2-*D* model fitting of a geomagnetic anomaly in the Soviet Carpathians

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Received March 1, 1985; accepted September 28, 1985.

ABSTRACT. In the present analysis the dense array of magnetovariational (MV) and magnetotelluric (MT) long-period observations in the Soviet Carpathians was projected on the International Geotraverse II; and a detailed 2-*D* geoelectric model of this cross-section of the Carpathian folded system was constructed using modern 2-*D* modelling and inversion techniques.

The subsurface conductivity in the model was based on the combined data obtained by geophysical prospecting methods and deep seismic soundings. The normal deep conductivity section resulted from the interpretation of MT soundings in conjunction with available geothermic and petrologic models. The anomalous geoelectric structure consists of a crustal anomaly (at the depth of 10-25 km with conductivity up to 2 S/m and longitudinal conductivity $3\text{-}5 \cdot 10^8$ S·m) and a conductive asthenospheric layer (at the depths of 70-170 km with conductivity 0.04 S/m and integrated conductivity 4000 S) to the east away from the Carpathians.

The shape of the crustal anomaly and of the eastern edge of the asthenospheric layer were optimized by a 2-*D* formalized inversion procedure applied to the 1 hour period profile MV data. The resulting model fits the experimental data fairly well within the limits of the 20 % observational accuracy.

Key words : modelling, geoelectric structure, inverse problem.

Annales Geophysicae, 1986, **4**, B, 3, 335-342.

INTRODUCTION

In constructing complex geophysical models of lithospheric structures it is very important to take geoelectric data into consideration. The magnetotelluric (MT) method is traditionally used as the main tool of deep geoelectrics. However recent applications of this method have shown that in many cases single-point MT soundings cannot yield adequate information about the deep conductivity. The fact is that as a rule magnetotelluric sounding (MTS) curves are substantionally distorted by horizontal geoelectric inhomogeneities of shallow and deep nature. Therefore, the formal 1-*D* interpretation of MTS data results in false geologic structures. Typical examples of MT field distortions and the corresponding interpretational difficulties can be seen in the Carpathian region where one of the largest electromagnetic (EM) anomalies is observed.

The natural way to eliminate non-uniqueness of MTS data interpretation consists in the combined application of MTS and magnetovariational profiling (MVP) techniques and, eventually, the development of a general deep EM sounding technique based on simultaneous array (profile) field recording over a wide frequency band. Such an observation scheme would produce the full space-time picture of EM field variations and would allow, in principle, to resolve both the vertical and the horizontal conductivity structure of the Earth. However, to implement this approach requires new interpretational methods, quite different from the classical approaches to MTS data interpretation.

These new methods generalize some ideas applied in the theory of interpretation of potential geophysical fields (Berdichevsky and Zhdanov, 1981; 1984). Several computer program packages for deep EM sounding data interpretation have recently been elaborated in

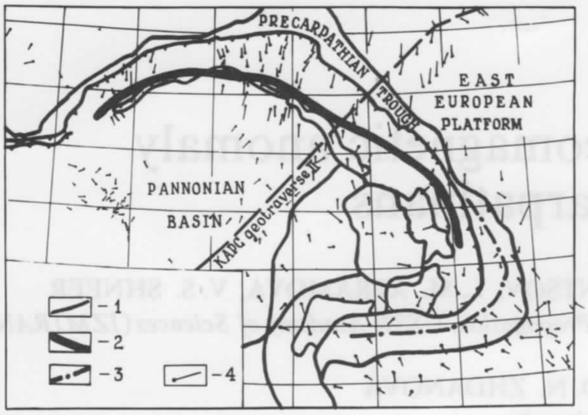

Figure 1

Geoelectric structure of the Carpathian region :
1) *boundaries of tectonic units ;*
2) *axis of geomagnetic anomaly connected with crustal conductivity anomaly ;*
3) *axis of geomagnetic anomaly connected with currents in conducting sediments of the Precarpathian Trough ;*
4) *induction arrows.*

IZMIRAN and their effectiveness has been demonstrated in different investigations. In the present paper we shall illustrate some advantages of the approach mentioned above when discussing the construction of a 2-*D* geoelectric model along the International KAPG Geotraverse II in the transition zone between the East European Platform and the Alpine region of the Carpathians.

