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Are the crustal and mantle conductive zones isotropic or anisotropic ?

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Abstract

One of the significant problems of modern magnetotellurics is the recognition of anisotropy in the crustal and mantle conductive zones. In the paper we perform numerical experiment comparing several 2D models of crustal and mantle prismatic conductors and examine conditions under which the magnetotelluric and magnetovariational response functions distinguish between isotropy and anisotropy. The resolution of MT and MV studies depends on the sediments conductance, lithosphere resistance and deep conductor width. Calculations show that the most favorable conditions for anisotropy studies are observed in the active regions characterized by small sediments conductance and moderate lithosphere resistance. However, in the stable regions, where sediments conductance exceeds 50-100 S and the lithosphere resistance comes up to 10^9 Ohm·m, the crustal and mantle anisotropic and isotropic conductors manifest themselves in the equivalent magnetotelluric and magnetovariational functions, which cannot distinguish between anisotropy and isotropy and admit both the interpretations.

Key words: magnetotellurics, anisotropy, Earth's crust, lithosphere, asthenospere, mantle.

1. INTRODUCTION

Figure 1 shows generalized resistivity-depth profiles for stable (SR) and active (AR) regions, compiled from geothermal and geoelectric data as well as from laboratory measurements (Vanyan 1997). In stable regions, the resistivity decreases monotonically from 10^4-10^5 Ohm·m near the Earth's surface to 10 Ohm·m at depths of the order of 400 km. This global resistivity decay is conditioned by the gradual warming-up

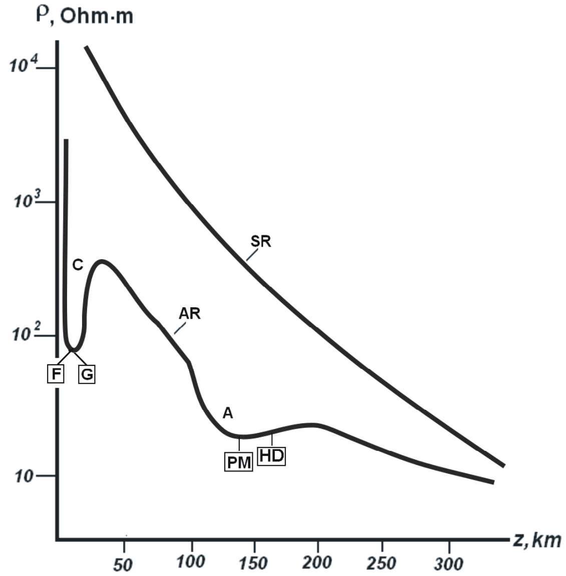

Fig. 1. Geoelectric resistivity–depth profiles in a tectonically stable and a tectonically active region (after Vanyan 1977). SR – stable ("cold") region, AR – active ("hot") region, C – zone of decreased resistivity in the crust, F – fluidization, ρ = 10-250 Ohm·m, G – graphitization, ρ = 0.5-250 Ohm·m, A – asthenonspheric zone of decreased resistivity, PM – partial melting, HD – hydrogen diffusity, ρ = 10-50 Ohm·m.

of the Earth's interior and its phase changes. The total resistance of the lithosphere is about 10^9 Ohm·m^2 in stable regions and 3×10^8 Ohm·m^2 in active regions (Kuvshinov 2004). Two local minima of resistivity can be recognized against this background in active regions: one in the crust (C), and the other in the upper mantle (A). The resistivity minimum in the Earth's crust is explained by the fluidization (ρ = 10-250 Ohm·m) or the graphitization (ρ = 0.1-100 Ohm·m) of crystalline rocks. The resistivity minimum in the upper mantle is caused by asthenospheric partial melting and hydrogen diffusity (ρ = 10-50 Ohm·m). Studying the deep conductive anomalies, C and A, we can obtain unique information on the fluid regime, petrophysics, reology, thermodynamics and geodynamics of the Earth's interior.

One of the significant problems of modern magnetotellurics is the recognition of anisotropy in the crustal and mantle conductive zones (Bahr and Duba 2000, Bahr and Simpson 2002). The difficulty is that the isotropic and anisotropic deep conductors located in or under a highly resistive medium may manifest themselves in the equivalent magnetotelluric and magnetovariational response functions, which cannot distinguish between isotropy and anisotropy and admit both the interpretations.

