Magnetotelluric investigation of the Sorgenfrei-Tornquist Zone and the NE German Basin

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Abstract

The Sorgenfrei-Tornquist Zone (STZ) is the northwestern branch of the Trans-European Suture Zone (TESZ). The TESZ runs along more than 2 000 km through the North Sea, South Scandinavia, the Baltic Sea, and Poland into the Black Sea. It divides old Precambrian lithosphere in the northeast from younger, Caledonian and Variscan one in the southwest. Data, dimensionality analysis and 2D models of a long-period magnetotelluric (LMT) profile crossing this prominent tectonic border in South Scandinavia are presented and a possible interpretation of conductivity anomalies below Rügen Island and south of Strelasund Basin is given. Furthermore these models map the saline aquifer of the Northeast German Basin. The "North German Conductivity Anomaly" is perhaps mainly due to the effect of the basin edges.

Introduction

The EMTESZ project (Electromagnetic Study of the Trans-European Suture Zone) was a multinational research project to study the electrical conductivity of the Trans-European Suture Zone (TESZ), which is one of the largest tectonic boundaries in Europe. It separates the East European Platform from the Paleozoic mobile belt of central and western Europe and is traced from the Black Sea through Poland and Southern Scandinavia into the North Sea (Gee (1996); Pharaoh (1999)). In the northeast the margin is marked by the lineaments of the Sorgenfrei-Tornquist Zone (STZ) and the Teisseyere-Tornquist Zone (TTZ, which runs in a SE-NW direction through Poland and the Baltic Sea, fig. 1). Several seismic refraction and reflection experiments have been carried out (BABEL and BASIN 9601 in Northeast Germany, POLONAISE and the LT surveys in Poland). Major results include a sedimentary thickness in the Northeast German Basin and below the TTZ of 4 to more than 11 km. Also sharp lateral boundaries, a Moho from 32-35 km in the SW to 40-45 km in the NE and a reflector below the STZ/TTZ at depth of 50-55 km are known. Most of the earlier EMTESZ measurements were carried out in 2003 to 2005 (e.g., Brasse et al. (2006), Ernst et al. (2008)). Profiles MVB and MVS were conducted in 2006 and 2009.

The long period magnetotelluric profile shown here is one of these EMTESZ profiles. The direction of this profile was chosen because of earlier measurements by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in the 1990ies. Due to tipper data along this profile and of site MAT deployed in 2005 on Rügen Island (MT working group Free University of Berlin) a direction

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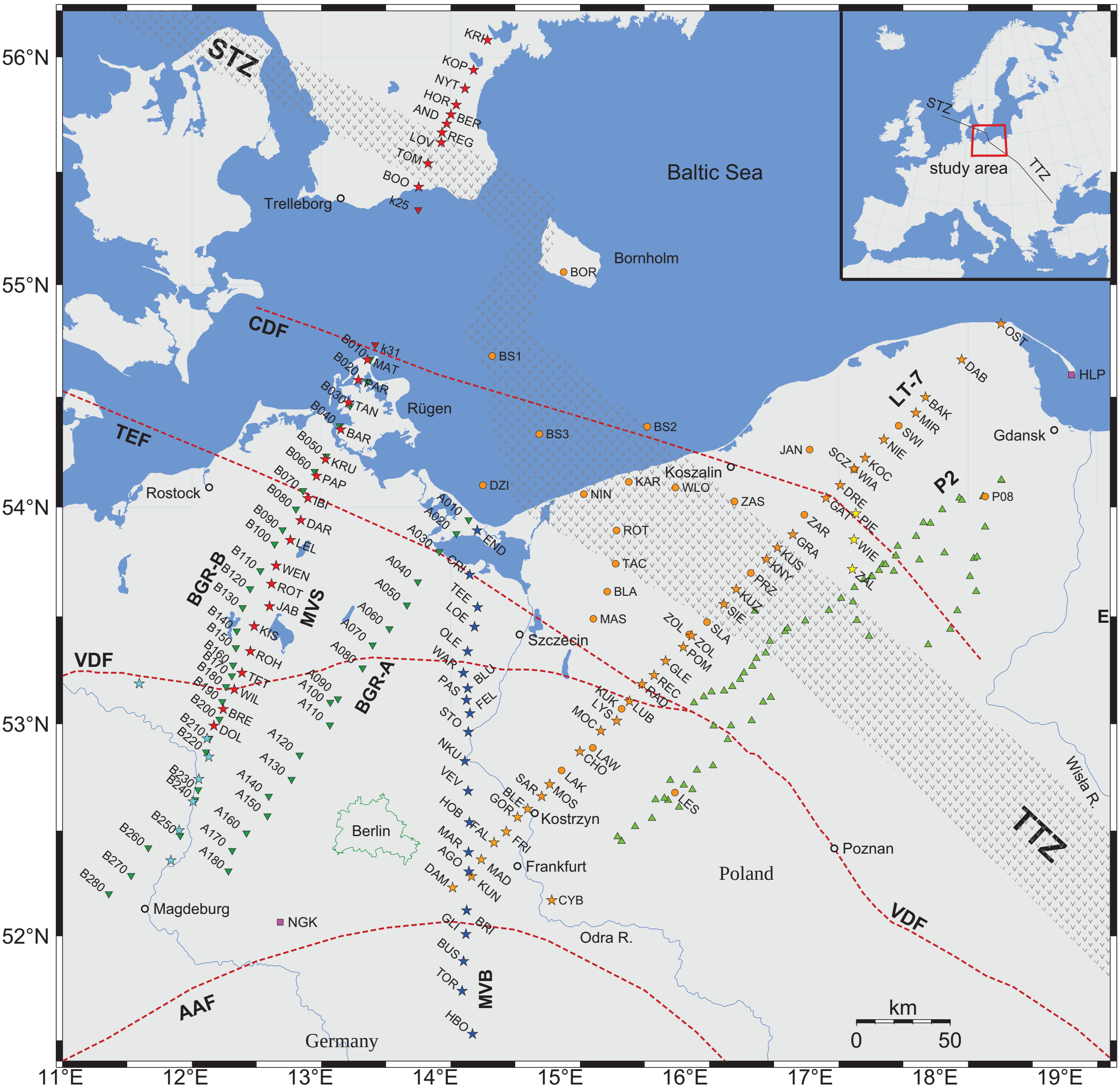

