Acta Geodaetica et Geophysica (2024) 59:285–310
https://doi.org/10.1007/s40328-024-00434-1

ORIGINAL STUDY

The Pannon LitH$_2$Oscope magnetotelluric array in the Pannonian Basin

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Received: 29 September 2023 / Accepted: 15 January 2024 / Published online: 16 February 2024

Abstract
The Pannonian Basin is one of the best natural laboratories in the world to study the lithospheric response to continental extension and subsequent tectonic inversion. Here we address the topic of lithospheric structure by a combined geochemical and magnetotelluric analysis, which has been carried out in the framework of the Pannon LitH$_2$Oscope project. The main objective was to detect the resistivity distribution over the entire lithosphere by magnetotelluric measurements, considering the lithological resistivity properties and relate the results to the structure and evolution of the Pannonian Basin. The Pannon LitH$_2$Oscope MT array was used to estimate the depth of the Lithosphere-Asthenosphere Boundary (LAB), considering the legacy MT data and compared to previous estimates for the region. Using the MT and geomagnetic response functions, major structural zones of the Pannonian basin, such as the Mid-Hungarian Shear Zone or fault systems like the Makó Trough and the Békés Basin, were also imaged. In addition, we used the apparent resistivity soundings to compare 1D resistivity models computed from geochemistry and obtained from field MT measurements. This comparison provided new constrains for the composition, fluid and melt content variations at the local lithosphere-asthenosphere boundary. The Pannon LitH$_2$Oscope MT dataset and the results presented in this paper provide input for more complex 3D inversions and further investigations of the lithospheric structure in the Carpathian-Pannonian region.

Keywords Magnetotellurics · Pannonian Basin · Lithosphere-Asthenosphere Boundary (LAB) · Geochemistry

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1 Introduction

The geodynamics of the Pannonian Basin's lithosphere has been the subject of many stimulating and pioneer studies since it is one of the best natural laboratories in the world to study continental extension and subsequent tectonic inversion (Bada et al. 2007; Horváth 1993; Tari et al. 1999). There are other extensional basins worldwide such as the Basin and Range (North America), the Aegean Region (South-East Europe) and narrow rifts including the Baikal Rift and East African Rift system (e.g., Çemen 2010). The advantage of studying the Pannonian Basins, on the one hand, it is geologically very young; as extension terminated only around 9 Ma (Balázs et al. 2016; Matenco and Radivojevi 2012), while basin inversion (compression and shortening) is still ongoing (e.g., Bada et al. 2007; Békési et al. 2023; Porkoláb et al. 2023; Tari et al. 2020, 2023). On the other hand the area is easily accessible and has been the subject of several large scale geophysical surveys (e.g., CELEBRATION 2000 (Janik et al. 2009); Pannon Geotraverz (Posgay et al. 1995); Carpathian Basins project (Ren et al. 2012), AlpArray (Gráczer et al. 2018)). It has been always clear that a more complex understanding of these young tectonic events in the Pannonian Basin is only possible by joint efforts combining geochemical, petrologic, geologic and geophysical (e.g., magnetotellurics, seismology) approaches. This was aimed in the Pannon LitH$_2$Oscope Research project combining seismological, magnetotelluric (MT) and geochemical data from new MT and seismological network with unparalleled resolution and quality. The ultimate aim, besides refining the geological structure of the lithosphere-asthenosphere system beneath the Pannonian Basin, is to understand the nature of the lithosphere-asthenosphere boundary (LAB). The origin of the LAB is still controversial and several contrasting physical phenomenon have been already suggested (see Kovács et al. 2021 for a review). The Pannonian Basin is an excellent site for this purpose as the LAB is known to be shallow (Ádám 1996; Babuška et al. 1987 , 1992; Čermák 1993; Horváth 1993; Kalmár et al. 2019, 2023; Tari et al. 1999), and a vast body of structural and geological data are available from the previous decades (Csontos et al. 1992; Fodor et al. 1999; Haas 2012; Haas et al. 2014). Our study is timely, since more than six decades after the discovery of the modern plate tectonic theory (Dewey et al. 1973; Dietz 1962; Holmes 1965; Wilson 1966) it is still a hot topic what process(es) are responsible for the variation of the physical properties at the so-called lithosphere-asthenosphere boundary, which separates the rigid outer shell of the Earth from the deeper, low-viscosity interior, giving rise to the process of plate tectonics. In the research of lithosphere dynamics, an important question is how to define the LAB, what can be regarded as the thickness of the lithosphere, and what kind of physical parameter changes are relevant. Definitions of the boundary layer between the more 'rigid' lithosphere and the underlying much less viscous and rheologically weaker asthenospheric mantle are based on a number of various geophysical and geochemical proxies (Burov 2011; Tesauro et al. 2009). In the most probable concept, the asthenosphere is the consequence of partial melting (Green et al. 2010; Kovács et al. 2021) in the upper mantle. In a very recent receiver function study Hua et al. (2023) proposed that there is a globally present partially molten layer between the LAB and a horizon at ~ 150 km depth which could be equated with the low velocity zone (LVZ). However, alternative explanations for the LAB, such as elevated water content in nominally anhydrous minerals (Mierdel et al. 2007), elastically accommodated grain boundary sliding (Karato et al. 2015); variation in anisotropy (Rychert and Shearer 2011), stress induced amorphization of olivine grain boundaries (Samae et al. 2021) have also been proposed. The widely adopted thermal definition considers the lithosphere where the geotherm intersect the ~ 1300 °C upper mantle adiabat (Artemieva and Mooney 2001). In their pioneer paper Pollack and Chapman (1977) proposed a thermal definition for the mechanical lithosphere stating that the LAB coincides where the temperature exceed 85% of the dry solidus, which usually equals to 1100–1200 °C in most tectonic settings. The common characteristic of these explanation for the LAB is that they all have the capacity to explain to some extent the slower propagation of seismic shear waves and their higher attenuation at this boundary, however, many of these are unable to explain the commonly observed conductivity increase at the LAB (Eaton et al. 2009).

The presence of partial melt is known to increase the electric conductivity of rocks and decrease the seismic wave velocity (Jones et al. 2010). The decreasing shear wave velocity at the LAB creates a negative phase in seismic receiver functions which is used to infer the depth of the LAB (e.g., Kalmár et al. 2023; Kind et al. 2012). The higher electric conductivity enables us to detect the upper boundary of the asthenosphere in the Pannonian Basin using magnetotelluric deep soundings (Ádám 1963, 1965). The term LAB is used flexibly based on the specific geophysical method and the processing technique employed. The MT defines the so-called electrical LAB (eLAB), while our study also uses the seismic S-receiver function known as sLABrf also for a comparison. This distinction highlights that LABs determined through different methods are sensitive to variations in various lithospheric rock physical parameters. The latest seismic and MT determinations of the lithospheric thickness beneath the Pannonian Basin happened more than fifteen years ago, so it is rather actual to update and refine these results benefiting from data made available by the so far most dense seismic and MT networks and advanced evaluation methodologies. The new large-scale Pannon LitH_2Oscope MT array was used to discover several lithospheric features: (1) to estimate the depth of the lithosphere-asthenosphere boundary (eLAB) beneath the central part of the Pannonian Basin also including the legacy MT data from this region.; (2) the MT response functions were used applying the phase tensors and geomagnetic data (tipper vectors) to reveal the geoelectric structure of the lithosphere-asthenosphere system.; (3) apparent resistivity soundings were utilized to compare geochemically computed 1D resistivity models with field MT measurements. This comparison provides information on the conductivity variations at the eLAB and the possible geochemical and physical factors controlling this (e.g., water contents, presence of melt, temperature etc.).

1.1 The geological and research history background

The study area is an interesting terrain for lithospheric-scale MT array, where the continental lithosphere can be divided into two microplates (basement mega-units) with different tectonic histories: the ALPACA on the north and the Tisza-Dacia on the south, juxtaposed by the Mid-Hungarian Shear Zone (Fig. 1, e.g., Csontos and Nagymarosy 1998; Csontos and Vörös 2004). The two major microplates differ in their origin and Mesozoic strata as the ALCAPA unit show African affinity, while the Tisza-Dacia was rifted off the European margin (e.g., Haas 2012). In addition, near surface geology has a significant impact on the field MT measurements, as the aforementioned crystalline basement units of the Pannonian Basin are covered by up to 6–8 kms of sediments in the main depocenters, creating contrast with respect to the mid-mountains where the basement is exposed on the surface. This contrasting near surface geology (Tari et al. 2023) could cause variable quality of the MT soundings. Under these regional conditions, a new MT array can provide relevant additional geological results on the lithosphere of the Pannonian Basin.

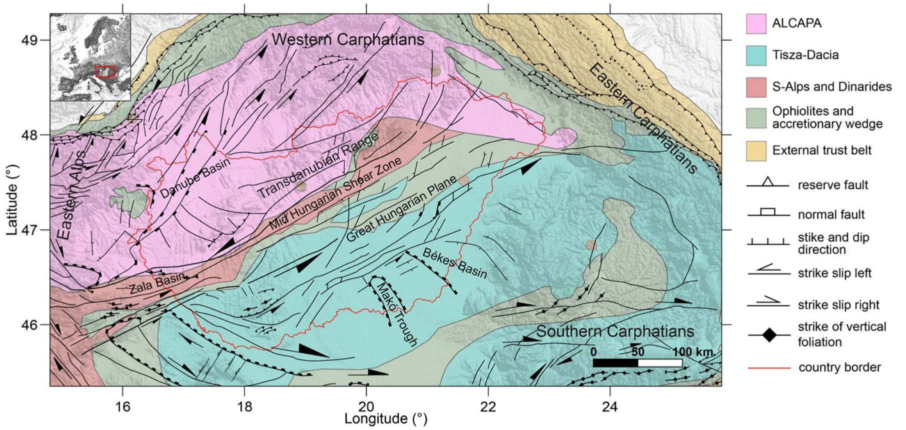

Fig. 1 Structural map of the Carpathian-Pannonian region with the main faults after Horváth et al. 2015 and main tectonic units after Schmid et al. 2008. The red line indicates the Hungarian border, which corresponds to the study area

The Pannonian Basin is a back-arc basin and has been formed in several consecutive steps over the past 20 My (Balázs et al. 2016; Fodor et al. 1999; Horváth 1993; Horváth et al. 2006; Tari et al. 1999). The ALCAPA mega-unit was extruded and rotated counterclockwise into the Carpathian embayment from the late Oligocene till the late Miocene (e.g., Balla 1988; Kazmer and Kovacs 1985). The Tisza-Dacia mega-unit occupied the Carpathian Embayment by clockwise rotation (Fodor et al. 1999). The occupation of the Carpathian Embayment by these two microplates was in part contemporaneous with significant extension of the lithosphere and resulted in the attenuated position of the asthenosphere (Horváth et al. 2006). After the two microplates occupied the embayment a new tectonic episode, the tectonic inversion stage commenced (e.g., Horváth 1993; Matenco et al. 2007; Tari 1994). This recent and still ongoing tectonic inversion is driven by the NE-SW convergence between the Adriatic plate and the stable European platform (Bada et al. 2007; Békési et al. 2023; Porkoláb et al. 2023). The main phase of the extension was accompanied by large scale mainly intermedier to felsic calc-alkaline magmatism, whereas the tectonic inversion was coeval with more localized and less voluminous alkaline basaltic volcanic activity (Harangi 2001; Kovács and Szabó 2008; Szabó et al. 1992; Seghedi et al. 2004). The two major mega-units are separated by the left lateral transpressional Mid-Hungarian Shear Zone (MHSZ), which experienced significant deformation during the extrusion and rotation of the microplates (Csontos and Nagymarosy 1998; Palotai and Csontos 2010). The MHSZ has been reactivated during the tectonic inversion and some of its parts are still currently active (Koroknai et al. 2020). There are two regionally significant young and very deep sub-basins (i.e., Békés Basin and Makó Trough) in the SE part of the Great Hungarian Plain (GHP), with their axes oriented perpendicular to the NE-SW compression direction (Békési et al. 2023). The MOHO is irregular at several locations in the vicinity of these deep basins and the asthenosphere is in a highly elevated position at ~ 40 km depth (Kalmár et al. 2019, 2021; Michailos et al. 2023; Posgay 1993; Tari et al. 1999) which is the shallowest in the Pannonian Basin.

