

## **Electrical Structure of the Upper Mantle Beneath Central Europe: Results of the CEMES Project**

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### **A b s t r a c t**

In the years 2001-2003, we accomplished the experimental phase of the project CEMES by collecting long-period magnetotelluric data at positions of eleven permanent geomagnetic observatories situated within few hundreds kilometers along the south-west margin of the East European Craton. Five teams were engaged in estimating independently the magnetotelluric responses by using different data processing procedures. The conductance distributions at the depths of the upper mantle have been derived individually beneath each observatory. By averaging the individual cross-sections, we have designed the final model of the

geolectrical structure of the upper mantle beneath the CEMES region. The results indicate systematic trends in the deep electrical structure of the two European tectonic plates and give evidence that the electrical structure of the upper mantle differs between the East European Craton and the Phanerozoic plate of west Europe, with a separating transition zone that generally coincides with the Trans-European Suture Zone.

**Key words:** mantle structure, Central Europe, electromagnetic soundings.

## 1. INTRODUCTION

In view of the recent interest in complex geoscientific studies in the area of the Trans-European Suture Zone and a manifestation of this first-order geological lineament down to great depths of the Earth's mantle (Wilde-Piórko *et al.* 2006), a particular project of deep electromagnetic induction soundings in Central and East Europe was initiated by the Institute of Geophysics of the Polish Academy of Sciences in Warsaw in 2001, under the acronym CEMES (Central Europe Mantle geoElectrical Structure), and joined by nine research institutes from different countries in the region. The main objective of CEMES was to provide reliable estimates of the distribution of electrical conductance in the upper mantle beneath the region, based on a joint interpretation of long-period magnetotelluric (MT) data with already available deep magnetovariation (MV) sounding results from eleven permanent geomagnetic observatories in Central and East Europe. A detailed description of the CEMES experimental layout has been given by Semenov *et al.* (2003).

Previous studies of the upper mantle in the region were based mainly on MT soundings carried out by individual teams on a national basis, and aimed primarily at detecting the conductive asthenosphere and estimating its depth beneath particular areas of investigation. The conductive asthenosphere was first detected by Ádám (1965) beneath the Pannonian Basin in Hungary. Over years, a number of geophysicists reported either the presence or absence of the asthenosphere, and interpreted a fairly broad range of depths to the top of the sublithospheric conductive layer beneath Central Europe from the individual deep sounding results (see, e.g., Ádám 1993, Astapenko *et al.* 1993, Burakhovich *et al.* 1998, Červ *et al.* 2001, Fainberg *et al.* 1998, Praus *et al.* 1990, Stanica and Stanica 1984). The highest precision map of the depth of the asthenosphere top has been obtained from MT soundings in Hungary because of a relatively very shallow position of this conductive layer beneath the region of the Pannonian Basin (Ádám and Wesztergom 2001).

Though local interpretations could give a rough idea about the topography of the asthenospheric layer on a regional scale, even the simplest modeling of an abrupt elevation in the topography of the asthenosphere shows that

the adjustment distance of the corresponding response in the apparent resistivity on the surface extends over hundreds of km from the bench step (Semenov *et al.* 2007). Consequently, a more accurate regional tracing of the asthenosphere necessarily requires synchronizing the effort of many countries and collecting and interpreting the long period induction data jointly over the entire region of interest. In this respect, several authors have exploited both the historical and recent geomagnetic observatory data and used the local MV responses for the interpretation of the electrical structure of the deep upper mantle on the extended scale of whole Europe (Olsen 1998, Schmucker 2003, Semenov and Jóźwiak 2006). Considering and rendering reliable electrical transitions in the continental uppermost mantle, however, requires the period range of the electromagnetic soundings to be further extended towards shorter periods, and to involve the long period MT data in the analysis as well (Jones 1999).

Combined localized geomagnetic depth sounding (GDS) responses (e.g., Roberts 1984) and long period MT curves were used to analyze the electrical conductivity throughout the whole upper mantle by Egbert and Booker (1992) and Schultz *et al.* (1993). By the same approach, deep MT soundings from a 700 km long profile crossing the Trans-European Suture Zone (TESZ) along the seismic profile POLONAISE'97 (Guterch *et al.* 1999) have been interpreted jointly with GDS responses from the observatories Niemegek (NGK), Belsk (BEL), and Minsk (MNK), situated on different tectonic units. A high conductivity zone in the upper mantle beneath the TESZ has been revealed (Semenov and Jóźwiak 2005), with the total conductance distribution exactly fitting the high temperature anomaly beneath Central Poland obtained from the heat flow data (Majorowicz 2004). While the above deep mantle electrical investigations were mainly based on exploiting data from individual observatories, the CEMES project has been initiated for cooperative long period electromagnetic experiments on a broad regional scale. In what follows, we present the results of this project from the point of view of the electrical structure of the upper mantle across the TESZ in Central Europe.

## 2. MAGNETOTELLURIC MEASUREMENTS AND DATA PROCESSING

MT data have been collected directly at or in the immediate vicinity of the observatories that participated in CEMES. Positions of the sites are shown in Fig. 1 on the background of a structural scheme, and are labeled by their international codes. Unfortunately, not all of the observatories could operate in conditions fully adequate to the requirements of the project. Part of them was equipped with analog recording hardware only (KIV and ODE), and one station (MNK) was just testing a digital recording system. The observatory

