Magnetotelluric Approximations for the Asthenospheric Depth Beneath the Békés Graben, Hungary

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The paper describes the apparent changes of the depth of the conducting asthenosphere caused by different EM field distortions beneath the 7 km deep narrow 3-D Békés graben (extensional basin) along the Pannonian Geotraverse. The real depth of the asthenosphere is approximated first by 1-D inversion and 2-D modelling techniques to show their value in case of 3-D structure. Then, 3-D thin sheet model computations—together with references to the previous theoretical modelling results—are used to select sites and curve orientation where the least distorted depth estimation is expected along a 2-D profile in case of 3-D structure. Of course, preliminary geological-tectonical information (e.g. basin contour) is needed to find the most probable asthenospheric depth.

1. Introduction

The Pannonian Geotraverse crosses very different geological formations and structures in Eastern Hungary. Among these formations there are resistive Miocene volcanites on the surface in the north, a flysch belt with strike slip zone in its central part and a narrow extensional graben (the Békés graben) covered by approximately 7 km thick sediments in the south.

Along the Geotraverse deep magnetotelluric (MT) and seismic soundings and traditional gravity, magnetic, geothermal, etc. measurements have been carried out.

In this paper, attention has been paid to the very special, 7 km deep sedimentary basin, the so called Békés graben, where due to the near-surface geological formations and tectonic structures, strong EM field distortions make the deep MT interpretation difficult.

After describing the observed electromagnetic field distortions, 1-D, 2-D and 3-D numerical modeling approximations are made in order to estimate the depth of the high-conductivity asthenosphere beneath the Békés graben. 3-D thin sheet model computations are especially useful in selecting sites and curve orientations where the least distorted depth estimation is expected.

2. Distortions Observed in the Measured MT Data

In the Békés region seven deep MT soundings were carried out by the Geodetic and Geophysical Research Institute (Fig. 1).

As the conductance inside the basin reaches 1300 siemens, there is no hope to determine the conducting layer in the lower crust, whose conductance is only some hundreds of siemens; hence, the asthenosphere is indicated by the decreasing branches of the resistivity curves (Ádám et al., 1990). The distribution of the apparent depth values (h) of the conducting asthenosphere and their relation to the observed horizontal electric conductance values of the surface sediments (S1) are as follows (see Fig. 2):

- h reaches its highest values if the $\theta_{\text{max}}$ direction varies vs. period (MT sites 1 and 4);
Fig. 1. The southern part of the Pannonian Geotraverse crossing the isopach map of the Békés graben with MT sites, showing their $\varphi_{\text{max}}$ direction. The map has been constructed on the basis of boreholes and seismic reflection profiling (HORVÁTH and ROYDEN, 1981). Thickness isolines are given in kms. The upper inset shows the position of the Békés graben in Eastern Hungary.

Fig. 2. Apparent asthenospheric depth values ($h$) vs. horizontal electric conductance ($S_1$) of the basin sediments in the Békés graben.
The fitted model (layer sequence)
Thickness ($h$): 0.1 3.4 150 km
Resistivity ($\rho$): 0.5 3.0 20.0 200 $\Omega$ m

VIM $1-1, T$

(a)

The fitted model (layer sequence)
Thickness ($h$): 0.15 and 70 km
Resistivity ($\rho$): 1.5 6.5 220 0 $\Omega$ m

(b)

Fig. 3. Extreme resistivity and impedance phase curves are shown at MT site 7 with their layer models obtained by joint 1-D inversion.
*The static shift most clearly appears in the \( h_{\text{q,max}} \) values of MT sites 2, 3, 5 and 6, where the sediment thickness continuously increases with site number;*

*The \( q_{\text{max}} \) curve of site 7 lies in the strike direction according to isopach map shown in Fig. 1, therefore it is a quasi-E polarization curve. \( h_{\text{q,max}} \) value derived from it represents an outlier to the \( h-S_1 \) diagram of sites 2, 3, 5 and 6;*

*The \( h_{\text{q,min}} \) values are much lower than the \( h_{\text{q,max}} \) values. At the rim of the Békés graben (sites 1, 2 and 3) another linear relation appears between \( h_{\text{q,min}} \) and \( S_1 \);*

*In sites 5 and 6, i.e. in the graben area, \( h_{\text{q,min}} \) values stabilize around 30-40 km;*

*In sites 4 and 7 \( h_{\text{q,min}} \) is only about 20 km!*

The most different \( q_{\text{min}} \) and \( q_{\text{max}} \) curves of MT site 7 are shown in Fig. 3 with their 1-D model. It is questionable how much the apparent depth to the asthenosphere is influenced by this 3-D sedimentary basin structure, and what is the most realistic asthenospheric depth beneath this region.

