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2D magnetotelluric image of the Dobrá Voda seismoactive area

Lenka ONDRÁŠOVÁ[1,2,*], Ján VOZÁR[1], Jozef HÓK[3], Andrej CIPCIAR[1], Dominika GODOVÁ[1,2], Radek KLANICA[4]

[1] Division of Geophysics, Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovak Republic

[2] Department of Engineering Geology, Hydrogeology and Applied Geophysics, Faculty of Natural Sciences, Comenius University, Mlynská dolina, Ilkovičova 6, 842 48 Bratislava, Slovak Republic

[3] Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University in Bratislava, Mlynská dolina, Ilkovičova 6, 842 48 Bratislava, Slovak Republic

[4] Institute of Geophysics, Czech Academy of Sciences, Boční II/1401, 141 31 Praha 4, Czech Republic

Abstract: Dobrá Voda village is located in the Malé Karpaty Mts. (Brezovské Karpaty) and is well known for its increased seismic activity. For a better understanding of the processes preceding earthquakes, this area has been studied using several methods. One of them is magnetotellurics. Magnetotellurics provides an image of the distribution of electrical conductivity within the Earth and helps to determine individual tectonic structures, specifically faults. The shallow conductive structures are associated with Neogene sediments of the Danube Basin, sedimentary fill of the Dobrá Voda Depression, and partial nappes of Hronicum, probably saturated with water. Less conductive structures are the Fatricum sediments and the lowest conductivity values belong to crystalline basement of the Tatricum tectonic unit. Whole structure of the Dobrá Voda seismoactive area along our magnetotelluric profile is disrupted by NE–SW oriented normal faults. Based on the location of earthquake hypocentres, we can identify main seismoactive areas as crystalline complexes of Tatricum.

Key words: geoelectrical model, magnetotellurics, seismoactive area, Dobrá Voda

1. Introduction

The Dobrá Voda seismoactive area (DVSA; *Fojtíková et al., 2010*) is situated at the contact of the Bohemian Massif, the Western Carpathians, and the Eastern Alps (Fig. 1), and is an integral part of the Dobrá Voda seismic source zone, which represents the most significant zone in terms of seismic

*corresponding author, e-mail: geofleon@savba.sk

hazard in Slovakia (*Hók et al., 2016*). This area with its increased seismic activity has been studied by several authors in the past (e.g. *Began et al., 1984; Marko et al., 1991; Michalík et al., 1992; Šefara et al., 1998; Kováč et al., 2002; Fojtíková et al.,2010; Hók et al., 2018*).