Figure 1: Measured profiles of the EMTESZ project and profile B from the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR-B). Location of MT sites in Poland, Germany, Sweden and Bornholm (Denmark); STZ-Sorgenfrei-Tornquist-Zone; TTZ-Tornquist-Teiseyre-Zone; TEF-Trans European Fault; CDF-Caledonian Deformation Front; VDF-Variscan Deformation Front; AAF-Amorica Avalonia Fault.

perpendicular to the assumed strike-direction of the Sorgenfrei-Tornquist Zone (see fig. 1) was chosen. It runs over about 370 km with a site spacing from 6 to 12 km.

Data examples

Stable transfer functions result from remote reference analysis according to Egbert & Booker (1986). The remote data is from the observatories of Belsk and Niemegk and simultaneous measuring sites. In figure 2 three representative data examples for sites of profile MVS are shown.

Site ROT, which is located in the southern part of the profile, shows the characteristic curves for the North German Basin. Apparent resistivities at short periods are very low until 100 s (1 to 3 Ωm), pointing to a very good conductor near the surface. With increasing periods app. resistivity is growing, accompanied by a splitting of impedance components Z_{xy} and Z_{yx}, reflecting

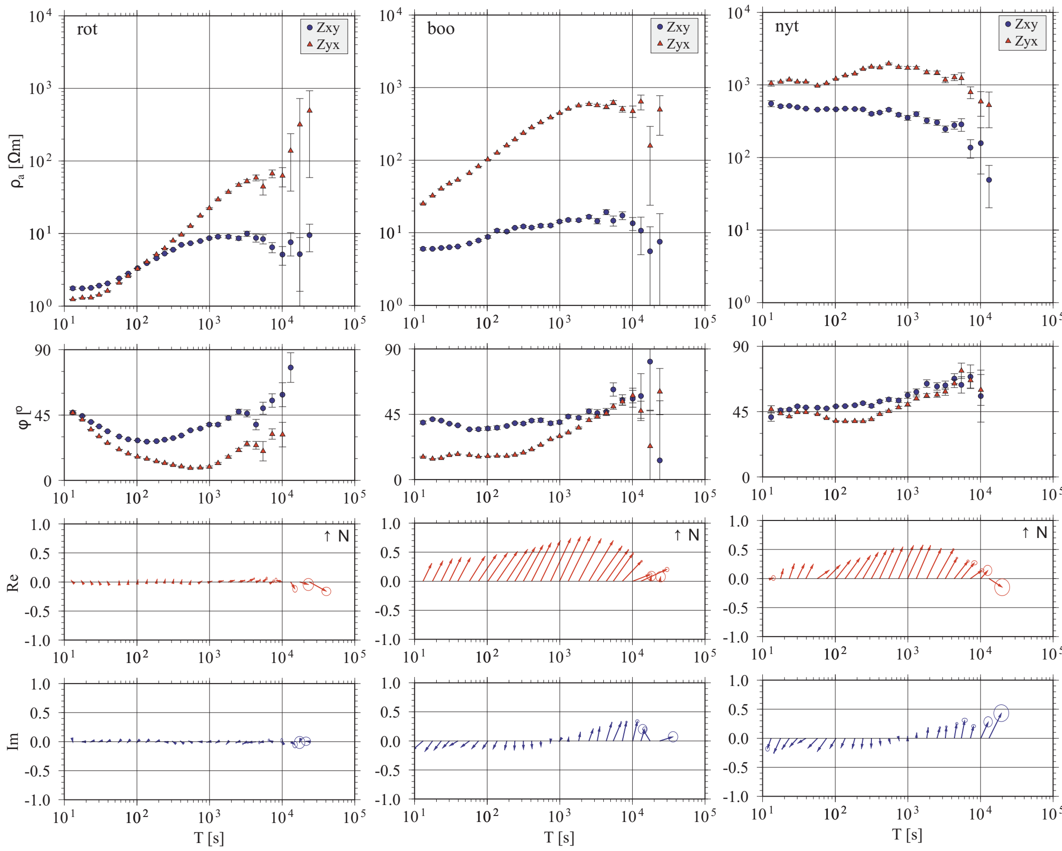

Figure 2: Examples of transfer functions for sites of the profile (ρ_a-apperent resistivity, ϕ-Phase and Re-Real part, Im- imaginary part of induction arrows as function of period). Site ROT as an example for the southern part of the profile shows low resitivity in short periods, which shows the thick sedimentary covers of North German Basin (ρ_a at low periods around 1-3 Ωm), for longer periods it shows higher resitivity. BOO is the site at the most southern part of the swedish part and shows the margin of the sedimentary basin. NYT is an example for the northern part of the profile in Southscandinavia. There the profile reaches the crystalline basement (ρ_a has higher values even for low periods).

