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Three-dimensional magnetotelluric model along seismic profile 2T: An improved view on crustal structure in central Slovakia (Western Carpathians)

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Abstract: We present the crustal-scale geophysical model based on the magnetotelluric method focused on 3-D modelling of the seismic 2T profile crossing the major Western Carpathian tectonic units in central Slovakia. The results of the 3-D modelling show substantial improvement in previous 2-D models of deep crustal structure in central Slovakia, mainly of the physically distinct tectonic segments and major geo-electrical regional structures like the zone of the Carpathian Conductivity Anomaly, which indicates the occurrence of the large-scale shear zone in the contact zone of the European platform and Inner Western Carpathians. High detail geo-electrical data in 3-D magnetotelluric (MT) cross section also allowed a better interpretation of other conductive anomalies. In the final integrated interpretation (combination of 3-D geo-electrical model, gravity data and seismic reflectors), it is shown that frontal part of the Inner Western Carpathians plate exhibits the transpressional tectonic style of the back-thrust Outer Western Carpathians (Flysch Belt) and Pieniny Klippen Belt units over the progressing Inner Western Carpathian thrust wedge. These back-thrusts form the southern branch of the accretionary structural fan – a large-scale transpressional flower structure typical mainly but not only for oblique convergent regimes. The southernmost segment of the profile with high whole-crust conductivity due to a higher heat flow caused by young volcanic activity indicates partial melting in the middle and lower crust.

Keywords: 3-D magnetotellurics, integrated interpretation, back-thrusting, accretionary prism, block boundary faults, Western Carpathians.

Introduction

The Western Carpathians play an important role in understanding of the lithospheric and sublithospheric interaction and thermal evolution in the area of the contact between the European Platform and the Alpine−Carpathian−Pannonian region. The interplay of contraction, strike-slip, and extension within the structures within this region were studied by numerous authors (e.g. Csontos et al. 1992; Plašienka et al. 1997; Kováč 2000; Bielik et al. 2004; Froitzheim et al. 2008; Alasonati-Tašárová et al. 2016; Plašienka 2018).

The profile 2T (Tomek et al. 1989) is a unique geophysical exploration section in the central part of the Western Carpathian arc (Fig. 1). The profile runs across all of the main tectonic units of the Outer and Inner Western Carpathians (this division is after Tectonic map of Slovakia, Bezák et al. 2004). Diverse geophysical data and models were gathered along this profile or in this area. The initial and the most important geophysical databases are based on the deep seismic reflection profile project (Tomek 1993). The area was also included and supported by geophysical data gathered in the framework of the large regional seismic project CELEBRATION 2000 (CEL-01) (Guterch et al. 2003; Środa et al. 2006; Grabowska et al. 2011), the regional models of seismic velocities based on global waveform tomography (Schaeffer et al. 2016) and the Atlas of Slovak seismic profiles (Vozár & Šantavý 1999).

The interpretation and studies of deep structures of the region, which were published, are mostly based solely on seismic or gravity data. The original deep seismic reflection model by Tomek et al. (1989), clarification studies (Tomek 1993; Tomek & Hall 1993) and reinterpretations (Buday et al. 1991; Bielik et al. 2004) have emerged during the last decades. They accentuated overthrust tectonics, but the most recent studies showed an important role of young steep shear zones in the geological evolution of the Western Carpathians (e.g. Ratschbacher et al. 1993; Marko et al. 2017).

The first deep geo-electrical studies based on geomagnetic transfer function in this area were focused on the most significant linear conductive crustal structure at a depth of 10–20 km known along the whole Western Carpathian arc (Jankowski et al. 1985; Červ et al. 2001; Kováčiková et al. 2005), the Carpathian Conductivity Anomaly (CCA) (Jankowski et al. 1977). The CCA was lately investigated by the magnetotelluric (MT) method, which combine magnetic and electric field, in a profile crossing the Vysoké Tatry Mts. (Ernst et al. 1997). Just recently, the integrated 2-D geological interpretation of the different geophysical models with included magnetotelluric (MT) data was published (Bezák et al. 2020). This study showed that

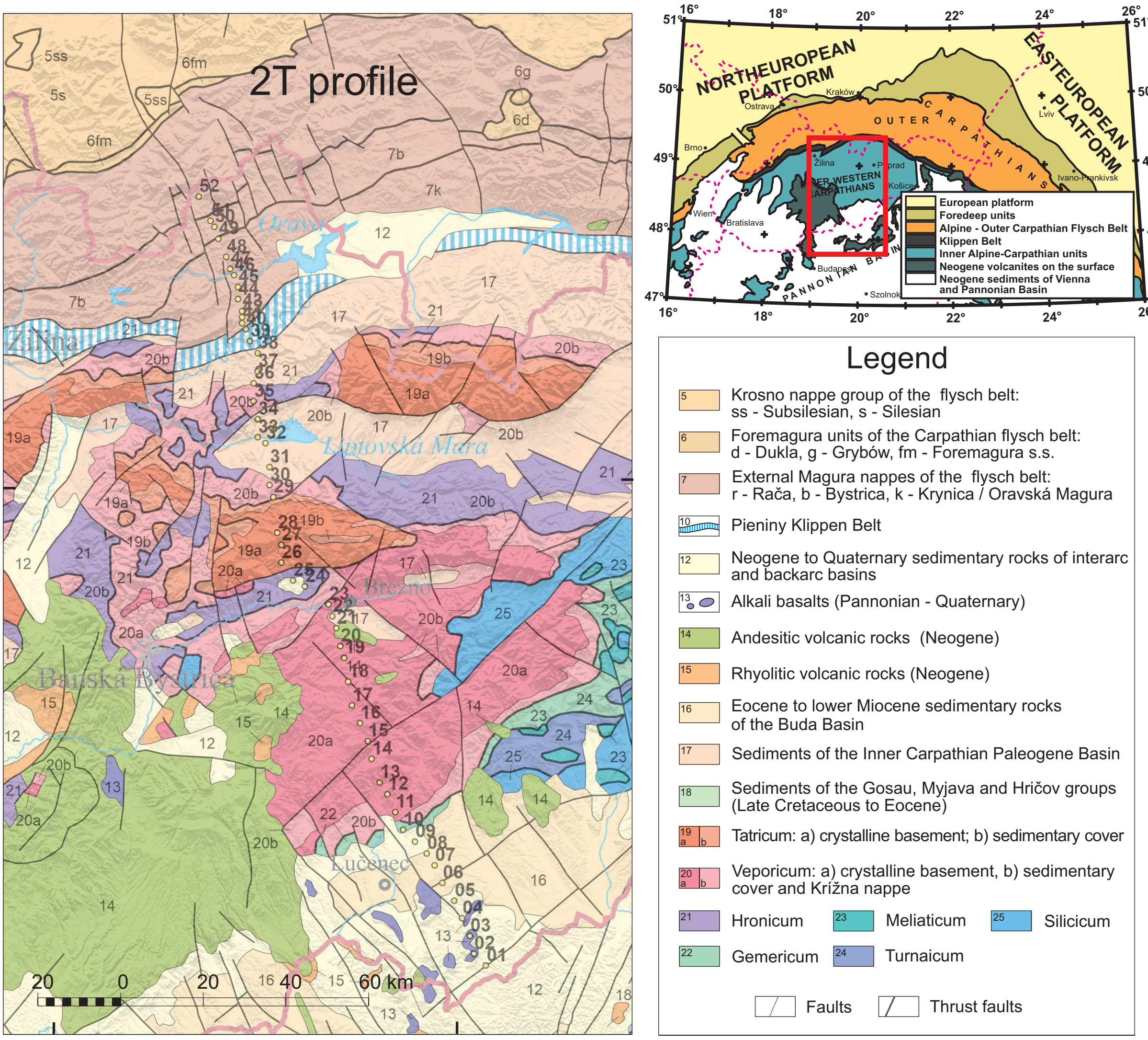

Fig. 1. Left: the geological map after Lexa et al. (2000) with position of magnetotelluric sites used in modelling on the 2T profile. Top right: the tectonic scheme after Majcin et al. (2018) with position of the profile area in the Carpatho–Pannonian region.

distinct crustal zones, divided by subvertical tectonic interfaces, exist within the Carpathian block itself. These structures were interpreted in this work as Cenozoic strike-slip faults, along which compositionally distinct parts of the crust with contrasting physical parameters were juxtaposed in the Western Carpathian crust. However, the detailed synthetic 3-D models based on the newest magnetotelluric data, which map the effects of neighbouring thin lithosphere in the Pannonian Basin, have been missing for this area up to now.