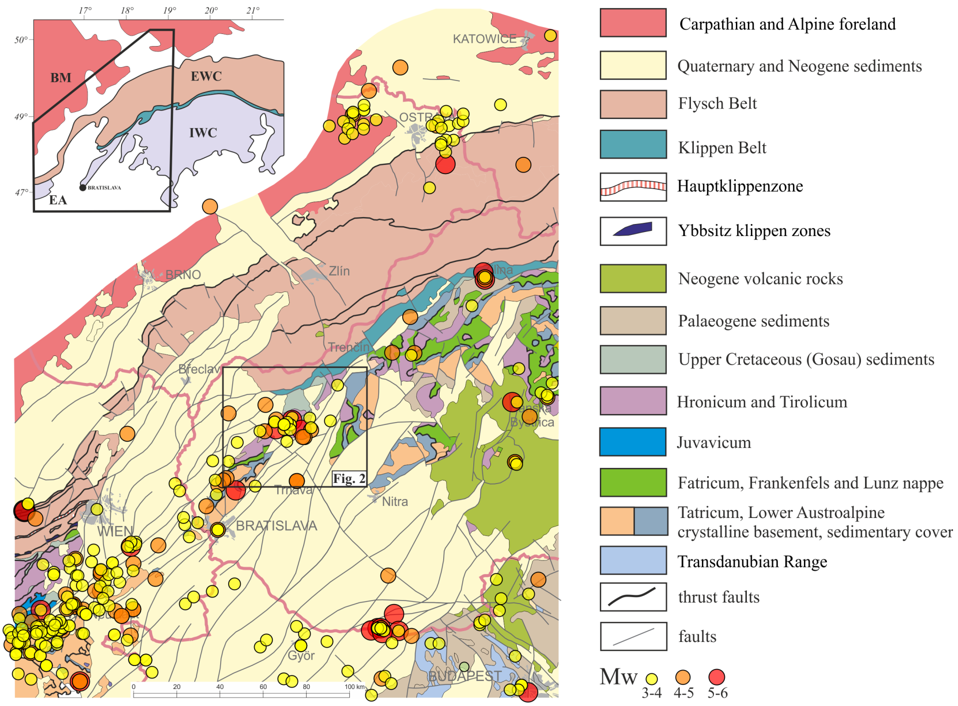

Fig. 1. Simplified geological map of the Western Carpathians and adjacent areas (simplified after *Lexa et al., 2000*). Earthquake epicentre locations are adapted from *SLOVEC (2011)*. BM – Bohemian Massif; EA – Eastern Alps; EWC – External Western Carpathians; IWC – Internal Western Carpathians; Mw – moment magnitude.

The seismic activity is continuously monitored by local and regional seismic (*Csicsay et al., 2018*) as well as micro-displacement monitoring networks. Several geophysical studies were carried out in this and surrounding areas include seismic, gravimetric and electromagnetic methods. Based on collected data the tectonic settings and stresses in the DVSA were studied through focal mechanism of micro-earthquakes (*Fojtíková et al., 2010*). This study confirmed the orientation of main fault system and showed differently oriented subfaults in the area, which indicate complex tectonic setting. Based on data from the Slovak Bouguer anomaly map (*Pašteka et al., 2017*), the gravimetric modelling was applied to the profile crossing our investigated area to provide a density description of structures (*Šamajová et al., 2018*), which is a similar mechanical parameter to seismic velocities.

The nearest magnetotelluric (MT) measurements were performed in the Vienna Basin area, where the structure of pre-Cenozoic basement was studied by *Šamajová et al. (2019).* Another nearby magnetotelluric profile MT15 with NW–SE orientation spanning from the south of Trenčín nearly to the eastern end of Šahy. The profile is crossing the major regional tectonic elements (*Bezák et al., 2014*). Next is a MT profile, extending along the Deep Seismic Sounding (DSS) profile No. VI, crossing the contact zone between Bohemian Massif and Western Carpathians in NW–SE direction (*Červ et al., 2001*). New detailed magnetotelluric measurements along the presented DVMT01 profile were carried out to supplement the geoelectrical parameters directly for the DVSA. The magnetotelluric profile DVMT01 is oriented in the NNW–SSE direction across the main tectonic structures of the Hronicum, the Dobrá Voda Depression and the Danube Basin in order to clarify the tectonic character of the DVSA structure (Fig. 2) and for a better understanding of the kinematics of its fault structures.

2. Geological setting

DVSA mainly occupies a triangular depression (Dobrá voda Depression) containing Neogene carbonate to siliciclastic sediments and Quaternary fluvial deposits surrounded by Mesozoic sediments (*Šujan et al., 2019*). The Mesozoic carbonate complexes belong to the Hronicum cover nappe composed from two partial nappes dipping generally to the northwest (*Hók et al., 2018; 2019*). The Dobrá Voda partial nappe represents lower part and consists of the basinal facies of Triassic sediments. The Považie partial nappe contains the shallow water Triassic sediments (see *Havrila, 2011*). Internally imbricated Dobrá Voda facial sequence was penetrated in the borehole DV-1 situated NE of Dobrá Voda village (*Michalík et al., 1992*). Both partial nappes of Hronicum were identified in the borehole DV-5 (*Kováč et al., 1991*) situated about 4 km southeast of Dobrá Voda village (Fig. 2). The deeper basement contains the Fatricum cover nappe and the Tatricum thick-skinned tectonic unit (*Hók et al., 2018*). Normal faults with negligible oblique component oriented generally in NW–SE and NE–SW direction, have been identified by geological mapping (*Hók et al., 2018*) and density modelling (*Šamajová et al., 2018*). Mentioned knowledge is in contradiction to the interpretation of the "push up" transpression/positive flower structure of the Mesozoic sediments, which is squeezed between two right-stepping sinistral faults, named the Dobrá Voda Fault zone (*Marko et al., 1991*) later interpreted as a segment of the Vienna Basin Transfer Fault (*Hinsch and Decker, 2011*).

