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Models of geoelectrical anomalies in Czechoslovakia

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Abstract. Previous and new magnetotelluric measurements, performed at 12 localities distributed along the international deep seismic sounding (DSS) profile No. VI in Czechoslovakia, were investigated by an approach which takes into account the effects of surface inhomogeneities. The minimum disturbed curves were selected and interpreted by inversion methods in terms of the internal geoelectrical structure. Geomagnetic variation data from 1-D arrays traversing the south-eastern part of the Bohemian Massif (BM) and the transition zone between the BM and the West Carpathians (WCP) were analysed to give induction response characteristics. All the results, together with other electromagnetic and geophysical characteristics, were used in suggesting models that approximate the distribution of the electrical conductivity within the Earth. For such models we calculated the electromagnetic response by the numerical method of finite differences and compared the results with the actually observed electromagnetic characteristics.

Key words: Czechoslovakia – International DSS profile No. VI – Magnetotelluric/magnetovariational characteristics – 2-D geoelectrical model

Introduction

During recent decades, large volumes of new data have been obtained from geophysical investigations into the deep structure of the Earth's crust and the uppermost part of the upper mantle. In Europe, the investigations were confined to certain profiles which, following new geological knowledge, were situated so as to cross recent and/or old principal structural units and their contacts. Along these research traverses, as many geophysical fields as possible were recorded and analysed so that their normal and anomalous parts could be found and interpreted in terms of the internal structure.

In the Czechoslovak territory, DSS profile No. VI represents such a research line, being part of the more than 2,000-km long geo-traverse No. V which crosses several tectonic regions and structural units that can be grouped into two huge megablocks due to their different origin. The first of these represents the consolidated Variscan and Epivariscan blocks belonging to the very eastern part of the Central European Platform and the other, much younger and still orogenically active block, constitutes the Alpine folded zone in south-eastern Europe. The structure of the Earth's crust on geo-traverse No. V was investigated by the DSS and other geophysical methods. The results obtained were summarized in the paper by Beránek and Dudek (1972) and in the monograph by Sollogub et al. (1980). In our contribution we shall confine ourselves to the results that are relevant to the Czechoslovak territory and to adjacent areas. This section, representing the international DSS profile No. IV, is very exceptional and notable since complete geophysical information, including the results of electromagnetic soundings, is available for further investigations. The results of electromagnetic soundings are of special importance as they furnish information on the electrical conductivity at crustal and upper mantle depths and, thus, provide a closer insight into the structure of the asthenosphere and other important sections of the Earth.

The results of electromagnetic studies

Extensive electromagnetic investigations have been performed by applying the methods of magnetotelluric (MTS) and magnetovariational (MVS) soundings in Czechoslovakia during the last two decades. MTS were performed at 12 localities distributed along DSS profile No. VI. Taking into account the effects of surface inhomogeneities on the principles formulated by Berdichevsky and Dmitriev (1976), we selected the minimum disturbed curves for interpretation in terms of the internal geoelectrical structure. In the first step, only the depths of zones with increased electrical conductivity were estimated and a tentative model of the structure was proposed (Pěčová et al., 1976). In the next step, the model was refined by solving the 1-D inverse MTS problem for all MTS curves by methods which have been developed in our group (Pěč et al., 1977; Pek and Červ, 1979). The inversion results made it possible to estimate all the parameters of a 1-D layered medium, i.e. the depths and thicknesses of individual layers and their specific resistivities. The geoelectrical cross-section based on this analysis was discussed by Pěčová et al. (1980) and Praus et al. (1981).

In the next step we performed further data processing for previous and new MTS localities by applying the methods of power spectral analysis and by solving the tensor relations between the field components to obtain impedances in both the geographical and principal directions. An

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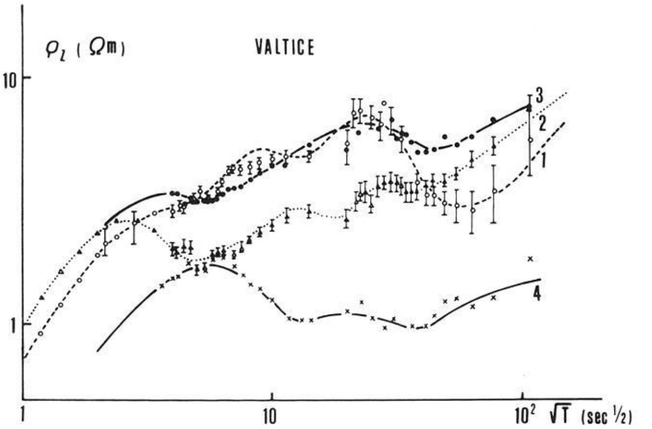

Fig. 1. The MTS curves at the locality of Valtice (Va). Explanation: 1 – curve $\rho_{xy}=F_1(\sqrt{T})$; 2 – curve $\rho_{yx}=F_2(\sqrt{T})$; 3 – curve $\rho_{\max}=F_3(\sqrt{T})$; 4 – curve $\rho_{\min}=F_4(\sqrt{T})$