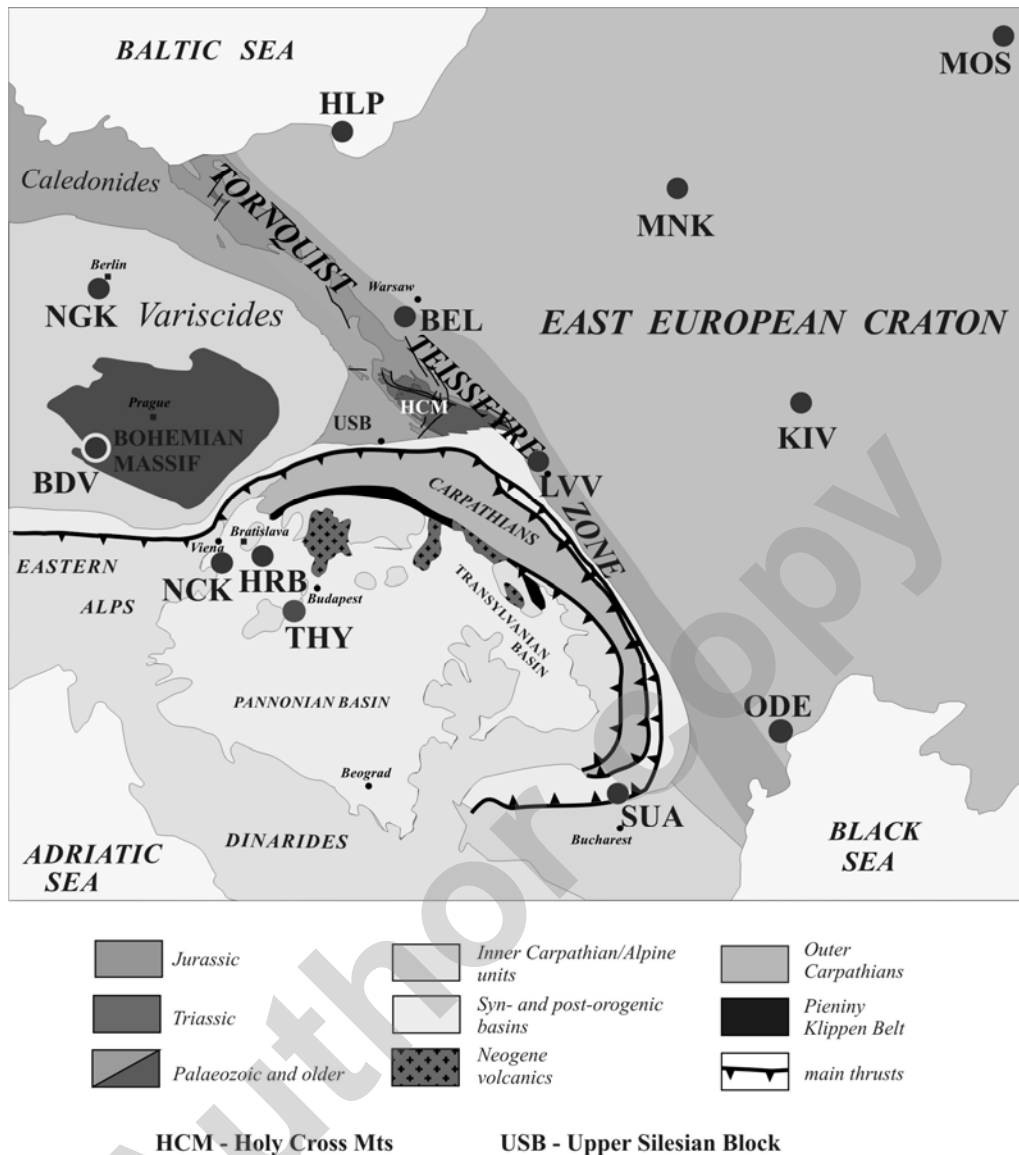


Fig. 1. The schematic tectonic map of the Central Europe region with locations of the geomagnetic observatories (marked by international codes) taking part in the CEMES project.

LVV acquired its digital equipment during the CEMES operation period, and it is now a member of the Intermagnet network. As to the MT part of the experiment, Polish MT equipment devised at the Belsk observatory (Jankowski *et al.* 1984) was operating at all the CEMES observatories except NGK. At some sites, the MT systems had to be set up out of the observatory place, mainly for reasons of excessive local artificial noise, known geoelectrical anomalies directly beneath the observatory, or other. Separated recording of the magnetic and telluric fields (MOS, LVV) may have resulted in a slight non-synchronicity of the time series within the one minute sampling interval assumed; however, this happens in the Intermagnet data, too.

The recorded MT time series of an average length of about three months were submitted by individual national teams as ASCII or binary files. The Belsk observatory (BEL) was used as a common reference site because it was the only observatory that provided continuous MT records for a period of two years, i.e., throughout the whole CEMES experiment. All data were collected, verified, converted to UT (Universal Time) and presented in a binary format on a CD, along with a detailed description of the measurement setup and conditions for each observatory. The data files on the CD supplemented with a visualization program are now available for free to the scientific community.

Data pre-processing included unification of the measurement directions, as the MT stations were set up according to the magnetic coordinates while the observatories have been recording either in geomagnetic or geographical coordinates. At some sites, the azimuths of the electrical dipoles had to be selected in general directions because of local conditions (BDV, MNK, BEL, MOS, NGK, and LVV). Polish electrodes used for the CEMES telluric measurements (Semenov *et al.* 2001), showed noticeable sensitivity to the daily temperature fluctuations of the ground at depths of about 0.8 m in the very hot summer of 2001, and, for this reason, the time-harmonics of the telluric daily variations had to be removed entirely from the data before the further processing.

In the initial phase of the data processing, MT impedances in the geographical coordinates were estimated separately by five national CEMES teams. Three different data processing routines were applied: Egbert and Booker's (1986) procedure by the Prague and Lviv groups, a spectral analysis procedure (Semenov and Kaikkonen 1986) in Bratislava and in Warsaw, and a time-domain processing routine (Nowożyński 2004) in Warsaw. The telluric data of the observatory BDV were too noisy to be processed. The resulting impedances were further converted to the tensor components of the complex apparent resistivity (see the Appendix). Figure 2 shows a comparison of the estimates of the complex apparent resistivities (eq. A2) obtained by different authors for the Belsk observatory. The geometric means for the modules and the appropriate arithmetic means for the phases with two standard deviations are also shown in this figure.

Further, polar diagrams for the apparent resistivities were constructed by applying the known formulas for the rotation of  $2 \times 2$  tensor elements. Then a complicated problem has arisen, how to merge the MT tensor and MV scalar apparent resistivities for the deep mantle soundings. Perhaps this problem may have ambiguous solutions in practice. We assumed that the mantle is laterally quasi-homogeneous as it is required by the corresponding impedance boundary condition IBC (see the Appendix). In this case any direction could be considered for merging the MT and MV data because the static dis-

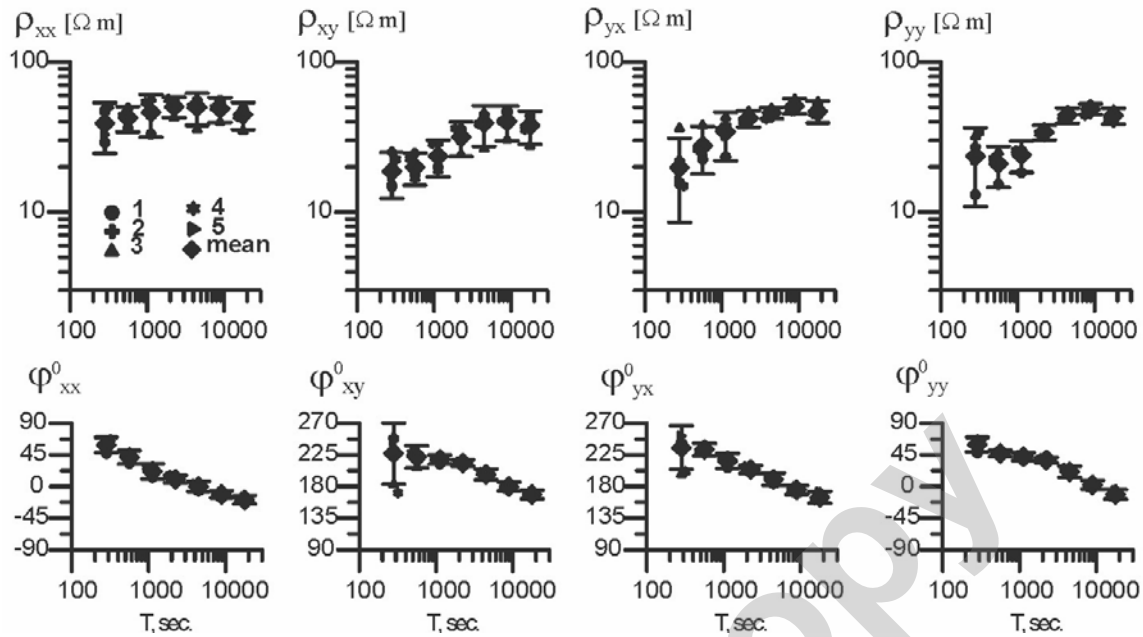


Fig. 2. An example of the complex apparent resistivities estimated by five different teams for the observatory Belsk and their average values with the 90% confidence limits.