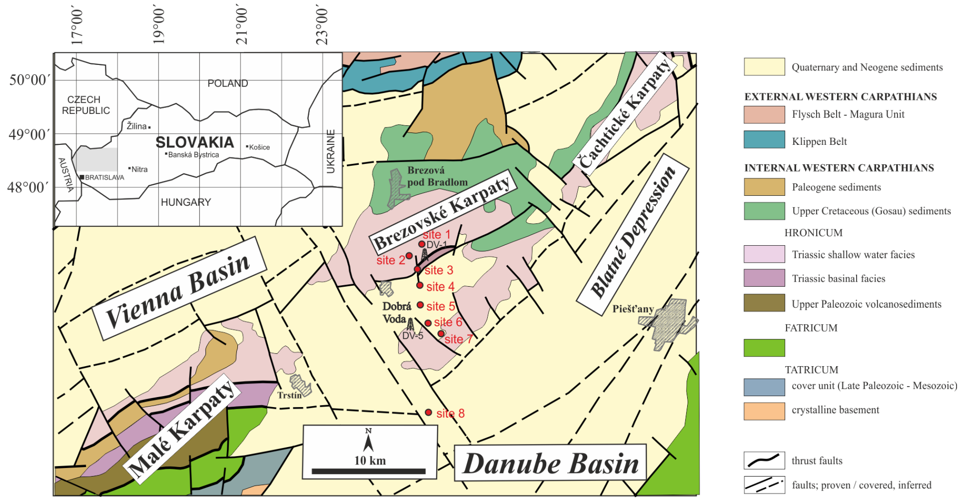

Fig. 2. Simplified geological map (*Bezák et al., 2004; Hók et al., 2018*) with positions of MT sites in the area (DVMT01 profile).

3. Methods

Magnetotellurics is a passive geophysical method, which uses naturally occurring variations of electromagnetic fields as an energy source. This method is used for investigating the distribution of electrical conductivity within the Earth (e.g. *Tikhonov, 1950; Cagniard, 1953*). Electrical conductivity varies based on changing lithology and tectonics. Not only highly conductive lithology materials, but also fluid accumulations can be indicated by increased values of electrical conductivity. Faults often contain fluids because their disrupted structures create a natural pathway for fluid migration.

The magnetotelluric profile DVMT01 is situated north-east to the village of Dobrá Voda and its orientation is NW–SE, based on previous works (e.g. *Hók et al., 2018; Šamajová et al., 2018*) roughly perpendicular to investigated faults. Profile consists of 8 measured sites and its length is about 12 km (the distance between the farthest sites). The spacing between individual sites is about 1 km − 1.5 km. The planned inter-site spacing was larger, however to achieve better results, additional sites were installed particularly in the north-eastern part of the profile. Due to the necessity to reduce the electromagnetic noise from the nearby villages, most south-eastern site 8 in the Danube basin was installed in a greater distance from other sites.

The 4-component electromagnetic data were collected by using the equipment from Metronix company for one day at each site. Horizontal components of the electric field Ex and Ey were being recorded in two orthogonal directions. The magnetic field component Hx is perpendicular to Ey, whilst component Hy is perpendicular to Ex. For the magnetic field measurements, only two induction coils were available, therefore vertical component Hz of the magnetic field was not recorded.