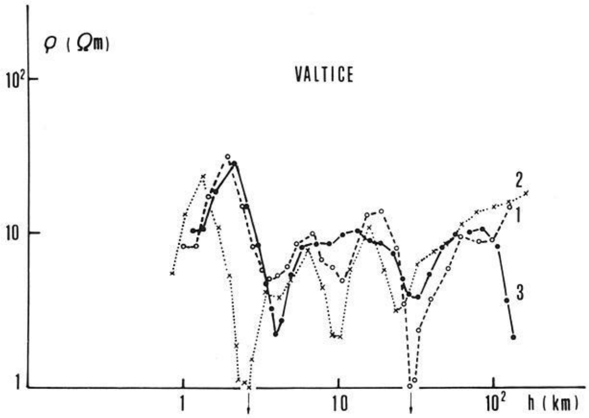

Fig. 2. The functions $\rho=f_i(h)$, $i=1, 2, 3$ as a result of approximate inversion of the MTS curves at Valtice (Va). The curves are labelled according to Fig. 1

example of MTS curves obtained in this way for a new locality, Valtice, is given in Fig. 1.

For a subsequent analysis of the MTS curves in the Pannonian section of the DSS profile we took into account the distortion effects of conducting sediments investigated by numerical modelling techniques based on the solution of Price's equation for a low frequency telluric field, the inductive interaction of electric currents being neglected (Vanyan et al., 1978). Exploiting the conductance map of sediments and assuming a circularly polarized field, Ádám and co-authors obtained the telluric field distribution in the Pannonian Basin and adjacent areas characterized by major and minor axes of the calculated field ellipses (Fig. 3 in Ádám et al., 1982). The authors conclude that minor axes are less distorted by changes of conductance than the major ones and, therefore, $\rho_{\min}$ curves should be preferred in the investigations into the deep conductivity structure in the Pannonian part of the model.

The effects of surface sediments and their variable thickness at different MTS localities were also roughly removed by transforming the MTS curves according to the relation between the admittance and the near-surface longitudinal conductance S (in Siemens): $Y_0=Y+S$, where Y_0 is the value actually observed at the Earth's surface and Y is the admittance without the conductance S (Ádám et al., 1982). Analysing the behaviour of MTS curves in an N-layered model with a non-conducting basement ($\rho_N \to \infty$), we find this relation to be valid for periods $(T/5\rho)^{1/2} < 4\pi S \cdot 10^{-4}$, where $S=\sum_{m=1}^{N-1} h_m/\rho_m$ is the longitudinal conductance.

The phase curves needed for the determination of the real and imaginary parts of the admittance were calculated by Vanyan's formula (Vanyan et al., 1961)

$$\varphi(\omega_k)=\pi^{-1}\int_{-\infty}^{+\infty}\frac{d\ln|\rho_\omega|}{d\omega}\ln\left|\frac{\omega+\omega_k}{\omega-\omega_k}\right|,$$

where ρ_ω are numerical values of apparent resistivity at angular frequencies ω, and ω_k is the angular frequency for which the phase $\varphi(\omega_k)$ is calculated. The near-surface conductance at individual stations was estimated from the conductance maps (Ádám et al., 1982; Shilova and Sanin, 1982), supplemented in detail by recent bore-hole data from the vicinity of some MTS stations, specifically in the transition zone between BM and WCP. The MTS curves, transformed to remove the distortions of a sedimentary layer, were approximately inverted according to the formula in Berdichevsky et al. (1980). An example of $\rho=f(h)$ dependence is shown in Fig. 2. Performing the transformation and subsequent inversion of MTS curves for all the stations in the profile and taking account of previous models, we were able to suggest a working model of the geoelectrical structure.

In suggesting the geoelectrical model, we took into consideration the additional information provided by the MVS field experiments. The most recent stage of the results is summed up in a schematized map of the relevant part of the Czechoslovak territory and adjacent areas (Fig. 3). The experiments were confined to the transition zone between the WCP and the surrounding geological units – specifically the BM in our actual situation on DSS profile No. VI. A pronounced zone of anomalous induction was mapped on a regional scale in the proximity of the Carpathian arc. It was interpreted as a zone of high electrical conductivity marking the margin of the Carpathian lithospheric plate (Praus et al., 1981). This highly conductive zone is sure to reveal a regional boundary of crucial geological and geophysical importance and has to be incorporated into the geoelectrical model.

Recent MVS field experiments in the south-eastern part of the BM and the induction vector distribution on profiles P-81, P-82 and P-83 (Fig. 3) seem to indicate the existence of another pronounced geoelectrical boundary striking north-eastwards in the south-eastern margin of the Moldanubian block (Praus et al., 1982; Petr et al., 1984). According to geological information, the anomalous zone seems to define a deep-seated internal zone within the BM, where two sub-units of different orogenic systems – the Variscan and the Assynthian – make their contact.

