Geological interpretation of magnetotelluric sounding in the southern part of seismic profile 2T (Central Slovakia)

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Abstract: In this paper we present a geological interpretation of magnetotelluric sounding along the southern part of the seismic 2T profile situated in the southern Central Slovakia. The complexes with higher conductivity are imaged in the shallow depths, formed by the Tertiary sediments and volcanics. In the northernmost part of the profile, the influence of non-conductive complexes composed of orthogneisses and overlying Mesozoic carbonates is significant. In the central part of the profile, the low conductive granitoid complexes are superposed over the metamorphic rocks with higher conductivity. This structure is a remnant of the Hercynian middle crust nappes. The most outstanding phenomenon of the profile is the sudden, almost step change in the conductivity parameters of the crust in the southern part. The significantly high conductivity of the crust in this area is most probably not related to its lithological composition, but by the abundant supply of fluids in the crust connected with the Neogene tectonic and volcanic processes.

Key words: magnetotellurics, 2T profile, geological structures, Central Slovakia, Western Carpathians

1. Introduction

The north-south 2T seismic profile plays an important role in understanding tectonic processes in the Inner and Outer Western Carpathian structures. The geological interpretation of the geophysical data from this profile was

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for the first time presented by *Tomek et al. (1989)* and later reinterpreted by several authors (*Buday et al., 1991; Bezák et al., 1993*). The profile runs across principal tectonic units of the Western Carpathians in the area of Central Slovakia. The seismic image shows the main tectonic boundaries of these units, but their lithological composition could not be differentiated. For this reason, magnetotelluric (MT) measurements were carried out along the profile (*Varga and Lada, 1988*) with the main objective of supplementing information on the tectonic units in terms of their conductivity properties. The MT sounding geoelectrical model exhibits some very interesting findings mainly in the southern part of the profile. This part of the profile was re-measured by our team in 2013 with newest MT instruments and processing codes. The results confirmed the original results on the conductivity structure of the crust in this section. Due to a large amount of information, only the southern part of the profile 2T from the Hron Valley to the Hungarian border is interpreted (Fig. 1) in this work. A method of interpretation has been similar as in the case of the profile MT-15 (*Bezák et al., 2014*).

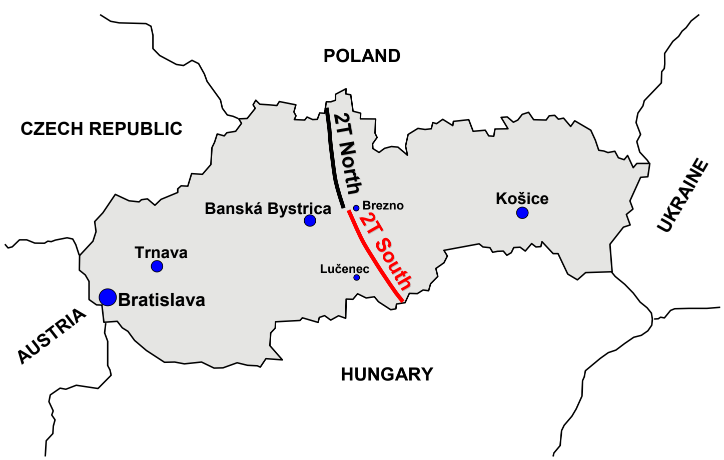

Fig. 1. Location of the profile 2T.

2. Geological setting

The location of the MT measurements is shown in Fig. 2. The profile is situated in the area of Slovenské Rudohorie Mts. – western part and Lučenská kotlina basin. Geology of this area was processed in regional geological maps 1 : 50 000 (*Bezák et al., 1999; Vass et al., 1992*). The profile passes through two basic Alpine crustal units – Veporicum and partly Gemericum and through the Tertiary covering sediments and neovolcanic complexes (the area of Breznianska kotlina basin and Lučenská kotlina basin).