4. MT data processing

Robust statistical processing methods from Metronix company (*Friedrichs, 2021*) and by *Smirnov and Egbert (2012)* were used for processing of measured time series of electric and magnetic field variation into impedance transfer function. These functions are plotted in the form of the sounding curves that show apparent resistivity and impedance phases as a function of period (Fig. 3). The processed period range was roughly between 0.001 s to 1000 s. Due to adverse conditions at the site 7 it was only possible to obtain information from a period up to 0.1 s. We performed quality check of resulting four-component MT transfer function and edited out data points, which did not fulfil physical conditions for MT data or had high error bars. Final MT transfer functions were smoothed by using robust methods (*Smirnov, 2003*) to eliminate data outliers.

The distribution of MT sites along profile, which is perpendicular to main geological units in the area, suggests 2D modelling of MT data as most suitable method to create subsurface model of conductivity. To confirm

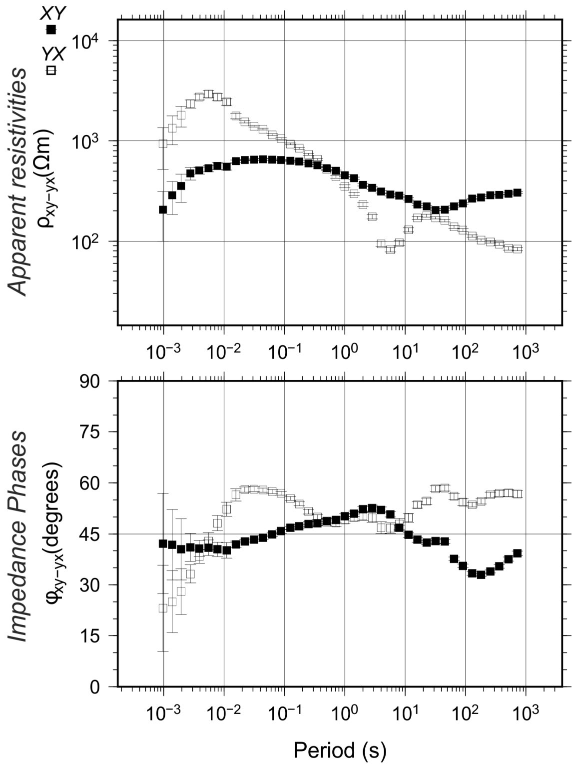

Fig. 3. Example of MT sounding curves from two main components of MT responses for site 1.

the appropriateness of 2D modelling approach we performed dimensionality analysis, which were estimated for all sites and all periods based on a phase tensor (*Caldwell et al., 2004*) using Python toolbox MTpy (*Krieger and Peacock, 2014*) and we identified 1D and 2D character of impedances. The ellipses in Fig. 4 graphically represents phase tensor, where 1D data are shown as circle and for the 2D case the major or minor ellipse axis is aligned with geoelectrical strike. The 3D information in MT data can be indicated by the magnitude skew beta, which should be significantly greater than 3° (*Booker, 2014*).

As a part of preparation of MT data for 2D modelling, we performed regional strike analysis based on Groom and Bailey decomposition of input MT transfer functions (*Groom and Bailey, 1989*). This method allows elimi-