The model and its electromagnetic characteristics

Exploiting previous and new information from MTS and MVS results, together with recent geological knowledge of the deep structure of the Earth's crust, we propose a further version of a working model of the internal geoelectrical

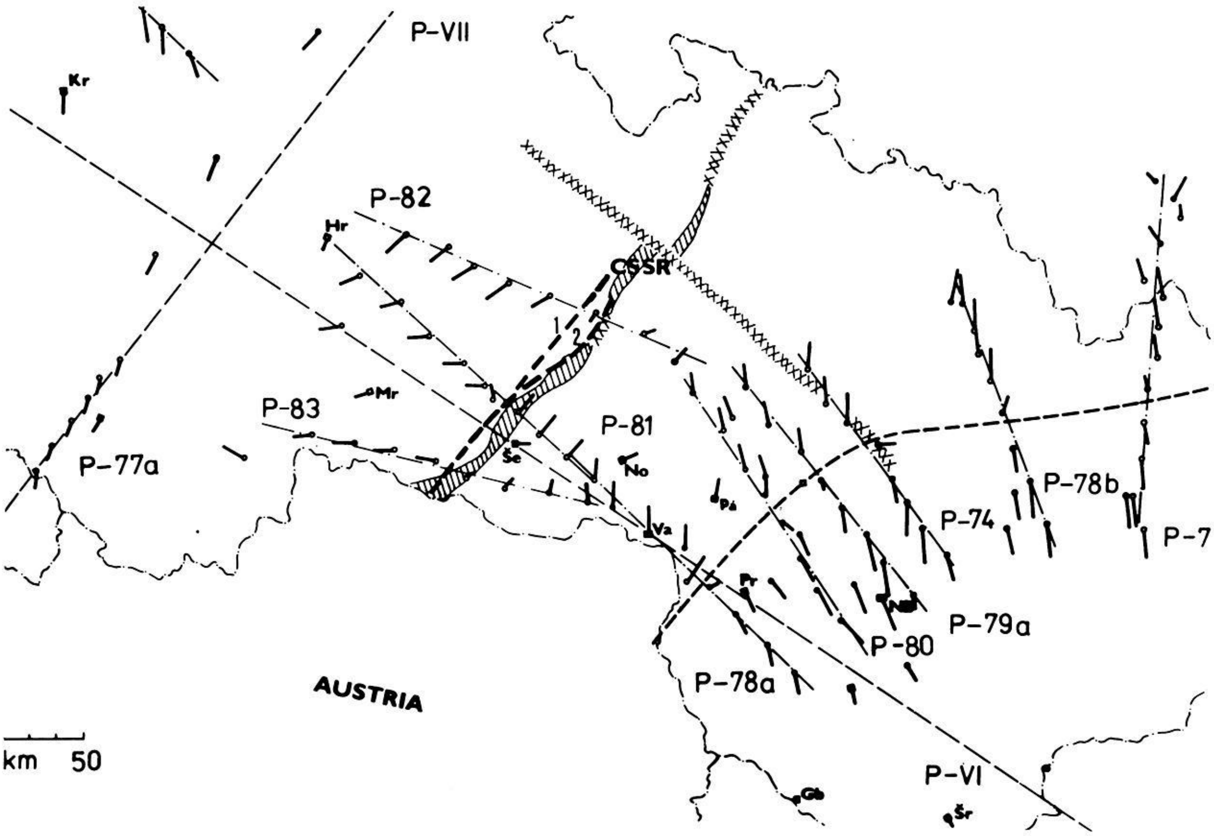

Fig. 3. The present stage of MVS results in the proximity of DSS profile No VI (marked as P-VI). The MTS localities used in modelling are: Kr = Krupá; Hr = Hrádek; Mr = Mrákotín; No = Nosislav; Še = Šemíkovice; Va = Valtice; Pa = Pánov; Pr = Prievaly; NB = Nitrianská Blatnica; Gb = Gabčíkovo; Šr = Šrobárová. The induction vectors are shown together with the traces of important anomalies (*dashed lines*) and tectonic elements (*crosses*)

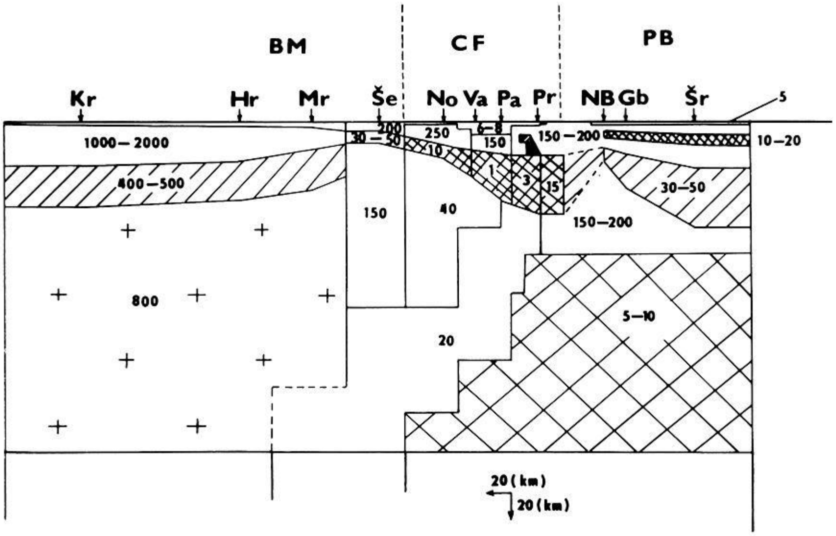

Fig. 4. The geoelectrical model of the cross-section based on previous investigations and with the recent MTS + MVS results considered. The same notation as in Fig. 3 was used for the MTS stations. The principal structural units are shown: BM = the Bohemian Massif; CF = the Carpathian foredeep (the transition zone); PB = the Pannonian block

structure along the profile (Fig. 4). It can be characterized by the following features:

a) Three blocks with different internal structure are clearly discriminated: (i) the consolidated block of the BM beneath the MTS stations of Boží Dar (beyond the limits of the model), Kr, Hr, Mr, Še; (ii) the autonomous block of the transition zone between the BM and WCP under MTS stations No, Va, Pa, Pr (CF-Carpathian foredeep in Fig. 4); (iii) the Pannonian block (PB in Fig. 4) of the Inner Carpathian basin, MTS stations NB, Gb, Šr.