1. PREVIOUS INVESTIGATIONS : DATA AND MODELS

The Carpathian region has attracted the attention of scientists in geoelectrics for a long time. The anomalous character of natural EM field variations was first discovered in the western Carpathians (Wiese, 1965). This anomaly was connected with the effect of current concentration in the elongated zone of increased conductivity.

The subsequent MTS and MVP investigations (Bondarenko *et al.*, 1972 ; Jankowski *et al.*, 1975, 1979 ; Àdàm *et al.*, 1975 ; Rokityansky, 1975 ; Rokityansky *et al.*, 1975 ; Stanica M., and Stanica D., 1981 ; etc.) made it possible to trace the anomaly along almost the entire Folded Carpathians (fig. 1).

1.1. MT field observations in the Soviet Carpathians

The most detailed study of this anomaly was undertaken in the Soviet Carpathians where more than 60 MVP and 20 MTS observations were carried out on several profiles along the International Geotraverse II in the 400 km interval from Korets on the Ukrainian shield to Beregovo in the Pannonian basin (fig. 2). These observations began in the late sixties (Bondarenko *et al.*, 1972) and were recently continued with the close cooperation of IZMIRAN, the Institute of Geophysics (Kiev) and the Institute of Applied Problems of Mathematics and Mechanics (Lvov) of the Ukrainian SSR Academy of Sciences on Soviet territory, and the Geophysical Research Institute of the Hungarian Academy of Sciences in north-eastern Hungary. The measurements were performed with the Soviet three-component MV and five-component MT stations IZMIRAN-4 and IZMIRAN-5.

The processing of the observed data produced simultaneous MT field values and induction vectors in the frequency range from 10 min to two hours, as well as traditional deep MTS curves.

1.2. Crustal conductivity structure

The interpretation of the profile geomagnetic data allowed us to localize the crustal conductivity anomaly in the region of the junction of the Folded Carpathians and the Transcarpathian Trough and to make preliminary estimates of the most important parameters of this anomaly. Initially the bedding depth of the anomalous zone was determined to be less than 40-60 km (Bondarenko *et al.*, 1972). Later, using MVP forward problem solutions for simple shape structures, the upper edge of this zone was fixed at a depth of 17 km and the value of its longitudinal conductivity $\Sigma_{cr} = 2\cdot 10^8$ S·m was calculated (Rokityansky, 1975 ; Rokityansky *et al.*, 1975). At the same time the formal interpretation of longitudinal MTS curves obtained above the axis of the geomagnetic anomaly gives the depth to the anomaly as $H_{cr} = 16$ km (Rokityansky *et al.*, 1975). A further refinement of the parameters of the conducting crustal inclusion was achieved by means of modern EM field separation and analytic continuation techniques (Zhdanov *et al.*, 1983 ; Varentsov, 1981). In these last studies the simple model of a homogeneous halfspace ($\sigma = 10^{-3}$ S/m) with a realistic subsurface thin sheet conductivity distribution was considered. The deep nature of the EM anomaly was confirmed (fig. 3) and, using the formalized fitting procedure (Berdichevsky and Zhdanov, 1981 ; 1984 ; Zhdanov and Varentsov, 1983 ; Varentsov, 1981), the structure of the conducting inclusion was determined as an isometric body with depth $H_{cr} = 10$ km, conductivity $\sigma_{cr} = 1$ S/m and longitudinal conductivity $\Sigma_{cr} = 0.7\cdot 10^8$ S·m (fig. 4).

Similar ideas about the origin of the Carpathian geomagnetic anomaly were elaborated for the western Carpathians (Jankowski *et al.*, 1975 ; 1977). In the Romanian Carpathians the crustal conductivity anomaly still exists in the eastern part (on the International KAPG Geotraverse V), while in the southern Carpathians it disappears and the EM anomaly originates entirely from currents in the thick sediments of the Precarpathian Trough (M. Stanica and D. Stanica, 1981). This situation is well illustrated by the regional distribution of induction vectors (fig. 1).