tortions caused by the subsurface inhomogeneities only shift the 1D scalar impedance module but leave the impedance phase undistorted in any direction. Then we could invert (1D) the phases only and take into consideration the resistivity value estimated by the magnetovariation method (GDS) at longest periods. This approach has additional advantages: phases of the GDS method do not depend on co-latitudes (Anderssen *et al.* 1979). Additionally we can assume that the homogeneous mantle can be also weakly laterally anisotropic as it has been mentioned repeatedly in literature. Then we select for interpretation the preferential directions of the MT data taken from the MT polar diagrams and satisfying the condition of  $\min |Z_{xx} \cdot Z_{yy}|$ , i.e., for  $|Z_{xx}|$  and/or  $|Z_{yy}|$  close to zero. Comparison of the preferential directions with the Swift principal directions (Swift 1967) is shown in Fig. 3 for one specific impedance tensor. In this way we minimize the effect of small deviations of the true structure from a 1D distribution, can use the same common formula (A1) to convert MT tensor and MV scalar impedances to the apparent resistivities, and furthermore establish the simplest linear relation between two field components for both the MT and MV methods, with phases that in this case are free from bias.

However, two preferential MT directions are usually found and we are going to select the one which is the nearest to the extreme case, known as a TE-polarization of the 2D structure, most sensitive to the deep structure, (Berdichevsky and Dmitriev 2002). In a weakly 3D structure, such a direction is characterized by the maximal spatial dimension of the conductivity

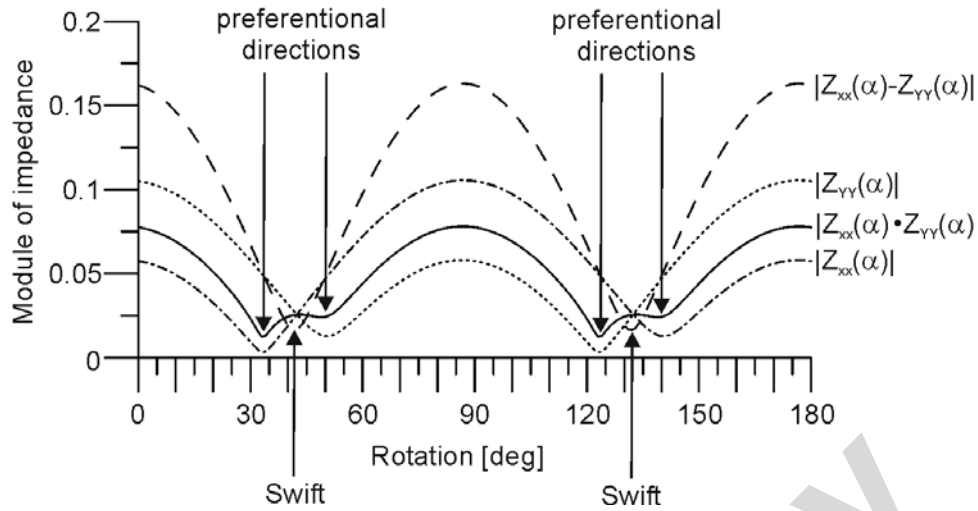


Fig 3. Selection of the preferential directions with requirement  $-\min |Z_{xx} \cdot Z_{yy}|$  to reduce the influence of the minor impedances on calculation of the apparent resistivities by conversion (A2) instead of (A1) in comparison with the Swift's procedure:  $\min |Z_{xx} - Z_{yy}|$ .

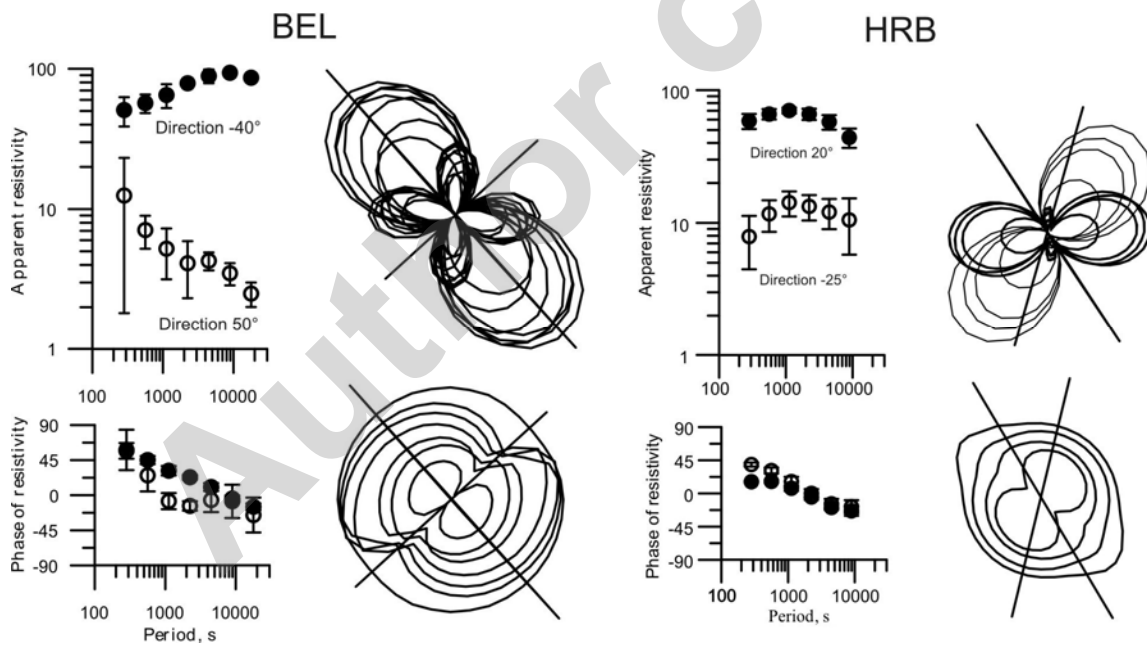


Fig. 4. Examples of the complex apparent resistivities (left columns) selected in the preferential directions on the background of the polar diagrams of their apparent resistivities (right columns), for two observatories: BEL and HRB.

variation in accordance with the IBC demand (see the Appendix). To establish such a direction we use the induction arrows showing a direction with the largest change of conductivity variations and another one which may be orthogonal to it. The use of another technique to select directions which are most sensitive to the deep structure and also appropriate for being merged

with the GDS impedances in a rational way is also possible and could be a subject of a future study.

So, in practice the MT and MV data were merged immediately for the impedances taken from the MT preferential direction (satisfying the condition of  $\rho_{xy}$  and/or  $\rho_{yx}$  being close to zero within the period range of 300 up to about 20,000 s) which is quasi-orthogonal to the induction arrows. If the azimuth of that direction was varying slightly within the period range considered, the value for the longest period was assumed for all shorter periods. Figure 4 shows examples of the selection of the preferential directions for two of the CEMES observatories.

We found those directions to be orthogonal for four observatories, specifically at BEL, KIV, MNK, and LVV. At other sites, these preferential directions were either non-orthogonal or only weakly expressed (SUA). The direction which was quasi orthogonal to the local induction arrow was chosen for further interpretation together with magnetovariation responses. The complex apparent resistivity curves at those directions were assumed as the MT sounding results of the CEMES project.