b) Layers of increased electrical conductivity are suggested at crustal and crust-mantle boundary depths. In the Pannonian block we assume a layer (I) with resistivities between 10 and 20 Ωm at depths between 10 and 18 km, rising slightly to the Earth's surface when we approach the Carpathian core mountains. Here, it seems to be cut off (according to MTS results at MTS station Pr). In the BM a corresponding layer (I) is suggested under the north-western part of the profile starting approximately from the region between the MTS localities of Še and Mr, where its

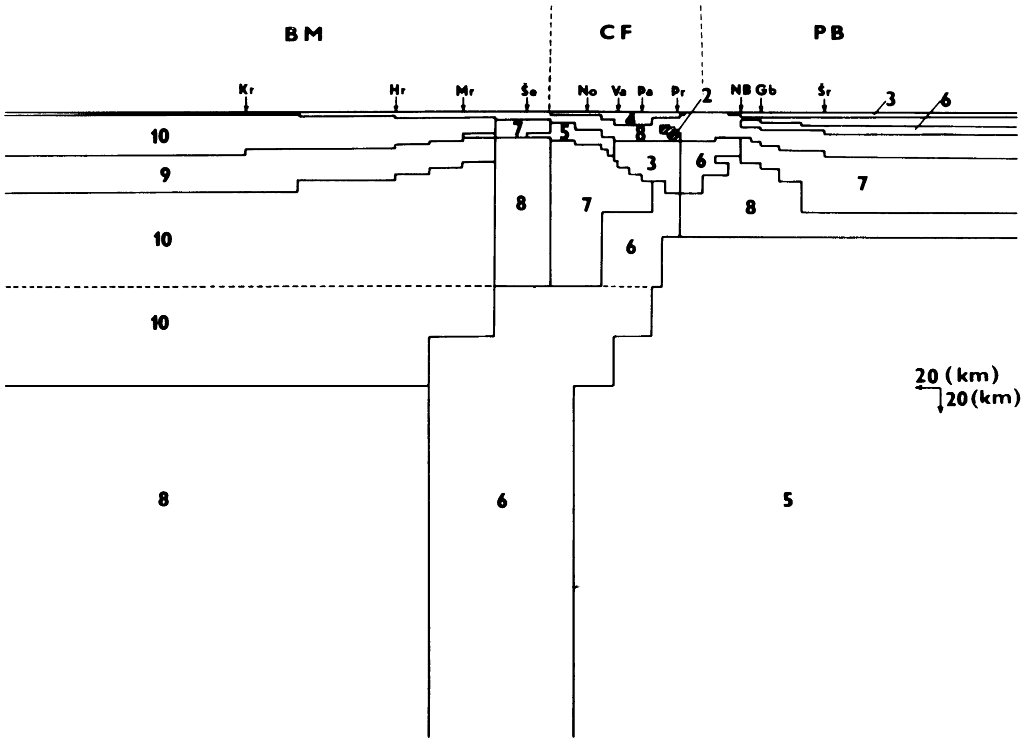

Fig. 5. Schematized and generalized geoelectrical structure for finite difference modelling. The sub-regions are numbered from 2–10. The resistivities in Ωm are: $\rho_1 \rightarrow \infty$; $\rho_2 = 1$; $\rho_3 = 5$; $\rho_4 = 7$; $\rho_5 = 10$; $\rho_6 = 20$; $\rho_7 = 50$; $\rho_8 = 200$; $\rho_9 = 800$; $\rho_{10} = 2{,}000$. *Dashed line* defines another version of the cross-section at asthenospheric depths (see the text). The same notation as in Fig. 4 was used to mark principal structural units

depth is about 20 km. The layer dips to about 40 km depth north-westward. Its resistivity is assumed to be between 400 and 500 Ωm. Thus, the layer represents a zone of increased conductivity about 20 km thick within a poorly conducting crystalline block with resistivities of 1,000–2,000 Ωm.

The structure of the transition zone, the north-western margin of which we suppose to be shifted as far as the induction vector inversion between MTS stations Mr and Še, seems to be specific. The crustal layer of increased conductivity (I) is assumed to submerge from about 10–25 km depth, at the same time thickening from 10–50 km and, simultaneously, becoming more conductive with resistivities that decrease from 50 to 1–2 Ωm from the north-western margin toward the WCP. We suggest that the Pericarpathian zone as defined by Beránek and Weiss (1980) be regarded as the eastern limit of the transition block. It represents a deep-rooted zone of the highest order and of basic geotectonic importance as it separates two tectonic blocks differing in the character of their Precambrian structural elements, in the sialic parts of the crust and in crustal thicknesses.