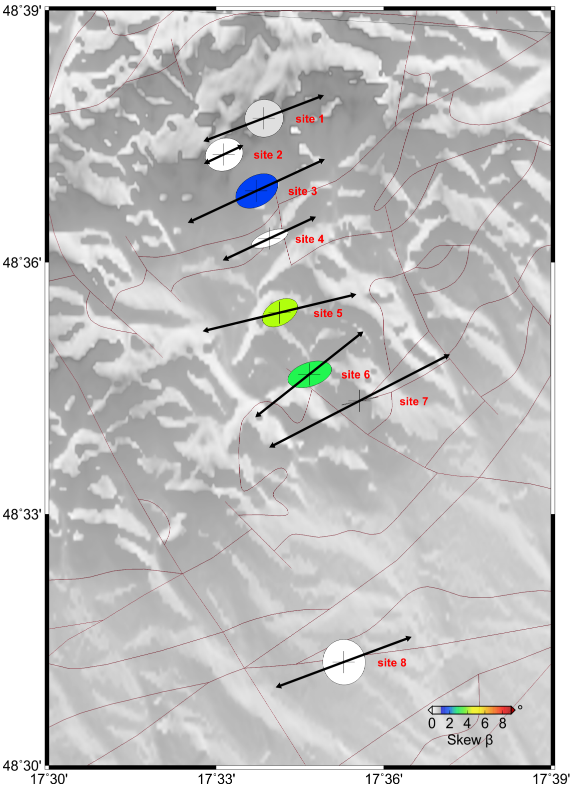

Fig. 4. Ellipses represent phase tensors for period 1 second in each site, where colour indicating skew Beta value. The arrows show orientation of geoelectrical strike estimated for all periods in each station independently, where the length of arrows indicate quality of estimations. The background is shaded topography with boundaries of main geological units in the area.

nation of distortion elements affecting apparent resistivity and phase values from the impedance transfer function and regional geoelectrical strike. We used multi-site and multi-period Strike code (*McNeice and Jones, 2001*) based on this approach and estimated direction of 2D geoelectrical regional structures in studied area. Examples of strike estimation for each site independently are shown in Fig. 4. Comparison of these results with phase tensor ellipses orientation confirms quite good agreement between these two independent methods. The final azimuth of the structures for all sites and recalculated Niblett-Bostic depth range approximation (*Niblett and Sayn-*

Wittgenstein, 1960) from 50 m to 10 km from corresponding periods was estimated as N67.5°E and all impedance data were decomposed to this direction.

5. 2D inversion modelling of MT data

In the next step, we carried out 2D modelling in the WinGLink inversion code (*Rodi and Mackie, 2001*). We repeated quality check and editing of sounding curves after decomposition and bad data are masked. The program does not include these values in the calculation. For 2D modelling situation, electromagnetic waves propagate in two basic modes: as transverse electric (TE – with Ex, Hy components) mode, where currents flow along 2D structures and as transverse magnetic (TM – with Hx, Ey components) mode with perpendicular current directions to previous mode. In WinGLink software we can invert TE mod or TM mode separately or together, where TE mode corresponds to main xy component of our decomposed MT data and yx component of data is set as TM mode data.

Setting of the frequency range for inversion is based on desired penetration of included MT data points. The expected penetration depth (pT) in metres depends on given period (T) and apparent resistivity of the uniform half-space (ρ_{a}) given by the formula: $\mathrm{pT} \approx 500\sqrt{\mathrm{T}\rho_{\mathrm{a}}}$ which follows from the solution of Maxwell equation. Inversion process starts from a uniform half-space with the same value of apparent resistivity for the whole model set to 100 Ohm.m. Before starting the inversion process, it is needed to set the values of the inversion parameters. The period range for calculation is set between 0.0001 s and 100 s. It is enough for reach the depth of our interest. The inversion code is using finite difference numerical method for forward solution of discretized 2D model. For stability of the numerical solution, the size of the model is several times bigger than the profile area.

The quality of geoelectrical inversion model is evaluated by quality of data fit. The fit for all modelled MT data points is evaluated by normalized residuals between the modelled data and the observed data. For simplification, the one value is calculated from these residuals called RMS (root mean square), where its value 1 means perfect fit. However, this RMS simplification can be misleading (*Grayver et al., 2013*) and the full data fit should be always checked. For the standard error estimations, the reasonable final

RMS value would be up to 2, depending on the data quality. However, values up to 3 are sufficient for final inversion model and are acceptable data fit in most cases. Full data fit of final model with normalized residuals by data error is included as supplementary material on the Fig. 1S.

The residuals are normalized by the estimated data errors. However, the decomposition of MT data destroys original errors from processing and they are replaced by very low error bars corresponding to decomposition estimations process. Therefore, we have to introduce new, so-called, error floors. The error floor is defined as the lowest acceptable error entering into the calculation. Model assigns larger weight to lower errors and that increases RMS. We set these values at 5% for phases and 20% for apparent resistivity of TM mode and 40% for apparent resistivity of TE mode. In this case, the TE mode is more affected by errors, so higher value is needed to lower the RMS. The inversion code also allows the correction of the static shift distortion error in modelled data. It is a shift of the apparent resistivity curves mostly caused by small near-surface bodies with conductivity contrast to the surrounding area.