1.3. Upper mantle conductivity structure

It should be emphasized that the main object of almost all the previous interpretations of the Carpathian anomaly was the crustal conductivity inhomogeneity. Rather less attention was paid to the geoelectric structure of the upper mantle. At the same time the considerable changes in the geothermal conditions of the East European Platform and the Pannonian Basin (Stegena, 1976 ; Àdàm, 1980 ; Burianov *et al.*, 1978,

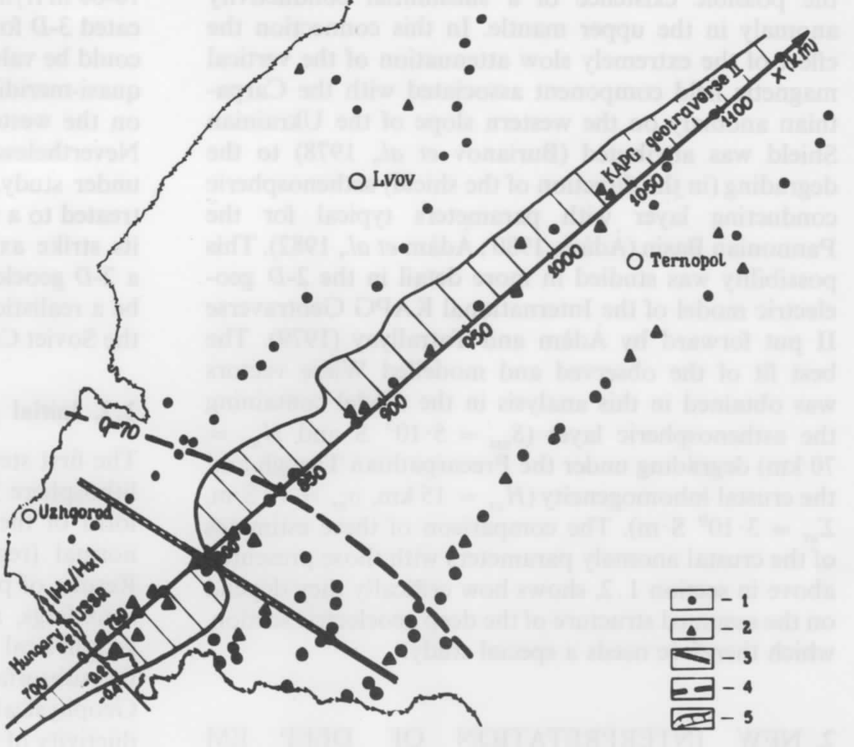

Figure 2
Geoelectromagnetic investigation in the Soviet Carpathians :
1) MVP *observations ;*
2) MTS *observations ;*
3) *axis of geomagnetic anomaly connected with crustal conductivity anomaly ;*
4) *heat flow isoline* (mW/m²) *;*
5) *profile graph of* $|H_z/H_x|$.