In order to map lateral 3-D geo-electrical structures, we modelled old and newly collected MT data along the 2T profile using the modular ModEM 3-D MT inversion code (Kelbert et al. 2014; Meqbel et al. 2014). The 3-D models exhibit several features, which was not unveiled by previous simple 2-D MT and seismic models (Bezák et al. 2020). This profile can provide a significant contribution to information about major active faults important for description of the geodynamic evolution of the area. The resulting models derived from the integrated approach are interpreted in terms of the tectonic evolution of the crust and lithosphere in central Slovakia.

Geological setting

The Western Carpathians covering the whole territory of Slovakia represent one part of the Cenozoic Alpine–Himalayan orogenic fold and thrust belt. To the west the Western Carpathians are orographically linked to the Eastern Alps (Fig. 1) and to the east they continue as the Eastern Carpathians. Although the Alps and Carpathians belong to the same Alpidic system, there are differences in the Neo-alpine evolution of individual segments of orogen. The Alps represent the zone of shortening due to typical frontal continental collision with very deep orogenic roots, while the Carpathians are the result of tectonic extrusion of microplates (e.g. Inner Western

Carpathian plate, Pelsó, and Tisia) from the Alpine domain (Ratschbacher et al. 1991) to the area of subducting oceanic lithosphere of the flysch basin creating the embayment in the European plate. It led to the oblique collision of the Inner Western Carpathian microplate with the European plate and stack of flysch deposits into the pile of nappes forming the current Outer Carpathians accretionary wedge – Flysch Belt.

The Inner Western Carpathians comprise amalgamated tectonic units of older orogenic periods, mainly consolidated during the Paleo-alpine (Cretaceous) and Hercynian (Paleozoic) orogens. Meso-alpine units are preserved only in rudimentary form at the northern margin of the Inner Western Carpathians, they are incorporated to the Neo-alpine structure of the Pieniny Klippen Belt. The basement of the Inner Western Carpathian crust is composed of the Hercynian units – medium to high-grade metamorphic crystalline complexes intruded by granitoids (Bezák et al. 1997). During the Paleo-alpine tectonic evolution, together with the Upper Paleozoic–Mesozoic complexes they were incorporated into the new tectonic mega-units – basement nappes of the Tatricum, Veporicum, and Gemericum and overthrust by superficial Mesozoic nappes of the Fatric, Hronic and Silicic thin-skinned nappe systems. The latest studies show that the Inner Western Carpathian block is composed of several particular blocks, which were shifted along deep seated crustal strike-slip discontinuities (e.g. Ratschbacher et al. 1993; Sperner et al. 2002; Marko et al. 2017; Bezák et al. 2020). In the final stages of Carpathian evolution the crust was broken up into horsts and grabens accompanied by massive volcanic activity. The latest review of knowledge concerning the tectonic evolution of the Western Carpathians is presented e.g. in Froitzheim et al. (2008), Bezák et al. (2011) and Plašienka (2018).

The modelled 2T profile crosscutting all the main tectonic units is situated in the central part of Slovakia (Fig. 1). In the north there are units of the Outer Western Carpathians, then the very narrow and tectonically complicated Pieniny Klippen Belt, then follow two mountain ranges separated by sedimentary deposits of the Central Carpathian Paleogene Basin. The northernmost mountains are formed by a narrow horst of the Chočské vrchy Mts. composed of Mesozoic thin-skinned nappe complexes, and southern mountains represented the horst of the Nízke Tatry Mts., which contains the Hercynian crystalline basement, Mesozoic cover sequences, and nappe pile of thin-skinned tectonic units. The Middle part of the 2T profile intersects the Veporicum composed of the Hercynian crystalline complexes. The southern part of the profile cuts the Neogene sediments and volcanites underlain by the Gemericum and non-specified exotic crystalline basement probably of Cadomian age is expected underneath.

Magnetotelluric modelling

Magnetotellurics is a unique geophysical method using passive natural-source electromagnetic sounding technique that employs a range of variations from kilohertz to thousands of seconds to image subsurface distribution of electrical conductivity. The natural magnetic field is used as the source field for the method and is generated in the ionosphere and magnetosphere. The source field induces an electric field within the Earth and orthogonal electric and magnetic field variations measurements are collected on the surface (Tikhonov 1950; Cagniard 1953). Electrical conductivity, which varies over 10 orders of magnitude (Haak & Hutton 1987; Bedrosian 2007), is the important physical property and plays a significant role in understanding dynamical, compositional, and transport properties of the geological units.

The 3-D inversion of the 2-D distribution of MT data, where sites are distributed along the profile, is used to improve geo-electrical image of structures (Meqbel et al. 2016; Kirkby & Duan 2019). The advantage of 3-D inversion codes is the possibility to use more information from primary sounding MT data, namely a full four components of impedance tensor instead of two, derived phase tensor data (Caldwell et al. 2004) or interstation horizontal magnetic tensor (Egbert & Booker 1989). We investigated these 3-D features in this area and used robust primary data with full impedance and geomagnetic transfer functions (GTF) components. There are several studies, which show importance of modelling the full impedance matrix to reveal additional information about lateral structures (along strike changes in conductivity) from measurement designed for 2-D modelling (Ledo et al. 2002; Kiyan et al. 2014; Campanyà et al. 2016). Application of 3-D modelling allows adding into models new 3-D structures, which improve the geo-electrical image and fit of original data. In previous 2-D models this lateral information was treated as a distortion and they were neglected or could be incorrectly introduced in models as unreal structures. In addition, we faced the change of the 2-D regional strike in northern and southern parts of the profile (Bezák et al. 2020) in our 2-D modelling of MT data. The splitting of data modelling to two groups is avoided by application of 3-D approach, so transition zone between the northern and southern parts of the profile is not affected by the regional strike change.

For the 3-D MT modelling we used the Modular system for Electromagnetic inversion code (called ModEM) (Egbert & Kelbert 2012; Kelbert et al. 2014), which allows parallel calculation of the inversion of impedance and GTF electromagnetic data on the high-performance computing cluster. The finite difference mesh used in this code has to have an oversized central investigation part of the mesh and his size was 141×71×40. The elevation variations in the investigated area are small in comparison to the modelled area and therefore the simple flat modelling approach was used. The different starting geo-electrical models were tested in the beginning of study and we selected simple constant resistivity half-space models with 100 Ωm resistivity, which was used in the final best fitting inversion model.