The magnetotelluric (MT) method has been used in Hungary since the 1960s for studying the deep structure of the lithosphere (Ádám 1963). Up to the present day, many MT surveys have been implemented in the Pannonian Basin, some for scientific purposes, others for explorations. After the early applications, it soon became clear that this passive electromagnetic technique could be used to obtain information about the specific electrical resistivity structure of the entire lithosphere, including its thickness, since the resistivity of the underlying asthenosphere was believed to be significantly lower (Ádám 1978). In the Pannonian Basin the most recent lithosphere-asthenosphere boundary depth map based on MT data was published by Ádám and Wesztergom (2001) and an MT review study was compiled by Ádám et al. (2017). In the last three decades, the advance of digital broadband instrumentation and the use of robust data processing techniques for electromagnetic (EM) time series have brought significant development in MT measurements and data processing, which all made available better quality and wider period range MT datasets. On the other hand, many geophysical, geological, and geochemical observations and results were achieved in relation to the Pannonian Basin, making it timely to accomplish a new MT array in line with the state of the art tools.

2 The Pannon LitH$_2$Oscope MT dataset

2.1 Field campaign and measurements

The planning of the new large-scale Pannon LitH$_2$Oscope MT array started in 2018 and took almost 4 years to accomplish the planned measurements. We have installed an array of 40 long-period temporary MT stations covering the Hungarian parts of the Pannonian Basin (Fig. 2). The number and density of the MT stations were planned according to the positions of the broadband seismological stations which were also involved in the project. We aimed to minimize the distance between MT and seismological stations to achieve maximum combined sensitivity of the different geophysical measurements. In addition, it was also important to keep as much distance as possible from the electrical infrastructure

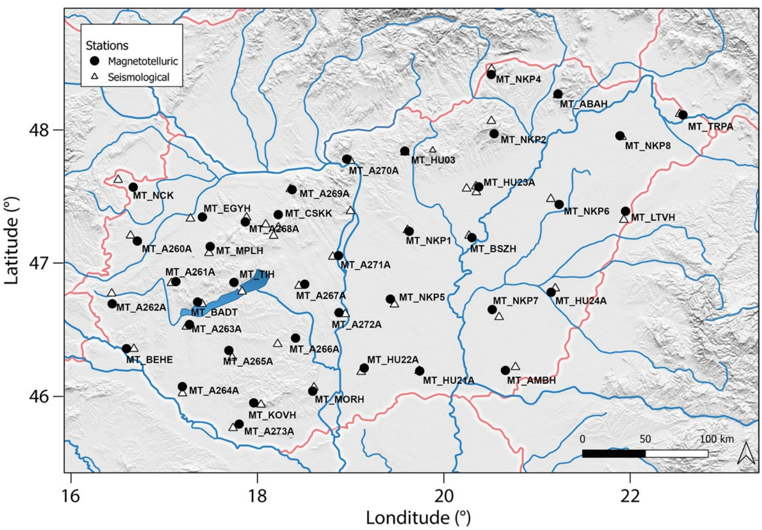

Fig. 2 Location of the MT measurements in the Pannon LitH$_2$Oscope campaign and the permanent seismological stations in the Pannonian Basin

including power grids and railway lines to reduce anthropogenic interference. These two prerequisites required a trade-off between the distance and the data quality as seismological stations are typically located on the outskirts of small settlements, which is usually not ideal for MT. Reference MT station was not used for the EM time series processing, making undisturbed field conditions particularly important. In most cases, the MT stations were located in national parks, set-aside cultivated areas or in wooded pastures and clearings. The LEMI 417 measuring system was used to record the five components (E_x, E_y, H_x, H_y, H_z) of the EM field with 4 Hz sampling. The duration of the MT measurements was on average 2 or 3 weeks, which in theory is sufficient to obtain stable, high-quality soundings up to at least 10,000 s. Based on a priori knowledge from the Pannonian Basin lithosphere (Tari et al. 1999), the penetration depth of this period must exceed the bottom of the lithosphere beneath the Pannonian Basin.

2.2 Time series processing and data quality

The time series processing of the EM field was performed using the EMTF code in single station mode at 48 frequencies on average (Egbert and Booker 1986; Egbert and Livelybrooks 1996). After pre-filtering and the frequency domain transformation, the most reliable period range of long-period soundings was between 50 s and 10,000 s. Periods shorter than 50 s usually show a truncation, so that part of the data was removed. Periods above 10,000 s were usually ignored from the individual soundings during the evaluation due to increasing uncertainty (large deviations from the trend). The soundings can be found in Supplementary Material 1a. Some MT stations were excluded from further interpretation steps because their soundings did not show a continuous trend and had significant uncertainties. These MT stations are MT_EGYH, MT_A262A, MT_A261A, and MT_MPLH.

The data quality of the MT stations was visually checked. The best quality data were recorded in the plain areas, where the sediment thickness is several kilometres and the topography is nearly horizontal, with a variation of a few meters only. In contrast, mountainous and hilly regions provided poorer results. Even where the basement crystalline rocks are not exposed on the surface but only covered by a thin sediment layer, sounding trends could be distorted and shifted. A plausible reason for this difference in quality could be the presence of high-resistivity rocks close to the measurement site, or the variable topography, which could result in a highly distorted telluric current configuration around the MT stations (Jones 1983). The static shift of the MT soundings was corrected using nearby archival MT station data, but otherwise the dataset was not modified, and theoretical decomposition transformations were not used in the interpretation.

3 Methodology

3.1 eLAB depth maps from MT data

The thickness of the lithosphere in MT inversion models can be determined from the position and magnitude of the resistivity drop at the depth of the eLAB (Heinson 1999; Jones et al. 2010; Korja 2007). On this boundary, both the lithospheric mantle and the asthenosphere resistivities depend on depth, therefore the magnitude of the contrast is less important than the actual depth of the eLAB. Our simple approach was to use 1D simple layered inversion of the MT soundings, then use Kriging interpolation of the estimated 1D eLAB depth values for map-view visualizations. The challenge in this approach lies in the ambiguous models of the 1D MT inversions.

The inversion was performed using the invariant (INV) mode sounding (average of TE and TM modes) in WinGLink software (GEOSYSTEM SRL 2008). The fitting usually included three layers, but in some cases the fit was better if different layer settings were applied. The reliability of the inversion was confirmed by the low root mean square (RMS) misfit values achieving the best fitting between the observed data and the computed model results. The depth of the lowest boundary layers of the 1D MT inversion models were considered as the depth of the eLAB. MT stations with inadequate data quality or without a decreasing apparent resistivity trend at higher periods were not suitable for eLAB depth estimation and hence were excluded from the further interpretation. We note that eLAB depth maps could also be created by applying 3D MT inversions. However, in this case, it would be challenging to rigorously define the position of the eLAB because of the depth-dependent variability in apparent resistivity. For this reason, we preferred to use the more straightforward multi-1D approach outlined above.

3.2 Geoelectric structure

The geoelectrical structure of the lithosphere was analysed using induction arrows and phase tensor ellipses based on the stable period range of the MT dataset between 100 s and 10,000 s. The results were plotted using the MTPy python toolbox (Fig. 6; Kirkby et al. 2019; Krieger and Peacock 2014). Geomagnetic data can be used to determine the 'induction arrows' or tipper vectors, which represent the relationship between the horizontal H_x, H_y and the vertical H_z magnetic field components. In our study, the Parkinson's convention was used where the arrows point towards the well-conducting anomaly, in other words, to the electric current concentration (Parkinson 1959; Wiese 1962).

The MT phase tensor was determined to analyse the geoelectric structure of the medium (Bibby et al. 2005; Caldwell et al. 2004). The phase tensor can be expressed in terms of the real and imaginary parts of the impedance tensor, which is theoretically free from galvanic distortion effects caused by resistivity distributions. This tensor, as any second rank matrix, can be represented graphically with an ellipse. In a 1D layered uniform medium, two parameters are used to describe the phase tensor, the minimum and maximum values of the phase, which are the minor and major axes of the ellipse. These are equals in 1D, thus a circle is obtained, because there is no horizontal change in the resistivity. If the geometry is 2D, the diagonal elements of the matrix might differ, in which case the minor and major axes are no longer equal, therefore an ellipse is obtained. As a consequence, a new parameter becomes necessary: the ellipse can be rotated by an α azimuth angle with respect to the major axis, which defines the direction of the geoelectric strike (i.e., the orientation of the higher electrical conduction). In general, when the resistivity geometry becomes 3D, none of the tensor elements are zero anymore. For such cases, one other parameter has to be defined, called the skew angle β, the deflection angle of the ellipse's orientation with respect to the strike. The β skew angle specifies the asymmetry of the impedance tensor. If the skew angle is beyond the range between -3° and 3°, the subsurface resistivity distribution is considered increasingly 3D.

3.3 Forward models of electrical resistivity in lithosphere-asthenosphere columns

Electrical properties of rocks are influenced by several factors besides pressure and temperature, such as modal composition, iron, 'water' (i.e., structurally bound hydroxyl) content of minerals, and the amount of partial melt in the rock matrix. Having an a priori range of these parameters, forward models can be constructed to calculate the electrical resistivity in a particular lithological column. These 1D resistivity profiles can be transformed into synthetic MT soundings and compared with field MT soundings, to constrain the depth-dependence of the geochemical parameters.

Resistivity profiles were calculated for the lower crust and the mantle, up to 120 km depth. Resistivities for the upper crust (i.e., between the Conrad discontinuity and the surface) were estimated from shorter period MT measurements in the vicinity of the stations. For the lower crust, a simple Arrhenius equation was used with enhanced water concentration, for an average composition of 30 vol % clinopyroxene, 10 vol % orthopyroxene, 20 vol % plagioclase and 40 vol % garnet with water contents of 200, 50, 50 and 10 ppm, respectively. This lower crustal modal composition is in line what is observed in lower crustal xenoliths from the Pannonian Basin (Dobosi et al. 2003; Kovács and Szabó 2005; Török 2007; Török 2012; Török et al. 2014). Parameters in 'wet' conditions were taken from Yang et al. (2011) for clinopyroxene, from Yang et al. (2012) for orthopyroxene and plagioclase, and from Liu et al. (2019) for garnet.

Mantle resistivities were calculated following the steps detailed by Kovács et al. (2018), using equations provided by Fullea (2017), which account for different conduction types (small polaron, ionic and proton conduction) at high temperatures. We used the parameterisation 'PC1'; parameters for amphibole were adopted from Hu et al. (2018). To obtain depth-dependent temperature profiles, geotherms calculated for different surface heat flow values (Liptai et al. 2017) were applied at the different locations based on the heat flow map of Hungary (Lenkey et al. 2021). For the mantle composition, a lherzolitic mineral assemblage averaged from mantle xenolith data all over the Carpathian-Pannonian region (Aradi et al. 2017; Falus et al. 2008; Liptai et al. 2017) was applied with an Mg-number of 0.9 for both olivine and pyroxenes. Water contents of the nominally anhydrous mantle minerals (olivine, orthopyroxene, clinopyroxene and garnet) were considered in three different hydration states. 'Dry' mantle was based on water contents from xenoliths of the Nógrád-Gömör Volcanic Field (Patkó et al. 2020); 'intermediate' water contents were taken from xenoliths of the supra-subductional mantle of the Styrian Basin (Aradi et al. 2017); and 'wet' mantle was based on the experimental water-saturated conditions at 2.5 GPa (Kovács et al. 2012). Finally, the effect of small amount of partial melt with dissolved H_2O and CO_2 was calculated with the method of Sifré et al. (2014) for the asthenosphere. In the melt different H_2O and CO_2 contents were assumed as these volatiles are known to significantly influence the conductivity even in small concentrations (< 1 wt %). Depths of the LAB were considered as the negative phase depths of Kalmár et al. (2023). For the details see Supplementary Table 1.