The geoelectrical anomaly mapped on the Carpathian scale by MVS research represents a prominent geophysical characteristic in the Pericarpathian zone. It was probably formed as a consequence of processes (subduction) which were going on in the contact zone of two lithospheric plates. The anomaly is, therefore, reflected in the model as a highly conductive slab submerging under the WCP. At depths of about 20 km, the slab merges with a conductive layer at crustal and upper mantle depths.

c) In the Pannonian block an uncertain intermediate layer (II) of slightly decreased resistivity between 20 and 50 Ωm might exist according to one possible interpretation of MTS curves (see Fig. 4).

d) The asthenosphere seems to be well developed over the Inner Carpathian region in accordance with conclusions by Ádám et al. (1982). In our model it is characterized by low resistivities of 5–10 Ωm at depths of 80–100 km under the Pannonian block. Under the transition zone, however, it seems to submerge gradually to depths greater than 250 km according to the results obtained at MTS stations Kr, Hr, Mr in the BM. Also the resistivity of the blocks increases north-westward at upper mantle depths. This structure seems to fit the models of stable regions suggested by Vanyan (1981). An alternative asthenospheric structure is discussed later.

Analysis of the model and the results

The model represents a 2-D geoelectrically inhomogeneous structure with the axis of homogeneity striking north-eastward, perpendicular to the profile. This 2-D approximation seems to be supported by the directional characteristics of deep-rooted fault systems, as a rule striking in the SW-NE directions and roughly coinciding with the axis of homogeneity. They represent a system of longitudinal Variscan discontinuities which are documented geophysically (anomalous fields) and geologically (volcanism of different ages) (Pokorný and Štovíčková, 1982). On the other hand, we shall see later that other geophysical factors indicate a rather general 3-D character for some parts of the structure along the profile.

The validity of the proposed geoelectrical structure was tested by solving the direct electromagnetic problem numerically. The cross-section was approximated by several

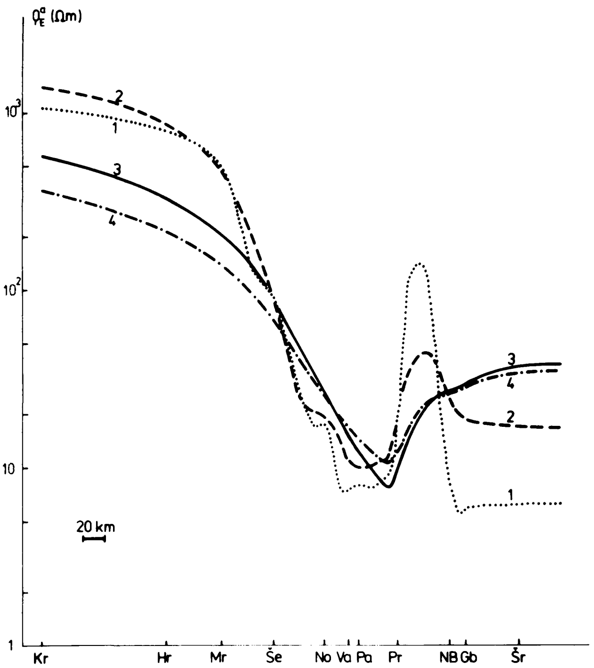

Fig. 6. The apparent resistivities in the grid points at the surface of the model (*E*-polarization) for the following periods (in s): 1–10, 2–100; 3–900; 4–1,800

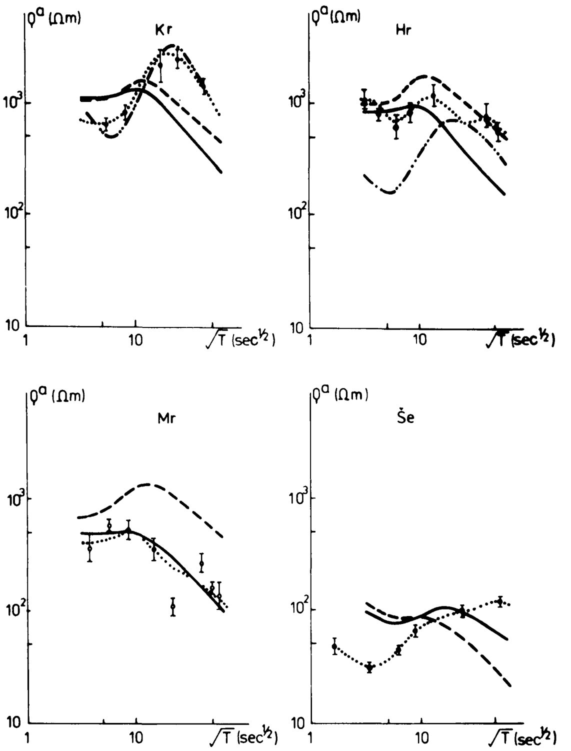

Fig. 7. Apparent resistivity curves $\rho^a(\Omega\text{m})$ at the surface of the model together with experimental MTS curves at stations in the BM. Explanation: *full line* = *E*-polarization curve; *dashed line* = *H*-polarization curve; *dotted line* = experimental $\rho^a:\rho_{\max}$ at Hr, Še, $\rho_{\min}$ at Mr ($\rho_{\max}$ highly distorted), ρ_{xy} (unrotated) at Kr; *dash-double dot* – $\rho^a:\rho_{yx}$ (unrotated)

blocks with different resistivities. Due to the limited number of sub-regions in the model we had to simplify its electrical differentiation (Fig. 5). The primary electromagnetic field for periods between 10 and 3,600 s was assumed to be a plane wave incident perpendicularly on the Earth's surface. To solve Maxwell's equations numerically for fields of *E*- and *H*-polarizations, we applied the method of finite differences (Červ and Praus, 1978). A full set of the field components and period-dependent characteristics of the medium, i.e. impedances, apparent resistivities and induction vectors (in the case of *E*-polarization) were obtained at the surface of the model.