The main MT datasets available for modelling of the crustal conductivity structure along the 2T profile are broad-band data (periods from 0.05 to approximately 500 s) from earlier measurements by ELGI Budapest and Geofyzika Brno in the 1980s at 52 sites, along a profile approximately 150 km long (Varga & Lada 1988). Ten sites in the southern part of the profile were re-measured to check the quality of these old data by new broad-band MT Metronix systems (periods from 0.001 to approximately 100 s) conducted by the Geophysical Institutes of the Czech and Slovak Academies of Sciences in 2013 (Bezák et al. 2015). The MT data were of acceptably good quality, except for a few stations in the section crossing the Liptovská kotlina Basin and Nízke Tatry Mts. (between 50–70 km), where an increased level in industrial noise over high-resistivity basement affected the MT curves, especially during longer periods. The full impedance and GTF data were inverted from 46 sites with error floors set at 5 % of geometrical average of off-diagonal components of the impedance tensor and 0.05 value for GTF components. The smoothing covariance parameter for roughness of the model was set to 0.5. We tested sensitivity of the inversion model to different subsets of primary input data to evaluate physical information within each subset, namely off-diagonal impedance components and GTF. The resulting fit of full dataset is represented by root mean square (RMS) misfit of reduced chi-square value and is 2.4, which is equivalent to average data fit quality. The final fit with all stations is presented in Fig. 2.

Geological interpretation of MT models

The final resistivity model is presented as horizontal slices at three crustal depths (Fig. 3a–c) and vertical section through a 3-D model (Fig. 4) along the 2T profile. Except for the area with distorted data in the Liptovská kotlina Basin, MT data provide sensitivity down to asthenospheric depths, which allows reliable identification of geo-electrical structures from depths of hundreds of metres into the lower crust.

The lateral extent of conductive and resistive zones in Fig. 3 is restricted based on distance from the modelled sites. The resistivity model is shown only for distances less than double the depth of a horizontal slice. This approach removes unreal structures, which are not based on information from inverted data, but only numerical effects of the inversion algorithm.

In this section, we have focused on the geological interpretation of conductivity anomalies in the 3-D MT model in the horizontal and vertical sections (shown in Figs. 3, 4). This interpretation is based on the following two basic pillars: relevant information on the geological structure of the area and conductivity properties of the participating rock complexes.

All conductive complexes with limited depth along the entire length of the profile are mostly Cenozoic (and sometimes older, mostly Mesozoic) sedimentary deposits and volcanic rocks. Within the sedimentary complexes, Flysch Belt complexes (anomaly A1) deserve our attention because they extend to a depth of 5 to 7 km above the nonconductive European Platform (Figs. 3a,b, 4). The new perspective on the structure of the Flysch Belt was also enriched by the migrated seismic section in this area (Fig. 5a), which shows the flower structure from the axis of the former suture of the Neo-alpine zone. The Pieniny Klippen Belt complexes stand out in the southern wing of this structure.

Fault zones are another category of conductive structures. When the tectonic blocks move, rock is disrupted but also revived in order to facilitate the migration of fluids (water, hydrothermal mineralized solutions etc.), which are the main cause of high conductivity of these fault structures. Their penetration by fluids and degree of crushing is not continuous throughout their course. One such fault zone (anomaly A2) is taking shape in the 5 km horizontal section (Fig. 3a), it runs in the NNW direction. It is not very deep and it connects spatially to the Zázrivá fault in the north of the profile, where the Pieniny Klippen Belt is significantly shifted. The slice continues through the valley south of Ružomberok, which separates orographically the Nízke Tatry Mts. from the Veľká Fatra Mts. Maybe it could be linked to the south with the signs of shallow fault structures in the western part of the Nízke Tatry Mts. (anomaly A3). This A3 anomaly is combined with the Nízke Tatry fault (Nt in the Fig. 5a) and with the signs of sedimentary infill in the Horehronie Basin. Following this fault zone further to the SSE, we get to the volcanic centres of the Poľana and Javorie Mts.

The manifestation of the fault structures, which acts as the Osrblie–Pohorelá fault system (Phf) on the surface (anomaly A4 in all horizontal levels and in vertical section, Figs. 3, 4), is different. It consists of deep-seated fault structures with an old foundation, which were certainly restored also in the Neo-alpine period because their conductivity manifestations are quite striking and this zone is still seismically active (e.g. Madarás et al. 2012). Moreover, they form an interface between physically and thus geologically distinct blocks of the crust. These blocks are the granitic and orthogneissic complexes (mostly in the Tatricum unit but also in northernmost Veporic zone – Ľubietová zone) to the north of Phf and the mostly metamorphic prevailingly diaphthorized rocks to the south (Bezák et al. 2020). This means that the northern block is manifested as resistive and much lighter than the southern one (see new Bouguer gravity anomaly map, Pašteka et al. 2017). In connection to this it is interesting that these differences led Zoubek (1937) to include the Ľubietová zone in the Tatricum.

It is not entirely clear when convergence of these distinct blocks occurred, and it probably occurred in several stages. There is indicative evidence of this fault system as early as the Permian (Bezák 2002), when it was intruded by the Permian magmatites (Petrík et al. 1995). Furthermore, there are clues to its function even after the Paleo-alpine stage, because it is the boundary between the northern and southern Veporicum in terms of their Mesozoic covers. The shift along this fault does not contradict the Paleo-alpine nappe structure. Paleo-alpine thrusts in this zone are discussed in works such as Bezák & Olšavský (2008), but, at the same time, there is cutting of a series of tectonic slices of crystalline rocks separated by Mesozoic sediments by younger subvertical faults. The seismic model does not provide a reliably image of these