A general model test was conducted to investigate the effect of the geotherm, modal composition, structural hydroxyl content of nominally anhydrous minerals, pargasite (a common hydrous mineral in the upper mantle) and melt contents. In the parameter test calculations, the H_2O and CO_2 contents were also varied in given melt proportions (0.5 and 2%) in the 6–0.2 wt.% and 2–0.005 wt % ranges respectively (see Supplementary Table 1). These tests revealed that the geotherm, the structural hydroxyl contents of nominally anhydrous minerals and the melt content play the most prominent role, whereas the modal composition and the pargasite content have only a subordinate effect (Fig. 3). Based on these results for the actual lithospheric columns we adopted always the local geotherm and uniform modal compositions for the different layers (lower crust, lithospheric mantle, and asthenosphere) and constructed several alternative resistivity models with different structural hydroxyl contents (dry, intermediate, and wet) in NAMs and melt contents (Supplementary Table 1).

4 Results

31 out of 40 stations were found to be adequate for determining the eLAB depth, selected based on data quality and the suitability of the 1D inversion model results. In addition, we also used the data of legacy MT stations to constrain the eLAB depth. Legacy MT data selection was based on similar criteria as for the Pannon LitH$_2$Oscope MT array (Supplementary Materials 1b). There are hundreds of legacy MT stations in our database from the Pannonian Basin, but only 26 were suitable for estimating the eLAB depth applying our quality protocol. For characterizing the geoelectric structure

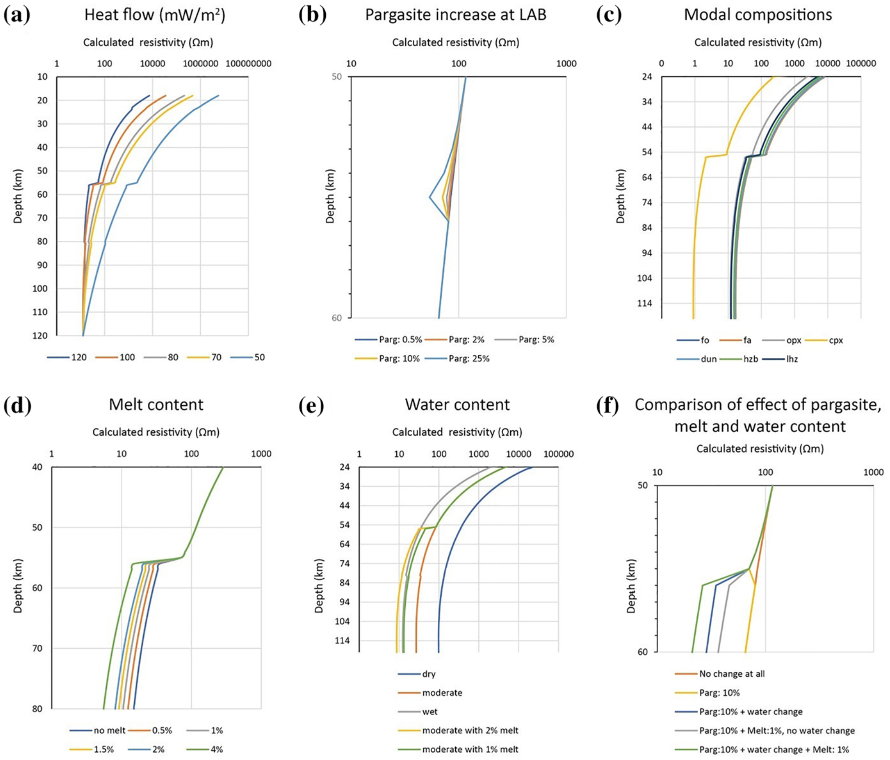

Fig. 3 Geochemical sensitivity test for the lithological resistivity columns: **a** The heat flux, **b** The pargasite level at LAB, **c** The modal composition of the lithological resistivity columns, **d** Melt content, **e** Water content and **f** The pargasite, melt and water combine effects. In the lithological columns the LAB depth was at 55 km. From **b** to **f** the 100 mW/m^2 heat flow geotherm was used for the calculations

of the basin, we only used the new MT array due to the lack of induction data in archive MT measurements. 36 MT stations were used to characterise the geoelectric structure, and only the stations with noisy data were omitted. Furthermore, to investigate the fit between measured and modelled lithospheric resistivity columns, 3 MT stations were chosen from different regions of the Pannonian Basin.

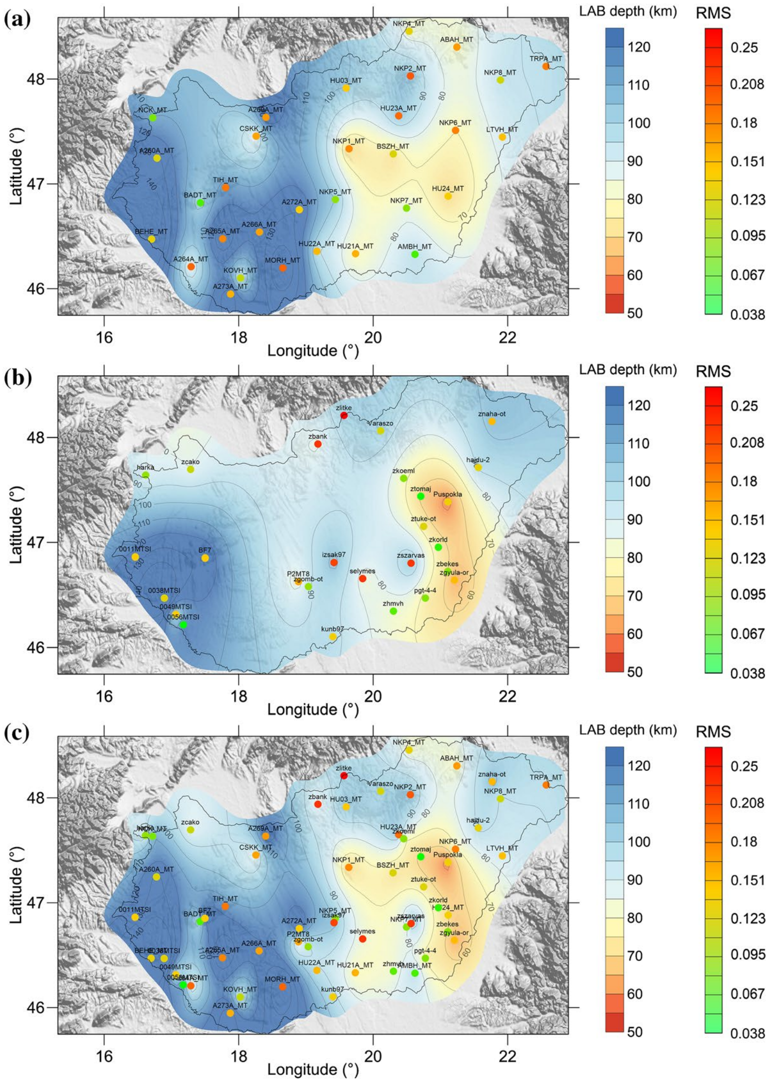

Fig. 4 eLAB depth maps from: **a** the Pannon LitH$_2$Oscope MT array, **b** the legacy MT stations and **c** the combined MT dataset. The colour of the MT stations shows the RMS value for the 1D inversion model fit

4.1 Soundings and eLAB depth maps

The construction of the eLAB maps was performed using different data sets: the Pannon LitH_2Oscope MT array, the legacy, and the joint MT datasets (Fig. 4). The Pannon LitH_2Oscope MT measurements provide a nearly uniform coverage in the Hungarian Pannonian Basin (Fig. 4a). However, close to the Transdanubian Range and the Danube Basin, the coverage was weak due to the insufficient MT stations for eLAB depth determination. The regional coverage of the legacy MT stations is worse than that of the Pannon LitH_2Oscipe MT array, therefore a major part of the legacy eLAB map is only interpolation (Fig. 4b). For the archive measurements, the Great Hungarian Plain measurements have the smaller fitting errors. We note that the low RMS misfit itself does not necessarily mean the good quality of the MT soundings (1D inversion fitting can be find in Supplementary Material 2). The legacy MT data has significantly greater uncertainties than the Pannon LitH_2Oscope MT array, hence the eLAB estimations from the old data are certainly less reliable. This is not surprising, since most of the archival MT measurements were made decades earlier in a series of different surveys (Ádám et al. 2008; Kiss and Madarasi 2012) and their purpose was to investigate just a certain parts of the lithosphere and not the whole in the Pannonian Basin.

The eLAB depth map based on the combined Pannon LitH_2Oscope and legacy MT data show that several regions have consistent eLAB depth values (Fig. 4). In the GHP, all the maps show thin eLAB depths between 60 and 100 km. The depth estimation in this region was affected by a significant anisotropy at longer periods. In the South Transdanubia, the estimated depth exceeded 100 km from most of the soundings, however, in some cases, it was difficult to identify the signal of the asthenosphere. Consequently, the eLAB depth determinations are less certain in this region. In the Transdanubian Range, some MT soundings from the Pannon LitH_2Oscope array were highly distorted. Similar distortions were observed for the archive long-period MT sounding from the same region. Based on the remaining MT soundings from here, the estimated eLAB depth is close to 100 km, but with a significant uncertainty. Approaching the Alps and the Carpathians the estimated eLAB depths increase over 100 km. It can be stated, from the whole MT dataset in the Pannonian Basin, the most reliable results are from the Great Hungarian Plain region.

4.2 Phase tensors and induction arrows in the Pannonian Basin

The geoelectric structure of the Pannonian Basin is characterized by the induction arrows and phase tensors computed from the Pannon LitH_2Oscope MT array (Fig. 5, further detailed maps, between 50 s and 10,000 s, can be found in Supplementary Material 3). For the lower periods (i.e., shallower depths) of the dataset, both quantities are strongly influenced by the geometry of the crystalline basement and its geometry in the Pannonian Basin (Fig. 5a). Here most of the induction arrows point towards deep sediment-filled basins, which represent well-conducting anomalies in the upper crust (Fig. 5b, d). Furthermore, along large normal faults and related steep basin margins, the elongated geometry of the phase tensor ellipses indicates the direction of the geoelectric strike. Good examples of such induction arrows and phase tensors are the Makó Trough and Békés Basin in the SE part of the Great Hungarian Plain (Fig. 5b), and the Zala Basin in the Transdanubian region (Fig. 5d). In these short periods, the geoelectric structure is dominated by local anomalies, which results in the frequent changing of induction arrows and phase tensor ellipses directions. The influence of the local anomalies becomes weaker as the period (and depth) increases. The induction arrows start to become