### 3. COMBINATION OF THE MT AND MV RESPONSES

The apparent resistivity curves of the deep electromagnetic soundings are characterized by a peak that marks a period for which the integrated induced currents in the sediments are the same as those in the mantle (Berdichevsky and Dmitriev 2002). Consequently, the most substantial portion of information about the mantle structures comes from the decreasing branch of the apparent resistivity curve. Reliable response estimates for the corresponding period range are associated with long period MT, and further mainly with the MV data. Here, we combine both the long period MT data (period range of 300 to 20,000 s) with the MV response functions obtained from geomagnetic observatory records for periods from the time harmonics of the daily oscillations up to a few years (Semenov and Jóźwiak 2006). This approach is not unambiguous within the accepted sounding theory, since the MT tensor and the MV scalar impedance are physically equivalent functions above laterally uniform structures only (Semenov *et al.* 2007).

We are going to jointly interpret three types of the impedance functions related to different excitation sources: (i) MT impedances due to the “plane wave” source field, rotated into the preferential directions, (ii) the MV scalar effective impedances for the daily oscillations (Olsen 1998), and (iii) the MV impedances directed along the geomagnetic parallels and associated with the ring current source (Fujii and Schultz 2002). Thus, for all the three impedance types, we will use in practice the same formula (A1) to compute the corresponding complex apparent resistivities. Fitting the impedances of



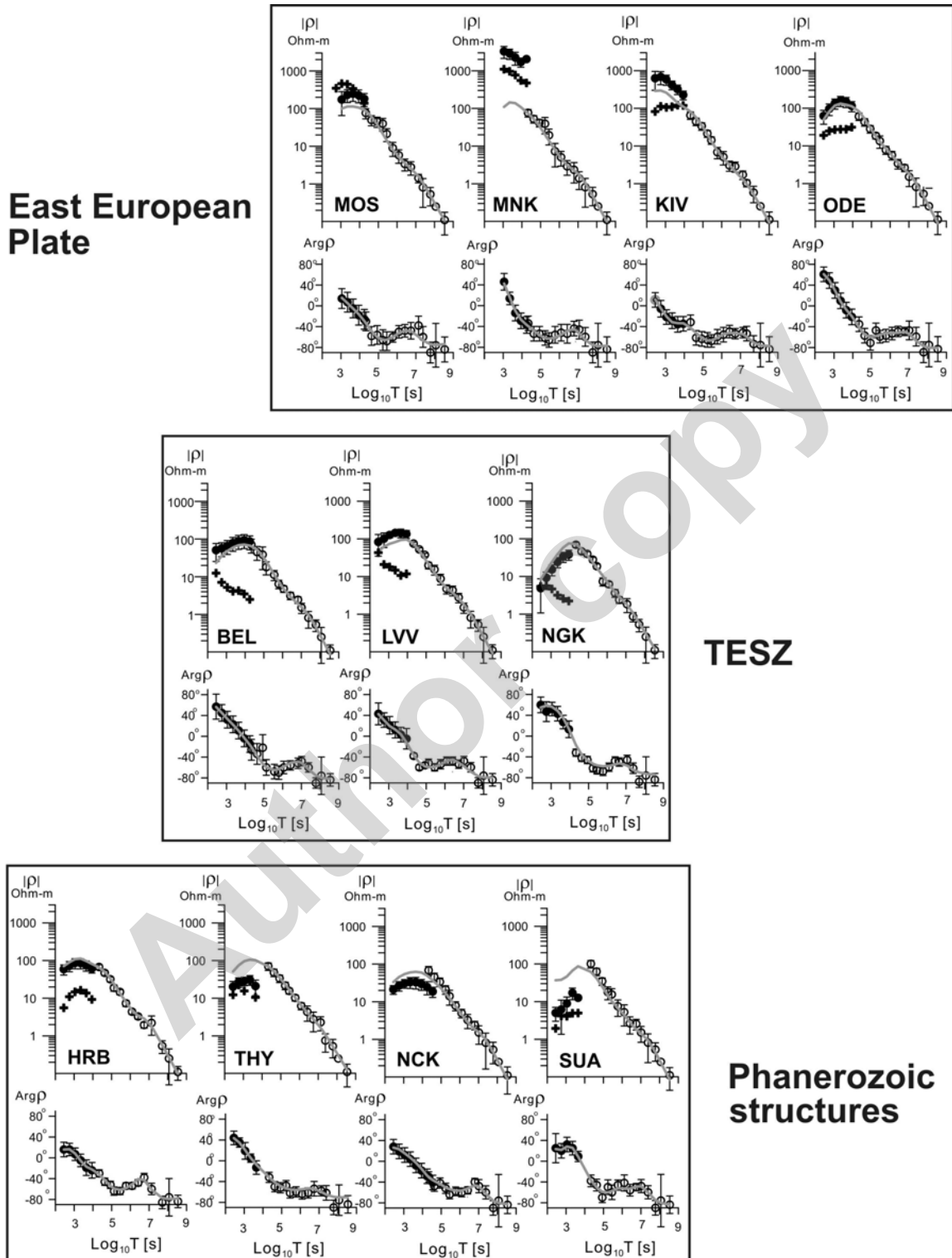


Fig. 5. Coupling of the quasi E-polarized (circles) and quasi H-polarized (crosses) complex MT apparent resistivities combined with the magnetovariation data and their coincidence with the 1D Occam inversion curves.

different origin in an arbitrary direction evidently gives rise to incompatible, discontinuous MT curves, so the selection of a justified MT direction as specified above is an essential part of the pre-modeling phase of our analysis. The link between the known MV observatory responses and the local MT curves in the preferential directions is shown in Fig. 5.

The joint MT and MV curves show a rather good link of the phases, whereas the modules of the apparent resistivities are evidently distorted by local shifts at the individual CEMES observatories which can be clearly seen in Fig. 5 where they are shown together with responses obtained by the 1D Occam inversion (Constable *et al.* 1987) with very high priority to the phase data. A remarkable feature of the data is a considerable split between two preferential directions in the MT apparent resistivities at three sites, specifically BEL, LVV, and NGK, all located within the TESZ. To verify this feature as a regional effect, additional long period MT measurements were carried out at two sites situated within the Pomeranian segment of the TESZ, roughly in the middle between the observatories BEL and NGK (Semenov *et al.* 2005). The corresponding MT apparent resistivities along and across the TESZ are shown in Fig. 6 with their D+ inversion (Parker and Whaler 1981) responses.