It is generally agreed that a stable difference between the principal values of the impedance tensors observed over a large area with 2D indications counts in favor of anisotropy. Is such an evidence reliable?

In our paper we would like to examine several 2D models of crustal and mantle prismatic conductors and estimate their width at which the equivalency between isotropic and anisotropic conductors is the case.

2. CRUSTAL CONDUCTIVE ZONES

Figure 2 presents the layered models ICC (isotropic crustal conductor) and ACC-I (anisotpopic crustal conductor). They simulate the conductive sediments and the resistive lithosphere underlaid with the conductive mantle. In the Earth's crust, at a depth of 20-35 km, the model ICC contains the isotropic conductor in the form of the two-dimensional homogeneous prism of a resistivity of 10 Ohm·m and width of 44 km. In the model ACC-I we have the same prism composed of alternating vertical dikes of resistivities of 5 and 1000 Ohm·m. The prism can be considered as an anisotropic (macroanisotropic) crustal conductor with the diagonal resistivity tensor

$$\left[\boldsymbol{\rho}_{\text{ACC-I}}\right] = \begin{bmatrix} \rho_{xx} & 0 & 0 \\ 0 & \rho_{yy} & 0 \\ 0 & 0 & \rho_{zz} \end{bmatrix}.$$

From Kirchhoff's laws, we have: $\rho_{xx} \approx 10$ Ohm·m, $\rho_{yy} \approx 500$ Ohm·m, and $\rho_{zz} \approx$ 10 Ohm·m. The apparent resistivity and tipper curves have been computed for different distances from the model midpoint ($y = 0, -22, -80$ km). The calculations performed by the finite-elements method (Wannamaker *et al.* 1986) show that the apparent-resistivity and tipper curves generated in the models ICC and ACC-I are so close to each other that it would be impossible to distinguish between them.

A similar equivalence is observed in Fig. 3. We have here the same model ICC with the isotropic crustal conductor in the form of the two-dimensional prism of resistivity of 10 Ohm·m and the model ACC-II with the prism composed of alternating horizontal layers of resistivities of 5 and 1000 Ohm·m. The prism can be considered as an anisotropic (macroanisotropic) conductor with the diagonal resistivity tensor

$$\left[\boldsymbol{\rho}_{\text{ACC-II}}\right] = \begin{bmatrix} \rho_{xx} & 0 & 0 \\ 0 & \rho_{yy} & 0 \\ 0 & 0 & \rho_{zz} \end{bmatrix}.$$

From Kirchhoff's laws, we have: $\rho_{xx} \approx 10$ Ohm·m, $\rho_{yy} \approx 10$ Ohm·m, and $\rho_{zz} \approx$ 500 Ohm·m. The apparent-resistivity and tipper curves computed for different distances from the model midpoint ($y = 0, -22, -80$ km) are also closely related to each other and cannot distinguish between isotropy and anisotropy.

The isotropy–anisotropy equivalence has a simple physical interpretation. The TE-mode is associated with longitudinal currents. It provides the anisotropic-isotropic equivalence since these currents penetrate into the anisotropic and isotropic conduc-