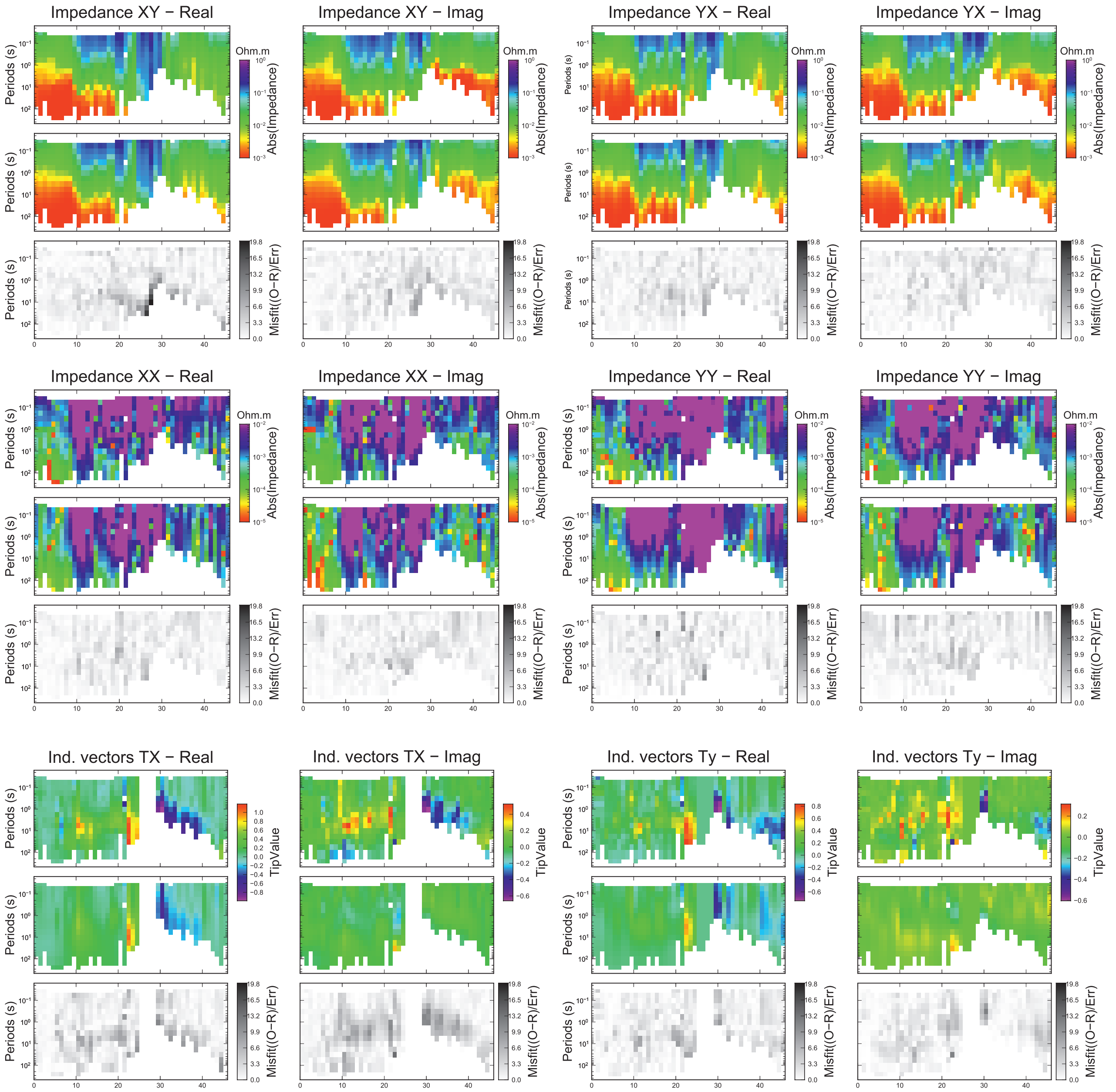

Fig. 2. Full data plots of original, predicted and misfit values for each data point complex component (sites from the south to north, periods) and data type (off-diagonal xy, yx; diagonal xx, yy; GTF tx, ty).

steep structures. It may not be visible in the bundles of seismic reflexes, although here the seismic image shows us rather significant difference between the tectonically heavily laminated southern block and the northern block (block II and III in Bezák et al. 2020).

Anomaly A5 is not very deep, its manifestation is only at the 5 km level (Fig. 3a) and it may be a young reactivation of the Divín–Muráň fault system (Mu in Fig. 5), which is also documented by seismic activity (Madarás et al. 2012).

The A6 anomalies come from the Neogene magma chambers in the volcanic centres (Poľana, Javorie volcanoes and basaltic chambers below the Cerová vrchovina Mts.). Their magmatic impact obviously progressed along the fault structures to the east to the Veporic crystalline blocks (anomalies A6a, b). The impact of volcanic activity and the associated hydrothermal activity in the southernmost block is extremely high (anomaly A6c). It is plausible that this extreme activity has its source in the mantle, as indicated by the enclaves of the mantle in the basaltic volcanics in this area (Huraiová & Konečný 1994). This activity was manifested by the physical changes (hydrothermal alterations) to the crystalline complexes (CBA in Fig. 5).

The deepest conductive anomalies, which go down to depths of more than 20 km, are manifested only in the horizontal

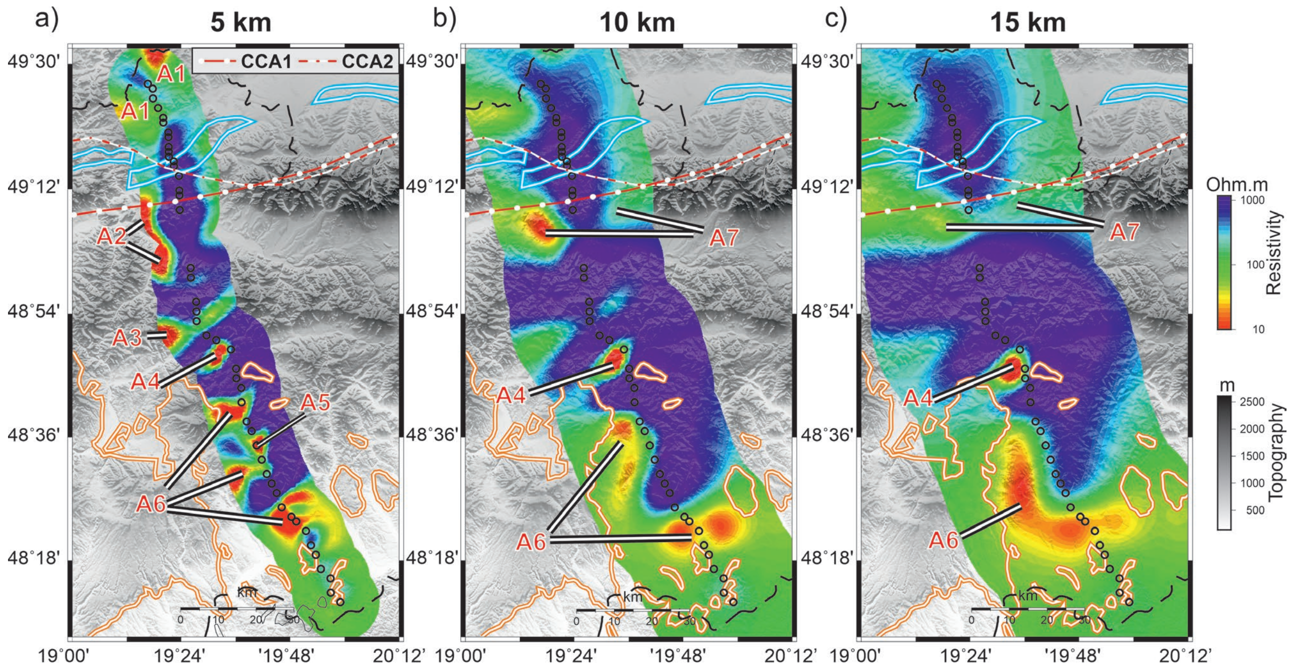

Fig. 3. The horizontal slices through 3-D resistivity inversion model of the 2T profile at depths 5 km (**a**), 10 km (**b**), and 15 km (**c**). Thick red lines in the northern part of the 2T slices image indicate expected position of the CCA. The line labelled as CCA1 is the position of CCA based on Jankowski et al. (1985) and the CCA2 line following from Červ et al. (2001). The black circles indicate position of the MT sites included in 3-D MT inversion modelling. Blue polygon indicates Pieniny Klippen Belt, and orange polygons are volcanic rocks. A1–A7 labels for conductive anomalies are described in the text.

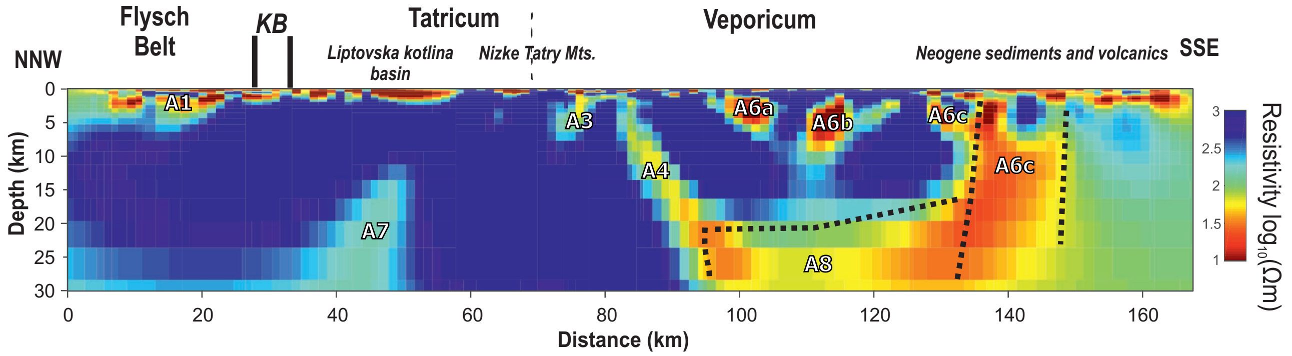

Fig. 4. Vertical cross-section through the MT 3-D model along measured sites. Conductive anomalies labelled as A1–A8 are described in the text.

slices 10, 15 km (Fig. 3b, c) or vertical section (Fig. 4). This is anomaly A7 that reflect the CCA zone and anomaly A8, which is probably caused by conductive metamorphic complexes under non-conductive granitic complexes in the central part of the profile. This is most probably a remnant of Hercynian superposition of middle crust nappes of granitic middle unit over mica-schist lower unit (Bezák et al. 1997). However, other geological and geophysical studies also suggest that there are mica-schist complexes under the granite complexes in the Veporicum (magnetic anomalies under the non-magnetic granites, fluid inclusions in the veins of the granites, which come from the metasediments (Hurai et al. 1994).