multidimensional structures at greater depths. Induction arrows are very small. For sites in the southern part of the profile a change of direction for induction arrows is observed. Site BOO is located at the edge of the East European Craton. Here real parts of induction arrows are very large (up to an absolute value greater than 0.8) and are perpendicular to the strike direction of the Sorgenfrei-Tornquist Zone. They point to a very good conductor in southeastern direction. Apparent resistivities for this site are even for short periods much higher than in the North German part of the profile and increase rapidly for large periods, which points to the resistive basement of the East European Craton. NYT is an example for the northernmost part of the profile and shows high apparent resistivity even for the lowest periods (about 1 000 Ωm), reflecting the crystalline basement of Baltica.

Magnetic transfer functions

Induction arrows at long periods increase from south to the north, hinting at well-conductive structures in the south, i.e., below the Baltic Sea. The apparent resistivities ρ_a in the north of the profile are relatively high and get lower at the southern sites, which agrees with the geological structure. The high resistivities in the north are caused by the crystalline basement and the low resistivities in the south by the sedimentary cover.

Figure 3 shows a map of the real part of induction arrows at a period 1 820 s for the EMTESZ profiles LT-7, MVB and the discussed profile MVS, according to Wiese-Convention (Wiese, 1962).

For profile MVS arrows are mainly perpendicular to the NW-SE striking direction. With values greater than 0.8, the unusually large induction arrows in the northern part of the profile indicate a good conductor below Rügen Island. Real induction arrows at the southernmost station of Sweden, the sites in the Baltic Sea and at the northernmost point of Rügen Island are largest.

The "flip-around" of induction arrows in Northern Germany and Poland was already recognized in the initial days of electromagnetic deep sounding. The underlying cause – a large conductivity anomaly at depth – was termed the North German-Polish Conductivity Anomaly (e.g., Schmucker (1959); Untiedt (1970); Jankowski (1967)). Until today, however, the depth extent of this anomaly is controversially discussed and models range from an upper mantle high conductivity zone to the simple effect of the basin edges. The magnitude of the inductive effect at the basin margins and their rapid decrease seem to favor the second explanation, which will also become evident from 2-D inversion (see later).