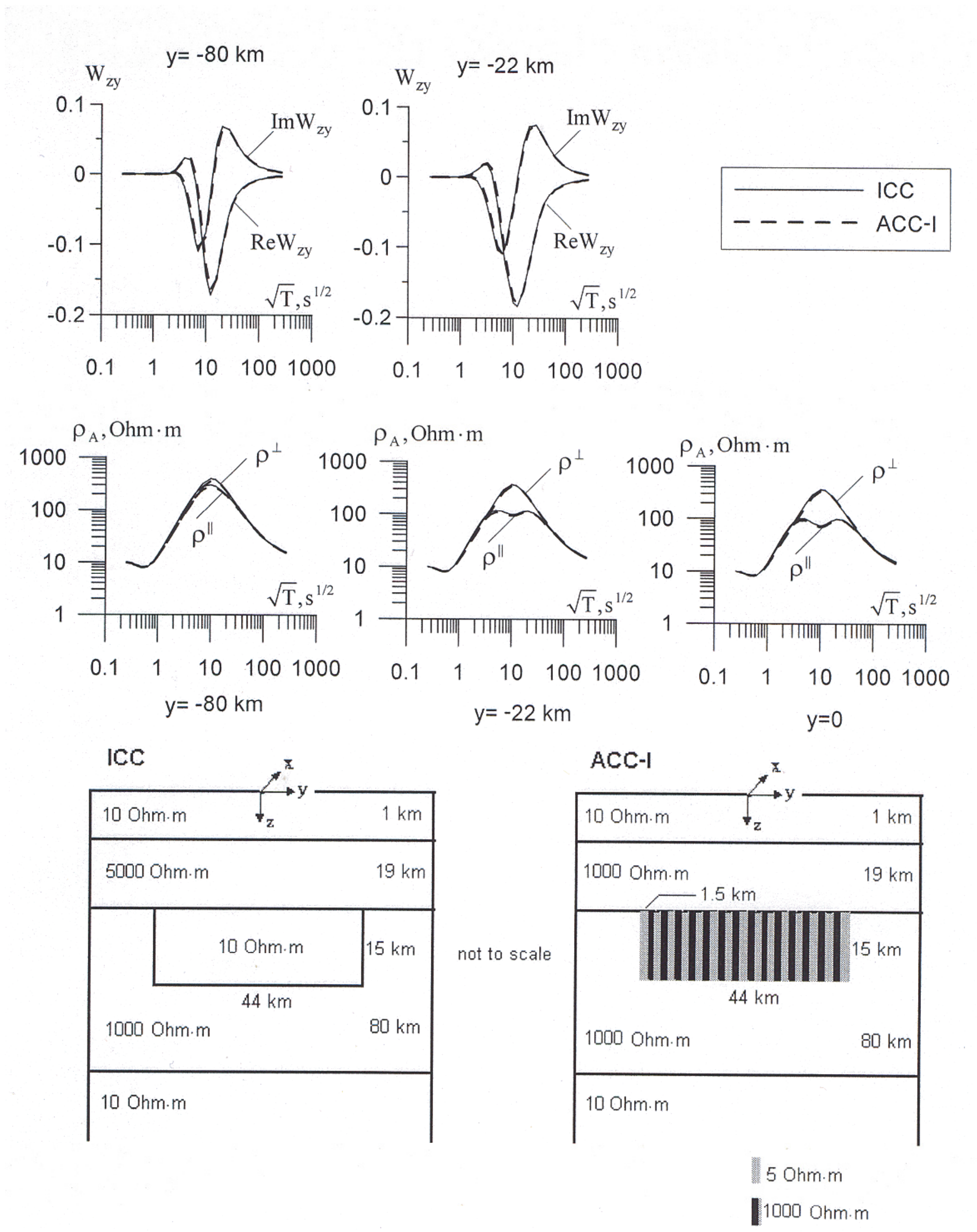

Fig. 2. Two-dimensional models of the crustal conductor. The model ICC contains an isotropic crustal conductor, the model ACC-I contains an anisotropic crustal conductor with alternating vertical layers of higher and lower resistivity.