Discussion

A geological interpretation of all 3-D conductive anomalies is presented in Fig. 5a and confronted with the results of 2-D modelling interpreted by Bezák et al. (2020) in Fig. 5b.

In the Fig. 5 we compare the new 3-D model to the previous 2-D MT modelling results (Bezák et al. 2020) and seismic deep reflection images (only in the northern part). We create the sections through geo-electrical 3-D models along the modelled 2T profile. The 2-D model shown in Fig. 5b is a stitched version of the inversion results of the northern sub-profile and the southern part of 2T. A conductivity 2-D model was

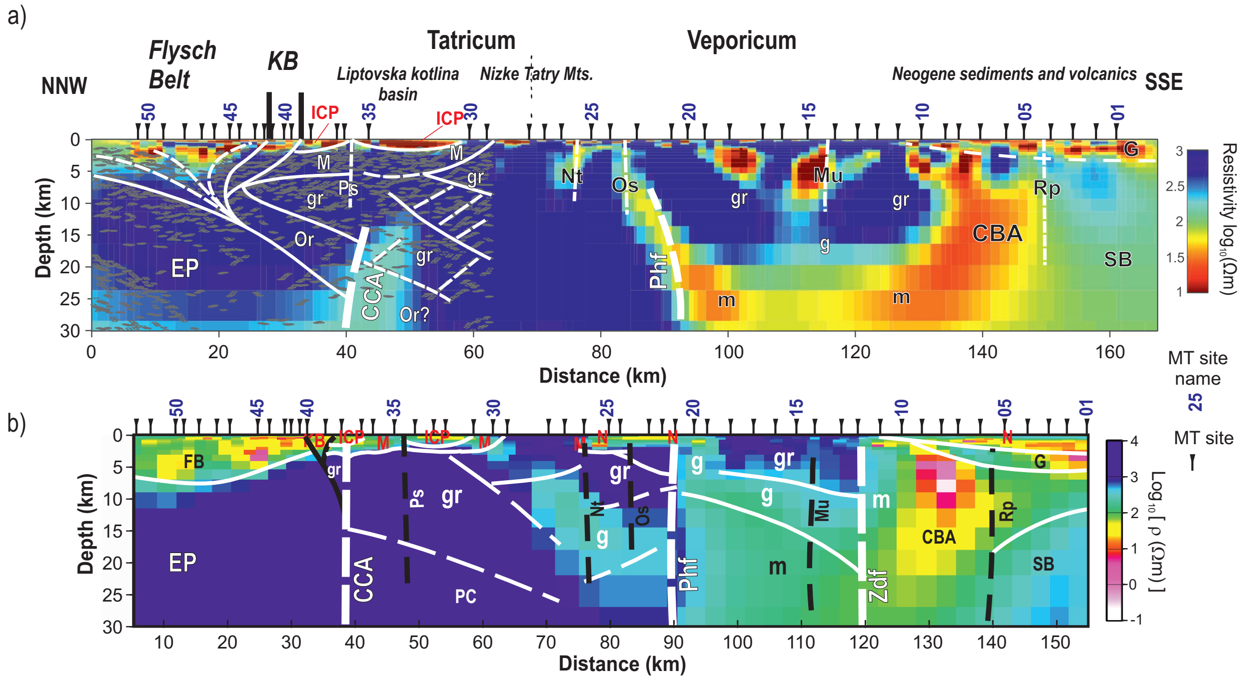

Fig. 5. Geological interpretation of MT models along 2T seismic profile: **a** — cross-section through the 3-D model (present work); **b** — 2-D model (Bezák et al. 2020). The layout of sites and length of the 2-D profile and 3-D model cross-section is slightly different, i.e. the 3-D section is longer. It follows from simple composition of 2-D profile (two lines), where the sites are projected to the lines perpendicular to geo-electrical strike, and detailed 3-D section, which is composed from multi-segment line as closely as possible following the MT site positions. Explanations: EP – European Platform, FB – Flysch belt, Or – Oravic basement (marked as PC – Pieninic crust in b), KB – Pieniny Klippen Belt, M – Mesozoic complexes, ICP – Inner Carpathian Paleogene Basin, N – Neogene sediments and volcanites, gr – Hercynian granitoids and granitized complexes, g – Hercynian gneisses, m – Hercynian mica-schists, G – Gemeric complexes, CBA – crystalline basement altered, SB – southern Cadomian basement. Principal shear zones: CCA – Carpathian Conductive Anomaly zone axis, Phf – Osrblie–Pohorelá fault zone, Zdf – Zdychava fault zone. Faults: Ps – Prosiek, Nt – Nízke Tatry, Os – Osrblie, Mu – Muráň–Divín, Rp – Rapovce. Antithetic north-dipping reflections (marked by dashed lines) in the crystalline complexes of the Tatricum are remnants of Hercynian middle crust thrusting (Bielik et al. 2004).

calculated by the algorithm for anisotropic conductivity structures (Pek et al. 2012) and the classic non-linear conjugate gradient algorithm of the MT inversion (Rodi & Mackie 2001). The model is composed of two segments with geo-electrical strike direction 60° and 45°.

As we can see from Fig. 5, the 2-D modelling alone is not recovering the higher complexity of geological structural geometries particularly in the northern part of the 2T profile (up to 80 km). The significant changes of structures in the 2-D geo-electrical strike directions are expected. More parameters in the input datasets and higher dimensionality cause possible greater variability within the 3-D model during inversion than in the 2-D modelling. There are well known problems of galvanic and induction effects of 3-D structures that cannot be removed by classic decomposition techniques (Ledo 2005; Jones 2012) for 2-D data preparation and the distribution of them has an effect on the both modes of 2-D MT data. Due to this presence of extra data information in diagonal impedance components, which could be sensitive to artificial noise, the possible effect of noisy data in 3-D MT inversions (area 50–70 km mentioned above) are usually compensated in very shallow parts of the inversion model and not in deeper parts as in the 2-D case. Fortunately, the image of the northern half of the area is dominated by high resistivity rocks and therefore any presence of conductive zone can be inferred with high probability even from heavily edited data without longer periods.

The CCA structure is the most significant geo-electrical structure in the region. It was well mapped by numerous magnetotelluric and magnetovariational field measurements performed during the last 30 years (Jankowski et al. 1985; Červ et al. 2001). It is known that the CCA lies along the Outer and Inner Western Carpathian contact zone from the Malé Karpaty Mts. to the Eastern Carpathians. The zone is about tens of kilometres wide in the depth range of 10–25 km and its length is approximately 1200 km (Buryanov et al. 1987). Its origin is probably caused by trapped fluids from the mantle and with combination of carbon derived from subducted metasediments (Hvoždara & Vozár 2004; Jankowski et al. 2008). In the 3-D model slice, it is present in a position as expected from these previous studies. The depth of the CCA is from 10 km up to 20–25 km, but the bottom boundary is not well constrained. The interface between the well conductive body and underlying resistive structures is hard to resolve by MT method due to its weakness from definition. The electromagnetic responses of the resistive structures are much weaker than from the conductive ones and therefore it is very hard to distinguish them from the surface.