Some of the results obtained by numerical modelling are summarized in Figs. 6–10. They were obtained by amending the specific resistivities of sub-regions in a series of steps to get a better fit with the experimental results. Analysing first the functions of apparent resistivities in Fig. 6 for the *E*-polarization mode, we noticed a pronounced decrease of apparent resistivities from the BM towards the transition block and to the WCP. The agreement with the actually observed resistivities according to MTS curves seems, in general, to be reasonably good. It was investigated in detail by comparing both the experimental and theoretical curves displayed in Figs. 7–9 grouped by principal structural regions.

In the BM reasonable agreement is observed between both the experimental ρ^a and the theoretical *E*-polarization curves at Hr and Mr. At Kr both the experimental curves show higher resistivities than the calculated ones and a pronounced maximum which seems to require higher resistivities and increased contrast in the structure. At Še only the order of apparent resistivities seems to be compatible with the experiment, while the deeper structure seems to require a further increase in resistivities to get a better fit at penetration depths corresponding to $\sqrt{T} > 20\ \text{s}^{1/2}$.

In the transition zone, the structure is obviously more complex than our schematized model. While a satisfactory agreement in form between theoretical *E*-polarization and experimental curves is observed at MTS stations Va and Pr, a systematic difference in magnitude of the resistivities seems to require a decrease of apparent resistivities in this region of the model. At MTS stations No and Pa rough agreement of the curves is obtained in the order of magnitude of apparent resistivities.

In the Pannonian Basin, the agreement between the $\rho_{\min}$ and the theoretical *H*-polarization curves is approximate with respect to their form and satisfactory in the order of magnitude of apparent resistivities. The best fit is seen for MTS station Šr, for penetration depths corresponding to $\sqrt{T} > 10\ \text{s}^{1/2}$. A misfit at shorter periods seems to be due to the use of too high a value in the crustal layer of increased conductivity (sub-region 6, Fig. 5). The necessary amendment would require greater subdivision of the model.

During the modelling we also tested two hypotheses for the structure of the asthenosphere under the profile. The results shown in Figs. 6–10 were obtained under the assumption of a well-developed asthenospheric layer of 10 Ωm at about 80–100 km depths under the Pannonian block in accordance with Ádám et al. (1982). The layer was supposed to dip gradually within the transition zone to depths over 250 km. Its resistivity increased from 10 Ωm through intermediate region 6 in Fig. 5 to 200 Ωm under the BM (region 8, Fig. 5). As shown in Figs. 7–9, the agreement between observational data and model computations was in general satisfactory. In the next modelling step we

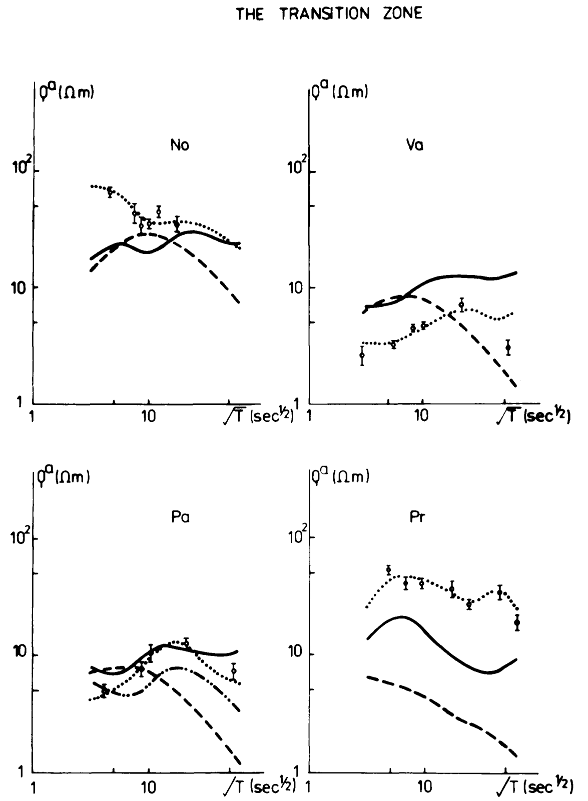

Fig. 8. Apparent resistivity curves ρ^a (Ωm) at the surface of the model together with experimental curves at MTS localities in the transition zone. Notation: *full* and *dashed lines*, *E*- and *H*-polarizations, respectively; *dotted* – $\rho^a:\rho_{\max}$ at No, Va, Pr, Pa ($\rho_{\min}$ distorted); *dash-double dot* – $\rho^a:\rho_{yx}$ (unrotated)