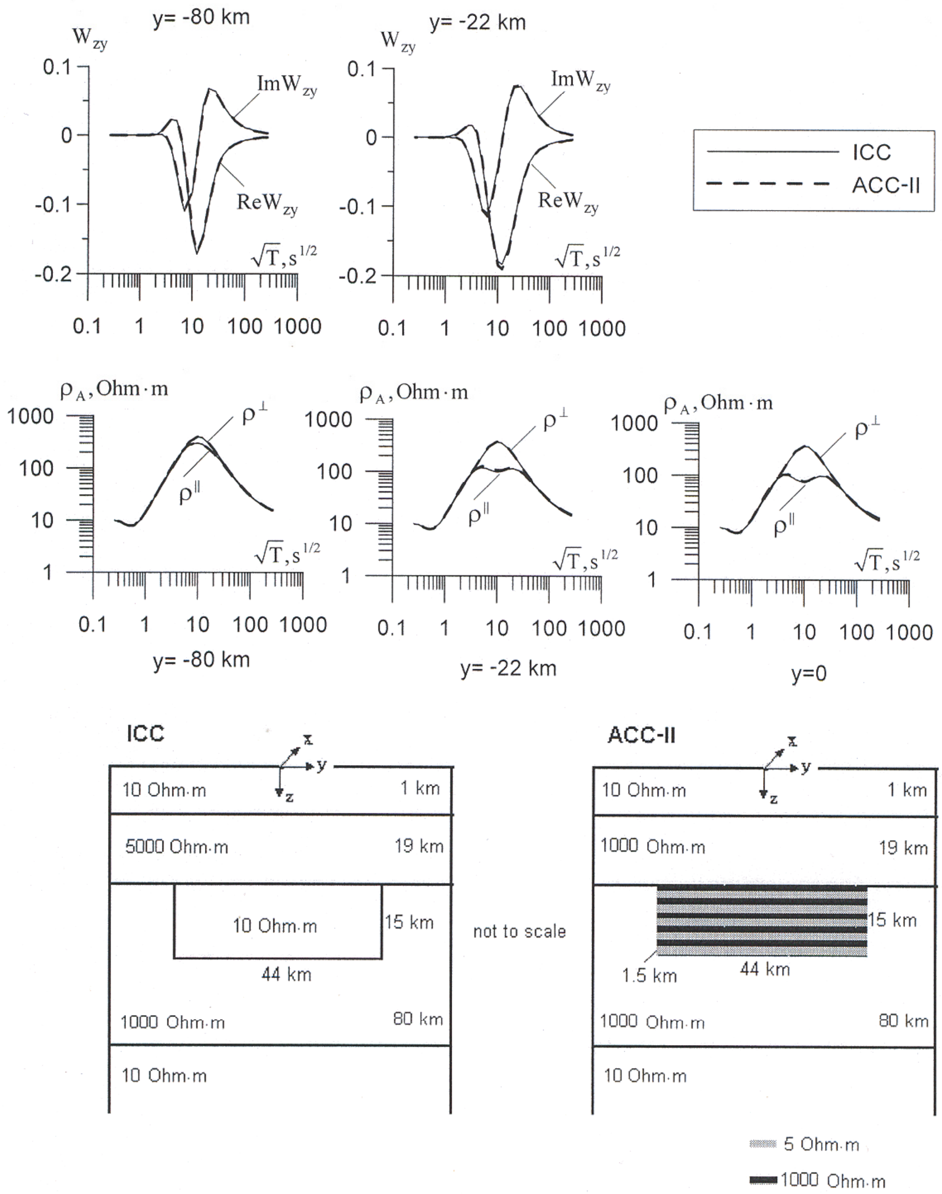

Fig. 3. Two-dimensional models of the crustal conductor. The model ICC contains an isotropic crustal conductor, the model ACC-II contains an anisotropic crustal conductor with alternating horizontal layers of higher and lower resistivity.

tors in a similar way and their integral effect is almost the same. The TM-mode reflects the behavior of the transverse currents, which may penetrate into the anisotropic and isotropic conductors in a different way and hence may detect the difference between anisotropy and isotropy. But the TM-mode can be subjected to galvanic screening and its informativeness depends on the screening-effect intensity. We suggest a straightforward rough criterion for the anisotropy-isotropy equivalence: the deep isotropic and anisotropic conductors are equivalent provided that $w < 2d$, where w is the width of the conductor and $d = \sqrt{SR}$ is the adjustment distance determined by the sedimentary conductance S and resistance R of strata separating the deep conductor from the sediments. In the equivalent models ICC, as well as ACC-I and ACC-II, from Figs. 2 and 3, we have $d = 43.6$–97.5 km and $w = 44$ km. Here $w \ll 2d$. Widening the crustal conductor or decreasing the resistance of the overlying layer, we arrive at models with transverse apparent-resistivity curves which distinguish between the isotropy and anisotropy. In models with a moderate resistance of the upper crust, say $R \approx 10^7$ Ohm·m^2, typical for active regions, the difference between the isotropic and anisotropic crustal conductors, 100-150 km wide, may be seen. Under these conditions, the studies of anisotropic crustal conductors make undoubted practical sense.