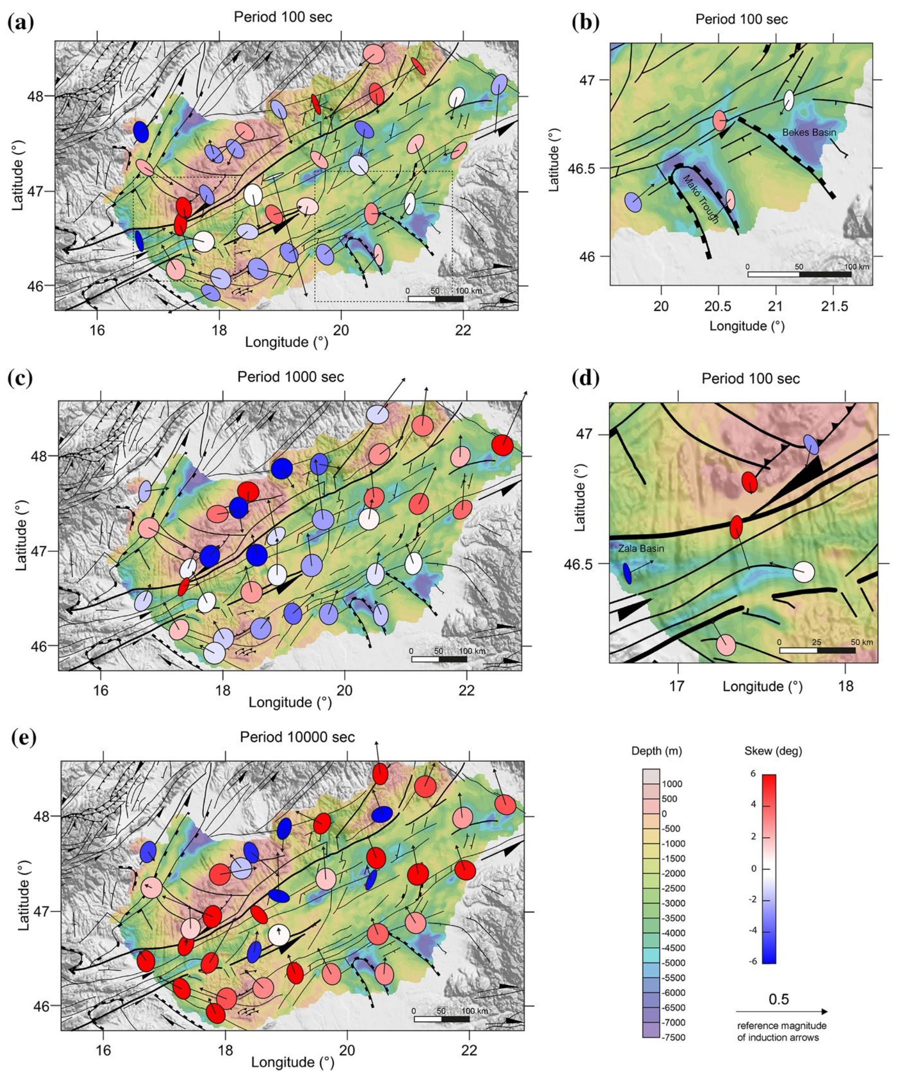

Fig. 5 Phase tensors and induction arrows of the Pannon LitH$_2$Oscope MT dataset in the Pannonian Basin for three periods of (**a**) 100 s, (**c**) 1000 s and (**e**) 10,000 s. The background colours show the depth of the pre-Cenozoic basement (i.e., sediment thickness), black lines indicate main faults. The behaviour of the induction arrows and phase tensors illustrated with two highlighted examples at 100 s for (**b**) the Makó Trough and the Békés Basin and (**d**) the Zala Basin. The induction arrows point towards the better conducting area (Parkinson convention). The major axis of the phase tensor ellipses shows the geoelectric strike when its shape is elongated. Otherwise, the more circular shape and the high skew angle indicate the geoelectric strike is not certain, and the dimension of the medium is close to 3D

visually more ordered at 1000 s, while the phase tensor ellipses become more rounded, making the geoelectric strike direction less dominant (Fig. 5c). The most evident anomaly at 1000 s is the opposite directions of the induction arrows along the Mid-Hungarian Shear Zone, which is a major fault zone in the Pannonian Basin separating the ALCAPA and Tisza-Dacia basement mega-units (e.g., Csontos and Nagymarosy 1998; Csontos and Vörös 2004). Except for the induction arrows in the NW area that point S-SE towards the fault zone, a general northward pointed ordering of the induction arrows is observed. At this period, the extent of near-surface effects must be negligible, therefore the depth of this conductive anomaly could even reach the lithospheric mantle in several tens of kilometres depth. Apart from the lower quality measurements with increasing periods a slight decrease occurs in the length of the induction vectors, with slight change in the shape of the phase tensor ellipses. The skew angle is remarkably high for many soundings over a significant range of periods, implying strongly 3D resistivity distribution in the Pannonian Basin. With few exceptions, all induction arrows in the 10,000 s period show a clear and consistent northward direction, which may originate from the lower part of the lithospheric mantle or the upper part of the asthenosphere (Fig. 5e). These deep northward pointing induction arrows suggest a regional north–south resistivity change in the geoelectric structure of the deep lithosphere-asthenosphere.

4.3 Geochemical parameter test

The MT array measurements were selected to be spatially representative and compared to the forward modelled resistivity profiles calculated from realistic lithospheric columns relevant for the measurement site taking into account the local geological structure and available petrological and geochemical information. The selected stations were the A260A from the Alpine region, the MORH from the South Transdanubia and the NKP6 measurement from the Great Hungarian Plain. As described in the methodology section, 20 different lithospheric rock column models were constructed for each MT station, with varying degree of melting and the hydration states (Supplementary Material 4). For a given melt content, five models were distinguished: dry, intermediate and wet lithospheric mantle and asthenosphere, and the rest were mixed, dry and intermediate lithospheric mantle with wet asthenosphere (Supplementary Table 2). In addition, two models are presented for the NKP6 station, which assume eLAB depths of 45 and 65 km, respectively. In general, it is observed that even significant changes in the parameterization of geochemical model results in synthetic soundings which are slightly different from the measured MT data. If the synthetic soundings are compared to the measured ones, it can be analysed which lithospheric column shows the best fit to the measured values, therefore inferences can be drawn for the physical properties in the lithosphere and their variation at the eLAB. The rock resistivity model, which is ‘dry’ in all aspects, is well separated and strongly overestimates the 1D inversion model resistivities at all MT stations (Fig. 6). For the two Transdanubian MT measurements the A260A (Fig. 6a) and MORH (Fig. 6b), the soundings of all other generated models show smaller resistivity compared to the inversion in the apparent resistivity soundings. The 1D inversion model sounding of NKP6 (Fig. 6c) in the GHP goes in the middle of the synthetic soundings in contrast with other two stations. Changing the depth of the eLAB at this station (Fig. 6d), has a minimal effect, resulting in a barely higher apparent resistivity.

5 Discussion

5.1 LAB depths in the Pannonian Basin

Stegena et al. (1975) among the firsts suggested that the thin lithosphere and high heat flow in the Pannonian Basin are connected. Royden et al. (1993b) demonstrated that the heat flow and the subsidence in the Pannonian Basin may be accounted for by non-uniform

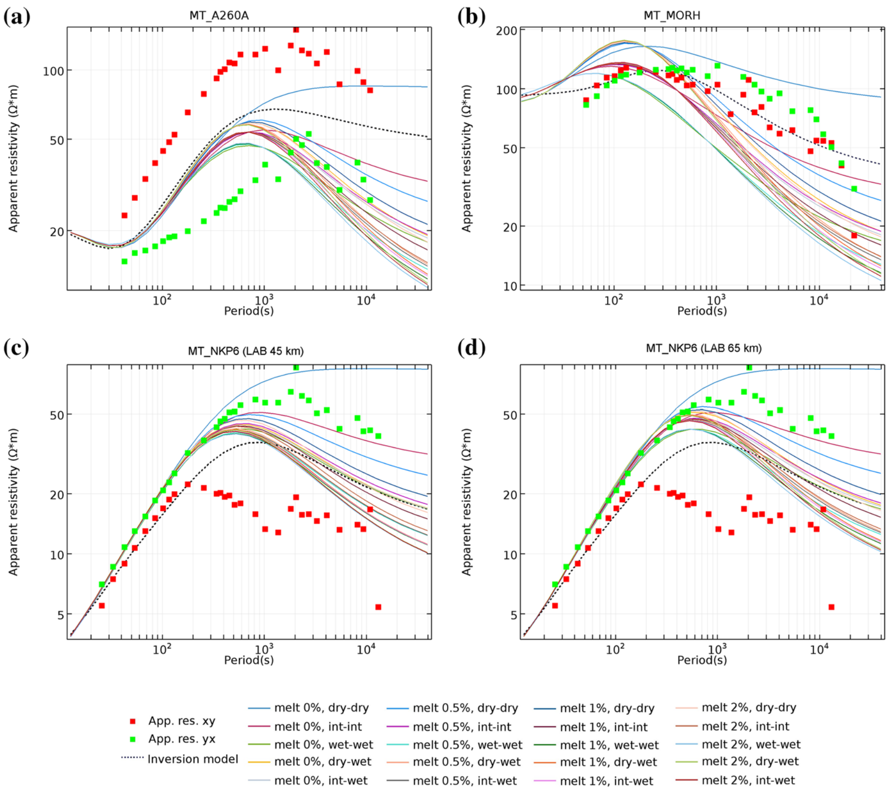

Fig. 6 Regionally selected MT soundings compared to geochemical forward models: **a** A260A MT station from Western Hungary close to the Eastern Alps, **b** MORH MT station from the Transdanubian Range and NKP6 MT station, **c**, **d** from the Great Hungarian Plain for various eLAB depths of 45 and 65 km, resp. The synthetic lithosphere resistivity models differ in the melt content (0%, 0.5%, 1%, 2%) and in the water content (dry, intermediate, and wet) of the lithospheric mantle and asthenosphere

thinning of the crust and lithospheric mantle. Kovács et al. (2017) calculated the depth of the 1050 and 1100 °C isotherms which resembles very closely other independently constrained LAB depths.

The velocity decrease of seismic waves at the LAB can be identified by several different methodologies. This velocity reduction generated a negative phase on the shear wave receiver functions (SRF) of which depth (i.e., the negative phase depth (NPD)), could be interpreted with the LAB in several geotectonic settings (e.g., Abt et al. 2010). The Carpathian-Pannonian region was included in the SRF study of Geissler et al. (2010), which presented LAB estimates for 4 stations in the Pannonian Basin: PSZ (~101 km), BUD (~74 km), SOP (~89 km), and PKSM (~103 km). Klébesz et al. (2015) in the northern Hungary at the Piszkéstető seismological station (i.e., PSZ) showed that the LAB depth is at 65 km (± 10 km). Kind et al. (2017) constructed a few 2D CCP migrated cross-sections through the Pannonian Basin. These NPD values are ~ 60–80 km in the Pannonian Basin. More recently Kalmár et al. (2023) have constructed an NPD map in the CPR which bears smaller uncertainty (± 6 km) than previous studies and seems to resemble closely the other LAB determinations for the Pannonian Basin, which is characterized by a thin lithosphere

(~ 60 km). Plomerová and Babuška (2010) carried out one of the first global tomographic studies to determine the depth of the LAB in the CPR. The authors concluded that in areas with thick sedimentary cover, such as the Great Hungarian Plain and Vienna Basin, the LAB is located at a depth of ~ 70 km. Babuška and Plomerova (1992) and Plomerova et al. (2002) identified the LAB as the depth where the direction of seismic anisotropy shifts from a lithospheric 'fozen-in' direction to the direction of absolute plate motions. The authors revealed that the LAB topography shows a broad lithospheric thinning beneath the Pannonian Basin.

Horváth (1993) presented a joint identification of the LAB based on seismic, seismologic and magnetotelluric data. His determination, which is in part also based on the studies of Babuška and Plomerová (1987, 1992, 1993), shows that the Pannonian Basin is characterized by thin lithosphere (~ 60 km). Posgay et al. (1995) along the Pannonian Geotraverse (PGT) deep reflection seismic profiles clearly revealed thin crust and lithosphere in the Pannonian Basin. Along the PGT lines the MOHO and LAB depths are generally around 25 and 60 km respectively, however, under the Békés Basin these corresponding depths are only 22 and 40 km. Tari et al. (1999) refined further the lithospheric structure in the Pannonian Basin. Bielik et al. (2022) integrating the results of Dérerová et al. (2006) demonstrated noticeable variations across the orogen, as well as along the strike of the Carpathians. The depth of the LAB varies from 240 km in the Eastern Carpathians to 75–110 km under the Pannonian Basin.