### 3. Conclusions from the Previous 3-D Modelling Results

In case of 2-D or 3-D basin structures—in agreement with what was found in the Békés region—the apparent asthenospheric depth is significantly distorted by the static shift or S-effect (BERDICHEVSKY and DMITRIEV, 1976).

1. With 2-D structures a relation (similar to the empirical one shown in Fig. 2) between the depth to the conductive layer (\( h \)) and the conductance of the surface sediment (\( S_1 \)) only characterizes the H polarized resistivity curves;

2. In case of 3-D structures such \( h-S_1 \) relations may appear in the parameters derived from both extreme resistivity curves \( q_{\text{max}} \) and \( q_{\text{min}} \). This effect depends both on the position of the measuring site over the 3-D structure, and on the elongation of the 3-D structure (see P. Kaikkonen’s model calculations for different elongated conducting prisms, personal communication, 1987).

![MTS curves over a 3-D elliptical inclusion model](image)

*Fig. 4. MTS curves over a 3-D elliptical inclusion model (\( a/b = 2, \sigma_1^2/\sigma_2^2 = 16; h_2/h_1 = 20; g_1^e \) and \( g_2^e \) are local 1-D sounding curves). The upper (a) part refers to the inclusion centre (site A), while the lower (b) part refers to site B, lying outside the inclusion (\( x/b = 0, |y| = 1.5 \cdot b \)) (after BERDICHEVSKY and DMITRIEV, 1976).*
According to 3-D model calculations by Berdichevskiy and Dmitriev (1976) (Fig. 4) and those by Wannamaker et al. (1984), the resistivity curves over the graben area, i.e. over the “conducting inclusion” give lower depth values to the deep $\sigma_3 = \infty$ layer (the asthenosphere). This peculiarity is expressed in field sites 3, 5 and 6, but most clearly by the $h$ value at site 6 lying over the almost deepest part of the graben.

According to the model calculations the $\varrho_{\text{max}}$ curves lie approximately in the direction of the long axis ($x$) of the elliptical inclusion (the basin). It is worth noting that in the Békés region the static shift appears most definitely on these $\varrho_{\text{max}}$ curves.

According to Fig. 4b (after Berdichevskiy and Dmitriev, 1976) and Wannamaker et al.’s (1984) sounding curves calculated for B, C and D sites (see Figs. 19, 20 and 21 in Wannamaker et al., 1984), outside the conducting inclusion the resistivity values measured perpendicular to the long axis ($x$, i.e. $\varrho_{xy}$) of the basin are much greater than the $\varrho_{yx}$ values and approximate quite well the apparent resistivities of the layer structure. This important aspect will be studied in more details in our 3-D modelling (see Figs. 10 and 11). Unfortunately, for the Békés graben the situation is more complicated, probably due to influence of the foreland structure and so the isopach lines are irregularly curved.

Site 7 lies over the steep eastern wall of the graben. The $\varrho_{\text{min}}$ curve here gives the shallowest depth to the conducting layer (18.5 km) in the dip direction, most probably as a consequence of the distortion caused by the current restriction of the wall (wall effect or edge effect).

4. Asthenosphere Depth Approximations

4.1 1st approximation: averaging

Outside the 3-D inclusion Berdichevskiy and Dmitriev (1976) proposed to use and average impedance defined as $1/2 (Z_{xy} - Z_{yx})$. The closer the elliptical inclusion is to a circle ($a/b = 1$), the more realistic is the impedance value obtained by this kind of averaging.