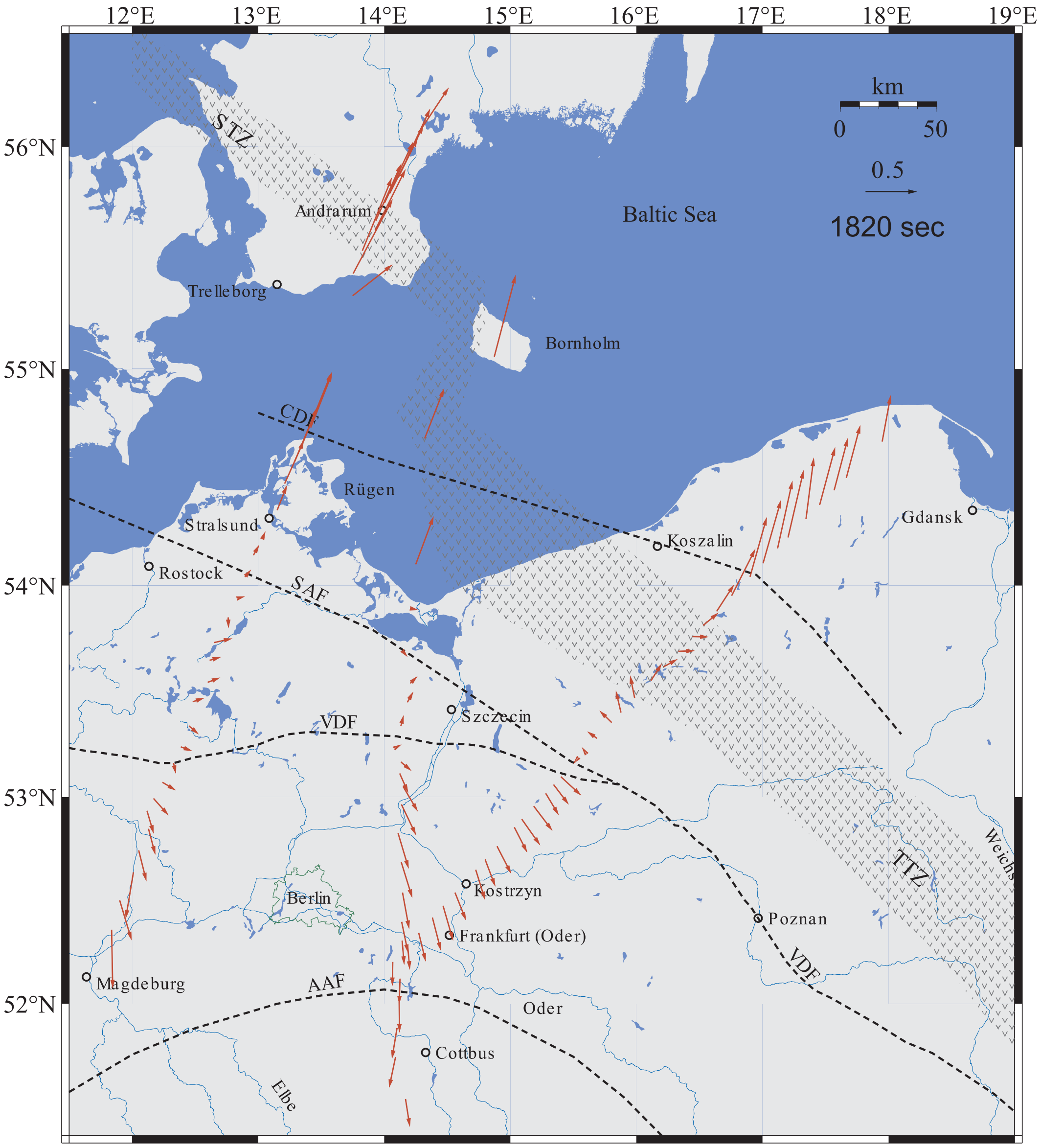

Figure 3: Induction arrows for profiles MVS, MVB and LT-7 (real part) at a period of 1 820 s. In South Sweden and north of Rügen Island induction arrows are very large. They obviously result from the edge of the Baltic Shield (STZ). The change of direction of the real parts in the center of the NE German and Polish Basins shows the effect of the so-called "North German-Polish Conductivity Anomaly". It can be seen in all profiles. Profile MVS shows this effect (sign reversal of real part) approximately at the location of the Stralsund-Anklam-Fault (SAF). In the northern part of profile MVS the induction arrows are very large. The highest absolute value with more then 0.8 is reached in the southern part of Sweden and 0.7 in the northernmost part of Rügen Island.

Dimensionality analysis

Strike angles were calculated for single and multi sites after Smith (1995), which allows to sort out bad data with a weighting matrix (see figure 4). The strike angle for profile MVS has a strong variation especially in the northern part; the average for the profile is around N67°W.

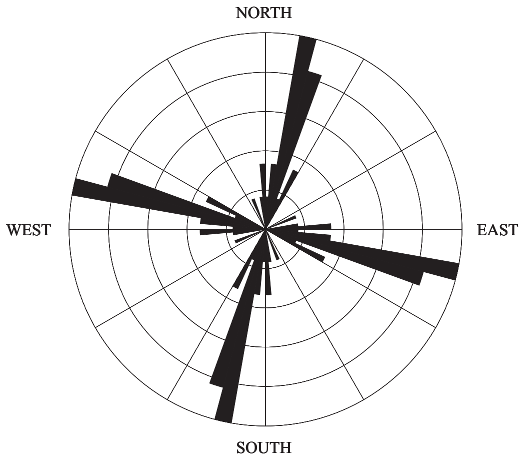

Figure 4: Average strike angle after Smith (1995) for profile MVS: N67°W.