The electrical LAB (eLAB) is traditionally identified by a rapid reduction in electrical resistivity (i.e., rapid increase in electrical conductivity) in the shallow upper mantle (Heinson 1999; Jones 1999). Korja (2007) studied the eLAB depth beneath Europe based on electrical conductivity estimated with magnetotelluric methods. Similar studies have been conducted in the Pannonian region (Ádám and Wesztergom 2001; Ádám et al. 1996), but constraining the LAB depth is challenging because the determinations varied in a relatively wide zone (~45–90 km) in the extensional Pannonian Basin. The eLAB derived from MT data and the sLABrf obtained from seismological S receiver functions suggest a statistically similar average depth range of 90–100 km in the Phanerozoic Europe (Jones et al. 2010).

We compare our new eLAB map of the Pannonian Basin with the most recently published sLABrf map (Kalmár et al. 2023). This sLABrf map aligns with previous LAB determinations in the Pannonian Basin (Horváth et al. 2006; Tari et al. 1999), except for the Alpine-Carpathian-Dinaridic orogenic system, where the S receiver functions yield a significantly shallower depth estimate. In the Great Hungarian Plain, the low topographic variation and thick sediments provided excellent field conditions for the MT stations. The eLAB depth estimation for the GHP is the most reliable, where the depth is between 60 and 100 km in Fig. 7a. The eLAB closely aligns with the sLABrf across different regions of the GHP compared with Fig. 7b.

It must be noted that, most of these MT soundings show significant anisotropy in apparent resistivity by approximately one order of magnitude. Since these measurements are barely affected by near-surface distortions, we believe that this separation between the TE and TM modes are due to geological factors. Although the exact geological reason is not yet known, it is evident that the upper mantle is highly anisotropic beneath the region as shown by seismic shear wave splitting data (Kovács et al. 2012; Liptai et al. 2022; Qorbani et al. 2016). This anisotropy arises from the lattice-preferred orientation of olivines (the most voluminous mineral of the upper mantle), which means that its crystallographic axes show well-defined orientation distributions and are not random. Besides the seismic velocity, the conductivity is also highly anisotropic in olivine, therefore the measured lattice

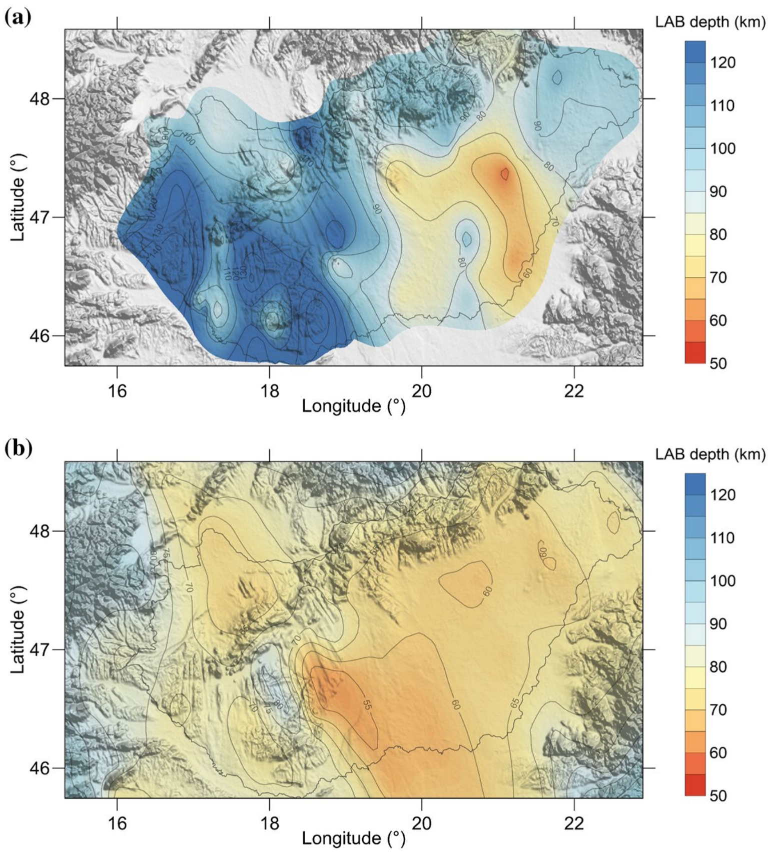

Fig. 7 The LAB depth of the Pannonian Basin is estimated using both legacy and new MT data in (**a**) this is the same eLAB as Fig. 4. **c** just without the MT stations. While the sLABrf is determined by seismological S receiver functions in (**b**), as outlined by Kalmár et al. 2023. The depths are presented on an identical colour scale

preferred orientation of olivine may also explain the anisotropy in the apparent resistivity. It is known; especially at higher temperatures, that there could be significant differences among the resistivities along the principal crystallographic axes of olivine (Dai and Karato 2014). Furthermore, the complex geology and well-defined tectonic directions of some sub-basins (e.g., Békés Basin and Makó Trough) may also could be a reason (Tari et al. 1999).

The estimated eLAB depth increases away from the GHP and approaching to 100 km in the Transdanubian Range, even in some cases jumping up to 30 km between adjacent MT stations (Fig. 4). These variations lack a geological explanation and only due to different quality of the soundings. It seems likely, the eLAB depth generally increases towards the Carpathians. An interesting area for the MT measurements was in the Transdanubian Range close to the Tihany Peninsula. The local MT data showed a large anisotropy and noisy soundings similar to the legacy data. In this area a major well conductive crustal anomaly is known at ~ 10 km depth (Ádám et al. 2017). For this reason, at the Tihany (TIH) MT station, we consider that the estimated eLAB depth is of lower confidence, which was approximately 100 km, but still consistent with the further measurements in the region. In the Danube Basin and the West Transdanubian region, there were only a few eLAB estimations from MT data. Approaching the Alps, the eLAB depth increases fast.

It is obvious at the very first sight that the eLAB depths for the South Transdanubia in Fig. 7a differ significantly from previous LAB determinations (Horváth et al. 2006; Kalmár et al. 2023; Tari et al. 1999), as shown in Fig. 7b. In this region the MT results indicate a significantly thicker lithosphere. This obvious discrepancy may stem from the nature of the applied geophysical methods (seismology and MT) or different properties of the LAB in various parts of the South Transdanubian region. However the eLAB depths for this area in Fig. 7a significantly overestimates the sLABrf in Fig. 7b, but there is a contrast in both datasets nearly the same place close to the transition of the GHP and the South Transdanubian region. Generally it is expected that the lithosphere thickness would increase towards the Dinarides, and may start even from the centre of the Pannonian Basin roughly following the line of the river Danube. Even if there is no robust geological interpretation for this E-W variation in eLAB determinations and this could be solely due to MT quality issues, there are other observations which seem to be broadly consistent with this pattern. The delay time of seismic anisotropy is smaller in the areas characterised by thicker LAB (Liptai et al. 2022), meaning that upper mantle and may be also the lower crust is less anisotropic under this area. The other interesting geological feature of the western part of the Pannonian Basin is the presence of a negative velocity anomaly at greater depths (> 300 km, Ren et al. 2012) and different directions of seismic anisotropy (Liptai et al. 2022). It is also interesting, that there are clear petrologic and geochemical evidence for a proximal and a geologically young subduction in the lithospheric mantle under the Transdanubian Range (Bali et al. 2008; Kovács et al. 2007). Another interesting feature is that earthquakes seem to occur more frequently along this zone separating the western and eastern part of the region (Süle et al. 2020). More future research is certainly needed to understand this discrepancy in eLAB depths and other changing geophysical properties in the area, but it appears to be a plausible initial hypothesis that there are variations in the general physical properties of the lithosphere in the central part of the Pannonian Basin roughly parallel to the Danube. The different properties of the western part may be due to the fact that prior Mesozoic subductions may affected more this area causing its enhanced refertilisation which is reflected in the observed physical differences (Bali et al. 2008; Kovács et al. 2007).

In general, the previous studies on the LAB in the Pannonian Basin (Ádám and Wesztergom 2001; Horváth et al. 2006; Kalmár et al. 2023; Tari et al. 1999) resulted similar estimates for the GHP region, where the thickness of lithosphere is approximately 60 km (Fig. 7a, 7b). The new eLAB estimates from MT data for other parts of the Pannonian Basin are generally 10–30 km deeper than those described in previous studies. One of the most interesting observations is that, when comparing the latest results of MT and seismology in the Pannonian Basin, as shown in Fig. 7, the changes in LAB depth exhibit very similar contours. For example, approaching the Carpathians or in the Danube Basin, the major differences are in the rate of change. It is important to note that the deep eLAB values obtained in the South Transdanubian region, especially towards the Alps and the Dinarides, may appear somewhat exaggerated. Even if there is an apparent discrepancy in the absolute eLAB and sLABrf depths, the LAB maps reveal a broadly consistent pattern. This pattern shows the thickening of the LABs towards the west and the orogenic rim where the sLABrf determinations show a more gradual values and smoother transition. Consequently, even if there are several factors which could distort the LAB estimates our results still seem to map reliably the relative variation in physical properties associated with the LAB.

5.2 Geoelectric structure

The phase tensors ellipses and induction arrows at low periods correlate with the topography of the pre-Cenozoic basement (Fig. 5). A good example at 100 s period is the AMBH MT station located at the edge of the Makó Trough. The induction arrows point towards the basin center, where there is a greater volume of conducting sediment. The phase tensor ellipses are nearly perpendicular to the trough pointing towards the most conducting direction (Fig. 5a, b). Similar behaviour can be observed in the Békés Basin, but there the basin geometry is less elongated. The thickness of the sediment is less variable in the rest of the Great Hungarian Plain, but the direction of the induction arrows still appears to be influenced by local variations in the sediment thickness (Fig. 5a).

As the period increases, the arrows become more ordered, the influence of the basin geometry becomes less dominant and at 1000 s the characteristic north–south direction starts to appear (Fig. 5c, e). Their magnitude decreases until 8000 s after the alignment, but then starts to increase again, slowly turning to north-west. In these longer periods and therefore greater depths, the phase tensors become more circular meaning that the geoelectric strike direction is essentially smoothed out in the deeper crust and the lithospheric mantle. Interestingly, the skew angle is high throughout, and this is also true for the other soundings in the Pannonian Basin, so the majority of MT stations reveal strongly 3D resistivity geometry in the lithosphere. The geoelectric structure outside the GHP is quite diffuse on the 100 s period map. If there is nearby sediment accumulation this determines the direction of the induction vectors as we pointed out above. The Zala Basin with significant sediment thickness is a good example for this, but this is not the case for all the MT stations. As the period increases, the induction arrows of the MT stations close to the Mid-Hungarian Shear Zone point towards the zone, while the phase tensors show a somewhat parallel direction to the fault zone. The opposite direction of the induction arrows on the two sides of the fault zone suggests that the fault zone has low resistivity. The fact that this features appear at the 1000 s period (Fig. 5c) implies that the fault zone represents a major conductive zone reaching down to the deeper parts of the lithosphere. The well-conducting characteristic of the fault zone may be related to fluid-accumulations in the more permeable damage zones and/or to lithological changes in the fault rocks due to lateral displacements or to the reworking (cataclasis, re-cementation) of the damage zone rocks. Based on the MT array data, the 1000 s period induction arrows and phase tensors indicate that this fault zone is a well-conducting tectonic unit. This is consistent the origin of MHSZ, which separated major tectonic microplates and underwent significant deformations after the Oligocene (Csontos and Nagymarosy 1998) and some of its parts are still active (Koroknai et al. 2020). The novel element of our results is that it implies that the MHSZ is not only constrained into the crust but goes into the lithosphere much deeper. As the period increases, all the induction arrows tend to settle to the north, and the phase tensors do not show clear conduction directions.