Another approximation is the geometric mean ($h_{\text{av}}$) of the $h_{\varrho_{\text{max}}}$ and $h_{\varrho_{\text{min}}}$ values, similar to the $h_{\text{eff}}$ value, i.e. $h_{\text{av}} = \sqrt{h_{\varrho_{\text{max}}}h_{\varrho_{\text{min}}}$. These values are shown in Fig. 2 and given in Table 1. Except for the extreme values in site 1, the scatter of these $h_{\text{av}}$ is much smaller and their average ($h_{\text{av}} = 58$ km) approximates both the magnetotelluric and the seismic asthenospheric depths in other parts of the Pannonian basin of high heat flow (Ádám et al., 1989) and beneath the Rumanian side of the Hungarian-Rumanian border (Enescu, 1987).

Nevertheless, this depth seems to be underestimated. From the great EM distortions—appearing mainly in the extremely low $\varrho_{\text{min}}$ values—we came to the conclusions that below the Békés graben the depth to the asthenosphere should be greater than the average asthenospheric depth in the Pannonian basin. The following 2-D modelling also hints at the plausibility of this supposition.

4.2 2nd approximation: 2-D numerical modelling

The Eötvös Loránd Geophysical Institute/Budapest made MT soundings between our MT sites 1–7 with much shorter intervals (Varga and Ránér, 1990). As the measured periods were not long enough, their 1-D MT inversion for the asthenosphere was only based on the phase curves. From this inversion (carried out for the quasi H polarized sounding curves) a 2-D model was constructed and E- and H-polarized model curves were calculated (see Fig. 5). It has to be remarked that the measured phase curves ($\varphi_{\varrho_{\text{max}}}$), being certainly less distorted by static shift in this 3-D case, give practically the same asthenospheric depth as the E polarization model curves. The depth values derived from the H polarization and $\varrho_{\text{min}}$ curves strongly differ from each other, hinting obviously at the 3-D character of the structure.
Table 1. Relation between the horizontal electric conductance values (computed from the sediment thickness and mean resistivity values) and the estimated asthenospheric depths.

<table>
<thead>
<tr>
<th>Site number</th>
<th>Sediments thickness [km]</th>
<th>Mean sediment resistivity [Ωm]</th>
<th>$S_1$ (from $\rho_{\text{max}}$) [siemens]</th>
<th>Estimated depth to the asthenosphere $[\text{km}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.5</td>
<td>6.2</td>
<td>564</td>
<td>56.0 176 99</td>
</tr>
<tr>
<td>2</td>
<td>3.5</td>
<td>5.2</td>
<td>673</td>
<td>46.0 106 70</td>
</tr>
<tr>
<td>3</td>
<td>4.5</td>
<td>5.5</td>
<td>818</td>
<td>31.0 89 53</td>
</tr>
<tr>
<td>4</td>
<td>5.0</td>
<td>6.3</td>
<td>793</td>
<td>19.6 136 52</td>
</tr>
<tr>
<td>5</td>
<td>6.0</td>
<td>5.5</td>
<td>1083</td>
<td>36.5 76 53</td>
</tr>
<tr>
<td>6</td>
<td>6.5</td>
<td>5</td>
<td>1300</td>
<td>31.0 58 42</td>
</tr>
<tr>
<td>7</td>
<td>8.1</td>
<td>4.9</td>
<td>1330</td>
<td>18.5 78 38</td>
</tr>
</tbody>
</table>

Fig. 5. A 2-D model of the Békés graben and asthenospheric depth values, calculated from the measured and numerically modelled MT sounding curves (VARGA and RÁNER, 1990). This profile starts from site 1 (52) and ends at site 7 (75) in Fig. 1.
4.3 3rd approximation: 3-D thin sheet modelling

The Békés graben has been modelled using the 3-D thin sheet modelling program developed by Tarits (personal communication, 1990). In the thin sheet algorithms resistivity values are allowed to vary only in a thin sheet. Therefore in our calculation all resistivity changes in the Békés region are concentrated into a 0.4 km thick thin sheet, lying at 4 km depth. Resistivity values in an 8 x 8 array (each block had a 2 km x 2 km lateral extent) were in such a way that thin sheet and field conductances at any given site were the same (Fig. 6). Besides this limitation all other geometric and electromagnetic parameters were set to the known field values.

The five electromagnetic field components were determined for a larger area, in a 20 x 20 array (with side length of 2 km) having in its center the Békés model. Computations were carried out not only on the surface, but also at different depth levels:
- at 2 km ("half") depth
- at 3 km ("three-quarter") depth
- at 3.5 km ("7/8") depth.