3. MANTLE CONDUCTIVE ZONES

In studying the upper mantle, we may face the same anisotropy-isotropy equivalence. Asthenospheric conductive zones located under the highly resistive lithosphere can manifest themselves in the equivalent response functions, which do not distinguish between isotropy and anisotropy and admit both the interpretations.

Let us consider two examples concerning the asthenosphere uplift.

Figure 4 shows the two-dimensional models IAU-I (isotropic asthenosphere uplift) and AAU-I (anisotropic asthenosphere uplift). The model IAU-I contains the isotropic asthenosphere uplift of a resistivity of 9.1 Ohm·m, width of 200 km and amplitude of 50 km. In the model AAU-I we have the same uplift composed of alternating vertical layers of resistivities of 5 and 50 Ohm·m. The uplift can be considered as an anisotropic conductor with the diagonal resistivity tensor

$$\left[\boldsymbol{\rho}_{\text{AAU-I}}\right] = \begin{bmatrix} \rho_{xx} & 0 & 0 \\ 0 & \rho_{yy} & 0 \\ 0 & 0 & \rho_{zz} \end{bmatrix}.$$

From Kirchhoff's laws, we have: $\rho_{xx} \approx 9.1$ Ohm·m, $\rho_{yy} \approx 27.5$ Ohm·m, and $\rho_{zz} \approx 9.1$ Ohm·m. The calculations performed by the finite-elements method (Wannamaker *et al.* 1986) show that the apparent-resistivity and tipper curves obtained in the models IAU-I and AAU-I are close to each other. The models demonstrate the anisotropy-isotropy equivalence.

Next consider Fig. 5, which presents the two-dimensional models IA-I (isotropic asthenolith) and AA-I (anisotropic asthenolith) with the lithosphere resistance of 1.5×10^9 Ohm·m^2. The model IA-I contains the deep-seated extended isotropic asthenolith of resistivity of 18.2 Ohm·m, width of 500 km and amplitude of 100 km. In the model AA-I we have the same asthenolith composed of alternating vertical layers of resistivities of 10 and 100 Ohm·m. Here

$$[\boldsymbol{\rho}_{\text{AA-I}}] = \begin{bmatrix} \rho_{xx} & 0 & 0 \\ 0 & \rho_{yy} & 0 \\ 0 & 0 & \rho_{zz} \end{bmatrix},$$