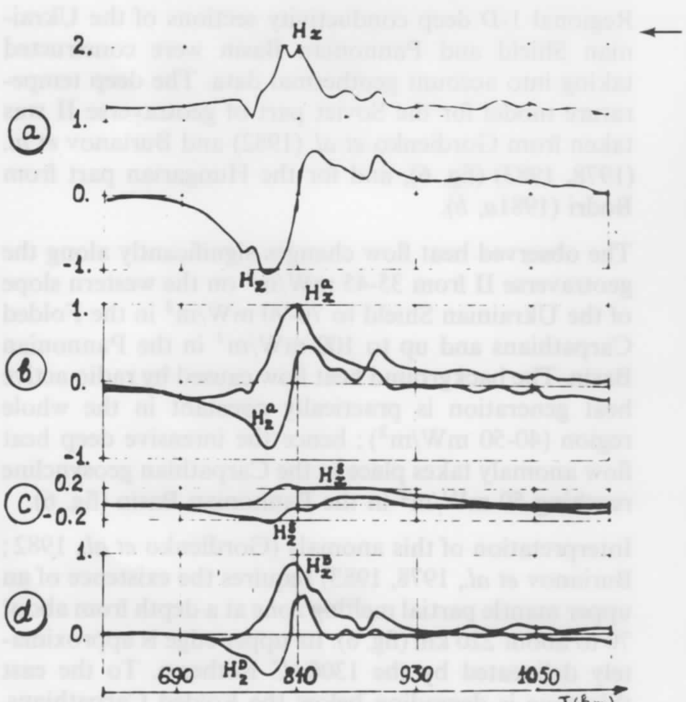

Figure 3
Separation and analytic continuation of geomagnetic fields on KAPG *geotraverse* II :
a) *observed fields* $|H_x|, |H_z|$ *;*
b) *anomalous fields* $|H_x^a|, |H_z^a|$ *;*
c) *surface part of the anomaly ;*
d) *deep part of the anomaly ;*
e) *map of continued* $|H_z|$ *field ;*
f) *map of continued magnetic field flux function.*

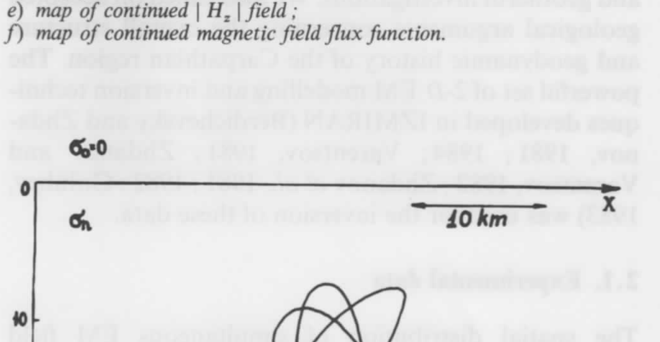

Figure 4
Fitting of shape of crustal conducting inclusion in the Soviet Carpathians using the tightening surfaces method :
1) *initial approximation ;*
2) *fitting result ;*
3) *fitting direction (initial and final misfit is shown above arrow).*

1983; Bodri, 1981*a*, *b*; Gordienko *et al.*, 1982) suggested the possible existence of a substantial conductivity anomaly in the upper mantle. In this connection the effect of the extremely slow attenuation of the vertical magnetic field component associated with the Carpathian anomaly on the western slope of the Ukrainian Shield was attributed (Burianov *et al.*, 1978) to the degrading (in the direction of the shield) asthenospheric conducting layer with parameters typical for the Pannonian Basin (Àdàm, 1980; Àdàm *et al.*, 1982). This possibility was studied in more detail in the 2-*D* geoelectric model of the International KAPG Geotraverse II put forward by Àdàm and Tatrallyay (1979). The best fit of the observed and modelled Wiese vectors was obtained in this analysis in the model containing the asthenospheric layer ($S_{\text{ast}} = 5 \cdot 10^3$ S and $H_{\text{ast}} =$ 70 km) degrading under the Precarpathian Trough and the crustal inhomogeneity ($H_{\text{cr}} = 15$ km, $\sigma_{\text{cr}} = 10$ S/m, $\Sigma_{\text{cr}} = 3 \cdot 10^9$ S·m). The comparison of these estimates of the crustal anomaly parameters with those presented above in section 1.2, shows how critically they depend on the assumed structure of the deep geoelectric section, which therefore needs a special study.

2. NEW INTERPRETATION OF DEEP EM SOUNDING DATA IN THE SOVIET CARPATHIANS

To construct a detailed geoelectric model of the Korets-Beregovo-Debrecen extent of the International Geotraverse II, the deep simultaneous multi-frequency array EM data were combined with geoelectric information from prospecting EM surveys and well loggings, as well as with materials from deep seismic soundings and geotherm investigations. We also called on accepted geological arguments concerning the overall structure and geodynamic history of the Carpathian region. The powerful set of 2-*D* EM modelling and inversion techniques developed in IZMIRAN (Berdichevsky and Zhdanov, 1981; 1984; Varentsov, 1981; Zhdanov and Varentsov, 1982; Zhdanov *et al.*, 1981; 1982; Golubev, 1983) was used for the inversion of these data.

