Phase Splitting: Evidence for mantle anisotropy?

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1 Introduction

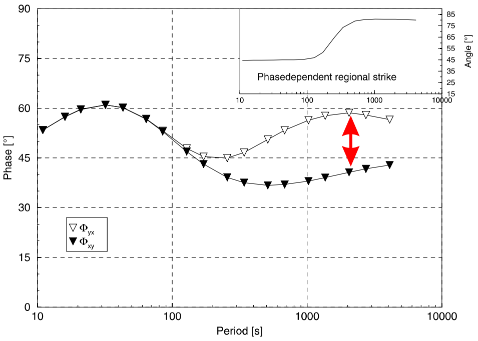

Figure 1: Example for a phase split of both off-diagonal elements of the impedance tensor at long periods.

Phase split describes the splitting of the MT phase curves of both off-diagonal components at long periods as shown in Fig. 1. This behaviour is commonly observed, however, in LMT experiments with a large site spacing in the order of a couple of hundred kilometres. The phase split and strike directions, especially their lateral homogeneity over the entire experiment array is often used to deduce that the Earth's mantle is anisotropic. For long periods and a penetration depth into the Earth mantle, it is often presumed that the phase curves of both off-diagonal elements join at 45^o (1D conditions) and thus any observed laterally homogeneous phase split is due to electrical anisotropy. In the following I will cite some examples from the literature.

Leibecker et al. [2002] interpreted LMT data in the western part of Germany within the Eifel Plume project. In order to explain the measured data they used a 3D model, fitting the magnetic transfer functions and the phase split. The apparent resistivities of the diagonal components were disregarded. Their publication shows responses of 15 sites out of 30. *Gatzemeier and Moorkamp* [2005] focused on the same LMT data but included data from more sites. They also computed a 3D model to fit the apparent resistivities of the off-diagonal components. The diagonal components and the induction vectors were neglected. Responses of two sites out of 64 were shown. *Simpson* [2002] shows LMT data at 4 sites in Australia. By means of a 1D model of the two off-diagonal components she deduced an anisotropic mantle beneath Australia. The diagonal components and the induction vectors were neglected. Only the response of one site is shown. *Shalivahan and Bhattacharya* [2005] explained the MT data of 11 sites across the Eastern Indian Craton. By means of 1D models of the two off-diagonal components of one site they deduced an anisotropic mantle beneath India. Please note that for the given examples I can only refer to what is shown in the publications, however, it might be possible that the authors fitted more MT parameters.

In the cases described above we can find a common, simple architecture of models used to produce the observed phase split. Figure 2 shows a basically layered subsurface which includes an anisotropic layer at mantle depth. Even if 3D modelling is applied, the models are mainly based on a layered conductivity distribution. Anisotropic layers might account for different apparent resistivities of both off-diagonal components, however, we do not find complicated lateral conductivity contrasts to explain apparent resistivity and phase variations at long periods. These more or less 1D models are apparently supported by the lateral homogeneity of e.g. phase split, strike directions or induction vectors for certain long period ranges. Even if the apparent resistivity curves of of all impedance tensor elements indicate a more complex subsurface, electrical anisotropy is often automatically assumed because of the phase split. In the following I will show that large scale conductiv-

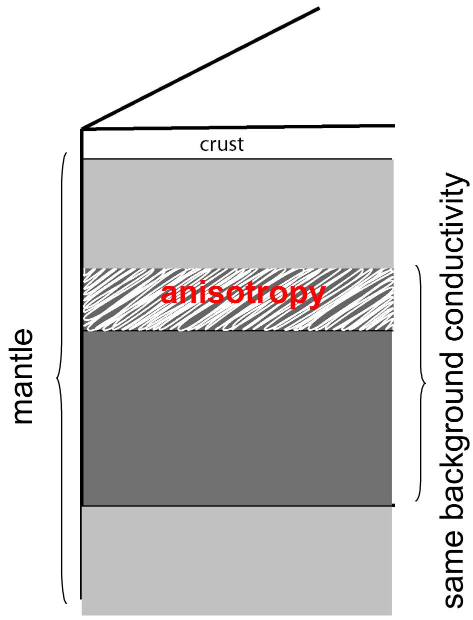

Figure 2: Even in different geological settings a general architecture of a layered subsurface is used to explain phase split and strike directions at long periods: Even in the case of a 3D model the layered conductivity structure remains dominant.

ity anomalies in the Earth's crust or mantle can also result in laterally homogeneous phase split and strike directions.