A significant difference can be seen in the case of only anticipated CCA, which was not visible in the 2-D cross section, while 3-D solution nicely shows this very high conductivity zone. This difference is a combination of impedance data quality, CCA geometry in the area, and balancing weights between GTF and impedances during inversion process. On the other hand, this conductivity zone in the 3-D cross section is spatially shifted to the south and the shape of the anomaly is more similar to the study by Červ et al. (2001). It coincides with the northern boundary fault of the Carpathian Shear Corridor (Marko et al. 2017) representing the left lateral transform boundary of extruded Inner Carpathian crustal segments. We regard the CCA as an expression of the major fault zone in the area between the European Platform and Inner Western Carpathians. However, the CCA does not always coincide with the contact (suture) zone between the European Platform and Inner Western Carpathians, which can be caused by other major shear zones. A sudden change in the Moho depth between the platform and the Inner Carpathians (e.g. Hrubcová & Środa 2015) is also an indicator of the tectonic contact of the two plates.

Another important piece of knowledge coming from the 3-D MT model is the new picture of the tectonic architecture north of the CCA zone. The northward dipping southernmost complexes of the Flysch Belt and frontal Inner Western Carpathian complexes (Pieniny Klippen Belt, northern part of the Tatricum, border zones of the Inner Carpathian Paleogene Basin) are clearly visible in the 3-D MT model with migrated seismic reflexes (Fig. 5a), as well as subduction suture, the main thrust plane of the Inner Western Carpathian block over the foreland respectively. This suture zone is not represented by the Pieniny Klippen Belt, but is situated further to the north of the present day Klippen Belt in the basement of the Flysch Belt. From the 3-D MT model, the tectonic style of the transpressional fan-like structure of the Outer Flysch Belt emerges. Its southern branch is formed by the back-thrust Flysch Belt units scraped off the Magura oceanic basin floor during subduction followed by oblique transpressional collision. The Pieniny Klippen Belt units are back-thrust as well and are incorporated within south-vergent back-thrusts over the wedge-shaped internal block created by the Inner Western Carpathian block and northernmost Pieninic (Oravic) crust block (see discussion below). These back-thrusts affected the Inner Western Carpathian units and the southern part of the Flysch Belt, in the contact zone, are stated in some previous studies. We interpret this as multiple back-thrusts affecting the frontal margin of the prograding microplate. These back-thrusts form the southern branch of the accretionary structural fan – a large-scale transpressional flower structure typical for oblique convergent regimes (e.g. Pešková et al. 2009; Marko et al. 2005). A similar style of accretionary prisms was described, for example, by Yeats (2012), Press et al. (2004).

In the final part of the discussion, we want to address the question of two Cadomian blocks, that once drifted from the platform and are now incorporated into a deeper Western Carpathian structure. They do not outcrop on the surface and their existence is based only on paleotectonic reconstructions and geophysical data. The first is the Cadomian block in the Tatricum basement, known as the Oravic basement (Or in Fig. 5a), more recently, the Pieninic crust (e.g Środa et al. 2006 – PC in Fig. 5b). It was the basement of the part of Mesozoic sedimentary complexes of the Pieniny Klippen Belt north of the Southern Penninic Ocean, which became a part of the Inner Western Carpathian block during the Meso-alpine collision.

The second Cadomian fragment is inferred in the southern part of the profile in the lower crust below the Cerová vrchovina Mts. and Novohrad–Nógrad Basin. It is the relatively resistive so-called southern Cadomian basement (SB in Fig. 5) in the sense of Bezák et al.(1997), the existence of which is indicated particularly by the xenoliths in basalts (Hovorka & Lukáčik 1972), but also by a severe magnetic anomaly (Kubeš et al. 2010). Originally, it was the lowest autochthonous element of the Hercynian tectonic structure at the time, which became part of the Veporicum in the Paleo-alpine orogenesis and later the Neo-alpine Inner Western Carpathian block.

Conclusion

The geophysical modelling by the MT 3-D method and its geological interpretation is presented in this study. The 3-D MT inversion ModEM package was used to obtain better-constrained crustal conductivity models of MT data collected along the 2T seismic profile crossing the major geological units within the Inner and Outer Western Carpathians in central Slovakia. The final model presented here substantially improves knowledge of deep crustal architecture in the region of central Slovakia and thus in a significant part of the Western Carpathians.

The first important output from our 3-D modelling is the presence of the CCA in our geo-electrical inversion results. The final model reliably identifies this prominent Neo-alpine boundary between the European Platform and Inner Western Carpathians. Such a recalculated geo-electrical model allows us to study crustal architecture with higher details. In combination with the deep reflection seismic data it gives a complex picture of this important crustal tectonic interface, where the frontal part of the Inner Western Carpathian plate exhibits the transpressional tectonic style of the back-thrust Outer Carpathian Flysch Belt and Pieniny Klippen Belt over the progressing Inner Western Carpathian thrust wedge. These back-thrusts form the southern branch of the accretionary structural fan – a large-scale transpressional flower structure typical mainly but not only for oblique convergent regimes.

The southernmost segment with high conductivity in the entire crust has a similar image in both 2-D and 3-D MT methods. This phenomenon has already previously been interpreted as the effects of young volcanism and the associated hydrothermal processes. In addition to identifying the classic near-surface sedimentary and volcanic complexes, some of the conductive anomalies in the model are associated with major fault zones within the investigated area. The example of these fault structures is associated with the surface trace of the Pohorelá fault, which has a very deep root. This structure forms an interface between the very compact resistive northern block mostly represented by the granitic and orthogneissic complexes and the mostly metamorphic rocks in the southernmost block. Therefore, our final 3-D geo-electrical model proves that it can identify physically and thus geologically distinct blocks, which allows the crustal-scale interpretation of geological and geodynamic processes.

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References

Alasonati Tašárová Z., Fullea J., Bielik M. & Środa P. 2016: Lithospheric structure of Central Europe: Puzzle pieces from Pannonian Basin to Trans-European Suture Zone resolved by geophysical-petrological modeling. *Tectonics* 35, 722–753. https://doi.org/10.1002/2015TC003935

Bedrosian P.A. 2007: MT+, integrating magnetotellurics to determine Earth structure, physical state, and processes. *Surveys in Geophysics* 28, 121–167. https://doi.org/10.1007/s10712-007-9019-6

Bezák V. 2002: Hercynian and Alpine strike-slip tectonics – a dominant element of tectonic development of the Inner Western Carpathians. *Geologica Carpatica* 53, Special Issue, 17–22.

Bezák V. & Olšavský M. 2008: Large overthrusts in the Northern Veporicum (Western Carpathians). *Mineralia Slovaca* 40, 121–126 (in Slovak).

Bezák V., Jacko S., Janák M., Ledru P., Petrík I. & Vozárová A. 1997: Main Hercynian lithotectonic units of the Western Carpathians. In: Grecula P., Hovorka D. & Putiš M. (Eds.): Geological evolution of the Western Carpathians. *Mineralia Slovaca – Monograph, Geocomplex*, Bratislava, 261–268.

Bezák V., Broska I., Ivanička J., Reichwalder P., Vozár J., Polák M., Havrila M., Mello J., Biely A., Plašienka D., Potfaj M., Konečný V., Lexa J., Kaličiak M., Žec B., Vass D., Elečko M., Janočko J., Pereszlényi M., Marko M., Maglay J. & Pristaš J. 2004: Tectonic map of Slovak republic 1:500 000. *Ministry of Environment of the Slovak Republic*, *ŠGÚDŠ*, Bratislava.

Bezák V., Biely A., Elečko M., Konečný V., Mello J., Polák M. & Potfaj M. 2011: A new synthesis of the geological structure of Slovakia – the general geological map at 1:200 000 scale. *Geological Quarterly* 55, 1–8.