2.1. Experimental data

The spatial distribution of simultaneous EM field amplitudes measured in the Soviet Carpathians confirms the almost 2-*D* character of the data. Therefore, in order to decrease the effects of observational errors and local conductivity anomalies the data of all MVP stations within a 100 km reach were projected on the geotraverse II (fig. 2). The axis of projection was chosen parallel to the axis of the crustal conductivity anomaly which is reasonably perpendicular to the geotraverse II. As a result, simultaneous amplitudes of vertical (H_z) and horizontal (H_x) components of the geomagnetic field with period about 1 h were determined at 40 points and the H_z/H_x ratio at more than 50 locations (fig. 5). This method of securing generalized geomagnetic data on a profile made it possible to estimate the data accuracy in the of 10-20 % range.

Here it should be mentioned that the regional structure of the conducting asthenosphere in the Pannonian Basin (Burianov *et al.*, 1983), contoured in plan by the 70-80 mW/m² heat flow isolines (fig. 2) takes a complicated 3-*D* form. Any knowledge about these 3-*D* effects could be valuable and in particular it might explain the quasi-meridional orientation of the induction vectors on the western slope of the Ukrainian Shield (fig. 1). Nevertheless, within the region of geotraverse II under study, the asthenospheric structure can also be treated to a first approximation as a 2-*D* structure with its strike axis perpendicular to the geotraverse. Thus a 2-*D* geoelectric model along geotraverse II seems to be a realistic picture of the conductivity distribution in the Soviet Carpathians.

2.2. Initial geoelectric model

The first step in constructing geoelectric models of the lithosphere is to synthesize *a priori* information in the form of the subsurface conductivity distribution and normal (regional) deep 1-*D* conductivity structures. Results of prospecting DC, MT and controlled-source soundings, and well loggings with reference to other geophysical and geological data were used to estimate the subsurface conductivity (Shilova and Sanin, 1982; Geophysical Transactions, 1981). The integrated conductivity of the 10 km subsurface layer ranges from less than 100-200 S in the Ukrainian Shield and Folded Carpathians, up to 1500 S in the Precarpathian Trough (fig. 1).

Regional 1-*D* deep conductivity sections of the Ukrainian Shield and Pannonian Basin were constructed taking into account geothermal data. The deep temperature model for the Soviet part of geotraverse II was taken from Gordienko *et al.* (1982) and Burianov *et al.* (1978, 1983) (fig. 6), and for the Hungarian part from Bodri (1981*a*, *b*).

The observed heat flow changes significantly along the geotraverse II from 35-45 mW/m² on the western slope of the Ukrainian Shield to 70-90 mW/m² in the Folded Carpathians and up to 100 mW/m² in the Pannonian Basin. The background heat flow caused by radio active heat generation is practically constant in the whole region (40-50 mW/m²); hence the intensive deep heat flow anomaly takes place in the Carpathian geosyncline reaching 50 mW/m² in the Pannonian Basin (fig. 6).

Interpretation of this anomaly (Gordienko *et al.*, 1982; Burianov *et al.*, 1978, 1983) requires the existence of an upper mantle partial melting zone at a depth from about 70 to about 220 km (fig. 6). Its upper edge is approximately delineated by the 1300 °C isotherm. To the east this zone is degrading below the Folded Carpathians. The degree of partial melting does not exceed 5 % which corresponds to a conductivity value less than 0.05 S/m. Another rather localized crustal partial melting zone could exist between the isotherm of 600 °C and the lower bound of metamorphic amphibole facies at the junction of the Folded Carpathians and the Transcarpathian Trough (fig. 6).