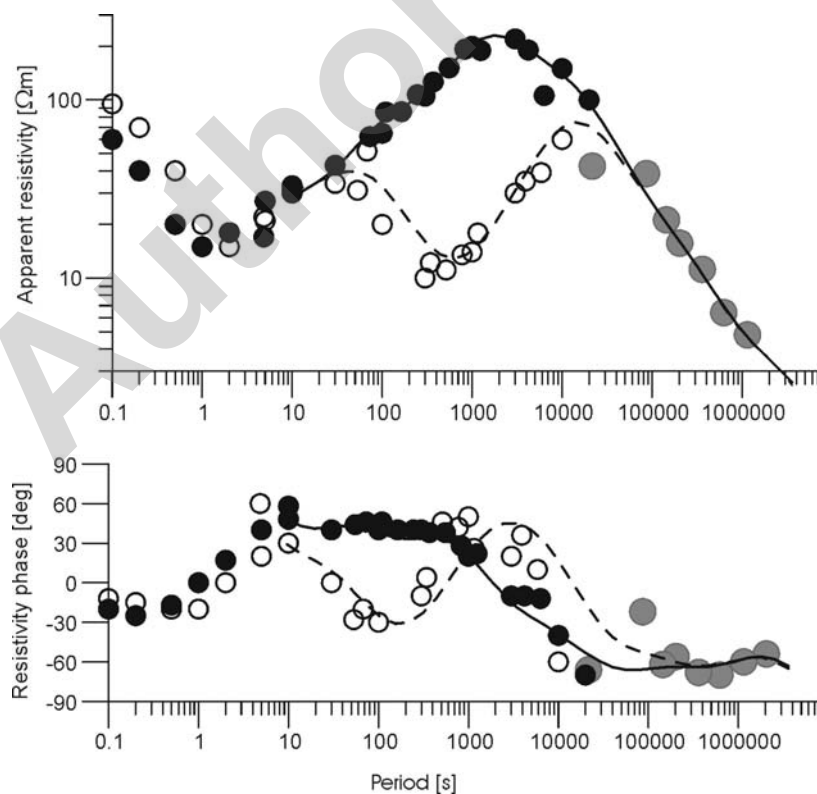


Fig. 6. Observed maximal divergence of both quasi E-polarized (black circles) and quasi H-polarized (empty circles) of the MT data jointed with the MV observatory responses (gray) obtained in the TESZ between BEL and NGK (zone of the low induction arrays) and their fitting by the D+ inversion (Semenov *et al.* 2005).

It can be seen that the parallel and transversal MT curves have completely different shapes in the period range of 20 to 20,000 s, but they converge together for periods longer than 20,000 s. Generally, this effect is in agreement with the sounding results at BEL, LVV, and NGK and consequently can be considered as a regional feature of the particular sector of the TESZ. Below, we present results of a schematic forward spherical modeling that attempted to relate the specific course of the above MT curves to the extensive regional conductive sedimentary basin overlying the TESZ.

We start with an analysis of the near-surface total conductance of the uppermost 400 km of the upper mantle which is about 2-10 kS (Semenov and Jóźwiak 2006). These values are commensurate with those of the continental sedimentary basins. Consequently, electromagnetic soundings into the upper mantle depths can be distorted heavily by the distribution of the near surface conductance. To quantitatively consider effects of the sediments on the CEMES data, we have used published data from Fainberg *et al.* (1998), Ingerov *et al.* (1987), Jóźwiak and Ernst (2005), Korja *et al.* (2002), Logvinov (2002), Nemesi (2000), Sheinkman *et al.* (2003), Tregubenko *et al.* (1989), as well as private communications from members of the CEMES Experimental Team, and collected estimates of the surface conductance obtained by the experimental MT soundings all over the CEMES region. All the regional estimates have been averaged onto a  $1^\circ \times 1^\circ$  mesh, agreed by the CEMES Experimental Team, and merged with older continental data and new conductance estimates from the oceans (Vozar *et al.* 2006).

To estimate the effect of the surface conductance on the regional apparent resistivities, we constructed a spherical model of the Earth covered by a non-uniform surface shell with the conductance adopted from the surface conductance map, updated as described above. The deep layered part of the model consisted of the crust, the upper and lower mantle, and the metallic core, with geometrical and electrical parameters given in (Vozar *et al.* 2006). This model was excited by two mutually orthogonal ionospheric sources, simulating the plane wave excitation, and one source of the magnetospheric excitation simulating the ring current. The electromagnetic fields on the Earth's surface were then computed numerically by the algorithm by Kuvshinov *et al.* (2005) for this model. From the modeled field components, we determined the MT complex apparent resistivities (eq. A2) for both the longitude and latitude directions and the GDS resistivities (eq. A1) for the longitude directions only, taking into account the specific source field configuration (Schultz and Larsen 1983). Results of the simulated MT responses for all the eleven CEMES observatories within the period range up to 2 days were extended by simulated GDS curves for these observatories for longer periods, up to 2 years. Then, by using the polar diagrams of the MT apparent resistivities, we found the MT preferential directions as those cor-

responding to the minimum minor resistivities. The local directions were identified with the MT azimuths approximately perpendicular to the local induction arrows, similarly as earlier for the experimental data. The MT data obtained in this way are presented in Fig. 7.

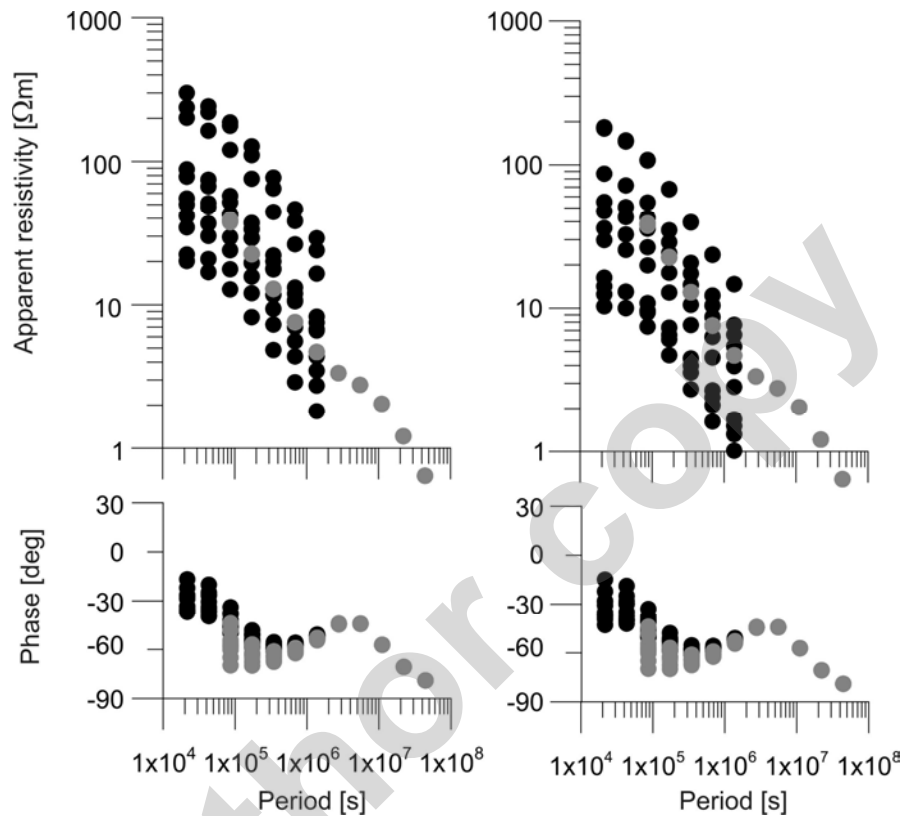


Fig. 7. The effects of the subsurface inhomogeneities in the CEMES region estimated by the forward spherical modeling for both quasi E- (left) and quasi H-modes (right) for the MT preferential directions (black points) extended by the GDS responses (gray points) for all observatories of the CEMES region.

The model results clearly show a strong ‘shift effect’ in the MT responses, with a scatter in the apparent resistivity modules extending over one decade up and down with respect to the module of the quasi undistorted resistivity obtained from the GDS. However, the phase data from the MT on the one hand, and from the GDS on the other, fit quite well, and the degree of their scatter is not prohibitive for the application of an inverse procedure to the data. By rotating all the MT impedances into their respective preferential directions, the scatter of the complex MT apparent resistivities decreases considerably, about two times in the modules. Thus, a smooth fit of the MT and GDS phases can justify joining the experimental MT and GDS data sets. In a joint inversion, however, the phase data have to be given high priority so that we suppress the distorting effect of the shifted resistivity modules on the inversion results as much as possible. It is worth mentioning that the

phase fit can be missed if only real and imaginary parts of the  $C$  responses are considered.