2 3D model without anisotropy

A large scale isotropic 3D model which is shown in Fig. 3a) was computed using WinGLink. It comprises a layer with some conductivity anomalies in the upper crust which cannot be seen in the depiction of the entire model and is not of importance for this study. The main conductivity anomaly is a large $2\Omega m$ structure (C) in a depth region between 50 and $120km$. It is located outside the array, dipping in southward direction. This feature is terminated approximately $200km$ north of the array in a depth of $120km$ (see top view in Fig. 3b)). The background conductivity distribution is layered. The model itself is mainly based on the general architecture of the above mentioned anisotropic models in terms of its conductivity contrasts and layering. Only the anisotropic layer is replaced by a conductive structure outside the station array.

The phase split as well as the phase sensitive strike directions *Bahr* [1988] of the synthetic responses for a set of 160 sites on top of the isotropic

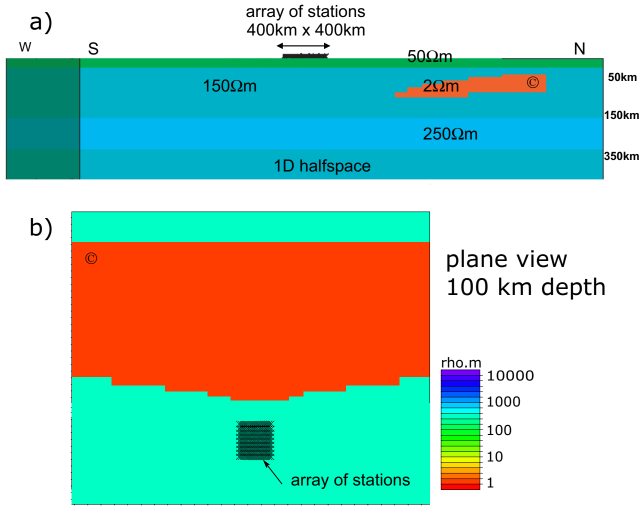

Figure 3: Isotropic 3D model: This model is mainly based on the general architecture of the above mentioned anisotropic models in terms of its conductivity contrasts and layering. Only the anisotropic layer in upper mantle depth is replaced by a conductive structure outside the station array. a) Side view of the inner 3D block. b) top view of a z-layer in $120km$ depth. The conductive feature (C) outside the station array is terminated $200km$ north of the array and has a slightly roundish boundary.

3D model are computed for a period of $10000s$ (see Fig. 4). In general, we observe a homogenous behaviour over an area on $400km^2$. In the northern part the strike directions are slightly influenced by the roundish boundary of the conductive feature (C). The induction vectors (not shown here) for all sites indicate very consistently a conductivity contrast further to the north.

Apparent resistivities and phase curves (Fig. 5) for all four components at a site in the middle of the array, show a phase split in the order of 20^o at long periods ($10000s$). A smaller phase split at shorter periods ($200s$) is caused by a layer with a lateral conductivity contrast in the crust, which is not of importance to this study. At long periods we also observe larger diagonal components, however, they are smaller than the off-diagonal components.

3 Fitting only off-diagonal components?

To answer the question whether solely fitting the off-diagonal components of the impedance tensor with anisotropic modelling leads to meaningful

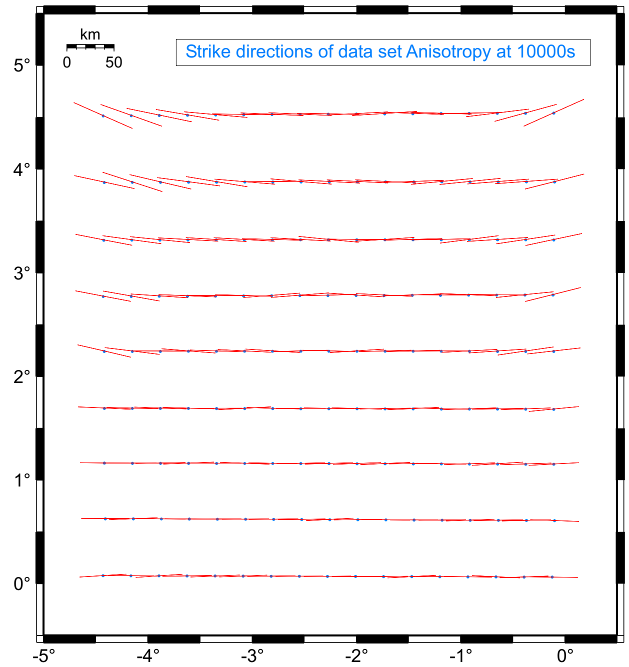

Figure 4: For a period of 10000s the strike directions after *Bahr* [1988] are shown the length of the red bars is scaled by the phase difference of both off-diagonal components. In the northern part the strike directions are slightly influenced by the roundish shape of the conductive feature.