Balance between smoothness of the model and data fit is represented by the parameter τ. This parameter reduces complexity or roughness of the geoelectrical structures in the model and favours realistic smooth models. Lower values of τ increase roughness of the model and minimize RMS error. However, too low values of τ produce unrealistic artefacts in conductivity structures. Numerous values of parameter τ were tested, starting from higher values down to the value of 0.5.

Jones Catechism (named after Alan G. Jones and described in *Schmoldt, 2011*) is implemented for magnetotelluric inversion. Firstly, the only phase of TE mode is inverted, then phase of TM mode. Generally, phases are inverted first, because they are not affected by static shift. Subsequently, the apparent resistivities of TE mode and TM mode are introduced into the inversion process. With the approach of starting the inversion with the least affected parameters by distortion, we were trying to achieve the best model fit between the modelled and observed data. After achieving a good data fit in the north-western part of the model, we locked the values of the resistivity in this area to avoid influence of more distorted data in the middle and south-eastern part of model. In our final model, the resistivity values were locked in the area of short periods to a depth of about 1500 m.

6. 2D inversion modelling of MT data

Several models were calculated using different settings of inversion parameters. For geological interpretation, we have chosen the final model with RMS value of about 2.64. This higher value is caused by data fit of phases and apparent resistivities in TE mode and sites 4, 5, 6 (see Fig. 1S).

The final model (Fig. 5) is characterized by the near-surface conductive structures. In the south-eastern part of the profile, these structures represent Neogene sediments of Danube Basin to a depth of approximately 1000 m. In the vicinity of the village of Dobrá Voda (sites 4, 5, 6), the conductive structures corresponds to approximate position of the Dobrá Voda Depression up to depth of roughly 500 m. A strong conductive structure in the north-western part of the profile, which deepening in this direction, is not identifiable on the surface (most probably Hronicum). It is located to a depth of 4000 m. There is a relatively large area in the model with transient conductivity values. The structures between site 1 and site 6 at depths higher than 4000 m are significantly resistive. Upper boundary of this unit can be shallower due to resolution problem of MT method, where

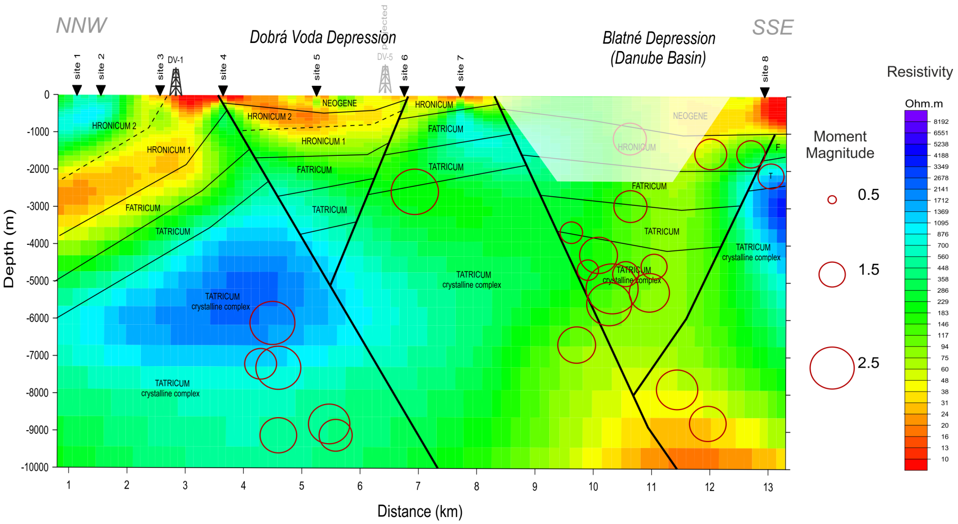

Fig. 5. The final 2D model of the MT profile DVMT01with interpreted tectonic structures and positions of earthquake hypocentres according Table 1 from *Fojtíková et al. (2010)*. Shaded area indicates low resolution part of the model.