Besides, the above modeling results have also evidenced that the split of the apparent resistivity curves observed at the observatories situated within the TESZ could not be explained by the regional quasi layered sedimentary structures alone. Both modes had the same forms of amplitudes and phases in the modeling results while the experimental responses are completely different there (see Figs. 5 and 6). The source of this highly anomalous effect is most likely situated in the crust, as suggested, e.g., by Červ *et al.* (2005) and maybe even deeper (Semenov and Jóźwiak 2005, Pushkarev *et al.* 2007).

#### 4. INVERSION OF THE COMBINED MT AND MV DATA SETS

The combined sets of the MT and observatory MV responses were inverted for local 1D conductivity distributions beneath each observatory, with largely increased weights given to the phase data. The data were inverted independently by five CEMES teams: in Kiev, Moscow, Warsaw and Prague using their preferred inversion algorithms: the standard Occam inversion (Constable *et al.* 1987) extended by Weidelt's (1972) transformation for the spherical Earth, the stochastic spherical method (Jóźwiak 2001) and the Monte-Carlo method (Grandis *et al.* 1999). The piecewise continuous spherical structures were obtained by regularized inversion (Pushkarev *et al.* 1999), the examples of which for all CEMES observatories are shown in Fig. 8.

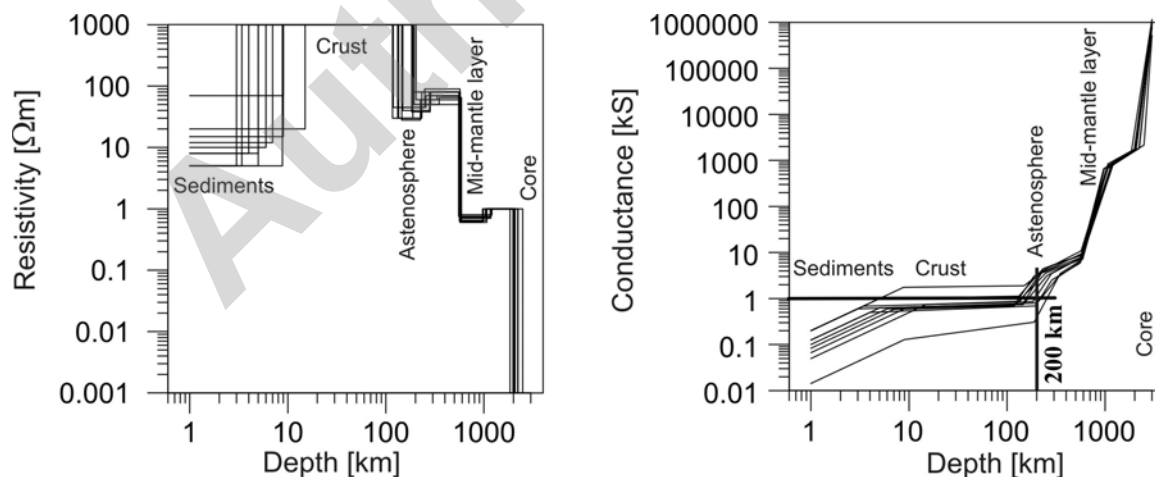


Fig. 8. The 1D inversion results obtained by the individual team in Moscow for all CEMES observatories subdividing the structure to the several shown layers.

The model included the following differentiation: sediments, the crust, a layer with high conductivity in the upper mantle (asthenosphere), the global mid-mantle conductive layer, and the core. This figure demonstrates the possible differences in the resistivities and conductance beneath the Central Europe region.

Though the uncertainties of the inversion results of the individual teams were smaller than the uncertainty of the results obtained by different groups, we believe to have removed possible systematic bias due to individual processing routines by the averaging step. Besides, in order to avoid unstable details of structures, we further consider the total conductance as a function of depth to study the mantle. Such a consideration provides more stable result than those for its derivative, the conductivity, which varies largely under the same conductance distribution (Berdichevsky and Dmitriev 2002). As an example we show in Fig. 9 a comparison of the total conductance and conductivity distributions beneath the BEL observatory obtained by the different inversion routines.

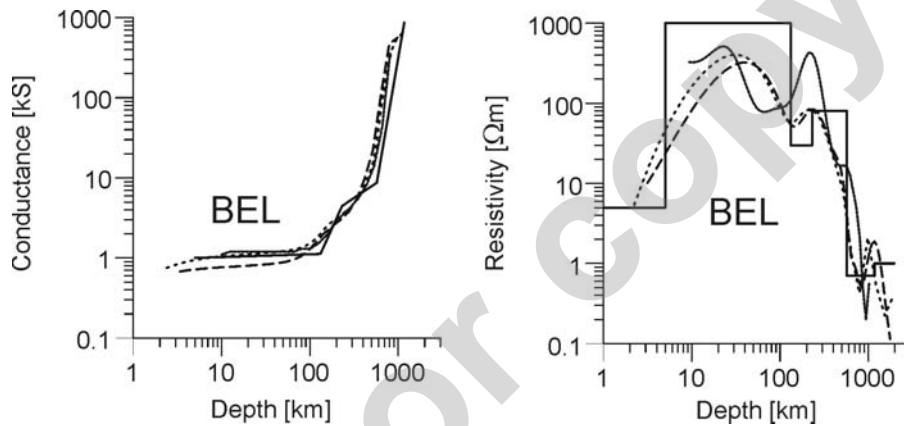


Fig. 9. Uncertainties obtained by different groups inverting the same responses for the observatory BEL by the 1D spherical inversions presented as the total conductance (left) and the resistivity (right) values.

The total 50-km conductance beneath each observatory was estimated from the 1D inversion results of the MT responses only. Their estimates provided by the individual teams as well as the mean values (with the mean median absolute deviation (MAD) being  $\pm 15\%$ ) are presented in Table 1 for all observatories.

Table 1

Subsurface (0-50 km) conductance (in kS)

Codes of stations:	MNK	BEL	LVV	KIV	MOS	ODE	SUA	THY	HRB	NCK	NGK
Kiev	0.13	1.20	0.90	0.20	0.70	1.20	1.02	0.70	1.00	0.29	1.38
Moscow	0.65	1.05	0.67	0.17	0.55	0.73	0.63	0.64	0.78	0.64	1.80
Prague	0.88	0.95	0.63	0.17	0.29	0.97	0.63	0.70	0.70	0.63	1.13
Warsaw-1	0.66	0.88	0.65	0.19	0.55	0.64	0.77	0.44	0.49	0.60	1.85
Warsaw-2	0.91	1.21	0.84	0.27	0.75	0.87	0.92	0.87	0.69	0.68	1.52
Mean:	0.65	1.06	0.74	0.20	0.57	0.88	0.79	0.67	0.73	0.57	1.54

The mean subsurface conductance was subtracted from the total conductance reconstructed beneath each observatory at all depths. The residual total conductance obtained after this reduction is characteristic of the upper mantle alone, and its spatial variations reflect the fine structure of the upper mantle at depths of 50-200 km (see Table 2). The mean MAD is  $\pm 22\%$  for values in Table 2.