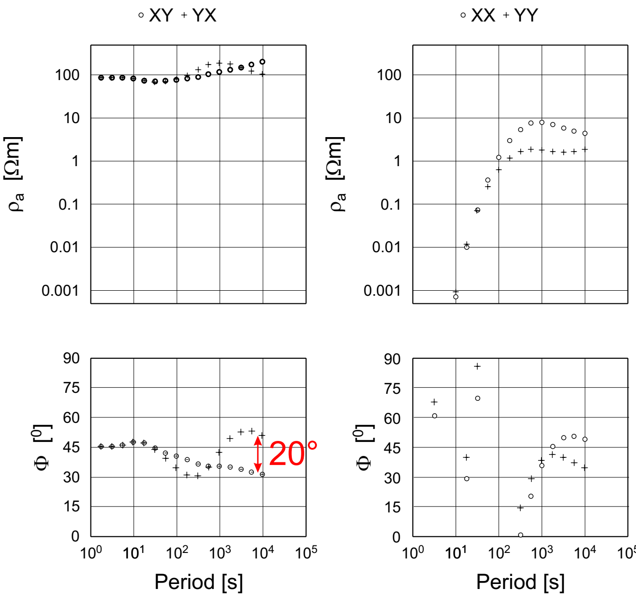

Figure 5: Apparent resistivity and phase curves of all impedance tensor elements of a station in the middle of the array. The small phase split at 200s is caused by a layer with lateral conductivity contrasts in the crust. For long periods of 10000s a phase split of 20^o can produced. Because of the simple structure of the model the diagonal elements are comparatively small.

models, I have chosen an arbitrary anisotropic 2D model. It is shown in Fig. 6a) and was computed using the 2D anisotropic forward modelling code by Pek and Verner [1997]. In 43km depth a 150km thick anisotropic structure (3/100Ωm, 40^o anisotropy strike) is placed to the right hand side of the model. The left side of the model contains an isotropic half layer of 50Ωm.

Fig. 7a) shows the synthetic responses at a site in the middle of the model (S1), which means to the right hand side of the conductivity contrast. For this study the shape of apparent resistivity and phase curves is not important, however, we should note that because of the anisotropy strike of 40^o and the conductivity contrast we do observe diagonal components, which differ significantly from zero.

In the following I will construct anisotropic 2D models by only fitting the off-diagonal components of the model (1). Fitting only the off-diagonal components is common practice particularly if we argue that the diagonal components are small compared to the off-diagonal components. In a first attempt I have been looking for an anisotropic model without any lateral conductivity contrast. This model was found by trial and error and has anisotropic layers with completely different conductivity contrasts than model (1), and an anisotropy strike of 0^o. All anisotropic layers have a total thickness of approximately 90km. The first layer of 55km thickness has a conductivity contrast of 13/45Ωm, the second 14km thick layer has 34/45Ωm and the last 20km thick layer has a contrast of 4/45Ωm. The response of this model at site (S1) is shown in Fig. 7b) in red colours, in black we have the response of model (1) for comparison. With this model I am able to reproduce the apparent resistivity and phase curves of both off-diagonal components. However, as the anisotropy strike equals 0^o there is no response in the diagonal components. In my last example I pretend that the subsurface has a strike direction of 60^o and no lateral conductivity contrast. This approach might reflect a situation where a certain strike direction would fit into an existing geological model and thus this direction is "desired". Again my model consists of three anisotropic layers with a total thickness of approximately 160km. The first 10km thick layer has an anisotropy contrast of 287/100Ωm (60^o anisotropy strike), the second 20km thick layer has 10/100Ωm (60^o anisotropy strike) and the last 128km thick layer has an anisotropy contrast of 6/75Ωm (60^o anisotropy strike). Fig. 7c) shows the response of this anisotropic model together with the response of model (1) in black. Again the off-diagonal components are perfectly reproduced whereas apparent resistivities and phases of both diagonal components differ from those of model (1).

4 Conclusions

Phase split at long periods can be produced by anisotropy, BUT isotropic models with crustal/mantle anomalies can also produce it. The phase split caused by mantle heterogeneities further away from the measurements area and the resulting strike directions are uniform over large areas (e.g. 500km x 500km). Induction vectors also show uniform behaviour. Exactly the same off-diagonal impedance tensor components can be generated by different anisotropic models. The diagonal components, however, show different behaviour. This 2D anisotropic modelling study clearly demonstrates that in order to get reliable models, we have to fit more than a few selected MT parameters!