The Veporicum in the northernmost part (Ľubietová zone) consists of mainly orthogneisses, granite porphyres and partly phylonites. This com-

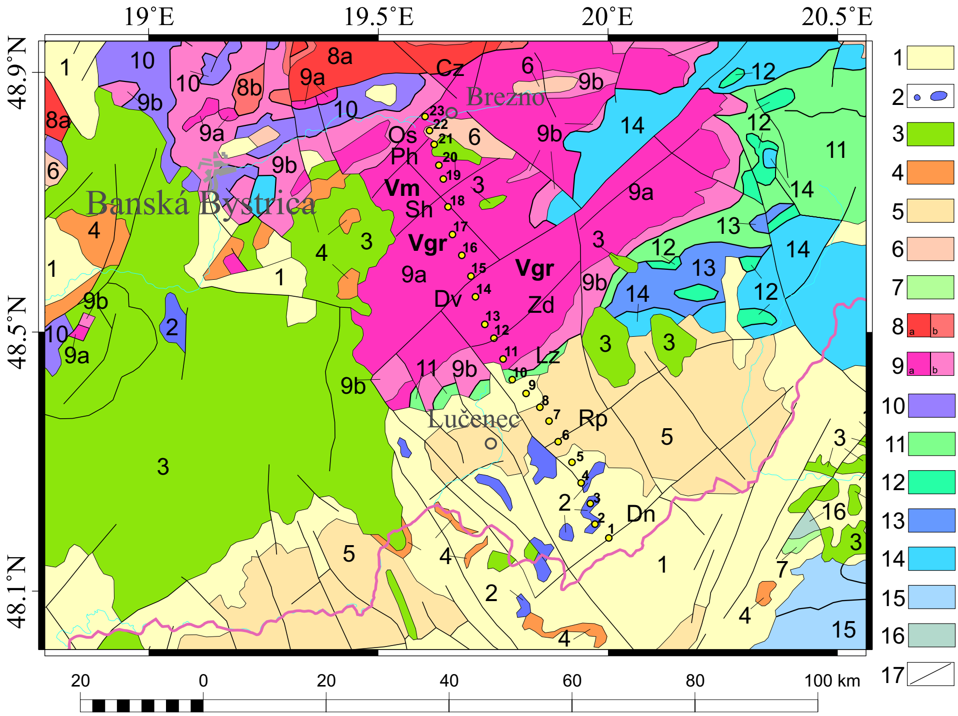

Fig. 2. Position of measured MT points on the profile 2T-South. Geological map after *Lexa et al. (2000)*. Faults after *Bezák et al. (2004)*. 1 – Neogene to Quaternary sedimentary rocks, 2 – Alkali basalts (Pannonian-Quaternary), 3 – Andesitic volcanic rocks (Neogene), 4 – Rhyolitic volcanic rocks (Neogene), 5 – Eocene to Early Miocene sedimentary rocks of the Buda Basin, 6 – Sediments of the Inner Carpathian Paleogene, 7 – Upper Createous sediments, 8 – Tatricum: a) crystalline basement; b) sedimentary cover, 9 – Veporicum: a) crystalline basement, b) sedimentary cover and Fatricum nappe, 10 – Hronicum, 11 – Gemericum, 12 – Meliaticum, 13 – Turnaicum, 14 – Silicicum, 15 – Dinaricum, 16 – Uppony-Szendrő Paleozoic, 17 – faults. Other signs see Fig. 3.

plex is overlain by the Mesozoic cover sequences and nappe units of Hronicum in the Hron Valley, composed mainly of carbonates. Deep underground, the northern Veporicum is overthrusted along the Čertovica shear zone on the lowermost crustal unit Tatricum. To the South of the Ľubietová zone, beyond the Osrblie tectonic zone are outcropping mylonitized paragneisses with pockets of orthogneisses and amphibolites. In this section, the profile continues into the Breznianska kotlina basin with Tertiary sedimentary fill, and into the neovolcanic complexes in the Čierny Balog area. The central part of the Veporicum is formed mainly by massive granitoid bodies on the surface. Geological studies indicate that these bodies lay tectonically on metamorphic complexes. They were overthrusted from the north on the metamorphic complexes (*Bezák et al., 1999*). The structures indicate a ductile deformation within the depth of the crust. Therefore, these cannot be considered as Alpine nappes, but rather as the remnants of Hercynian middle crustal nappes – a product of Hercynian tectonics (*Bezák et al., 1997*). This structure is affected by north-vergent Alpine overthrusts, strike-slips and normal faults.

