Joint Inversion of long-period magnetotelluric data and surface-waves dispersion curves for anisotropic structure: application to Central Germany

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SUMMARY

Joint inversion of different kinds of geophysical datasets has the potential to improve model resolution. Joint inversions have been commonly undertaken with datasets sensitive to the same physical parameter. This problem is more challenging when datasets are sensitive to different physical parameters.
Our work involves inverting simultaneously surface wave dispersion curves and long-period magnetotelluric measurements (sensitive to shear-wave velocity and electrical conductivity respectively) in a one-dimensional anisotropic media. The approach is based on a joint inversion using a genetic algorithm (stochastic search through model space) developed by Moorkamp et al. (2007) for a 1D isotropic structure.

We apply this new anisotropic joint inversion to real data from Central Germany. Our results show two strongly anisotropic layers at lower crustal and asthenospheric depths, with a coincident most conductive / seismic fast-axis direction. Such a result is consistent with previous independent MT and seismic studies in this area. We also improve the resolution of a common electrical / seismic lithosphere – asthenosphere boundary whose depth is constrained between 83 and 90 km depth.

Keywords: joint inversion, anisotropy, magnetotellurics, surface-waves, Germany

INTRODUCTION

The main discontinuities in the Earth (Moho, Lithosphere/Asthenosphere boundary, or LAB) correspond to physical and compositional changes of minerals and are thus correlated with changes of both electrical resistivity and seismic velocity (Jones et al., 2001). These two main interfaces are, to varying degrees, sensed by both seismology and magnetotellurics and we can thus expect to improve model of the upper mantle when combining these two datasets.

Moreover, an approximate agreement between electrical most conductive direction and seismic fast axis direction has been found in several regions, suggesting that a common underlying origin is plausible for both seismic and electrical anisotropy. This motivates our attempt to jointly invert magnetotelluric (MT) and surface waves data for one dimensional (1D) azimuthally anisotropic structure.
Our approach is based on a joint inversion using a Genetic Algorithm (GA) for a 1D isotropic structure using long-period MT data and teleseismic receiver functions (Moorkamp et al., 2007, 2010). The models were improved through additionally including surface wave dispersion curves (Moorkamp et al., 2010). Herein, we extend the work of Moorkamp et al. (2007, 2010) to allow the layers between the interfaces to be anisotropic. We adopt the same GA as Moorkamp et al., (2007, 2010), namely the Non-dominated Sorting Genetic Algorithm version II (NSGA-II) of Deb et al. (2002).

We apply an anisotropic joint inversion to datasets from Central Germany. In this region, qualitative comparisons have been made between the depth of the electrical LAB (eLAB) and those of the seismic LAB (sLAB). Moreover, we can expect an approximate agreement between the most conductive and the seismic fast-axis direction, at least, at asthenospheric depths. These observations suggest that a joint inversion of long-period MT data and surface-waves dispersion curves has the potential to improve model resolution.

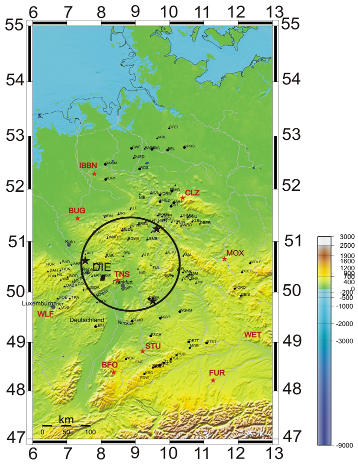

Figure 1. Topographic map of the region of study. Red stars show the seismic stations from the German Regional Seismic Network (GRSN) and black dots are the MT sites. Here, we will invert the MT site DIE together with 4 surface wave dispersion curves from different azimuths (15, 44, 96, 152). The circle represents the region sampled by the surface waves used in this study.

DATA AND INVERSION

Data

For seismic data, we use fundamental mode Rayleigh wave data recorded by the German Regional Seismic Network (GRSN) to resolve seismic azimuthal anisotropy. The array consists of 16 permanent broadband stations (STS-2s) installed in the early 1990s. We measure dispersion curves using a two-station method (Meier et al., 2004). Phase velocities were averaged for each path and derived between 10 s and 200 s periodicity (Bischoff et al., 2006). To avoid the influence of lateral heterogeneities, we extracted synthetic dispersion curves for selected azimuths from anisotropic phase velocity maps (Lebedev et al., 2007).

For MT data, we use long-period MT measurements presented in Leibecker et al. (2002) and Gatzemeier et al. (2005). We examined different sites for data quality, and selected site DIE (Fig. 1) as input data for our joint inversion. To diminish the effect of static-shift and other distortion artifacts, we invert the MT phase tensor rather than the MT impedance tensor, scaling the model by fixing the value of resistivity in the first layer to 80 ohm.m (Gatzemeier et al., 2005).