Bezák V., Pek J., Majcin D., Bučová J., Šoltis T., Bilčík D. &. Klanica R. 2015: Geological interpretation of magnetotelluric sounding in the southern part of seismic profile 2T (Central Slovakia). *Contribution to Geophysics and Geodesy* 45, 1–11. https://doi.org/10.1515/congeo-2015-0009

Bezák V., Pek J., Vozár J., Majcin D., Bielik M. & Tomek Č. 2020: Geoelectrically distinct zones in the crust of the Western Carpathians : A consequence of Neogene strike-slip tectonics. *Geologica Carpathica* 71, 14–23. https://doi.org/10.31577/GeolCarp.71.1.2

Bielik M., Šefara J., Kováč M., Bezák V. & Plašienka D. 2004: The Western Carpathians – interaction of Hercynian and Alpine processes. *Tectonophysics* 393, 63–86. https://doi.org/10.1016/j.tecto.2004.07.044

Buday T., Bezák V., Potfaj M. & Suk M. 1991: Discussion to the interpretation of reflex seismic profiles in West Carpathians [Diskuse k interpretaci reflexních seizmických profilů v Západních Karpatech]. *Mineralia Slovaca* 23, 275–276.

Buryanov V.B., Gordyenko V.V., Zavgorodnyaya O.V., Kulik S.N., Logvinov I.M. & Shuman V.N. 1987: A Geophysical Model for Tectonosphere of Europe. *Nauka Dumka*, Kiev (in Russian).

Cagniard L. 1953: Basic theory of the magneto-telluric method of geophysical prospecting. *Geophysics* 18, 605–635. https://doi.org/10.1190/1.1437915

Caldwell T.G., Bibby H.M. & Brown C. 2004: The magnetotelluric phase tensor. *Geophysical Journal International* 158, 457–469. https://doi.org/10.1111/j.1365-246X.2004.02281.x

Campanyà J., Ogaya X., Jones A.G., Rath V., Vozar J. & Meqbel N. 2016: The advantages of complementing MT profiles in 3-D environments with geomagnetic transfer function and interstation horizontal magnetic transfer function data: results from a synthetic case study. *Geophysical Journal International* 207, 1818–1836. https://doi.org/10.1093/gji/ggw357

Červ V., Kováčiková S., Pek J., Pěčová J. & Praus O. 2001: Geoelectrical structure across the Bohemian Massif and the transition zone to the West Carpathians. *Tectonophysics* 332, 201–210. https://doi.org/10.1016/S0040-1951(00)00257-2

Csontos L., Nagymarosy A., Horváth F. & Kováč M. 1992: Tertiary evolution of the Intra-Carpathian area: A model. *Tectonophysics* 208, 221–241. https://doi.org/10.1016/0040-1951(92)90346-8

Egbert G.D. & Booker J.R. 1989: Multivariate analysis of geomagnetic array data: 1. The response space. *Journal of Geophysical Research* 94, 14227–14247. https://doi.org/10.1029/jb094ib10p14227

Egbert G.D. & Kelbert A. 2012: Computational recipes for electromagnetic inverse problems. *Geophysical Journal International* 189, 251–267. https://doi.org/10.1111/j.1365-246X.2011.05347.x

Ernst T., Jankowski J., Semenov V.Y., Adam A., Hvoždara M., Jozwiak W., Lefeld J., Pawliszyn J., Szarka L.L. & Wesztergom V. 1997: Electromagnetic soundings across the Tatra Mountains. *Acta Geophysica Polonica* XLV, 33–44.

Froitzheim N., Plašienka D. & Schuster R., 2008: Alpine tectonics of the Alps and Western Carpathians. In: McCann T. (Ed.): The Geology of Central Europe. Volume 2: Mesozoic and Cenozoic. *Geological Society Publishing House*, London, 1141–1232.

Grabowska T., Bojdys G., Bielik M. & Csicsay K. 2011: Density and magnetic models of the lithosphere along CELEBRATION 2000 profile CEL01. *Acta Geophysica* 59, 526–560. https://doi.org/10.2478/s11600-011-0007-3

Guterch A., Grad M., Keller G.R.R., Posgay K., Vozár J., Špičák A., Brückl E., Hajnal Z., Thybo H., Selvi O. & CELEBRATION 2000 Experiment team 2003: CELEBRATION 2000 seismic experiment. *Studia Geophysica Geodetica* 47, 659–669. https://doi.org/10.1023/A:1024728005301

Haak V. & Hutton R. 1987: Electrical resistivity in continental lower crust. *Geological Society, London, Special Publications* 24, 35–49. https://doi.org/10.1144/GSL.SP.1986.024.01.05

Hovorka D. & Lukáčik E. 1972: Xenoliths in andesites of the Massif Karanč and Šiator (Southern Slovakia) and their geological interpretation. *Geologica Carpathica* 23, 297–309.

Hrubcová P. & Środa P. 2015: Complex local Moho topography in the Western Carpathians: Indication of the ALCAPA and the European Plate contact. *Tectonophysics* 638, 63–81. https://doi.org/10.1016/j.tecto.2014.10.013

Hurai V., Simon K. & Bezák V. 1994: Hercynian age of some Alpine-type fissures in the crystalline complexes of the Veporicum unit (Central Slovakia). *Mineralia Slovaca* 26, 355–361 (in Slovak).

Huraiová M. & Konečný P., 1994: Pressure-temperature conditions and oxidation state uf upper mantle in the southern Slovakia. *Acta Geologica Hungarica* 37, 33–44.

Hvoždara M. & Vozár J. 2004: Laboratory and geophysical implications for explanation of the nature of the Carpathian conductivity anomaly. *Acta Geophysica Polonica* 52, 497–508.

Jankowski J., Szymański A., Pěč K., Červ V., Petr V., Pěčová J., Praus O. & Hvožďara M. 1977: Anomalous induction in the Carpathians. *Studia Geophysica et Geodaetica* 21, 35–57. https://doi.org/10.1007/BF01615371

Jankowski J., Tarłowski Z., Praus O., Pěčová J. & Petr V. 1985: The results of deep geomagnetic soundings in the West Carpathians. *Geophysical Journal of the Royal Astronomical Society* 80, 561–574. https://doi.org/10.1111/j.1365-246X.1985.tb05111.x

Jankowski J., Jóźwiak W. & Vozár J. 2008: Arguments for ionic nature of the Carpathian electric conductivity anomaly. *Acta Geophysica* 56, 455–465. https://doi.org/10.2478/s11600-008-0004-3

Jones A.G. 2012: Distortion decomposition of the magnetotelluric impedance tensors from a one-dimensional anisotropic Earth. *Geophysical Journal International* 189, 268–284. https://doi.org/10.1111/j.1365-246X.2012.05362.x

Kelbert A., Meqbel N., Egbert G.D. & Tandon K. 2014: ModEM: A modular system for inversion of electromagnetic geophysical data. *Computers & Geosciences* 66, 40–53. https://doi.org/10.1016/j.cageo.2014.01.010

Kirkby A. & Duan J. 2019: Crustal Structure of the Eastern Arunta Region, Central Australia, From Magnetotelluric, Seismic, and Magnetic Data. *Journal of Geophysical Research Solid Earth* 124, 9395–9414. https://doi.org/10.1029/2018jb016223

Kiyan D., Jones A.G. & Vozár J. 2014: The inability of magnetotelluric off-diagonal impedance tensor elements to sense oblique conductors in three-dimensional inversion. *Geophysical Journal International* 196, 1351–1364. https://doi.org/10.1093/gji/ggt470

Kováč M. 2000: Geodynamic, paleogeographic and structural evolution of Carpathian and Panonian region in Miocene. New insight on Neogene basins of Slovakia. *Veda*, Bratislava, 1–202 (in Slovak).

Kováčiková S., Červ V. & Praus O. 2005: Modelling of the conductance distribution at the eastern margin of the European Hercynides. *Studia Geophysica et Geodaetica* 49, 403–421.