The Gemericum tectonic unit is overthrusted from the South along Lubeník thrust zone on the Veporicum. Gemericum is represented mainly by Ochtiná komplex in the study area. This complex is covered by Paleogene and Neogene sediments in the Lučenská kotlina basin. Products of alkali basaltic volcanism (Pontian and Pleistocenne age) are occurred here. An existence of Proterozoic crystalline basement has been assumed bellow the Gemeric and Veporic units (e.g. *Bezák et al., 1997*). Its fragments are brought to surface in the form of xenoliths in basalts. This Proterozoic basement is also a source of an expressive magnetic anomaly (*Kubeš et al., 2010*).

3. MT input data and modelling

Magnetotellurics is a passive electromagnetic induction method that uses natural variations of the Earth's electromagnetic field recorded on the surface to investigate the electrical conductivity in the Earth. Electrical conductivity is a physical parameter with close ties to deep tectonics, indicating, by anomalously high values, either domains of fluid accumulations or faults or interfaces containing smeared-out, macroscopically interconnected electronic conductors, such as graphite or sulphides. On the contrary, low conductivity anomalies suggest dry compact rocks, or conglomerates with lack of conductive fractions, or lack of deformation for interconnected conductive paths to arise. As electromagnetic fields with longer periods penetrate deeper into the Earth, magnetotellurics provides electrical depths sections by employing electromagnetic variations from a broad frequency range of the natural magnetic fields.

For this study, targeted on the southern section of the profile 2T, two collections of MT data were available: (i) broad-band data (periods from 0.05 to about 500 s) from earlier measurements by ELGI Budapest and Geofyzika Brno in the 1980s at altogether 23 sites along the southern part of the 2T-profile, roughly 75 km long, between 19.98°E, 48.20°N in the south and 19.58°E, 48.81°N in the north (*Varga and Lada, 1988*), and, (ii) broad-band MT measurements (periods from 0.001 to roughly 100 s) by Geophysical Institutes of the Czech and Slovak Acad. Sci. from 2013 at 10 sites along the southernmost section of the profile, about 25 km long, between 19.93°E, 48.28°N in the south and 19.73°E, 48.49°N in the north (Fig. 2).

The MT curves in the region show moderate quality. The southernmost data, along roughly the first 30 km of the profile from the S, are of good quality while further to the N the data are more affected by industrial noise, partly also because of increased subsurface resistivity in that region, which results in enhanced propagation distance of artificial electromagnetic disturbances. Altogether, the data quality is acceptable for large-scale geological correlations.

A series of analytic steps was performed with the MT data, specifically a dimensionality and directional analyses, 2-D modelling and inversion of the MT curves and sensitivity checks for verifying relevant anomalous conductivity features in the final model suggested for interpretation. For the dimensionality assessment, we analysed the standard Swift's and phase-sensitive Bahr's skew parameters along the profile for the whole spectrum of periods available (see, e.g., *Simpson and Bahr, 2005*). The analysis suggests that the structure below the profile does not contradict a 2-D structural hypothesis except for two zones close to the southern and northern margins of the Southern Veporicum unit (sites 14–11, 23–20 in Fig. 2) where a 3-D structural pattern is obvious, especially at longer periods (greater depths).