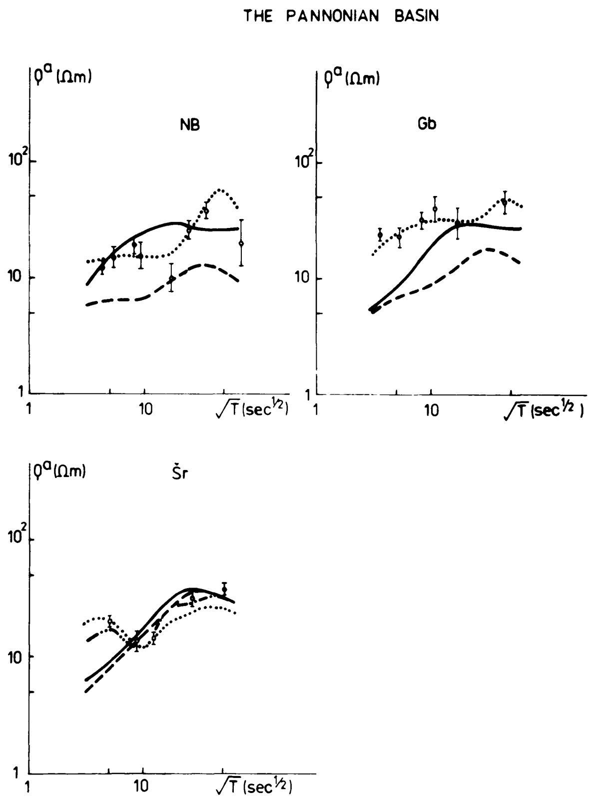

Fig. 9. Apparent resistivity curves ρ^a(Ωm) at the surface of the model together with experimental curves at MTS localities in the Pannonian block. Notation: *full* and *dashed lines*, *E*- and *H*-polarizations respectively; *dotted* – $\rho^a:\rho_{\min}$; *dash-double dot* – $\rho^a:\rho_{yx}$ (unrotated)

assumed the asthenosphere to be developed at depths along the whole profile. The asthenospheric layer was assumed to jump from 100–140 km under the transition zone but the resistivities were kept at 10 Ωm throughout (dashed line in Fig. 5 with region 5 extending along the whole model). The results of modelling (not reproduced here) are similar to those shown in Fig. 6, leaving the Pannonian and the transitional part of the profile essentially unchanged, while decreasing the apparent resistivities for periods of 900 and 1,800 s to about 100 Ωm within the BM. These values are substantially lower than those observed at localities Kr and Hr. According to these results we conclude that the first variant of the structure at asthenospheric depths should be preferred.

In all the modelling steps, real theoretical induction vectors were calculated together with apparent resistivities for the *E*-polarization mode. Induction vector estimates from MVS experimental data are available over about a 320-km long section of DSS profile No. VI. Interpreting their spatial characteristics in the framework of our modelling, we encountered a major discrepancy in the fact that experimental induction vector azimuths tend to coincide with the azimuth of the profile only on both sides of the WCP while deviating substantially from it in the marginal part of the transition zone and in the BM. Consequently, they do not seem to support the assumption of a 2-D character of the cross-section along the whole profile. The effects of increasing 3-D character of the structure are probably involved in the induction characteristics.

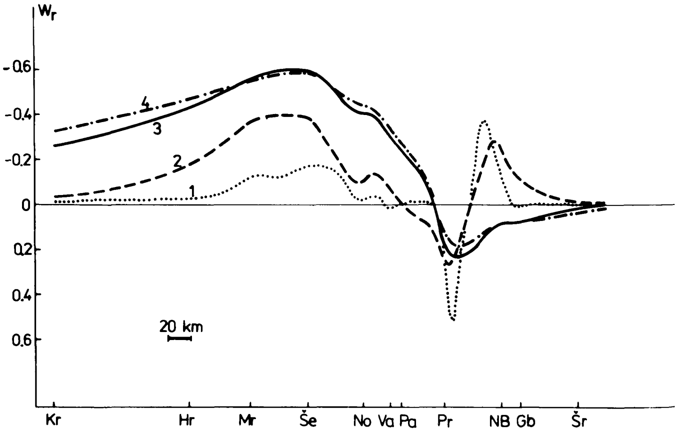

Fig. 10. The theoretical induction magnitude at the surface of the model. Curves are labelled according to periods (in s): 1–10; 2–100; 3–900; 4–1,800

In view of this remark, we consider the induction vector to be a crude characteristic marking, by a sudden change of azimuths or a reversal, mainly the pronounced zones of geoelectrical inhomogeneities. The results of the calculation of vectors for the geoelectrical model are displayed in Fig. 10. A remarkable feature in Fig. 10 is a well-developed reversal of the induction vectors for periods of 900 and 1,800 s between the MTS-MVS stations of Pa and Pr.