Figure 5 shows the phase tensor (Caldwell et al., 2004) for each site of the profile for two different periods. The orientation of the ellipses point to the strike direction of the conductive structures. The northwest-pointing direction of the main axis of the ellipse corresponds with the calculated strike direction.

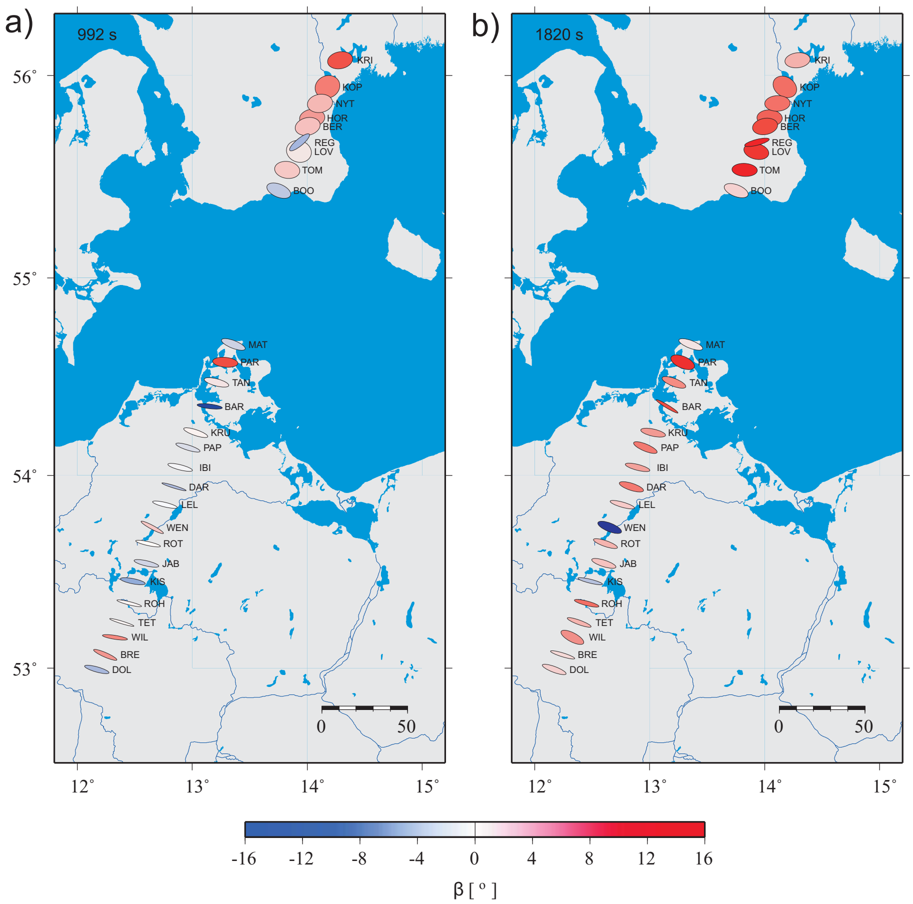

Figure 5: Phase tensor plot for periods of 992 s and 1 820 s calculated after Caldwell et al. (2004).

Skew angle β is small throughout the study area with the exception of the northernmost sites in Sweden. Summarizing, it suffices to carry out a 2-D modeling of the data.

2-D modeling

All presented 2-D inversion models were calculated with the CG-FD inversion algorithm of Rodi & Mackie (2001). First the data were rotated by -67°. A homogeneous halfspace of 100 Ωm and a fine grid for the start model was chosen. The smoothing factor was set to τ=15, which is the best trade-off between model roughness and data misfit (Hansen & O'Leary, 1993). For the inversion of the 2D-models in fig. 6 all components (TE-, TM-mode and tipper) were used. In these models all resolved structures can be seen; these models have the best fitting model response to the data (see examples in fig. 7). For a better overview of the modeled features, the profile intersecting geological structures in the respective locations are marked. Furthermore, the location of the basement is shown. Figure 6a shows the result of inversion of TE-, TM-mode and tipper data after 200 iterations. The resulting RMS is 2.27. The model shown in figure 6b also results from inversion of all components (TE-, TM-mode and tipper), furthermore a horizontal weighting function was used (β=1). The resulting RMS of this inversion after 200 iterations is with 2.67 worse then the RMS of the model without weighting function, but the model is more consistent with geological assumptions (Hoffmann & Franke, 2008).