Estimates of the regional strike and of MT decomposition parameters along the profile were obtained by employing a stochastic MT decomposition algorithm by *Červ et al. (2010).* Groom-Bailey composite model (*Groom and Bailey, 1989*) was fitted to MT impedances for multiple frequencies corresponding to three Niblett-Bostick penetration depth (*Niblett and Sayn-Wittgenstein, 1960; Bostick, 1977; Jones, 1983*) ranges of 0–3 km, 3–10 km and 10–30 km. The regional strike shows sufficiently consistent estimates close to N45°E (±90°ambiguity) along the whole profile except for the crustal segment 3–10 km beneath sites 9–5 in the S of the profile where the strike estimates cluster close to 0° (±90°). Since the structure is close to 1-DD in this part of the profile, we disregarded this directional anomaly and considered the regional strike to be N45°E for the subsequent modelling purposes, which also seems to be not particularly discrepant from the surface geology trends.

The MT curves were further inverted for a conductivity model by the 2-D algorithm for anisotropic conductivity structures (*Pek et al., 2012*). The motive for employing the anisotropic inversion was mainly to check in this way that no dramatic anisotropies appear in the inverse model, which would indicate large deviations from the two-dimensionality, and that observed secondary impedances can be, to a significant degree, explained by a simple rotation of isotropic data from the regional strike into the observation, NS-EW coordinate system. This check was successful, as no systematic anisotropy with the anisotropy ratio greater than about three appeared in the model. For moderately noisy data and depths of the order of kilometers, such anisotropy does not allow us to distinguish between true anisotropy and effects due to lateral inhomogeneities (*Pek et al., 2012*). Only weakly anisotropic domains, with the anisotropy ratio less than 10, showed at depth to the south of the southern margin of the Veporicum (sites 7–9 in Fig. 2), where a local distortion to the 2-D symmetry was suggested already earlier by the dimensionality analysis.

The final conductivity model suggested for further interpretation is shown in Fig. 3. It starts with a large resistor in the north (sites 23–21) which is, due to its marginal position in the model, not completely constrained by the data, but seems to continue further to the north from preliminary modelling tests for the northern part of the 2T profile. Another resistor, perhaps subdivided into several domains, is suggested in the upper crust beneath sites

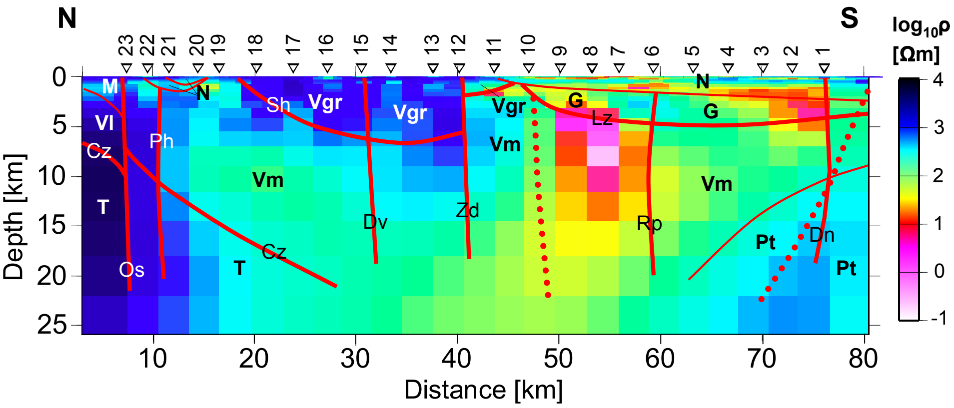

Fig. 3. Geoelectric model of the southern part of the 2T profile and its geological interpretation. Vl – Veporic crystalline of Ľubietová zone, M – Mesozoic, T – Tatricum, Vm – Veporic metamorphic complexes, Vgr – Veporic granitoid complexes, G – Gemericum, Pt – assumed Proterozic basement. Faults and thrusts: Cz – Čertovica, Os – Osrblie, Ph – Pohorelá, Sh – Sihla, Dv – Divín, Zd – Zdychava, Lz – Lubeník, Rp – Rapovce, Dn – Darnó; N – Neogene sediments and volcanics. Dotted lines – area of influence of volcanism and hydrothermal activity.