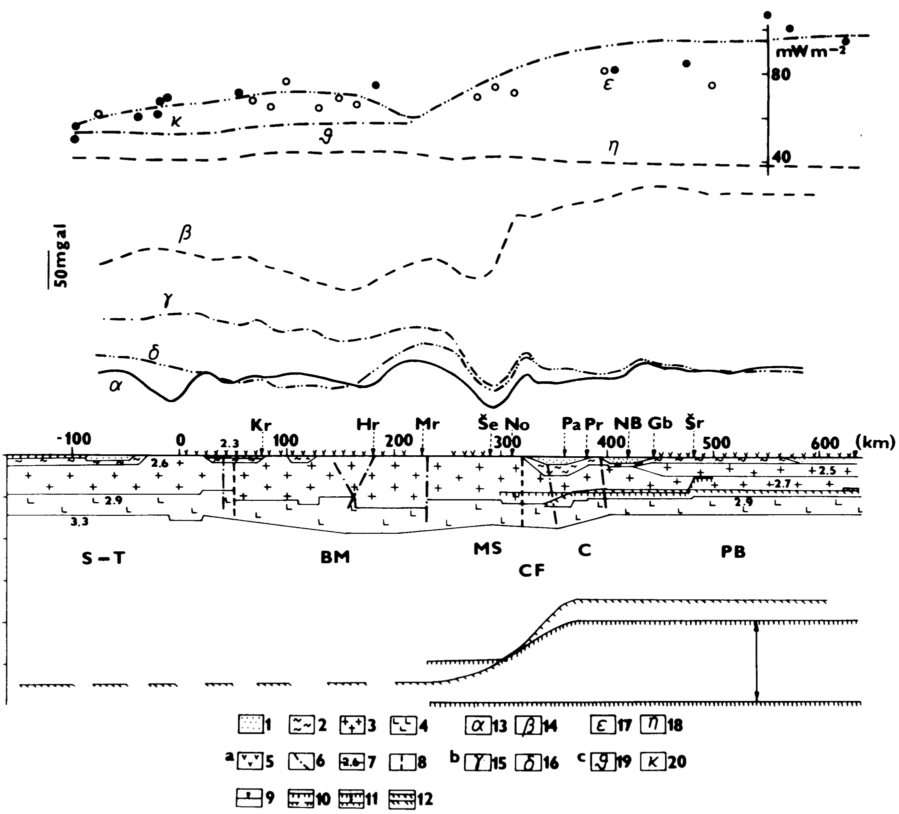

Fig. 11. The model of the internal structure under DSS profile No. VI proposed by Bur'yanov et al. (1980). Explanation of symbols: 1-sedimentary basins; 2-sedimentary rocks of folded basements; 3-granitic layer; 4-basaltic layer; 5-Neogene volcanics; 6-deep faults; 7-density boundaries; 8-boundaries with a different distribution of density; 9-MTS stations labelled according to notation in Fig. 3; 10-upper boundary of the layer of increased electrical conductivity; 11-limits of the conductive layer; 12-surface of partial melting; 13-gravity field; 14-effect of the Earth's crust in the gravity field; 15-effect of melting; 16-with the effect of thermal reduction of density; 17-results of heat flow measurements; 18-thermal background; 19-with a geosyncline source considered; 20-with the effect of magmatic activization of the platform considered

This is in excellent accord with the observed facts. In the BM, however, the results of modelling suggest larger moduli for the induction vectors than are observed along profiles P-81, P-82 and P-83. Attempts are being made to improve these results. They suggest that a block with increased conductivity between stations Mr and Še must be introduced to improve the behaviour of the vectors in such a way as to cause a partial reversal of their azimuths and to substantially reduce their amplitudes. The assumption of such a zone is fully justified on geological grounds. This amendment, however, made the fit with MTS results worse. A compromise must therefore be found. However, it requires a more detailed subdivision of the electrical model.

Conclusion

Summing up the main facts and conclusions which were arrived at in the process of numerical modelling, we wish to emphasize the following points:

1) The model, based on previous investigations and with recent MTS and MVS results considered, generalized and simplified for numerical modelling, accounts qualitatively for the main features of the electromagnetic characteristics observed or computed from the data at the Earth's surface. The theoretical resistivities obtained at individual MTS stations by modelling correspond to experimental values reasonably well with regard to the order of magnitude and, at some stations only, also with regard to the form of the MTS curve. Further amendments of the cross-section are required at some MTS localities in the transition zone with its very complicated internal structure to obtain better detailed agreement between both sets.

2) From a comparison of two possible structures at asthenospheric depths, the model with the asthenosphere at about 100 km depth under the Pannonian block, gradually submerging to depths over 250 km under the BM, seems to correspond better to the apparent resistivity estimates in the BM than the alternative model.

3) Good agreement between the theoretical induction vectors and those actually estimated was obtained for the Pannonian and near-Carpathian arc area of the profile. The induction vector reversal perfectly fits the experimental results.

4) There was a serious misfit between observed and computed induction vector magnitudes in the BM part of the profile. Subsequent analysis has shown that a zone of increased conductivity in the south-eastern margin of the BM can improve the results substantially.

5) Further improvement of the fit between the theoretical responses and those actually observed requires a higher differentiation of the model by increasing the number of sub-regions.

In concluding this contribution, we wish to compare our model with one proposed by Bur'yanov et al. (1980) based on interpretation of DSS results, heat flow data, gravity field anomalies and electromagnetic characteristics, published previously (Pěčová et al., 1976) and re-interpreted by these authors. The model is presented in Fig. 11, redrawn from the original in a simplified form. The authors suggest that the asthenospheric layer is at depths between 80 and 120 km under the Pannonian block and under the WCP, between 100 and 120 km under the south-eastern part of the BM, while is not defined geoelectrically under the north-western part of the profile. A layer of increased conductivity in the crust is shown to exist under the whole "Alpine part" of the profile (the Pannonian block) between 10 and 20 km depths and the layer is presumed to continue as far as the marginal area of the "Hercynian part" of the model (the

BM). It is satisfying to conclude that the interpretation of the same data by two independent approaches leads to results which are very close to each other in their determination of the important features of the models.

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