The northward orientation of the induction arrows is an interesting phenomenon, for which it is difficult to provide a clear geological explanation. The physical meaning of this phenomenon is that the conductivity increases towards the north in the deep lithosphere/shallow asthenosphere. This trend should be present under the whole Pannonian

Basin according to the MT data. While the explanation for this northward orientation is not yet fully clear, its origin may be explained. The Pieniny Klippen Belt in the Western Carpathians is known to be a prominent tectonic feature separating ALCAPA from the stable European platform. A recent MT study identified that there is a prominent well conductive sub vertical zone along the Pieniny Klippen Belt extending from the surface to at least until the lithospheric mantle (Jóźwiak et al. 2022). This well conductive zone is a dominant feature and has the capacity to explain the northward orientation of the induction arrows. Other smaller scale and less profound deformation zones presumably crosscutting the entire lithosphere were also proposed by Kovács et al. (2020) and Koptev et al. (2021) in conjunction with the alkaline basaltic volcanic activity. Their much smaller size and lower conductivity contrast, however, seem to be insufficient to account for the observed larger scale conductive zones needed for the explanations of the induction arrows. The Central Slovakian Volcanic Field is a specific area in the Carpathian-Pannonian region because the volcanic activity is almost uninterrupted in the past 20 My (Szakács et al. 2018) and recent studies discovered the presence of partial melt in the lithospheric upper mantle beneath the Nógrád-Gömör Volcanic Field on the north (Patkó et al. 2021). The continuous volcanic activity and the presence of partial melts can also account for the existence of well conductive zones on the north to which the induction arrows could point.

5.3 Geochemical implications for the nature of the eLAB

In this chapter we made a comparison between real and synthetic MT soundings based on forward modelled resistivity columns obtained from relevant petrological and geochemical data. The long-period MT soundings and those obtained from geochemical forward resistivity models generally resemble closely (Fig. 6, resistivity models can be found in the Supplementary Table 1 and Supplementary Material 4). This is due to the fact that all resistivity models down to the depth of the Conrad discontinuity follow the inversion model indicated in dashed blue. Below the Conrad discontinuity, the high resistivity of the crust has insignificant effect on the resistivity models. The apparent difference is induced by the exponentially decreasing trend of the resistivity. It can be stated that the lithological resistivity models with 0% melt, dry lithospheric mantle and asthenosphere overestimate the apparent resistivity of the real MT soundings. Therefore, melt-free asthenosphere and dry lithospheric mantle is not a likely geological explanation. For A260A and MORH, the wet and melt bearings models underestimate the resistivity of the associated MT soundings, which would imply a lithosphere may be drier with lower or no melt contents (Fig. 6a and b). In contrast, on the Great Hungarian Plain the NKP6 sounding, which includes the regionally typical lower apparent resistivity because of the thick covering layer of sediment, indicates an intermediate to wet lithosphere (Fig. 6c and d). The effect of changing the eLAB depths in the resistivity models has the smallest effect among the parameters on the modelled soundings. Based on the parameter testing for the Great Hungarian Plain's resistivity model with a melt content between 0.5 and 1% and an intermediate to wet lithosphere is the most plausible solution. The relationship between the forward models and the 1D inversion model was the most critical in the testing, depending on the quality of the real MT sounding. Ideally, the 1D inverse models should be as close as possible to the respective real lithospheric resistivity models. We find that this scenario is best fulfilled for the NKP6 site in the Great Hungarian Plain. While there is usually a stark resistivity drop is associated at the eLAB the deep MT soundings are unable to detect this as a stepwise resistivity variation. Instead this drop is smoothed out in the recorded real MT soundings also in part due to the exponentially decreasing resistivity in the lithospheric mantle. In other words, eLAB's 1D inversion estimation may not be most sensitive to the depth of resistivity contrast at the lithosphere–asthenosphere boundary, but rather provides an intermediate depth value in this more gradual transition zone between the lithosphere and the asthenosphere. The results from good quality MT soundings station confirm that the asthenosphere should contains some small (0.5–1%) fraction of partial melt and the lithospheric mantle is hydrous to some extent to best fit the observed data. Thus, our results imply that the eLAB is a boundary along which hydration takes place in the shallower lithosphere, whereas the deeper upper mantle partial melts are present. This suggests that most likely the eLAB is a horizon along which partial melting takes place based on the best quality of MT sounding data.

6 Conclusions

Our paper is focused on new eLAB maps of the Pannonian Basin, its geoelectrical structure, and geochemical features related to rock conductivity based on the Pannon LitH_2Oscope MT dataset. Our major achievements can be summarised as follows:

- According to the quality of the estimate, the most accurate eLAB depths are available for the Great Hungarian Plain and vary between 60 and 100 km. In the Transdanubian Range and Danube Basin, the eLAB depth is estimated with less confidence to be around 100 km, while in the South Transdanubia the eLAB is deeper than 100 km.
- In the Pannonian Basin, the thick sediments and large faults zones were visible on the MT response functions and the geomagnetic data. The thick sedimentary basins dominate the geomagnetic response functions, such as the Makó Trough and Békés Basin at the low 100 s period.
- The induction arrows and phase tensor ellipses at 1000 s delineate the Mid-Hungarian Shear Zone, which is separating the ALPACA and Tisza-Dacia mega-units.
- Approaching the asthenosphere at 10,000 s period, all the induction arrows turn to the north. An explanation for this northward decrease in resistivity is a possible indication for the effect of the Central Slovakian Volcanic Field and/or the Pienini Klippen Belt since these areas are known as large-scale well conductive zones.
- In the Great Hungarian Plain strong anisotropy was present in the long-period MT sounding which may be due to the already proposed regional scale seismic anisotropy in the upper mantle but this needs further investigation.
- The lithospheric resistivity under the Pannonian Basin is strongly influenced by the melt and water content of the upper mantle based on geochemical forward modelling.
- Based on the lithologically obtained forward modelled resistivity profiles, it is probable that the lithosphere of the Pannonian Basin is hydrated to some extent and there is a small fraction of melt present (0.5–1%) in the asthenosphere.
- In the future 3D MT and joint inversion techniques among seismic and gravity datasets offer promising further possibilities to improve spatial resolution and reliability of inverted geophysical parameters.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40328-024-00434-1.

Acknowledgements We are grateful for the financial, technical, and professional support of MTA FI Lendület Pannon LitH_2Oscope grant (LP2018-5/2019-2023) for the MT research in the Pannonian Basin, including the installation of the MT array, between 2018 and 2022. We would like to deeply acknowledge the reviewers, Gábor Tari, an anonymous reviewer, and the editor-in-chief György Hetényi for their significant contribution, which helped greatly to improve the quality of the paper.

Author contributions TR: Conceptualization, Methodology, Software, Investigation, Visualization, Writing original draft, Writing—review & editing. AN: Conceptualization, Methodology, Software, Investigation, Visualization, Writing original draft, Writing—review & editing. NL: Conceptualization, Methodology, Writing original draft, Software. KP: Conceptualization, Methodology, Writing original draft. CsM: Investigation. AG: Methodology, Software, Writing—review & editing. GM: Methodology, Software. VW: Conceptualization, Project administration. IJK: Conceptualization, Funding acquisition, writing original draft.

Funding Open access funding provided by HUN-REN Institute of Earth Physics and Space Science.

Declarations

Conflict of interest István János Kovács and Kristóf Porkoláb are associate and respectively guest editor for this journal respectively this special issue, for this reason have fully withdrawn themselves from the manuscript handling and reviewing process.

References

Abt DL, Fischer KM, French SW, Ford HA, Yuan H, Romanowicz B (2010) North American lithospheric discontinuity structure imaged by Ps and Sp receiver functions. J Geophys Res Solid Earth. https://doi.org/10.1029/2009JB006914

Ádám A (1965) Einige Hypothesen über den aufbau des oberen erdmantel in ungran. Gerlands Beiträge Zur Geophys 74:20–40

Ádám A (1978) Geothermal effects in the formation of electrically conducting zones and temperature distribution in the Earth. Phys Earth Planet Int 17:21–25

Ádám A (1996) Regional magnetotelluric (MT) anisotropy in the Pannonian Basin (Hungary). Acta Geodaetica Et Geophysica Hungarica 31:191–216

Ádám A, Wesztergom V (2001) An attempt to map the depth of the electrical asthenosphere by deep magnetotelluric measurements in the Pannonian basin (Hungary). Acta Geod Hung 44:167–1992

Ádám A, Kohlbeck F, Novák A, Szarka L (2008) Interpretation of the deep magnetotelluric soundings along the austrian part of the celebration-007 profile. Acta Geod Geophys Hungarica 43:17–32. https://doi.org/10.1556/AGeod.43.2008.1.2

Ádám A, Szarka L, Novák A, Wesztergom V (2017) Key results on deep electrical conductivity anomalies in the Pannonian Basin (PB), and their geodynamic aspects. Acta Geod Geophys 52:205–228. https://doi.org/10.1007/s40328-016-0192-2

Aradi LE, Hidas K, Kovács IJ, Tommasi A, Klébesz R, Garrido CJ, Szabó C (2017) Fluid-enhanced annealing in the subcontinental lithospheric mantle beneath the westernmost margin of the Carpathian-Pannonian extensional basin system. Tectonics 36(12):2987–3011. https://doi.org/10.1002/2017TC004702

Artemieva IM, Mooney WD (2001) Thermal thickness and evolution of Precambrian lithosphere: a global study. J Geophys Res Solid Earth 106:16387–16414. https://doi.org/10.1029/2000jb900439

Babuška V, Plomeroáv J (1993) Lithospheric thickness and velocity anisotropy—seismological and geothermal aspects. Tectonophysics 225(1–2):79–89. https://doi.org/10.1016/0040-1951(93)90250-N

Babuška V, Plomerová J (1992) The lithosphere in central Europe—seismological and petrological aspects. Tectonophysics 207(1–2):141–163. https://doi.org/10.1016/0040-1951(92)90475-L

Babuška V, Plomerová J, Šílený J (1987) Structural model of the subcrustal lithosphere in central Europe. Compos, Struct Dyn Lithos-Asthenos Syst 16:239–251. https://doi.org/10.1029/GD016p0239

Bada G, Horváth F, Dövényi P, Szafián P, Windhoffer G, Cloetingh S (2007) Present-day stress field and tectonic inversion in the Pannonian basin. Glob Planet Change 58(1–4):165–180. https://doi.org/10.1016/j.gloplacha.2007.01.007

Balázs A, Matenco L, Magyar I, Horváth F, Cloetingh S (2016) The link between tectonics and sedimentation in back-arc basins: new genetic constraints from the analysis of the Pannonian Basin. Tectonics 35(6):1526–1559. https://doi.org/10.1002/2015TC004109

Bali E, Zajacz Z, Kovacs I, Szabó CS, Halter W, Vaselli O, Török K, Bodnar RJ (2008) A quartz-bearing orthopyroxene-rich websterite xenolith from the Pannonian Basin, Western Hungary: evidence for release of quartz-saturated melts from a subducted slab. J Petrol 49(3):421–439

Balla Z (1988) Clockwise paleomagnetic rotations in the Alps in the light of the structural pattern of the Transdanubian range (Hungary). Tectonophysics 145:277–292. https://doi.org/10.1016/0040-1951(88)90200-4

Békési E, Porkoláb K, Wesztergom V, Wéber Z (2023) Updated stress dataset of the Circum-Pannonian region: implications for regional tectonics and geo-energy applications. Tectonophysics 856:229860. https://doi.org/10.1016/j.tecto.2023.229860

Bibby HM, Caldwell TG, Brown C (2005) Determinable and non-determinable parameters of galvanic distortion in magnetotellurics. Geophys J Int 163:915–930. https://doi.org/10.1111/j.1365-246X.2005.02779.x

Bielik M, Zeyen H, Starostenko V, Makarenko I, Legostaeva O, Savchenko S, Dérerová J, Grinč M, Godová D, Pánisová J (2022) A review of geophysical studies of the lithosphere in the Carpathian-Pannonian region. Geol Carpath. https://doi.org/10.31577/GeolCarp.73.6.2

Burov EB (2011) Rheology and strength of the lithosphere. Mar Pet Geol 28(8):1402–1443. https://doi.org/10.1016/j.marpetgeo.2011.05.008

Caldwell TG, Bibby HM, Brown C (2004) The magnetotelluric phase tensor. Geophys J Int 158:457–469. https://doi.org/10.1111/j.1365-246X.2004.02281.x