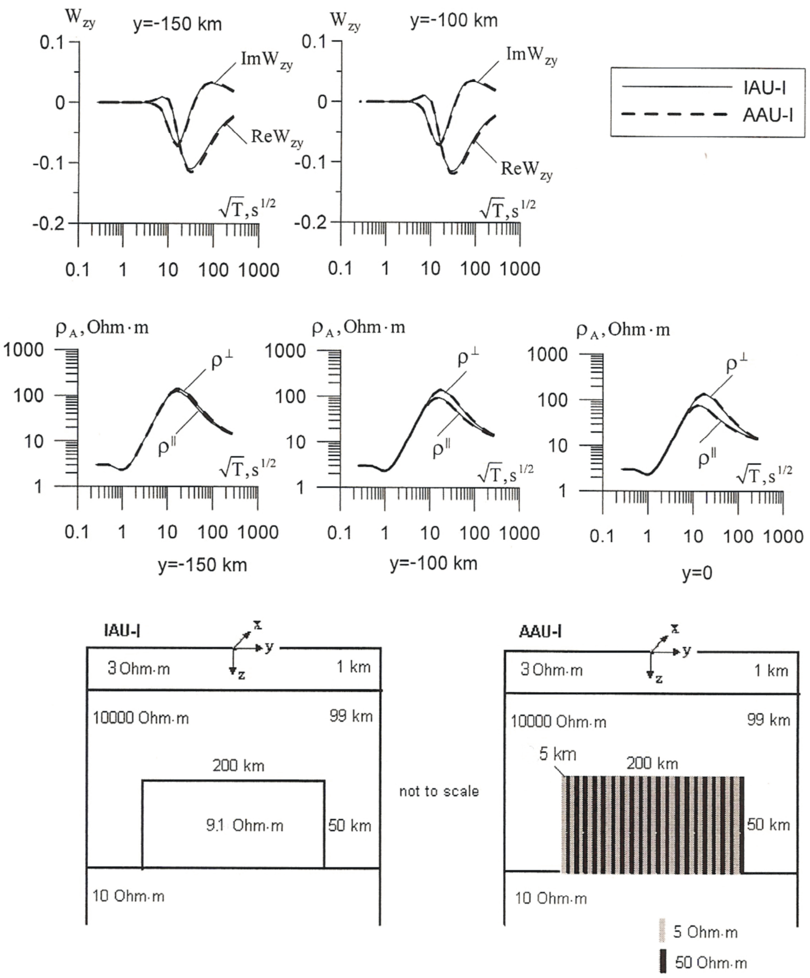

Fig. 4. Two-dimensional models of the asthenosphere uplift. The model IAU-I contains an isotropic asthenosphere uplift, the model AAU-I contains an anisotropic asthenosphere uplift with alternating vertical layers of higher and lower resistivity.

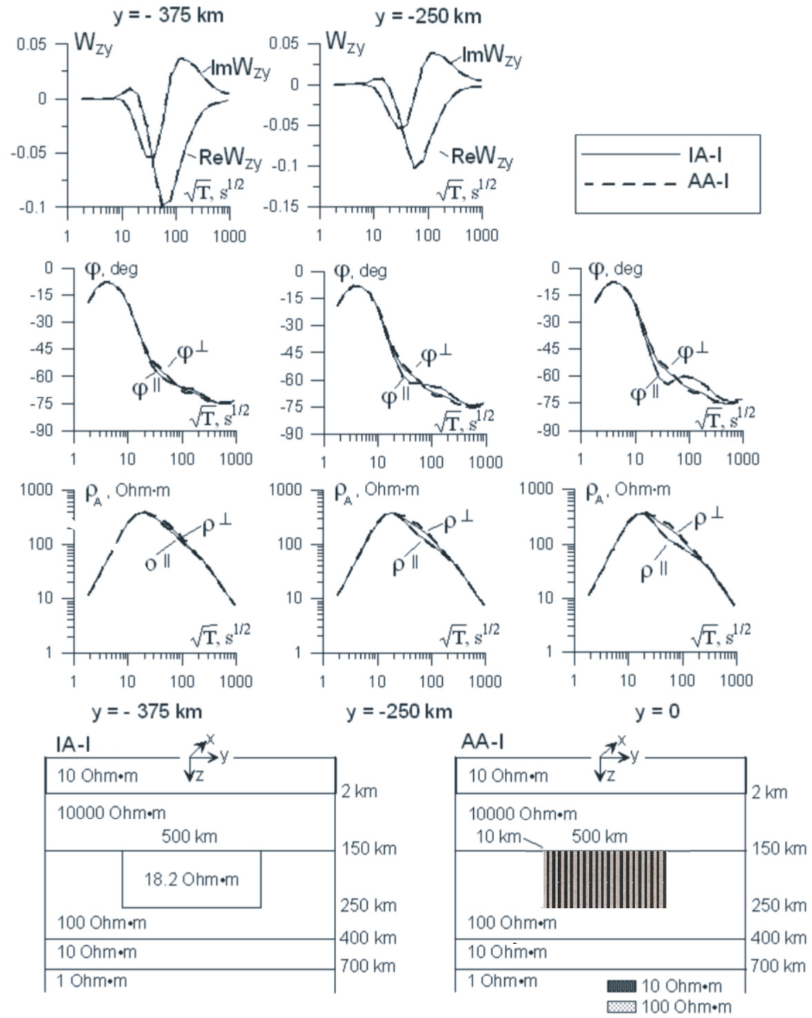

Fig. 5. Two-dimensional models of the asthenolith. The model IA-I contains an isotropic asthenolith, the model AA-I contains an anisotropic asthenolith with alternating vertical layers of higher and lower resistivity. The lithosphere resistance is 1.5×10^9 Ohm·m^2.

where $\rho_{xx} \approx 18.2$ Ohm·m, $\rho_{yy} \approx 55$ Ohm·m, and $\rho_{zz} \approx 18.2$ Ohm·m. We see that the apparent-resistivity and tipper curves obtained in the models IA-I and AA-I are close to each other (anisotropy–isotropy equivalence). But with decreasing lithosphere resistance, the equivalence between isotropy and anisotropy in the asthenolith disappears. Figure 6 shows the models IA-II and AA-II with the lithosphere resistance of 1.5×10^8 Ohm·m^2. Here the transverse apparent resistivity and impedance-phase curves obtained over the asthenoliths ($y = 0$) differ from each other.