Deep 1-*D* normal conductivity sections introduced in the initial geoelectric model (fig. 7), correspond to the deep temperature distribution discussed above and fit generalized MTS curves in the Pannonian Basin

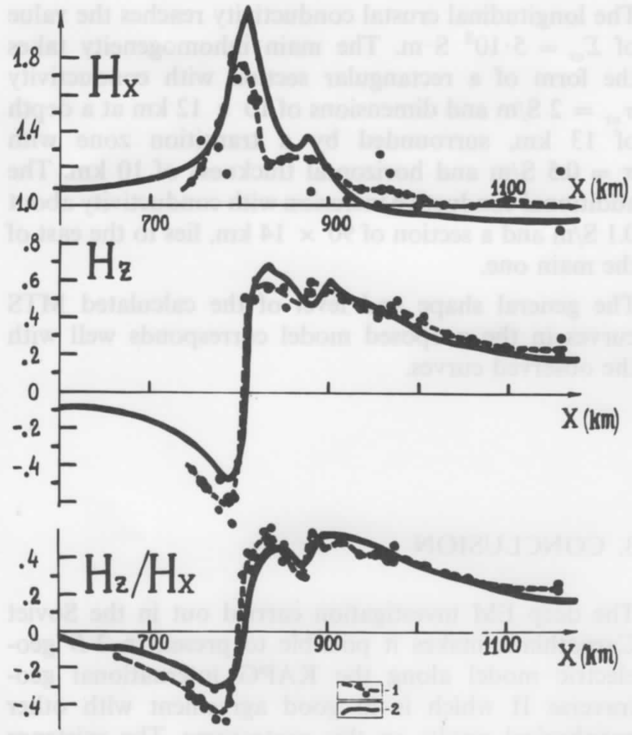

Figure 5

Geomagnetic data on KAPG *geotraverse* II :
1) *observed ;*
2) *modelled.*

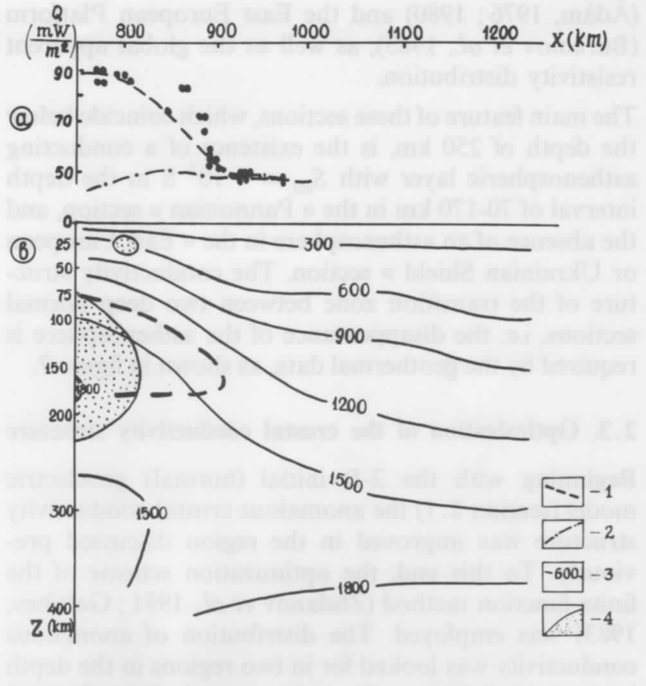

Figure 6

Geothermal model along KAPG *geotraverse* II *in the Soviet Carpathians (a) heat flow distribution, b) deep temperature section) :*
1) *observed and modelled total heat flow ;*
2) *modelled background heat flow ;*
3) *temperature isolines* (°C) ;
4) *partial melting zones.*