Çemen I (2010) Extensional tectonics in the basin and range the Aegean, and western Anatolia. Tectonophysics 488:326

Čermák V (1993) Lithospheric thermal regimes in Europe. Phys Earth Planet Inter 79(1–2):179–193. https://doi.org/10.1016/0031-9201(93)90147-2

Csontos L, Nagymarosy A (1998) The mid-Hungarian line: a zone of repeated tectonic inversions. Tectonophysics 297:51–71. https://doi.org/10.1016/S0040-1951(98)00163-2

Csontos L, Vörös A (2004) Mesozoic plate tectonic reconstruction of the Carpathian region. Palaeogeogr Palaeoclimatol Palaeoecol 210:1–56. https://doi.org/10.1016/j.palaeo.2004.02.033

Csontos L, Nagymarosy A, Horváth F, Kovac M (1992) Tertiary evolution of the Intra-Carpathian area: a model. Tectonophysics 208(1–3):221–241

Dai L, Karato S (2014) High and highly anisotropic electrical conductivity of the asthenosphere due to hydrogen diffusion in olivine. Earth Planet Sci Lett 408:79–86. https://doi.org/10.1016/j.epsl.2014.10.003

Dérerová J, Zeyen H, Bielik M, Salman K (2006) Application of integrated geophysical modeling for determination of the continental lithospheric thermal structure in the eastern Carpathians. Tectonics. https://doi.org/10.1029/2005TC001883

Dewey JF, Pitman WC, Ryan WBF, Bonnin J (1973) Plate tectonics and the evolution of the alpine system. Bull Geol Soc Am 84:3137–3180. https://doi.org/10.1130/0016-7606(1973)84%3c3137:PTATEO%3e2.0.CO;2

Dietz RS (1962) Ocean-basin evolution by sea-floor spreading. Cont Dr 3:289–298

Dobosi G, Downes H, Embey-Isztin A, Jenner GA (2003) Origin of megacrysts and pyroxenite xenoliths from the pliocene alkali basalts of the Pannonian Basin (Hungary). Neues Jahrb Für Miner: Abh 178:217–237. https://doi.org/10.1127/0077-7757/2003/0178-0217

Eaton DW, Darbyshire F, Evans RL, Grütter H, Jones AG, Yuan X (2009) The elusive lithosphere–asthenosphere boundary (LAB) beneath cratons. Lithos 109(1–2):1–22. https://doi.org/10.1016/j.lithos.2008.05.009

Egbert GD, Booker JR (1986) Robust estimation of geomagnetic transfer functions. Geophys J R Astron Soc 87:173–194. https://doi.org/10.1111/j.1365-246X.1986.tb04552.x

Egbert GD, Livelybrooks DW (1996) Single station magnetotelluric impedance estimation: coherence weighting and the regression M-estimate. Geophysics 61:964–970. https://doi.org/10.1190/1.1444045
Falus G, Tommasi A, Ingrin J, Szabó C (2008) Deformation and seismic anisotropy of the lithospheric mantle in the southeastern Carpathians inferred from the study of mantle xenoliths. Earth Planet Sci Lett 272:50–64
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 palaeostress data. Geologi Soc, Lond, Spec Publ 156(1):295–334. https://doi.org/10.1144/GSL.SP.1999.156.01.15
Fullea J (2017) On joint modelling of electrical conductivity and other geophysical and petrological observables to infer the structure of the lithosphere and underlying upper mantle. Springer, Netherlands
Geissler WH, Sodoudi F, Kind R (2010) Thickness of the central and eastern European lithosphere as seen by S receiver functions. Geophys J Int. https://doi.org/10.1111/j.1365-246X.2010.04548.x
Gráczer Z, Szanyi G, Bondár I, Czanik C, Czifra T, Győri E, Hetényi G, Kovács IJ, Molinari I, Süle B, Szűcs E (2018) AlpArray in Hungary: temporary and permanent seismological networks in the transition zone between the eastern Alps and the Pannonian basin. Acta Geod Geoph 53:221–245
Green DH, Hibberson WO, Kovács IJ, Rosenthal A (2010) Water and its influence on the lithosphere–asthenosphere boundary. Nature 467(7314):448–451. https://doi.org/10.1038/nature09369
Haas J (ed) (2012) Geology of Hungary. Springer Science & Business Media
Haas J, Budai T, Csontos L, Fodor L, Konrád GY, Koroknai B (2014) Geology of the pre-cenozoic basement of Hungary. Geological and geophysical Institute of Hungary, Budapest, pp 1–73
Harangi S (2001) Neogene to quaternary volcanism of the Carpathian-Pannonian region: a review. Acta Geol Hungarica 44:223–258
Heinson G (1999) Electromagnetic studies of the lithosphere and asthenosphere. Surv Geophys 20:229–255
Holmes A (1965) Rinciples of physical geology, 2nd edn. Ronald Press, New York, p 1288
Horváth F (1993) Towards a mechanical model for the formation of the Pannonian basin. Tectonophysics 226:333–357. https://doi.org/10.1016/0040-1951(93)90126-5
Horváth F, Bada G, Szafián P, Tari G, Ádám A, Cloetingh S (2006) Formation and deformation of the Pannonian Basin: constraints from observational data. Geologi Soc, Lond, Mem 32(1):191–206. https://doi.org/10.1144/GSL.MEM.2006.032.01.11
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. https://doi.org/10.1016/j.geothermics.2014.07.009
Hu H, Dai L, Li H, Sun W, Li B (2018) Effect of dehydrogenation on the electrical conductivity of Fe-bearing amphibole: implications for high conductivity anomalies in subduction zones and continental crust. Earth Planet Sci Lett 498:27–37
Hua J, Fischer KM, Becker TW, Gazel E, Hirth G (2023) Asthenospheric low-velocity zone consistent with globally prevalent partial melting. Nat Geosci 16(2):175–181. https://doi.org/10.1038/s41561-022-01116-9
Janik T, Grad M, Guterch A (2009) Seismic structure of the lithosphere between the east European craton and the Carpathians from the net of CELEBRATION 2000 profiles in SE Poland. Geologi Quarterly 53:141–158
Jones AG (1983) The problem of current channelling: a critical review. Geophys Surv 6:79–122. https://doi.org/10.1007/BF01453996
Jones AG (1999) Imaging the continental upper mantle using electromagnetic methods. Lithos 48(1–4):57–80. https://doi.org/10.1016/S0024-4937(99)00022-5
Jones AG, Plomerova J, Korja T, Sodoudi F, Spakman W (2010) Europe from the bottom up: a statistical examination of the central and northern European lithosphere–asthenosphere boundary from comparing seismological and electromagnetic observations. Lithos 120(1–2):14–29. https://doi.org/10.1016/j.lithos.2010.07.013
Jóźwiak W, Nowożyński K, Mazur S, Jeż M (2022) Deep electrical resistivity structure of the European lithosphere in Poland derived from 3-D inversion of magnetotelluric data. Surv Geophys 43:1563–1586. https://doi.org/10.1007/s10712-022-09716-1
Kalmár D, Hetényi G, Bondár I (2019) Moho depth analysis of the eastern Pannonian Basin and the Southern Carpathians from receiver functions. J Seismol 23:967–982. https://doi.org/10.1007/s10950-019-09847-w
Kalmár D, Hetényi G, Balázs A, Bondár I (2021) Crustal thinning from orogen to back-arc basin: the structure of the Pannonian basin region revealed by P–S converted seismic waves. J Geophys Res: Solid Earth 126(7):e2020JB021309. https://doi.org/10.1029/2020JB021309

Kalmár D, Petrescu L, Stipčević J, Balázs A, Kovács IJ (2023) Lithospheric structure of the Circum-Pannonian region imaged by S-To-P receiver functions. Geochem, Geophys, Geosyst 24(9):e2023GC010937. https://doi.org/10.1029/2023GC010937

Karato SI, Olugboji T, Park J (2015) Mechanisms and geologic significance of the mid-lithosphere discontinuity in the continents. Nat Geosci 8:509–514. https://doi.org/10.1038/ngeo2462

Kazmer M, Kovacs S (1985) Permian-paleogene paleogeography along the eastern part of the insubric-periadriatic Lineament system: evidence for continental escape of the Bakony-Drauzug unit. Acta Geol Hungarica 28:71–84

Kind R, Yuan X, Kumar P (2012) Seismic receiver functions and the lithosphere–asthenosphere boundary. Tectonophysics 536–537:25–43. https://doi.org/10.1016/j.tecto.2012.03.005

Kind R, Handy MR, Yuan X, Meier T, Kämpf H, Soomro R (2017) Detection of a new sub-lithospheric discontinuity in central Europe with S-receiver functions. Tectonophysics 700–701:19–31. https://doi.org/10.1016/j.tecto.2017.02.002

Kirkby A, Zhang F, Peacock J, Hassan R, Duan J (2019) The MTPy software package for magnetotelluric data analysis and visualisation. J Open Sour Softw 4(37):1358. https://doi.org/10.21105/joss.01358

Kiss J, András M (2012) Complex geophysical examination along PGT-1 profile. Magy Geofiz 53:29–54

Klébesz R, Gráczer Z, Szanyi G, Liptai N, Kovács IJ, Patkó L, Pintér Z, Falus G, Wesztergom V, Szabó C (2015) Constraints on the thickness and seismic properties of the lithosphere in an extensional setting (Nógrád-Gömör volcanic field, Northern Pannonian Basin). Acta Geod Geoph 50(2):133–149. https://doi.org/10.1007/s40328-014-0094-0

Koptev A, Cloetingh S, Kovács IJ, Gerya T, Ehlers TA (2021) Controls by rheological structure of the lithosphere on the temporal evolution of continental magmatism: inferences from the Pannonian Basin system. Earth Planet Sci Lett 565:116925. https://doi.org/10.1016/j.epsl.2021.116925

Korja T (2007) How is the European lithosphere imaged by magnetotellurics? Surv Geophys 28:239–272. https://doi.org/10.1007/s10712-007-9024-9

Koroknai B, Wórum G, Tóth T, Koroknai Z, Fekete-Németh V, Kovács G (2020) Geological deformations in the Pannonian Basin during the neotectonic phase: new insights from the latest regional mapping in Hungary. Earth Sci Rev 211:103411. https://doi.org/10.1016/j.earscirev.2020.103411

Kovács IJ, Szabó C (2005) Petrology and geochemistry of granulite xenoliths beneath the Nógrád-Gömör volcanic field, carpathian-Pannonian region (N-Hungary/S-Slovakia). Miner Pet 85:269–290. https://doi.org/10.1007/s00710-005-0090-8

Kovács IJ, Szabó C (2008) Middle miocene volcanism in the vicinity of the middle Hungarian zone: evidence for an inherited enriched mantle source. J Geodyn 45:1–17. https://doi.org/10.1016/j.jog.2007.06.002

Kovács IJ, Green DH, Rosenthal A, Hermann J, neill HStC O', Hibberson WO, Udvardi B (2012) An experimental study of water in nominally anhydrous minerals in the upper mantle near the water-saturated solidus. J Petrol 53(10):2067–2093. https://doi.org/10.1093/petrology/egs044

Kovács IJ, Lenkey L, Green DH, Fancsik T, Falus G, Kiss J, Orosz L, Angyal J, Vikor Z (2017) The role of pargasitic amphibole in the formation of major geophysical discontinuities in the shallow upper mantle. Acta Geod Geoph 52(2):183–204. https://doi.org/10.1007/s40328-016-0191-3

Kovács IJ, Patkó L, Falus G, Aradi LE, Szanyi G, Gráczer Z, Szabó C (2018) Upper mantle xenoliths as sources of geophysical information: the Perşani Mts. area as a case study. Acta Geod Geophys 53:415–438