18–12. Then, further to the south, the resistivity drops dramatically to less than 1 Ωm along a SE-dipping zone. Due to decreasing resistivities and, consequently, also penetration depths in this part of the profile, it is difficult to follow this zone further into depth. Another low-resistivity zone appears further to the south (sites 7–1) at much shallower depths. The moderately resistive domain at depths below 15 km beneath the southern part of the profile cannot be constrained sufficiently by the present data.

4. Geological interpretation of MT data

The northernmost part of the profile (Fig. 3) shows the presence of resistive units formed by Tatric crystalline complexes (T), crystalline complex of Veporicum Ľubietová zone (Vl) and overlying Mesozoic complexes (M).

This area consists mainly of low conductive orthogneisses and Mesozoic, mainly carbonate cover complexes and the Hronicum nappe. Higher conductivity areas for this section of the profile have been presented only in a shallow basin structure of the Breznianska kotlina basin and Neovolcanics

(N). To the South of Osrblie fault (Os), there are the Veporicum crystalline units formed of slightly conductive metamorphic complexes (Vm). These structures in the central part of the profile (from site 16–11) are overlaid by substantially resistive complex of granitoids (Vgr). These units are remnant of the Hercynian nappe structures originated during the main Hercynian collision in the Paleozoic (*Bezák et al., 1997*). Metamorphic rocks were transported to the higher level of the crust at younger Alpine thrusts or strike-slips.

The southern part of the profile (to the South of site 10) is predominantly characterized by highly conductive crustal structures. The higher conductivity values for shallower structures are associated with Neogene sediments (N) and Gemeric metasediments (G) containing graphitic shales. In the deeper parts of the crust, there are Veporicum crystalline rocks (Vm) and assumed Proterozoic basement (Pt). The composition of this basement is partially known from xenoliths brought to the surface by basaltic Neovolcanites. We do not expect presence of any exotic crust segment with high conductivity. According to our interpretation highly conductive structures in the crust here created by a prior intensive Neogene tectonic processes and volcanic activity associated with inflow of conductive fluids and ore mineralization. The effects of the low-conductivity Proterozoic crystalline fundament is manifested in the southernmost parts of the profile only. The conductive structures correspond to the volcanic activity area. This area is manifested by increasing of heat flow in geothermal model with assumption of partially melted masses in the depth of 60 km (*Majcin et al., 1998*). Partial increasing of lithosphere thickness is interpreted in this model as relics of litosphere duplicating during subduction of Meliata oceanic crust.

The profile crosses the several steep major tectonic lines, where their conductive traces are not so significant in MT model of profile 2T as in the more western MT-15 profile (*Bezák et al., 2014*) what can be explained by older age of some faults and/or their less conductive filling. The most important faults that pass through studied territory (Fig. 2) are: (from the North) – Osrblie (Os), Pohorelá (Ph), Sihla (Sh), Divín (Dv), Zdychava (Zd), Rapovce (Rp) and Darnó (Dn). The name and position of these faults are in concordance with the Tectonic map of Slovak Republic (*Bezák et al., 2004*).

5. Conclusion

Seismic profile 2T in the Central Slovakia brought a number of significant conclusions on the structure of the crust in this area. Subsequently, magnetotelluric measurements were made along the profile, yielding information about the conductive properties of the complexes involved in the composition of the crust.

In the shallow structures, complexes with higher conductivity are visible, formed by the Tertiary sediments and volcanics (the area of Breznianska kotlina basin and Lučenská kotlina basin). In the northernmost part of the profile, the influence of non-conductive complexes composed of orthogneisses and overlying Mesozoic carbonates is significant. In the central part low conductivity granitoid complexes are superposed over the metamorphic rocks with higher conductivity. This structure is a remnant of the Hercynian middle crust nappes and is was modified mainly by north-vergent Alpine thrusts and strike-slip faults. The most striking phenomenon in the MT profile is the abrupt, almost step change of the conductivity parameters in the crust in the southern part (Lučenská kotlina basin). The high conductivity of the crust is most likely caused by both the Tertiary sediments, metasediment complexes of the Gemericum at the top of the crust and in the deeper parts mostly by a disruption of the crust by young Tertiary tectonics and volcanic activity with abundant fluids.

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