The aim of this thin sheet study was to answer:
- what the main characteristic EM field distortions around this 3-D structure are, and
- how and where the apparent resistivities best approximate the true 1-D resistivities.

4.3.1 EM field distortions

Figures 7 and 8 show \(\rho_{xy}\) and \(\rho_{yx}\) resistivity maps of two perpendicular polarizations, Fig. 9 shows their unified map for four different depth levels. The isolines at the four depth levels (especially at great depths) reflect the distribution of electric charges, accumulated at resistivity interfaces in H polarization case.

Over the 3-D Békés model, these two different resistivity distributions (\(\rho_{xy}\) and \(\rho_{yx}\)) are much more similar to each other than the resistivity distributions over any regularly shaped and elongated model. This remarkable phenomenon explains the appearance of S effect on apparent resistivity curves having arbitrary orientation in Fig. 2, and the concentration of the isolines indicate the edges of the 3-D structure.

4.3.2 Distortions of the depth to the asthenosphere due to the basin structure

At first we compared the behaviour of the computed sounding curves to those by Berdichevsky and Dmitriev (1976) and to those by Wannamaker et al. (1984). From Fig. 10—here in the case of a simplified rectangular model—the same conclusion can be drawn as from Berdichevsky and Dmitriev's figure (Fig. 4b): along both perpendicular profile the quasi H polarization curves yield the best approximations for the resistivity of the 1-D model in the close vicinity of the edges.
Fig. 7. $\rho_{xy}$ resistivity maps over the 3-D thin sheet model of the Békés graben at four different depth levels at a period $T = 225$ s ($x$ and $y$ in km). The Békés model occupies a 16 km $\times$ 16 km area (8 $\times$ 8 array) in the centre of a 40 km $\times$ 40 km area (20 $\times$ 20 array) shown in this figure.
Fig. 8. $\varphi_{yx}$ resistivity maps over the 3-D thin sheet model of the Békés graben at four different depth levels at $T = 225$ s ($x$ and $y$ in km).
Fig. 9. A simple unification of $\varphi_{xy}$ and $\varphi_{yx}$ resistivity maps (Figs. 7 and 8) follows the shape of the Békés graben.
Fig. 10. $\rho_{xy}$ and $\rho_{yx}$ resistivity profiles over a rectangular thin sheet model (one of the simplified versions of the Békés graben) at a period $T = 225$ s. The plane view of the model is shown in the figure. The model resistivity is 0.4 $\Omega$m. The other parameters of the vertical cross section are the same as shown in Fig. 6. $\rho_{1-D}$ corresponds to the apparent resistivity of the 1-D model outside the graben model. a) The profile lies along the $y$ (the model's major) axis, b) the profile lies along the $x$ (the model's minor) axis.
The asthenospheric depth approximated by an 1-D inversion of the 3-D thin sheet model curves ($\varphi_{xy}$ and $\varphi_{yx}$) shows similar behaviour as the apparent depth values derived or the ones observed in the field from the measured curves although the thin sheet distortions are smaller than the observed ones. At points 6 and 7 inside the 3-D structure, there is an apparent rise of the asthenosphere, i.e. a decrease of its depth, and at the border of the structure (near point 5) the calculated asthenospheric depth best approximates the real one, as shown by a comparison of Fig. 2 and Fig. 11.

5. Conclusion

In this paper, the apparent depth of the conducting asthenosphere beneath the 3-D Békés graben has been approximated with different 1-D, 2-D and 3-D techniques. We have concluded from these and previous studies that the best approximation for the asthenospheric depth in these complicated 3-D structures is obtained by the quasi H polarized sounding curves measured at the border of the 3-D structures. Their border can be delineated by the current concentration caused by electric charges at resistivity interfaces, and by the $H_z$ (vertical magnetic component) or induction vector anomalies as shown by the 3-D thin sheet modelling.

The 3-D thin sheet model distortions are smaller than those observed in the field. This indicates that some parts of the field distortions come from unknown features of the graben.

According to these facts, the asthenospheric depth beneath the Békés graben is about 76 km determined by $\varphi_{max}$ curves at MT site 5, in agreement with depth values derived from the phase curves by VARGA and RÁNER (1990) (see 2-D approximation).

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REFERENCES