Kovács IJ, Patkó L, Liptai N, Lange TP, Taracsák Z, Cloetingh S, Török K, Király E, Karátson D, Biró T, Kiss J, Zs P, Aradi LE, Gy F, Hidas K, Berkesi M, Koptev A, Novák A, Wesztergom V, Fancsik T, Cs S (2020) The role of water and compression in the genesis of alkaline basalts: inferences from the Carpathian-Pannonian region. Lithos. https://doi.org/10.1016/j.lithos.2019.105323

Kovács IJ, Liptai N, Koptev A, Cloetingh S, Lange TP, Maţenco L, Szakács A, Radulian M, Berkesi M, Patkó L, Molnár G, Novák A, Wesztergom V, Szabó C, Fancsik T (2021) The 'pargasosphere' hypothesis: looking at global plate tectonics from a new perspective. Global Planet Change 204:103547. https://doi.org/10.1016/j.gloplacha.2021.103547

Krieger L, Peacock JR (2014) MTpy: a Python toolbox for magnetotellurics. Comput Geosci 72:167–175. https://doi.org/10.1016/j.cageo.2014.07.013

Lenkey L, Mihályka J, Paróczi P (2021) Review of geothermal conditions of Hungary. Földtani Közlöny 151:65. https://doi.org/10.23928/foldt.kozl.2021.151.1.65

Liptai N, Patkó L, Kovács IJ, Hidas K, Pintér Z, Jeffries T, Zajacz Z, O'Reilly SY, Griffin WL, Pearson NJ, Szabó C (2017) Multiple metasomatism beneath the Nógrád-Gömör volcanic field (northern Pannonian basin) revealed by upper mantle peridotite xenoliths. J Petrol 58(6):1107–1144. https://doi.org/10.1093/petrology/egx048

Liptai N, Gráczer Z, Szanyi G, Cloetingh S, Süle B, Aradi LE, Falus G, Bokelmann G, Timkó M, Timár G, Szabó C, Kovács IJ (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 845:229643. https://doi.org/10.1016/j.tecto.2022.229643

Liu Y, Hu D, Xu Y, Chen C (2019) 3D magnetotelluric imaging of the middle-upper crustal conduit system beneath the Lei-Hu-Ling volcanic area of northern Hainan Island, China. J Volcanol Geotherm Res 371:220–228. https://doi.org/10.1016/j.jvolgeores.2019.01.013

Matenco L, Radivojevi D (2012) On the formation and evolution of the Pannonian Basin: constraints derived from the structure of the junction area between the Carpathians and Dinarides. Tectonics. https://doi.org/10.1029/2012TC003206

Matenco L, Bertotti G, Leever K, Cloetingh S, Schmid SM, Tărăpoancă M, Dinu C (2007) Large-scale deformation in a locked collisional boundary: Interplay between subsidence and uplift, intraplate stress, and inherited lithospheric structure in the late stage of the SE Carpathians evolution. Tectonics. https://doi.org/10.1029/2006TC001951

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, SrodaP VJ (2023) Moho depths beneath the European Alps: a homogeneously processed map and receiver functions database. Earth Syst Sci Data 15(5):2117–2138. https://doi.org/10.5194/essd-15-2117-2023

Mierdel K, Keppler H, Smyth JR, Langenhorst F (2007) Water solubility in aluminous orthopyroxene and the origin of earth's asthenosphere. Science 315:364–368. https://doi.org/10.1126/science.1135422

Palotai M, Csontos L (2010) Strike-slip reactivation of a paleogene to miocene fold and thrust belt along the central part of the mid-Hungarian shear zone. Geol Carpathica 61:483–493. https://doi.org/10.2478/v10096-010-0030-3

Parkinson WD (1959) Directions of rapid geomagnetic fluctuations. Geophys J R Astron Soc 2:1–14

Patkó L, Liptai N, Aradi LE, Klébesz R, Sendula E, Bodnar RJ, Kovács IJ, Hidas K, Cesare B, Novák A, Trásy B, Szabó C (2020) Metasomatism-induced wehrlite formation in the upper mantle beneath the Nógrád-Gömör volcanic Field (Northern Pannonian Basin): evidence from xenoliths. Geosci Front 11(3):943–964. https://doi.org/10.1016/j.gsf.2019.09.012

Patkó L, Novák A, Klébesz R, Liptai N, Lange TP, Molnár G, Csontos L, Wesztergom V, Kovács IJ, Szabó C (2021) Effect of metasomatism on the electrical resistivity of the lithospheric mantle: An integrated research using magnetotelluric sounding and xenoliths beneath the Nógrád-Gömör Volcanic Field. Global Planet Change 197:103389. https://doi.org/10.1016/j.gloplacha.2020.103389

Plomerová J, Babuška V (2010) Long memory of mantle lithosphere fabric: European LAB constrained from seismic anisotropy. Lithos 120(1–2):131–143. https://doi.org/10.1016/j.lithos.2010.01.008

Plomerová J, Kouba D, Babuška V (2002) Mapping the lithosphere–asthenosphere boundary through changes in surface-wave anisotropy. Tectonophysics 358(1–4):175–185. https://doi.org/10.1016/S0040-1951(02)00423-7

Pollack HN, Chapman DS (1977) On the regional variation of heat flow, geotherms, and lithospheric thickness. Tectonophysics 38(3–4):279–296. https://doi.org/10.1016/0040-1951(77)90215-3

Porkoláb K, Broerse T, Kenyeres A, Békési E, Tóth S, Magyar B, Wesztergom V (2023) Active tectonics of the Circum-Pannonian region in the light of updated GNSS network data. Acta Geod Geoph 58(2):149–173. https://doi.org/10.1007/s40328-023-00409-8

Posgay K (1993) Formation of the crust-mantle boundary in the previous upper mantle. Geophys Trans: Eotvos Lorand Geophys Inst Hungary 37:243–251

Posgay K, Bodoky T, Hegedüs E, Kovácsvölgyi S, Lenkey L, Szafián P, Takács E, Tímár ZA, Varga G (1995) Asthenospheric structure beneath a Neogene basin in southeast Hungary. Tectonophysics 252(1–4):467–484

Qorbani E, Bokelmann G, Kovács IJ, Horváth F, Falus G (2016) Deformation in the asthenospheric mantle beneath the Carpathian-Pannonian region. J Geophys Res: Solid Earth 121(9):6644–6657. https://doi.org/10.1002/2015JB012604

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

Royden LH (1993) The tectonic expression of slab pull at continental convergent boundaries. Tectonics 12:303–325

Rychert CA, Shearer PM (2011) Imaging the lithosphere-asthenosphere boundary beneath the pacific using SS waveform modeling. J Geophys Res 116:B07307. https://doi.org/10.1029/2010JB008070

Samae V, Cordier P, Demouchy S, Bollinger C, Gasc J, Koizumi S, Mussi A, Schryvers D, Idrissi H (2021) Stress-induced amorphization triggers deformation in the lithospheric mantle. Nature 591(7848):82–86. https://doi.org/10.1038/s41586-021-03238-3

Schmid SM, Bernoulli D, Fügenschuh B, Matenco L, Schefer S, Schuster R, Tischler M, Ustaszewski K (2008) The alpine-carpathian-dinaridic orogenic system: correlation and evolution of tectonic units. Swiss J Geosci 101(1):139–183. https://doi.org/10.1007/s00015-008-1247-3

Seghedi I, Downes H, Szakács A, Mason PRD, Thirlwall MF, Emilian R, Pécskay Z, Márton E, Panaiotu C (2004) Neogene-quaternary magmatism and geodynamics in the Carpathian-Pannonian region: a synthesis. Lithos 72(3–4):117–146. https://doi.org/10.1016/j.lithos.2003.08.006

Sifré D, Gardés E, Massuyeau M, Hashim L, Hier-Majumder S, Gaillard F (2014) Electrical conductivity during incipient melting in the oceanic low-velocity zone. Nature 509(7498):81–85. https://doi.org/10.1038/nature13245

Stegena L, Géczy B, Horváth F (1975) Late Cenozoic evolution of the Pannonian basin. Tectonophysics 26(1–2):71–90. https://doi.org/10.1016/0040-1951(75)90114-6

Süle B, Bondár I, Czanik C, Gráczer Z, Győri E, Szanyi G, Wéber Z, Kovács IJ (2020) Így figyeljük hazánk földjének minden rezdülését. A csillagászati és földtudományi kutatóközpont geodéziai és geofizikai intézet kövesligethy radó szeizmológiai obszervatórium fejlődése és küldetése 2013-tól napjainkig. Magy Tud. https://doi.org/10.1556/2065.181.2020.9.7

Szabó C, Harangi S, Csontos L (1992) Review of neogene and quaternary volcanism of the Carpathian-Pannonian region. Tectonophysics 208:243–256. https://doi.org/10.1016/0040-1951(92)90347-9

Szakács A, Pécskay Z, Gál Á (2018) Patterns and trends of time–space evolution of Neogene volcanism in the Carpathian-Pannonian region: a review. Acta Geod Geophys 53:347–367. https://doi.org/10.1007/s40328-018-0230-3

Tari G, Dövényi P, Dunkl I, Horváth F, Lenkey L, SzafiánTóth PT (1999) Lithospheric structure of the Pannonian basin derived from seismic, gravity and geothermal data. Geol Soc Spec Publ 156:215–250

Tari G, Arbouille D, Schléder Z, Tóth T (2020) Inversion tectonics: a brief petroleum industry perspective. Solid Earth 11:1865–1889. https://doi.org/10.5194/se-11-1865-2020

Tari G, Bada G, Boote DRD, Krézsek C, Koroknai B, Kovács G, Lemberkovics V, Sachsenhofer RF, Tóth T (2023) The Pannonian super basin: a brief overview. AAPG Bull 107(8):1391–1417. https://doi.org/10.1306/02172322098

Tesauro M, Kaban MK, Cloetingh S (2009) How rigid is Europe's lithosphere? Geophys Res Lett. https://doi.org/10.1029/2009GL039229

Török K (2007) Osumilit-(Mg), egy új hazai ásvány egy badacsonyi buchit xenolitból. Földtani Közlöny 137:359–368

Török K (2012) On the origin and fluid content of some rare crustal xenoliths and their bearing on the structure and evolution of the crust beneath the Bakony-Balaton highland volcanic field (W-Hungary). Int J Earth Sci 101:1581–1597. https://doi.org/10.1007/s00531-011-0743-2

Török K, Németh B, Koller F, Dégi J, Badenszki E, Szabó C, Mogessie A (2014) Evolution of the middle crust beneath the western Pannonian Basin: a xenolith study. Miner Pet 108(1):33–47. https://doi.org/10.1007/s00710-013-0287-1

Wiese H (1962) Geomagnetische Tiefentellurik Teil II: die Streichrichtung der untergrundstrukturen des elektrischen widerstandes, erschlossen aus geomagnetischen variationen. Geofis Pura e Appl 52:83–103. https://doi.org/10.1007/BF01996002

Wilson JT (1966) Did the atlantic close and then reopen?: a commentary. Nature 211:676–681. https://doi.org/10.12789/geocanj.2016.43.109

Yang X, Keppler H, McCammon C, Ni H, Xia Q, Fan Q (2011) Effect of water on the electrical conductivity of lower crustal clinopyroxene. J Geophys Res 116(B4):B04208. https://doi.org/10.1029/2010JB008010

Yang X, Keppler H, McCammon C, Ni H (2012) Electrical conductivity of orthopyroxene and plagioclase in the lower crust. Contrib Miner Pet 163:33–48. https://doi.org/10.1007/s00410-011-0657-9

Ádám A (1963) Study of the electrical conductivity of the Earth's crust and upper mantle. Methodology and results (in Hungarian). Dissertation 111+XLV

GEOSYSTEM SRL (2008) WinGLink User's Guide. Italy., Release 2.20.02.02.

Kovács IJ, Csontos L, Szabó C, Bali E, Falus G, Benedek K, Zajacz Z (2007) Paleogene–early miocene igneous rocks and geodynamics of the alpine-Carpathian-Pannonian-Dinaric region: an integrated approach.

Tari G, (1994) Alpine tectonics of the Pannonian basin. PhD thesis, Rice university, Houston, Texas.