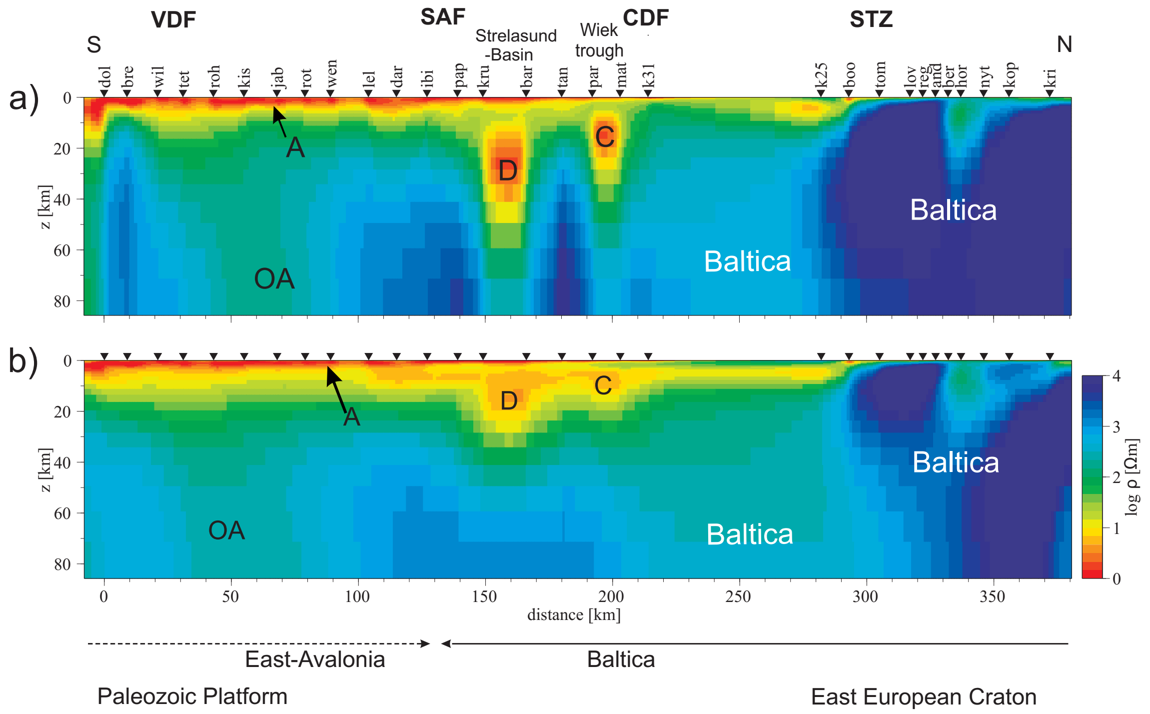

Figure 6: 2-D models for profile MVS inverted by applying Rodi and Mackie's algorithm starting from a homogeneous halfspace. a) For this model all components were inverted (TE-, TM-mode and tipper data). The resulting RMS after 200 iterations was 2.27. b) For inversion of this model all components were used (TE-, TM-mode and Tipper). A horizontal weighting function was used. Resulting RMS after 200 iterations was 2.67. For both models the smoothing factor was set to τ=15. Letters sign resolved conductivity structures: A-saline aquifer in Northeast Germany, Baltica-basement of the Baltic Continent, OA-basement, associated with the basement of the East-Avalonian plate. Also the assumed location of plates and fault zones is marked.

In both models one can see the underlying plate of Baltica in the north as a poor conductor, the sediments in Northeast Germany as a very good conductor (structure A) and two conductivity anomalies below Rügen Island (structure C) and south of Stralsund (structure D) in depths from 8 to 30 km. Figure 7 shows examples of model response of the inversion shown in figure 6a.

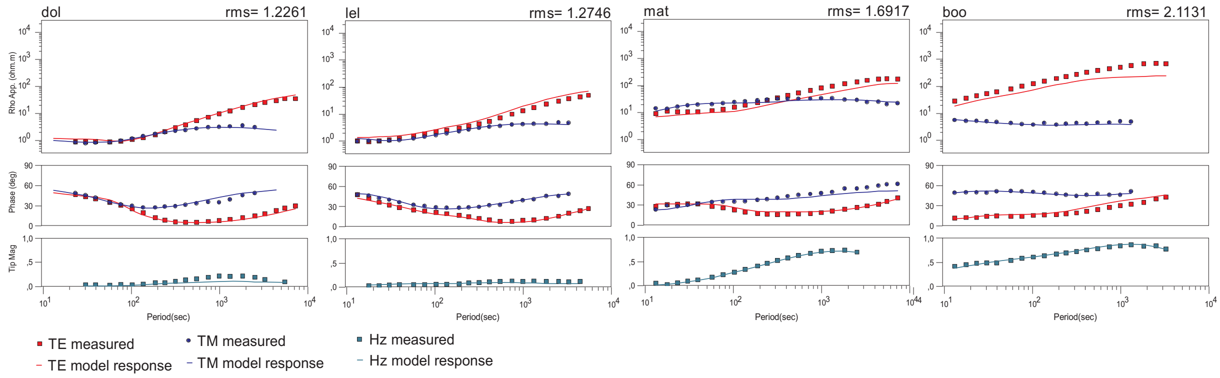

Figure 7: Examples of model responses for the 2-D inversion result as shown in fig. 6a.