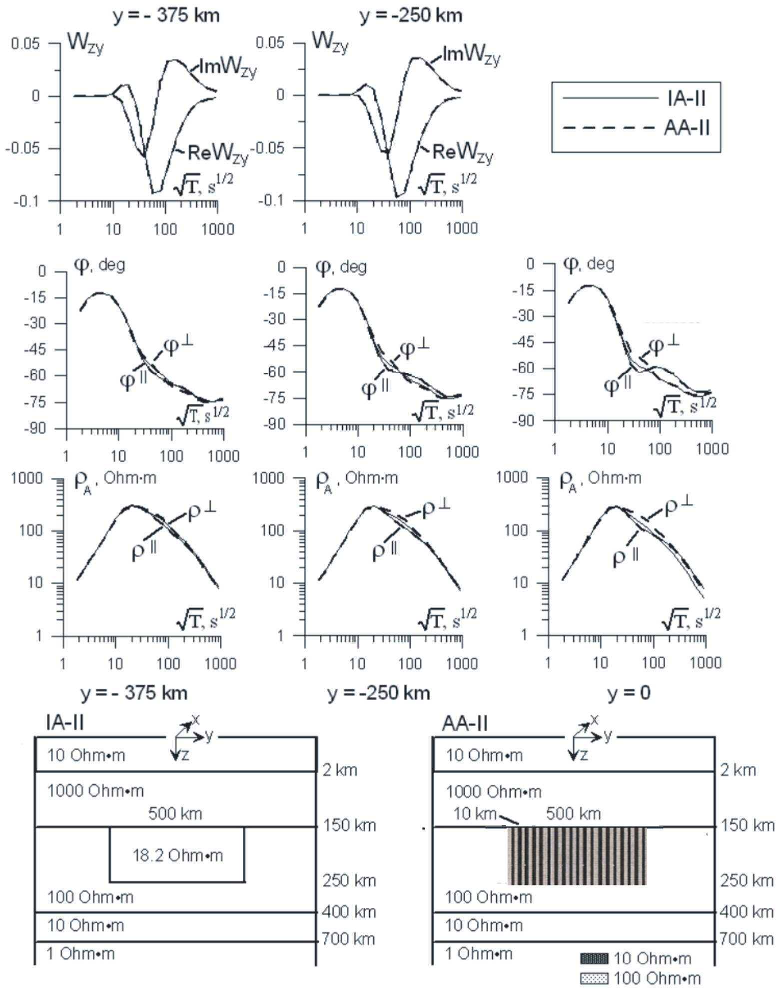

Fig. 6. Two-dimensional models of the asthenolith. The model IA-II contains an isotropic asthenolith, the model AA-II contains an anisotropic asthenolith with alternating vertical layers of higher and lower resistivity. The lithosphere resistance is 1.5×10^8 Ohm·m^2.

We would like to stress again that the main factor that conditions the equivalence between isotropy and anisotropy is the lithosphere resistance defining the screening effect. The least favorable for studying the anisotropic asthenosphere are the stable regions where the lithosphere resistance ranges up to 1×10^9–5×10^9 Ohm·m^2 and the TM-mode is characterized by the strong screening effect ($w < 2d$, where w is the asthenosphere extent, $d = \sqrt{SR}$ is the adjustment distance, S is the sedimentary conductance and R is the resistance of strata separating an asthenospheric conductor from the sediments). Here the anisotropy–isotropy equivalence may exist even at distances of about 300-500 km. Widening the asthenospheric conductor, we get models which expose the difference between isotropy and anisotropy at distances of about 750-1000 km. Does this result make practical sense? In active regions (especially with deep conductive faults) the lithosphere resistance drops to 1×10^8–5×10^8 Ohm·m^2 and the screening effect is not so dramatic (especially if the sedimentary conductance is small). Here, in all likelihood, we can differentiate between the anisotropic and isotropic asthenospheric conductors even at distances of the order of 300 km and obtain unique information on the state of the Earth's interior.

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