Table 2

Upper (50-200 km) mantle conductance (in kS)

Codes of stations:	MNK	BEL	LVV	KIV	MOS	ODE	SUA	THY	HRB	NCK	NGK
Kiev	0.04	1.63	1.45	0.72	1.00	0.53	1.35	0.67	1.53	1.75	1.08
Moscow	0.15	2.35	2.06	0.36	0.26	0.58	2.62	1.30	2.25	1.87	1.37
Prague	0.16	0.98	1.12	0.66	0.74	1.02	0.67	0.77	1.50	1.18	0.65
Warsaw-1	0.19	1.85	1.05	0.78	0.12	0.19	1.73	2.29	1.22	1.37	0.63
Warsaw-2	0.07	1.94	1.51	1.01	0.93	0.63	1.00	1.06	1.12	1.58	1.17
Mean:	0.12	1.75	1.44	0.71	0.61	0.59	1.47	1.22	1.52	1.55	0.98

In Fig. 10a, we present an image of the total mantle conductance up to a depth of 200-km, which was obtained by averaging all groups of the inversion results provided by the individual contributors. This schematic image is completely different from the conductance distribution of the near-surface inhomogeneities across the CEMES region (Vozar *et al.* 2006). It rather clearly indicates a boundary separating two different tectonic plates in Central Europe and well coincides with the surface trace of the TESZ.

Table 3

Depth (in km) until 1 kS of the mantle conductance

Codes of stations:	MNK	BEL	LVV	KIV	MOS	ODE	SUA	THY	HRB	NCK	NGK
Kiev	282	167	165	222	200	236	95	226	173	121	170
Moscow	254	160	170	232	237	216	145	187	162	161	185
Prague	315	203	188	232	234	201	268	225	150	178	267
Warsaw-1	262	136	195	211	265	231	134	148	179	172	231
Warsaw-2	330	142	164	200	208	222	199	174	192	149	154
Mean:	289	162	176	219	229	221	168	192	171	156	201

Finally, another 3D image has been constructed, showing the depth down to 1 kS of the total mantle conductance with the mean MAD of about  $\pm 10\%$

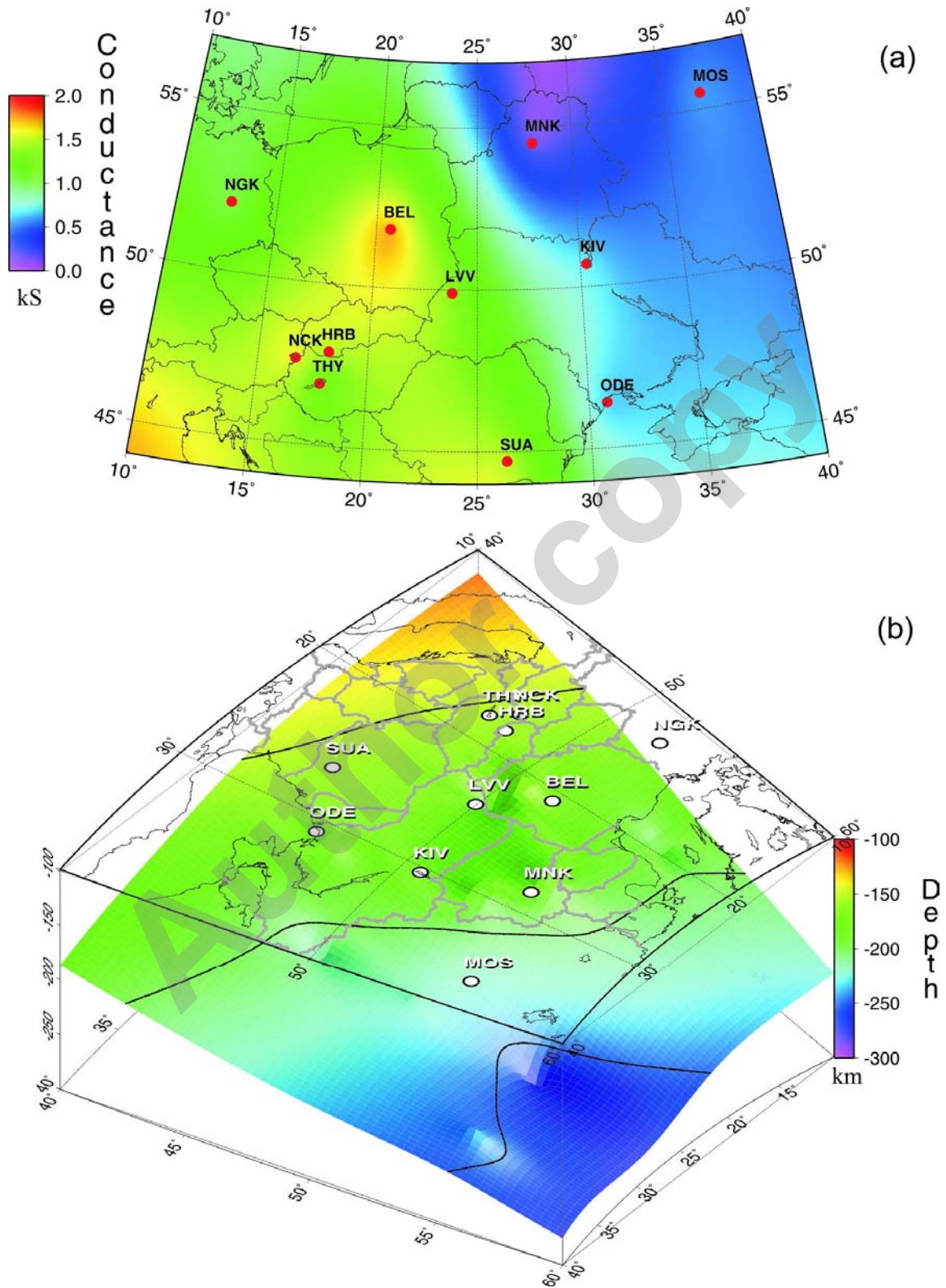


Fig. 10. The schematic map of the mantle conductance from 50-km to 200-km depth beneath the Central Europe region (a) and the image of trend of depths where the upper mantle conductance (without sediments and crust) reaches 1 kS (b).



(Table 3 and Fig. 10b). The 1 kS conductance level was selected to keep the investigations within the so-called ‘asthenosphere depths’, where a conductive layer can possibly exist between the bottom of the crust and a depth of 410 km (the latter depth marking the well-known phase transition zone within the upper mantle) (Zharkov 1983).

The transition zone matching the boundary between two European plates appears as a smoothly varying surface traversing between depths of 150 to 300 km, that is in general agreement with the other geophysical data discussed below.

## 5. CONCLUSIONS AND DISCUSSION

Electromagnetic soundings of the Earth’s upper mantle require the MT and MV response functions to be combined in a wide period range, from minutes up to months, or even more. The essential difficulty of merging two basically different data sets, specifically the MT tensor data with the scalar MV impedances, has been dealt with by numerically simulating the electromagnetic fields with the particular distribution of the near-surface non-uniform conductance equal to that estimated for the region under study by Vozar *et al.* (2006). The numerical results have justified the possibility of interpreting the joined MT and MV data sets provided the MT data are considered in a preferential direction, quasi orthogonal to the local induction arrow. In general, those types of impedance functions and apparent resistivities can be not the same for laterally non-uniform conductors (Semenov *et al.* 2007). There is a good reason to believe that a new formulation of the impedance boundary condition (Schmucker 2003, Shuman and Kulik 2002) could help in overcoming this problem in the future.