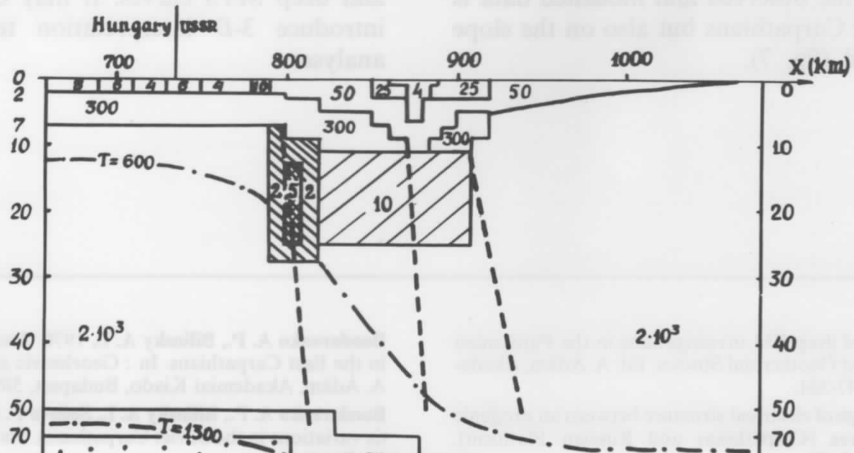

Figure 7

Geoelectric model of the Carpathian part of KAPG *geotraverse* II
1) *geoelectric boundaries and specific resistivities of blocks in* Ω·m ;
2) *deep faults ;*
3) *deep isotherms ;*
4) *conducting asthenosphere.*

(Àdàm, 1976; 1980) and the East European Platform (Burianov *et al.*, 1983), as well as the global apparent resistivity distribution.

The main feature of these sections, which coincide below the depth of 250 km, is the existence of a conducting asthenospheric layer with $S_{ast} = 4 \cdot 10^3$ S in the depth interval of 70-170 km in the « Pannonian » section, and the absence of an asthenosphere in the « East European or Ukrainian Shield » section. The conductivity structure of the transition zone between two deep normal sections, i.e. the disappearance of the asthenosphere is required by the geothermal data, as shown in figure 7.

2.3. Optimization of the crustal conductivity structure

Beginning with the 2-*D* initial (normal) geoelectric model (section 2.1) the anomalous crustal conductivity structure was improved in the region discussed previously. To this end, the optimization scheme of the finite function method (Zhdanov *et al.*, 1981; Golubev, 1983) was employed. The distribution of anomalous conductivity was looked for in two regions in the depth interval of 10-25 km, the main anomaly being located at the junction of the Folded Carpathians and the Transcarpathian Trough, and an additional anomaly below the Folded Carpathians and Precarpathian Trough.

The best fit between the 1 hour period MVP data and numerical calculations was obtained for the crustal conductivity structure shown in figure 7. The misfit amounts to about 15 % for the H_z and H_z/H_x components and approaches 20 % for the H_x field. The good agreement between the observed and modelled data is seen not only in the Carpathians but also on the slope of Ukrainian Shield (fig. 7).

The longitudinal crustal conductivity reaches the value of $\Sigma_{cr} = 5 \cdot 10^8$ S·m. The main inhomogeneity takes the form of a rectangular section with conductivity $\sigma_{cr} = 2$ S/m and dimensions of 10 × 12 km at a depth of 13 km, surrounded by a transition zone with $\sigma = 0.5$ S/m and horizontal thickness of 10 km. The additional conductive inclusion with conductivity about 0.1 S/m and a section of 90 × 14 km, lies to the east of the main one.

The general shape and level of the calculated MTS curves in the proposed model corresponds well with the observed curves.

3. CONCLUSION

The deep EM investigation carried out in the Soviet Carpathians makes it possible to present a 2-*D* geoelectric model along the KAPG international geotraverse II which is in good agreement with other geophysical results on this geotraverse. The existence of the horizontally degrading asthenospheric layer below the Carpathians seems confirmed. The location and the structure of the crustal conductivity anomaly can now be given with greater accuracy. This project has made it clear that the detailed study of the structure of the asthenosphere requires an increase in the amount and in the accuracy of EM data to be interpreted, i.e. it requires multi-frequency simultaneous MV arrays and deep MTS curves. It may even be important to introduce 3-*D* interpretation techniques in further analyses.

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