Kubeš P., Bezák V., Kucharič Ľ., Filo M., Vozár J., Konečný V., Kohút M. & Gluch A. 2010: Magnetic field of the Western Carpathians (Slovakia): Reflections on the structure of the crust. *Geologica Carpathica* 61, 437–447. https://doi.org/10.2478/v10096-010-0026-z

Ledo J. 2005: 2-D Versus 3-D Magnetotelluric Data Interpretation. *Surveys in Geophysics* 26, 511–543. https://doi.org/10.1007/s10712-005-1757-8

Ledo J., Queralt P., Martí A. & Jones A.G. 2002: Two-dimensional interpretation of three-dimensional magnetotelluric data: an example of limitations and resolution. *Geophysical Journal International* 150, 127–139.

Lexa J., Bezák V., Elečko M., Mello J., Polák M., Potfaj M. & Vozár J. 2000: Geological map of Western Carpathians and adjacent areas (1:500,000). *Ministry of the Environment of Slovak Republic and Geological Survey of Slovak Republic*, Bratislava.

Madarás J., Fojtíková L., Hrašna M., Petro Ľ., Ferianc D. & Briestenský M. 2012: Definition of the active seismic regions in Slovakia based on historical earthquake records and current monitoring of tectonic and seismic activity. *Mineralia Slovaca* 44, 351–364 (in Slovak).

Majcin D., Bezák V., Klanica R., Vozár J., Pek J., Bilčík D., Telecký J. 2018: Klippen Belt, Flysch Belt and Inner Western Carpathian Paleogene Basin Relations in the Northern Slovakia by Magnetotelluric Imaging. *Pure And Applied Geophysics* 175, 3555–3568.

Marko F., Vojtko R., Plašienka D., Sliva Ľ., Jablonský J., Reichwalder P. & Starek D. 2005: A contribution to the tectonics of the Periklippen zone near Zázrivá (Western Carpathians). *Slovak Geological Magazine* 11, 37–43.

Marko F., Andriessen P.A.M., Tomek Č., Bezák V., Fojtíková L., Bošanský M., Piovarči M. & Reichwalder P. 2017: Carpathian Shear Corridor – A strike-slip boundary of an extruded crustal segment, *Tectonophysics* 703–704, 119–134. https://doi.org/10.1016/j.tecto.2017.02.010

Meqbel N., Egbert G.D., Wannamaker P.E., Kelbert A. & Schultz A. 2014: Deep electrical resistivity structure of the northwestern U.S. derived from 3-D inversion of USArray magnetotelluric data. *Earth and Planetary Science Letters* 402, 290–304. https://doi.org/10.1016/j.epsl.2013.12.026

Meqbel N., Weckmann U., Muñoz G. & Ritter O. 2016: Crustal metamorphic fluid flux beneath the Dead Sea Basin: Constraints from 2-D and 3-D magnetotelluric modelling, *Geophysical Journal International* 207, 1609–1629. https://doi.org/10.1093/gji/ggw359

Pašteka R., Zahorec P., Kušnirák D., Bošanský M., Papčo J., Szalaiová V., Krajňák M., Marušiak I., Mikuška J. & Bielik M. 2017: High resolution Slovak Bouguer gravity anomaly map and its enhanced derivative transformations: New possibilities for interpretation of anomalous gravity fields. *Contribution to Geophysics and Geodesy* 47, 81–94. https://doi.org/10.1515/congeo-2017-0006

Pek J., Santos F.A.M. & Li Y. 2012: Non-Linear Conjugate Gradient Magnetotelluric Inversion for 2-D Anisotropic Conductivities. In: Proceedings of the 24th Schmucker-Weidelt-Kolloquium. 187–206.

Pešková I., Vojtko R.,Starek D., & Sliva Ľ. 2009: Late Eocene to Quaternary deformation and stress field evolution of the Orava region (Western Carpathians). *Acta Geologica Polonica* 59, 73– 91

Petrík I., Broska I., Bezák V. & Uher P. 1995: The Hrončok (Western Carpathians) type granite – a Hercynian A-type granite in shear zone. *Mineralia Slovaca* 27, 351–364.

Plašienka D. 2018: Continuity and episodicity in the Early Alpine tectonic evolution of the Western Carpathians: how large-scale processes are expressed by the orogenic architecture and rock record data. *Tectonics* 37, 2029–2079. https://doi.org/10.1029/2017TC004779

Plašienka D., Grecula P., Putiš M., Kováč M. & Hovorka D. 1997: Evolution and structure of the Western Carpathians: an overview. In: Grecula P., Hovorka D. & Putiš M. (Eds.): Geological evolution of the Western Carpathians. *Mineralia Slovaca – Monograph*, *Geocomplex*, Bratislava, 1–24.

Press F., Siever R., Grotzinger J. & Jordan T.H. 2004: Understanding Earth. 4th edition. *W.H. Freeman and Company*, New York.

Ratschbacher L., Frisch W., Linzer H.-G. & Merle O. 1991: Lateral extrusion in the eastern Alps, Part 2: Structural analysis. *Tectonics* 10, 257–271. https://doi.org/10.1029/90TC02623

Ratschbacher L., Frisch W., Linzer H.-G., Sperner B., Meschede M., Decker K., Nemčok M., Nemčok J. & Grygar R. 1993: The Pieniny Klippen Belt in the Western Carpathians of northeastern Slovakia: Structural evidence for transpression. *Tectonophysics* 226, 471–483. https://doi.org/10.1016/0040-1951(93)90133-5

Rodi W. & Mackie R.L. 2001: Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion. *Geophysics* 66, 174–187. https://doi.org/10.1190/1.1444893

Schaeffer A.J., Lebedev S. & Becker T.W. 2016: Azimuthal seismic anisotropy in the Earth's upper mantle and the thickness of tectonic plates. *Geophysical Journal International* 207, 901–933. https://doi.org/10.1093/gji/ggw309

Sperner B., Ratschbacher L. & Nemčok M. 2002: Interplay between subduction retreat and lateral extrusion: Tectonics of the Western Carpathians. *Tectonics* 21, 1-1-1-24. https://doi.org/10.1029/2001TC901028

Środa P., Czuba W., Grad M., Guterch A., Tokarski A.K., Janik T., Rauch M., Keller G.R., Hegedüs E., Vozár J. & CELEBRATION 2000 Working Group 2006: Crustal and upper mantle structure of the Western Carpathians from CELEBRATION 2000 profiles CEL01 and CEL04: seismic models and geological implications. *Geophysical Journal International* 167, 737–760. https://doi.org/10.1111/j.1365-246X.2006.03104.x

Tikhonov A. 1950: On determining electrical characteristics of the deep layers of the earth's crust. *Soviet Mathematics – Doklady* 73, 295–297.

Tomek Č. 1993: Deep crustal structure beneath the central and inner West Carpathians. *Tectonophysics* 226, 417–431. https://doi.org/10.1016/0040-1951(93)90130-C

Tomek Č. & Hall J. 1993: Subducted continental margin imaged in the Carpathians of Czechoslovakia. *Geology* 21, 535–538. https://doi.org/10.1130/0091-7613(1993)021%3C0535:SCMIIN%3E2.3.CO;2

Tomek Č., Ibrmajer I., Koráb T., Biely A., Dvořáková L., Lexa J. & Zbořil A. 1989: Crustal structures of the West Carpathian on deep reflection seismic line 2T. *Mineralia Slovaca* 21, 3–24.

Varga G. & Lada F. 1988: Magnetotelluric measurement on the profile 2T. Unpublished report, *ELGI* Budapest, *Geofyzika* Brno, 1–239.

Vozár J. & Šantavý J. (Eds.) 1999: Atlas of deep reflection seismic profiles of the Western Carpathians and their interpretation. *GSSR*, Bratislava.

Yeats R. 2012: Active faults of the world. *Cambridge University Press*. https://doi.org/10.1017/CBO9781139035644

Zoubek V. 1937: Le cristallin des Carpathes Tchécoslovaques. *Bulletin de la Societé géologique de France* 5, VII, 541–554.