resistive structures are hidden in stronger responses of overlaying conductive structures. Its north-western edge has the same slope as the conductive structure above it, so layered structures are expected there. Slightly more resistive are the areas from 0 to 1000 m below the site 1 and site 2, and the area between the horizontal distance 7.5 km and 9.5 km on the profile below the site 7 and at a depth between 1000 – 2000 m with a slight slope to the southeast. Structures on the southeast edge of the profile at a depth of about 2500 m appear to be strongly resistive, where the data is affected by noise, and may be affected by the numerical effects of the stabilization of the inversion calculations.

7. Geological interpretation

The geological interpretation of the magnetotelluric (MT) profile DVMT01 takes into account the surface geological structure (*Hók et al., 2018*), the results from boreholes (*Michalík et al., 1992; Kováč et al., 1991; Biela, 1978*), and geophysical interpretations (*Šamajová et al., 2018; Dostál et al., 1991, Dubovský, 1986, Dubovský, 1987*) mainly include the results and interpretation of vertical electrical sounding (VES) and gravimetric modelling. NW–SE oriented MT profile crosses the structure of Dobrá Voda and ends at NW margins of the Blatné Depression (*sensu Vass et al., 1988*). Surface geological structure of the Dobrá Voda area is formed by sediments of the Hronicum tectonic unit, which is superimposed in two structures with different lithofacial character (*Hók et al., 2018; Havrila, 2011*) and Miocene sediments. The total thickness of the Hronicum in the borehole DV-1 exceeds 1140 m (*Michalík et al., 1992*). Similar results were obtained by the borehole Dubová-2 (D-2), which drilled the Hronicum in the pre-Cenozoic basement of the Blatné Depression at a thickness of 903 m and the Fatricum Mesozoic sediments at a thickness 945 m (*Biela, 1978*). Due to the presence of the internally tectonically imbricated partial nappes of the Hronicum it is possible to estimate the total thickness of the Hronicum in the area of the Brezovské Karpaty at 2000 m. Underlying tectonic units are Fatricum and Tatricum. Tatricum is formed by Mesozoic sediments and crystalline rocks representing autochthonous unit with regard to the Fatricum and Hronicum. Geological interpretation operates with the demonstrable assumption that the thickness of Fatricum generally does not exceed 1000 metres, similar to the thickness of the Tatric Mesozoic cover. The thickness of Neogene sediments in the deepest part of the Dobrá Voda basin is geophysically estimated at 500 – 700 m (*Dubovský, 1987*). In the area of the interpreted MT profile (Blatné Depression), the thickness of the Neogene sediments reaches up to 2000 m (e.g. borehole Krupá-3, *Biela, 1978*). In the MT model, the crystalline complexes of Tatricum are represented by the highest values of resistivity. The tectonic slices of the Hronicum and Neogene sediments are mostly conductive, which can be caused by fluid saturation. According to Slovak earthquake catalogue (*SLOVEC, 2011; Cipciar et al., 2022*) and micro-earthquakes localisations according *Fojtíková et al. (2010)*, hypocentres of earthquakes are partly concentrated in crystalline basement of the Tatricum tectonic unit. This crystalline basement does not have homogenous resistive structure and contains parts with less resistivity. They can be explained by presence of conductive fluids and their circulation patterns within the structures. Active faults associated with earthquakes often create pathway for percolation of fluids from deeper structures to the surface. Earthquakes are often localized in resistive structures adjacent to conductive structures (*Platz et al., 2022*). Most of our projected earthquakes to modelled profile are localized near or directly in these less resistive areas (Fig. 5). The projection of hypocentres to profile line was done along geoelectrical 2D strike angle stated in previous section.