Inversion

We jointly invert long-period MT data and Rayleigh wave dispersion curves for a 1D horizontally anisotropic structure. As with the approach of Moorkamp et al. (2007, 2010), the connection between the seismic and MT models is established by the requirement of coincident interfaces. Within each layer, the different inverted parameters are electrical resistivity, shear-wave velocity and layer thickness. Electrical resistivity and shear-wave velocity are uniform in each layer but mutually independent. We define an anisotropic electrical coefficient as a ratio between the resistivity along and perpendicular to the strike and a seismic anisotropic coefficient scaling the peak-to-peak relative azimuthal velocity variations. The direction of anisotropy is the most conductive direction for the MT structure and the seismic fast axis direction for the seismic structure. Based on prior independent observations (Gatzemeier et al, 2005; Lebedev et al., 2007) we are inverting for the same anisotropic direction at lithospheric and sub-lithospheric (asthenospheric) depths, but within the crust the anisotropy directions are independent. To reduce the number of inverted parameters, we invert for a limited number of layers (2 layers for the upper crust, 1 for the lower crust, 1 for the lithosphere and 1 for the asthenosphere). The total number of parameters in each layer is seven – layer thickness, three seismic parameters (minimum and maximum velocity and direction of fast axis), and three electrical parameters (minimum and maximum conductivity and direction of maximum conductivity) – but in the lithosphere and asthenosphere is six as the two anisotropy directions are the same. Thus, the total number of free parameters is 33.

RESULTS

We perform a regularized joint inversion of MT and seismic datasets using a population size (i.e. the number of models in each iteration) of 900 members, for 200 iterations. Thus, in all 180,000 models are tested against the data.

The GA provides an ensemble of models lying between two end-members: one of them is the best fitting model for the MT dataset, the other one is the best fitting model for the seismic dataset. The tradeoff curve (Fig. 2), or so-called Pareto-optimum front (see Moorkamp et al., 2007, 2010, for explanation and examples), shows a pronounced L-shape which enables us to define one best model (named Model A) minimizing both datasets simultaneously.

GAs are useful as they not only provide one best fitting model but a set of possible solutions which give us an idea of the resolution of each inverted parameter. We will discuss our preferred model A (best fitting model for both datasets) together with a set of acceptable solutions (whose misfit do not differ by more than 30% from the misfit of the best model). By plotting all these models together, we can identify the main structural elements (Fig. 3).

Model A is characterized by a Moho at 30 km depth and an eLAB/sLAB at 83 km depth (Fig. 3).

The MT structure shows two clearly anisotropic layers: one at crustal depths with a NE/SW most conductive direction, another one below the eLAB with a nearly East-West most conductive direction (75 degrees).
This deep layer is characterized by a strong anisotropy coefficient. The along-strike resistivity, i.e., the minimum resistivity which is the maximum conductivity, is highly consistent for all the solutions plotted on Fig. 3 (~8 ohm.m) but the resistivity perpendicular to the strike is not well constrained. We can thus only resolve a minimum value for the electrical anisotropy coefficient of approximately one order of magnitude.

Model A shows also a strong anisotropy in the lower crust (fast-axis direction: 20 deg.), a moderate seismic anisotropy (4%) in lithosphere and a similar seismic anisotropy in asthenosphere (fast-axis direction: 75 deg.).

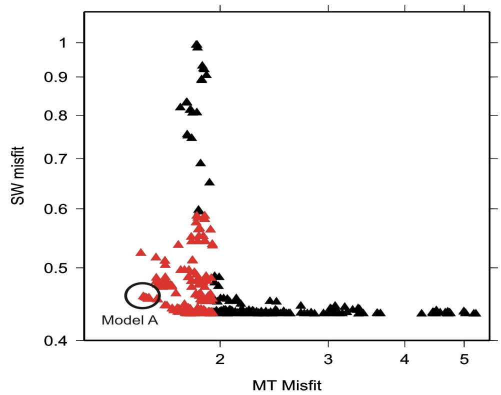

Figure 2. Misfit curve with a logarithmic scale illustrating the tradeoff between fitting the MT and the seismic datasets. Our preferred model is Model A. In red, we represent all the solutions which do not differ from the best misfit (Model A) by more than 30%.

DISCUSSION

Our anisotropic joint inversion of MT and surface-waves measurements has enabled us to resolve an LAB lying between 83 km and 90 km depth. Such a depth is slightly shallower than those found by Gatzemeier et al. (2005) of 100 km depth. However, this depth is consistent with previous seismic studies in this region, including surface-waves studies (sLAB resolved at 70 km depth from Mathar et al., 2006) or S receiver functions (sLAB between 80 km and 100 km depth from Geissler et al., 2010).

