working Group (2019) Shear wave velocity structure of the transition zone between the Eastern Alps and the Pannonian Basin from ambient noise tomography, *Second AlpArray Science Meeting* (13-15 November 2019, Frankfurt, Germany)

Timkó M, El-Sharkawy A, Wiesenberg L, Wéber Z, Lebedev S, Meier T, AlpArray Working Group (2021): 3D lithospheric structure of the Pannonian Basin from the joint inversion of earthquake and ambient noise surface wave tomography, *AlpArray Scientific Meeting*, 10-12 November 2021 (online)

Timkó M, Kalmár D, Süle B, Wéber Z (2021) Litoszféra-kutatás a Pannon-medencében: a magyar AlpArray program, *Magyar Tudomány Ünnepe 2021*

Timkó M, Szanyi Gy, Kalmár D, Gráczer Z, Bondár I, Süle B, Szűcs E, Wesztergom V, Wéber Z (2018) AlpArray in Hungary: Preliminary results, *First AlpArray Science Meeting* (29-30 August 2018, Zurich, Switzerland)

Timkó M, Wiesenberg L, El-Sharkawy A, Wéber Z, Meier T, AlpArray Working Group (2019) Ambient noise tomography in the Pannonian Basin, *Second AlpArray Science Meeting* (13-15 November 2019, Frankfurt, Germany)

Timkó M, Wiesenberg L, El-Sharkawy A, Wéber Z, Meier T, AlpArray Working Group (2019) Ambient noise tomography in the Pannonian Basin – Preliminary results, *AG Seismologie Science Meeting* (23-26 September 2019, Rastatt, Germany)

Wéber Z, AlpArray and PACASE Working Groups (2021) Earthquake focal mechanisms and recent stress field in the Pannonian basin, *AlpArray Scientific Meeting*, 10-12 November 2021 (online)

Wéber Z, Süle B, Czifra T, Gráczer Z, Kovács IJ, Schlömer A, Szanyi G, Szűcs E, Wesztergom V (2019) Towards a new era in seismological imaging of the lithosphere beneath the Pannonian Basin, *Understanding the multi-scale formation and evolution of orogens and sedimentary basins, ILP Task Force on Sedimentary Basins Workshop* (15-18 Oct. 2019, Hévíz, Hungary)

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