8. Conclusion

For better understanding the occurrence of earthquakes in DVSA, it is important to know its tectonic structure. In this study were results from previous geophysical studies supplemented by geoelectrical model from magnetotelluric method. Despite the fact that due to adverse conditions in the field, the DVMT01 profile has the part from 8 km to 12 km poorly covered by measured data, we used the additional information from the boreholes and other geophysical methods to interpret the geological structures also in this part. The results in other parts of the MT profile correlate with the results from the wells, surface geological mapping (*Hók et al., 2018*) and other geophysical models (e.g. density modelling, *Šamajová et al., 2018*). The main conductive and resistive features of our MT model show a good correlation with previous interpretations of tectonic structures in this area, and it is possible to identify geoelectric image of most of them. The structures of Neogene sediments of the Danube Basin (Blatné Depression) in the south-eastern part of the profile, sedimentary fill of the Dobrá Voda Depression, and partial nappes of Hronicum, probably saturated with water, are conductive. Less conductive structures are the Fatricum sediments and the lowest conductivity values have crystalline basement of the Tatricum tectonic unit. Entire structure of DVSA along DVMT01 profile is disrupted by NE–SW oriented normal faults. Combination of results obtained from several methods provides a picture of the tectonic structure of DVSA. With the support of data from the Slovak earthquake catalogue (*SLOVEC, 2011; Cipciar et al., 2022*) and micro-earthquakes according *Fojtíková et al. (2010)* about the location of earthquake hypocentres, we can identify main seismoactive areas as crystalline complexes of Tatricum. To the south of the profile, the most of the earthquakes are located in the most conductive structures of these crystalline complexes. This allow possible to assess the relationship between tectonics and earthquake occurrence in future integrated studies.

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Appendix

Supplementary material:

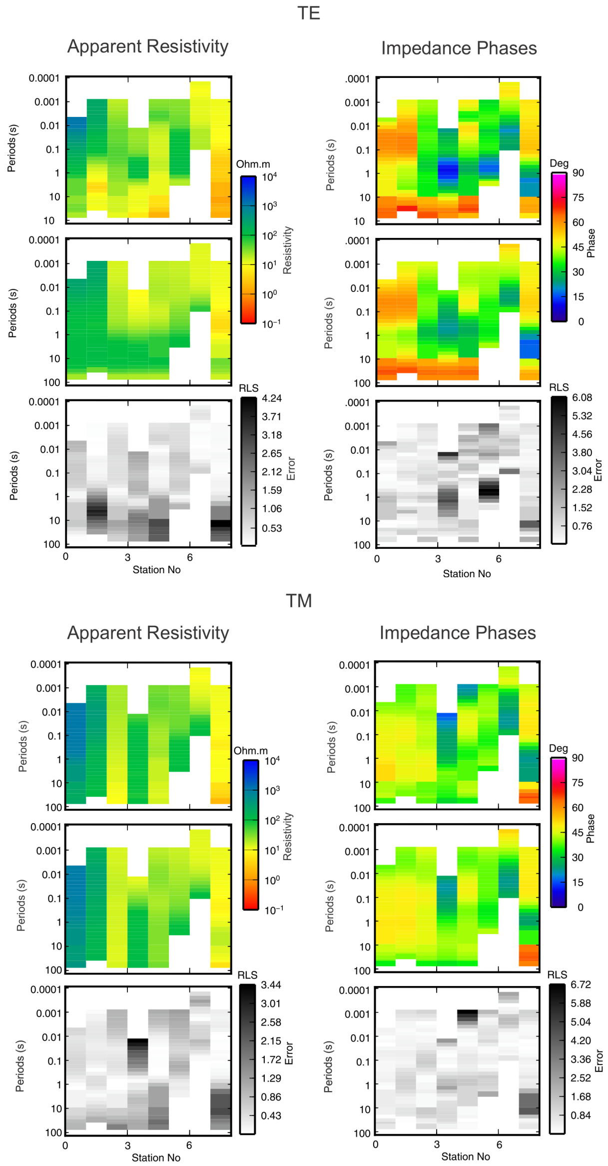

Fig. 1S: Full data fit of final model with normalized residuals by data error.