Geological Interpretation

Structure A seen in the models of fig. 6 is characteristic for the North German Basin; it represents the saline aquifer and is already known from previous measurements. This structure is resolved in all inversions of this profile and could be seen in all components (TE-, TM-mode and tipper) and with its vertical elongation and extension to depths of 3 to 4 km it is consistent with simulations of Magri et al. (2007) and models of the BGR-profiles in Hoffmann et al. (1997). This structure is resolved as a surface conductor in all other sections of the EMTESZ project (e.g., Brasse et al. (2006), Ernst et al. (2008)) and in the models of Houpt (2008) as well. It is caused by huge deposits of Zechstein salt, which is dissolved by deeper ground water. Through thermal and hydraulic transport mechanisms it reaches in some cases up to the surface (Magri et al., 2005). In some parts of the North German Basin salinities up to 350 g/l are observed (Hoth et al., 1997). The conductivity of such layers depends on the salinity of the fluid, the size and connection of the pore spaces. High salt contents and pore sizes of sediment layers in North Germany may cause conductivities well above 1 S/m.

Structure "Baltica" is also resolved in all inversions of profile MVS - a very poor conductor in the north of the profile. It represents the crystalline Precambrian basement of Baltica. This basement of Baltica is with an age of 1.9 billion years one of the oldest rocks in Europe. Its high resistivity is due to the strong compression of rocks at depth with almost no interconnected fluid inclusions left.

Extension and value of the conductivity of the good conductor below Rügen Island (structure C) can also be regarded as assured due to its shallow depth and the sensitivity tests carried out (Schäfer, 2010). Its boundary to the north is indicated by the size of the induction arrows at MAT, the northernmost station on Rügen Island. Structure C is located at about 8 to 20 km depth. This good conductor is depicted in all inversions as a structure separated from the surface conductor (structure A).

Also structure D, with a depth of 10 to 30 km is resolved in all models of the joint inversion of TE-, TM-mode and tipper, and also proofed by sensitivity tests as a separate structure from the surface conductor. Conductors in these depths were explained with the occurrence of highly-carbonated paleozoic black shales, the so-called Scandinavian alum shales (e.g., Hoffmann et al. (1998); Hengesbach (2006)).

These alum shales crop out at the Andrarum quarry in the southern Swedish province of Scania, near MT sites AND and REG, where they have been mined since centuries. In order to test the hypothesis of high conductivity, several DC-geoelectric array measurements were conducted in this area during a student field trip of the Free University of Berlin (Field Report Scania, 2006). Fig. 8 displays an example. It clearly shows the black shale (blue colors) as an intermediate conductor only, with resistivities in the range of 100 to 150 Ωm. Nevertheless, this does not exclude high conductivities of deeply buried shales; at or near the surface, the relatively high resistivity may be due to strong weathering, destroying the conductive paths, which are otherwise continuous in deeper layers.

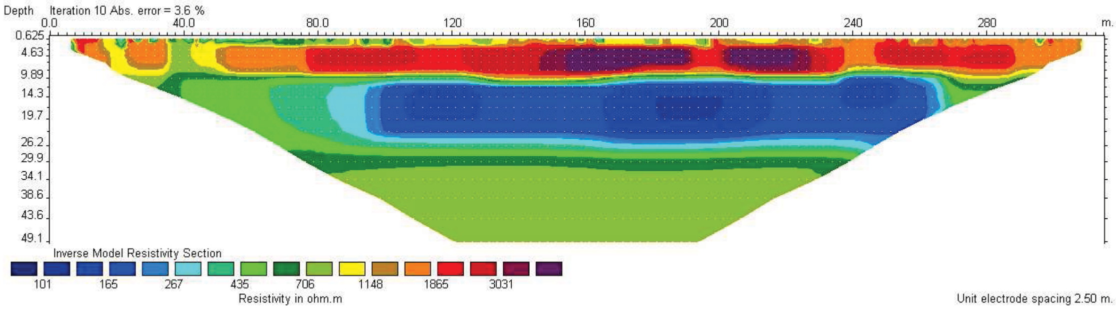

Figure 8: Geoelectric section near the Andrarum black shale quarry (South Sweden). Note the reverse color scale.