In order to reliably resolve variations in the upper mantle structures, we have to apply a high precision treatment to the data analysis and to the response functions on the decreasing branches of the apparent resistivity curves over distances longer than the depths of the soundings. To achieve this, we have (i) attributed high priority (weights) to the phase data in the 1D inversions of the combined data responses, (ii) expressed the inversion results through the total conductance in the mantle, as this approach guarantees more stable results than those for the conductivity sections and (iii) removed from the conductance distributions their estimated subsurface values, which may be of a comparable magnitude with respect to the investigated total conductance of the upper mantle beneath the crust down to depths of about 300-400 km.

From the numerical simulation results, the excessive split between two MT curves in the preferential directions observed at four sites along a 1000 km long segment of the TESZ between the western Ukraine and east-

ern Germany could not be explained only by the presence of sedimentary basins with a quasi layered structure. This typical feature of the regional MT data may suggest an essential crustal anomaly within this zone (Červ *et al.* 2005, Pushkarev *et al.* 2007, Ernst *et al.* 2008), or even an anomalous upper mantle beneath the TESZ (Semenov and Jóźwiak 2005). The conductive zones within the complex lithospheric structures (Grad *et al.* 2002) are in relation to those detected by seismic method within the international projects POLONAISE'97 (Guterch *et al.* 1999) and 'CELEBRATION 2000' (Guterch *et al.* 2001). A reasonable hypothesis about the nature of the crustal electrical anomalies in the region has been suggested by Hvozďara and Vozar (2004), namely, that these are zones of active contemporary metamorphism.

The regional-scale experimental results of the CEMES project have allowed us to estimate electrical structure of the mantle beneath Central Europe. As a principal feature of the upper mantle, two zones with different conductance have been detected at depths of 50 to 250 km. These zones are in a close agreement with the two European tectonic plates – the East European Craton and the Phanerozoic plate of west Europe, and comply well with their geothermal conditions (for the heat flow values of the plates) and their relation to the depth of the asthenosphere (Ádám 1978). The upper mantle beneath the EEC appears to be more resistive than that beneath the Phanerozoic plate. The existence of a conductive layer could be associated with an asthenosphere, the top of which would be situated about twice as deep beneath the old EEC than beneath the younger Phanerozoic plate. Such a structure would be in good agreement with the results of the BEAR project carried out at the neighboring territory of the EEC (Sokolova *et al.* 2007) and with the 3D density model recently obtained on the Polish territory (Swieczak *et al.* 2007). A similar gradient of the thickness of the seismically defined “tectosphere” has been reconsidered recently between the young oceanic (60-80 km) and old continental (200-250 km) areas. This observed discontinuity “may be associated with the bottom of the lithosphere, marking a transition to flow-induced asthenospheric anisotropy” (Gung *et al.* 2003). Though the interpretation of the deep conductivity distribution beneath the region of Central Europe may still be ambiguous, the regional electrical structure reported here indicates that the TESZ can be traced in the upper mantle, down to depths of first hundreds of km, similarly as has been shown by the seismic tomography (Zielhuis and Nolet 1994). Moreover, the increased seismic velocities in the upper mantle beneath the East European Craton correspond to a more resistive domain in the geomagnetic sounding results. This fact is in agreement with the empirical observation that rocks are characterized by the increased seismic velocities and electrical resistivities simultaneously (Vanyan 1997).

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## APPENDIX

### APPROACHES TO THE APPARENT RESISTIVITY CALCULATION

The experimental estimations of impedances in the magnetotelluric soundings are based on the impedance boundary conditions (IBCs) first obtained in a mathematically rigorous way for homogeneous media in the 1940s. These IBCs derived for the boundary between resistive (air) and conductive (earth) media are in the form of infinite power series relating the Fourier amplitudes and their spatial derivatives of the time-harmonic field components through impedances. They are valid also for a weakly homogeneous medium whose spatial characteristic dimensions of conductivity variations are larger than the field wavelength (e.g., Leontovich 1948), which is about 3,000–15,000 km in the Earth for the period range of hours – year mainly used for the mantle soundings. The IBCs approximate forms (assuming a tangential field source and the induced field constant along the surface, i.e.,

the “plane wave model”) serve the purpose of determining the impedances, independent of the temporal variations of the source power during recordings of the field components. Thus, while estimating impedances in the above period range we have to assume that the mantle medium is quasi-homogeneous.

The original IBCs were generalized and expressed in a vector form by Senior and Volakis (1995),

$$\mathbf{E}_\tau \approx Z_{\parallel}(\omega) \cdot (\mathbf{H}_\tau \times \mathbf{n}).$$

Here  $\mathbf{n}$  is a unit vector normal to the interface,  $Z_{\parallel}(\omega)$  is the impedance matrix,  $\mathbf{E}_\tau$  and  $\mathbf{H}_\tau$  are the electric and magnetic tangential fields, respectively. This IBC is known as Leontovich’ approximate IBC which is commonly used to estimate MT impedances from the observed data. In the special case of a uniform conducting half-space, the scalar impedance relates to the true resistivity by:

$$\rho = Z(\omega)^2 / i\omega\mu_0. \quad (\text{A1})$$

Thus, for a uniform homogeneous and isotropic medium the true resistivity can be found immediately. If a layered medium is considered,  $\rho(\omega)$  is a complex, frequency dependent value, termed the apparent resistivity in the soundings. We follow this rule and consider amplitude  $\rho(\omega)$  and phase  $\varphi(\omega)$  of the complex apparent resistivity value instead of the apparent resistivity module and phase of impedance. The argument of the complex apparent resistivity is equal to twice the negative impedance phase plus  $\pi/4$  (for the time-harmonic factor  $\exp(-i\omega t)$  considered).

The true components of the resistivity tensor can be also found immediately from the impedance matrix  $Z_{\parallel}(\omega)$  for a uniform half-space with a homogeneous, azimuthally anisotropic medium. This transformation has been derived first by Reilly (see in Weckmann *et al.* 2003) and, later, by substituting the Leontovich’ IBC directly into the Maxwell equations by Semenov (2000). The obtained expressions are as follows:

$$\begin{aligned} \rho_{xx} &= (Z_{xy}^2 - Z_{xx} \cdot Z_{yy}) / i\omega\mu_0, & \rho_{xy} &= Z_{xx} (Z_{yx} - Z_{xy}) / i\omega\mu_0, \\ \rho_{yy} &= (Z_{yx}^2 - Z_{xx} \cdot Z_{yy}) / i\omega\mu_0, & \rho_{yx} &= Z_{yy} (Z_{xy} - Z_{yx}) / i\omega\mu_0. \end{aligned} \quad (\text{A2})$$

While the scalar impedance  $Z(\omega)$  is connected with the true real resistivity above a uniform isotropic halfspace, the impedance matrix  $Z_{\parallel}(\omega)$  is connected with the true real resistivity tensor above a uniform horizontally anisotropic halfspace. If a layered medium is considered, these resistivities are complex and frequency dependent, and they can be considered as generalized apparent resistivities. Notice that the diagonal elements of the resistivi-

ty tensor (2) are given by only the off-diagonal elements of the impedance matrix if any of the minor impedances is zero, i.e.,  $Z_{xx} \cdot Z_{yy} = 0$ . Such directions are termed “preferential directions” here.

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