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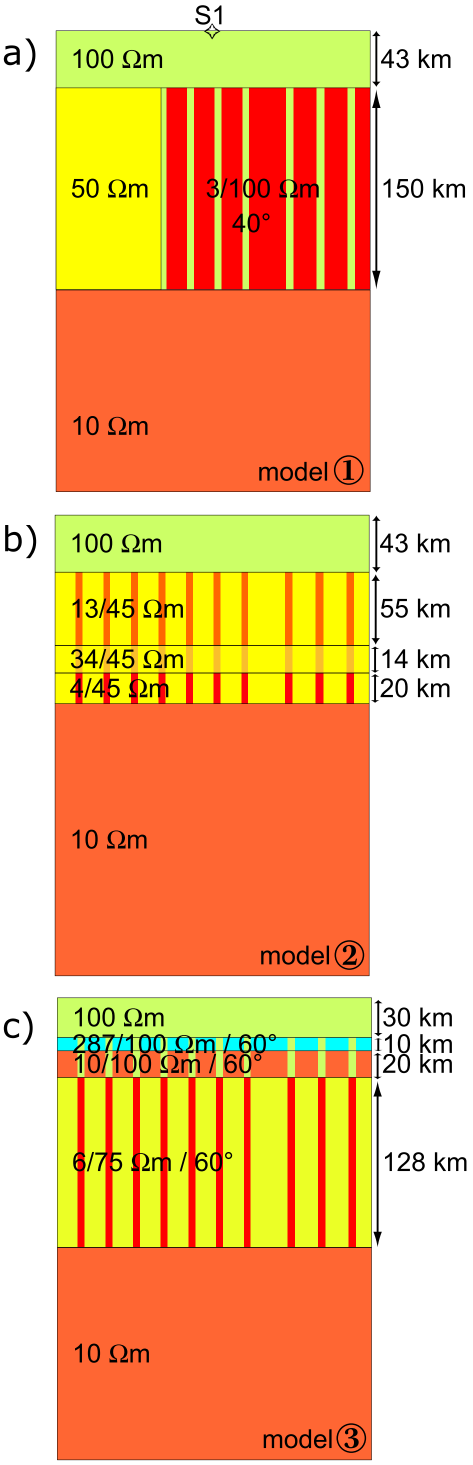

Figure 6: a) Anisotropic 2D model (1) with an 150km thick anisotropic half layer (with an anisotropy strike of 40^o) next to an isotropic half layer. b) Second anisotropic model (2) which has the same response in its off-diagonal elements as the initial model. c) Third anisotropic model (3) which had to fulfill the demand of an anisotropy direction of 60^o while reproducing the response in the off-diagonal elements of the initial model (see text).

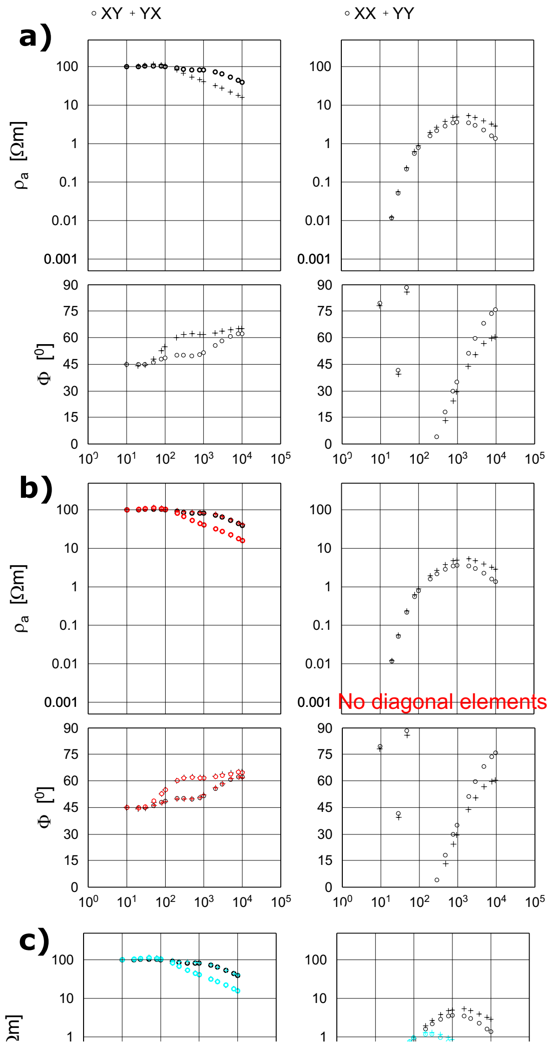

Figure 7: Apparent resistivity and phase curves of all 4 impedance tensor elements a) for the anisotropic model (1) (Fig. 6a)), b) the response of model (1) overlain by the response of the anisotropic model (2) (Fig. 6b)) and c) the response of model (1) overlain by those of model (3) (Fig. 6c)). Note that the second model has vanishing diagonal elements and the third model results in the same off-diagonal elements but has different diagonal components.