From laboratory studies and drilling black or alum shale at greater depths and without weathering it is obtained with conductivities of less than 1 Ωm (Duba et al., 1988). Black shale has been investigated by drilling in the well of G14 (north of Rügen Island) and Rügen 5, where it reaches thicknesses of 50 to 70 m. In the well Pröttlin I further south, black shales were found, too, but could not be fully intersected. In addition, studies demonstrated that the necessary pore size for an electrolytic conduction mechanism not exists in deeper sediment layers (Jödicke, 1991). This would exclude the interpretation of structure D as a deep sedimentary trough.

Thus, the conductive "layer" in the model of figure 6b can be seen as a reference to alum shale occurrence. However, this layer can be even more conductive because of hydrothermal waters, which are often rising in geological fault zones. Under high pressure and special temperature conditions in highly-carbonated black shales also graphite-structures may form, according to estimates from Duba et al. (1988) and Raab et al. (1998). With a layer of mostly continuous black shale or graphite surface, a relatively low-friction thrust faulting with little deformation of the plate boundaries in the collision of Eastern Avalonia and Baltica at the time of the Ordovician could be explained.

Furthermore, Raab et al. (1998) could demonstrate in laboratory experiments that pyrite inclusions (which often occur in black shale layers) may convert to much more conductive pyrrhotite at temperature and pressure conditions as encountered in the middle crust. Pyrrhotite usually occurs in dendritic form and increases conductivity even through small volumes.

Model experiments and sensitivity tests show that a 70 m thick alum shale layer at such depths is not sufficient, even if modeled with bulk resistivities as low 0.1 Ωm. Another possible explanation is the occurrence of intrusive bodies, which rose in the time of Rotliegend (Upper Carboniferous to Middle Permian). Their contact aureoles usually consist of highly conductive material (such as ilmenite or even graphite), and can extend over larger areas. So the high conductive structures C and D might be explained by a combination of highly conductive layers of black shales and such dykes. Motivation for this hypothesis emerged from the well Greifswald I, where intrusive granite bodies from the Rotliegend with apophyses could be found. This granite body is also known as Südrügen Pluton (Hoth et al., 1993) and is possibly extending to the south of Rügen Island.

In fact, the combination of these two interpretations, seems to be the best explanation of the high conductivities of structures C and D at depth. Thus, it is very likely a combination of graphitized black shale and intrusive bodies (e.g., Südrügen Pluton) with the accompanying conductive material and the associated apophyses. This interpretation would explain the very good conductivity in such depths and the resolution of the structures as an almost vertical body in the mid crust. Unfortunately no better resolution of these structures is possible due to the strong shielding effect of the saline aquifer.

The good conductor of model 6b ends in the south of the Stralsund Anklam Fault (SAF). The trend of the SAF, which is also indicated by magnetic transfer functions and their graphic presentation in fig. 3 fits very well to the results of Houpt (2008) and Ernst et al. (2008), which were obtained further east. According to these models and the induction arrows shown in fig. 3, the SAF appears to be a fundamental crustal boundary of Northeastern Europe which can be traced to the southeast of Szczecin in Poland.

Figure 9 shows a comparison with an interpretation of the BASIN 9601 project and 2 prolonging profiles in the Baltic Sea from McCann & Krawczyk (2001). There we observe a good correlation with underlying Baltica and the Zechstein base (strong reflector), and the well-conducting sediments in the upper layers of the Northeast German Basin.

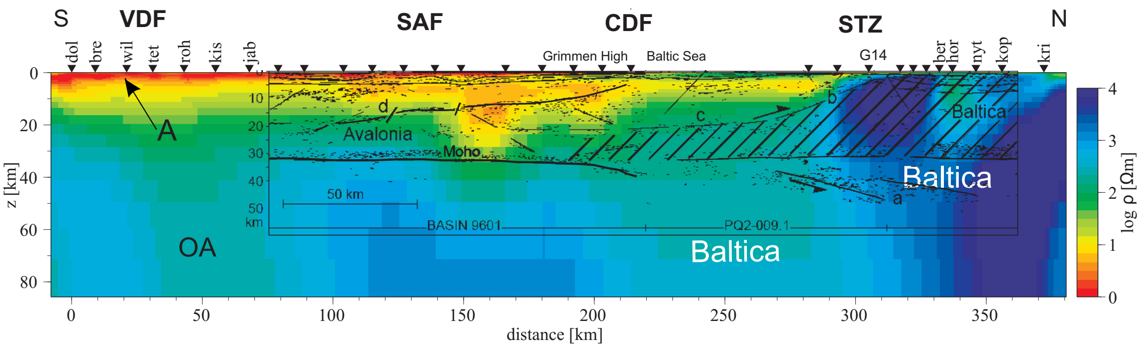

Figure 9: 2-D models for profile MVS with an overlayed interpretation of the seismic reflection/refraction profile BASIN 9601 and 2 prolonging profiles in the Baltic Sea from McCann & Krawczyk (2001).

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