The electrical anisotropic coefficient in the asthenospheric upper mantle is more difficult to constrain. We have resolved a ratio of just over one order of magnitude, lower than that found by Gatzemeier et al. (2005) of two orders of magnitude.

Consistent with previous independent MT (Gatzemeier et al. 2005) and seismic (Vinnik et al., 1994; Brechner et al., 1998) studies in this area, we found an approximate agreement between most conductive/fast propagation direction in the lower crust (NE / SW) and in the upper mantle (nearly EW). Such an agreement between the most conductive direction and the seismic fast axis at asthenospheric depths has been observed in several areas and it generally coincides with the present-day plate motion (Padliha et al., 2006; Eaton et al., 2004). In Central Germany, the present day plate motion determined by the HS2-Nuvel1 model (Gripp and Gordon, 1990) give a direction of 50-55 degrees, which is not consistent with either the anisotropic direction in lithosphere (well resolved at 40-45 degrees) or in the asthenosphere (well resolved at 75 degrees). Clearly, whatever is causing this anisotropy direction is not simply related to Absolute Plate Motion – possibly there is some flow effect beneath the region due to LAB topography causing deviation from the regional direction of 50-55 degrees for Central Europe, as proposed for Southern Ontario by Eaton et al. (2004).

CONCLUSIONS

These results demonstrate the capacity of out joint inversion algorithm to establish a 1D anisotropic structure for Central Germany. This joint model fits MT and seismic datasets equally well and provide new information about the deep structure in this region. The eLAB/sLAB was found to be at about 80 km depth and two anisotropic layers have been resolved at lower crustal and asthenospheric depths with coincident most conductive/seismic fast axis direction.

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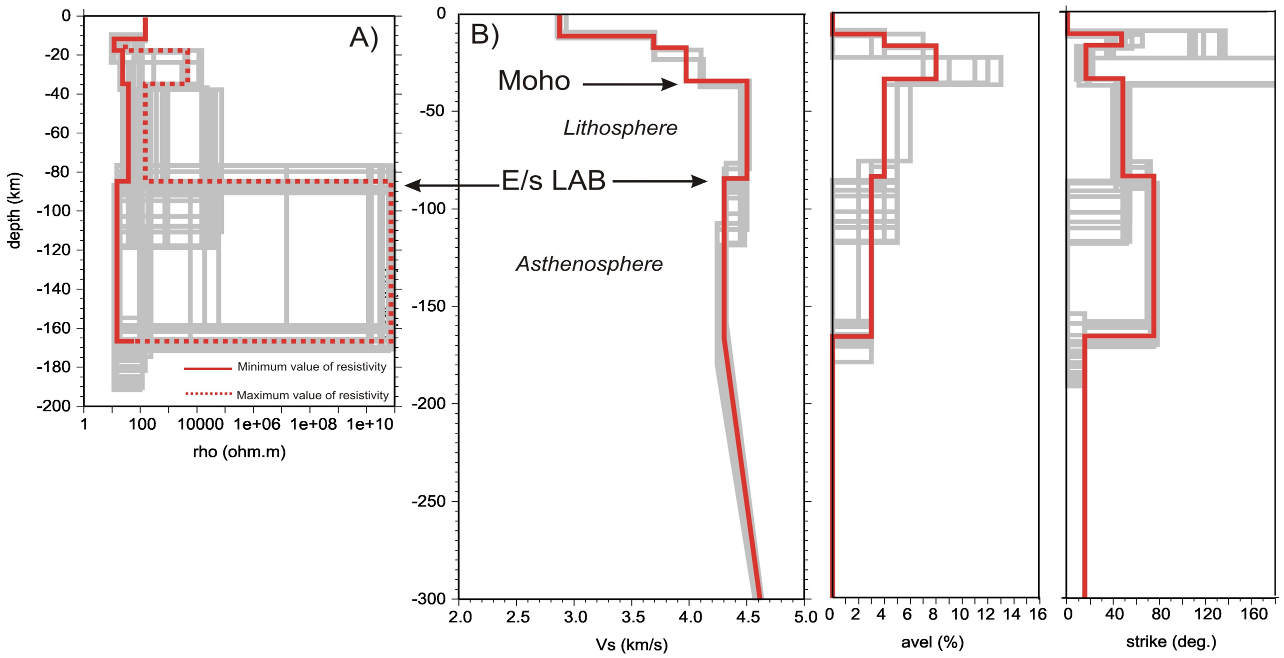

Figure 3. Joint MT (a) and seismic (b) model for one GA run. (a): In red, minimum (solid lines) and maximum (dashed lines) values of resistivity for Model A. In black, MT structure for the 30% best solutions. (b): Best solution named Model A (red lines) and 30% best solutions (grey lines). We plot the mean value of shear-wave velocity, the amount of seismic anisotropy and the anisotropic direction. The anisotropic direction is the same for seismic and MT structures in lithosphere and asthenosphere.