From Precambrian to Variscan basement: Magnetotellurics in the region of NW Poland, NE Germany and South Sweden across the Baltic Sea

Anne Neska[1], Anja Schäfer[2], Lars Houpt[2], Heinrich Brasse[2], and EMTESZ WG

Abstract

The Trans-European Suture Zone runs 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. 2D models of four magnetotelluric profiles crossing this prominent tectonic border are presented and an attempt to integrate them into quasi 3D view on the regional conductivity structure is made in this paper.

1 Introduction

The network of magnetotelluric (MT) stations used in this study consists of two older and two newer profiles plus some single sites in between. The older ones are called P-2 and LT7 (see fig.1 for locations), they have been measured in 2003 and 2004 in the framework of the EMTESZ (*E*lectro*m*agnetic investigation of the *T*rans-*E*uropean *S*uture *Z*one) project. This project has been introduced many times elsewhere (e.g. Brasse et al. [1]), so we will limit ourselves to its most necessary features here.

The aim of EMTESZ is the electromagnetic (i.e. MT) investigation of the Trans-European Suture Zone (TESZ) in NW Poland, a fundamental tectonic boundary dividing the old Precambrian Platform in the NE from the younger Paleozoic, i.e. Caledonian and Variscan, orogenic belts in the SW (see fig.1). The data at the SW end of the LT7 profile which is reaching into Germany suggested further measurements. In an electromagnetic sense, this region is dominated by the roughly EW-running North German Conductivity Anomaly, in contrast to the TESZ itself, where the conducting structures are striking rather NW-SE. In order to comprehend that structure properly, a NS running profile, called MVB, was established along the 14° E-Meridian in Germany close to the Polish border in 2006/07. This profile could benefit from some single sites measured earlier on Bornholm Island and in the Baltic Sea with a Polish offshore instrument.

Offshore technology from IFM Geomar Kiel was also important on the second new profile MVS which runs from the Lake Müritz in the German federal state Mecklenburg-Vorpommern via Rügen Island and across the Baltic Sea into Scania (South Sweden, see fig.1). It has also been measured in 2006/07. The direction of this profile has been chosen to follow a "historic" profile by the BGR from the

[1]Institute of Geophysics PAS, Ul. Ks. Janusza 64, 01-452 Warszawa, Poland, anne@igf.edu.pl
[2]Free University of Berlin, FR Geophysik, Malteserstr. 74-100, 12249 Berlin, Germany

1990ies and to lay perpendicular to the assumed strike of the Sorgenfrei-Tornquist Zone (STZ), a branch of the TESZ (see fig.1).

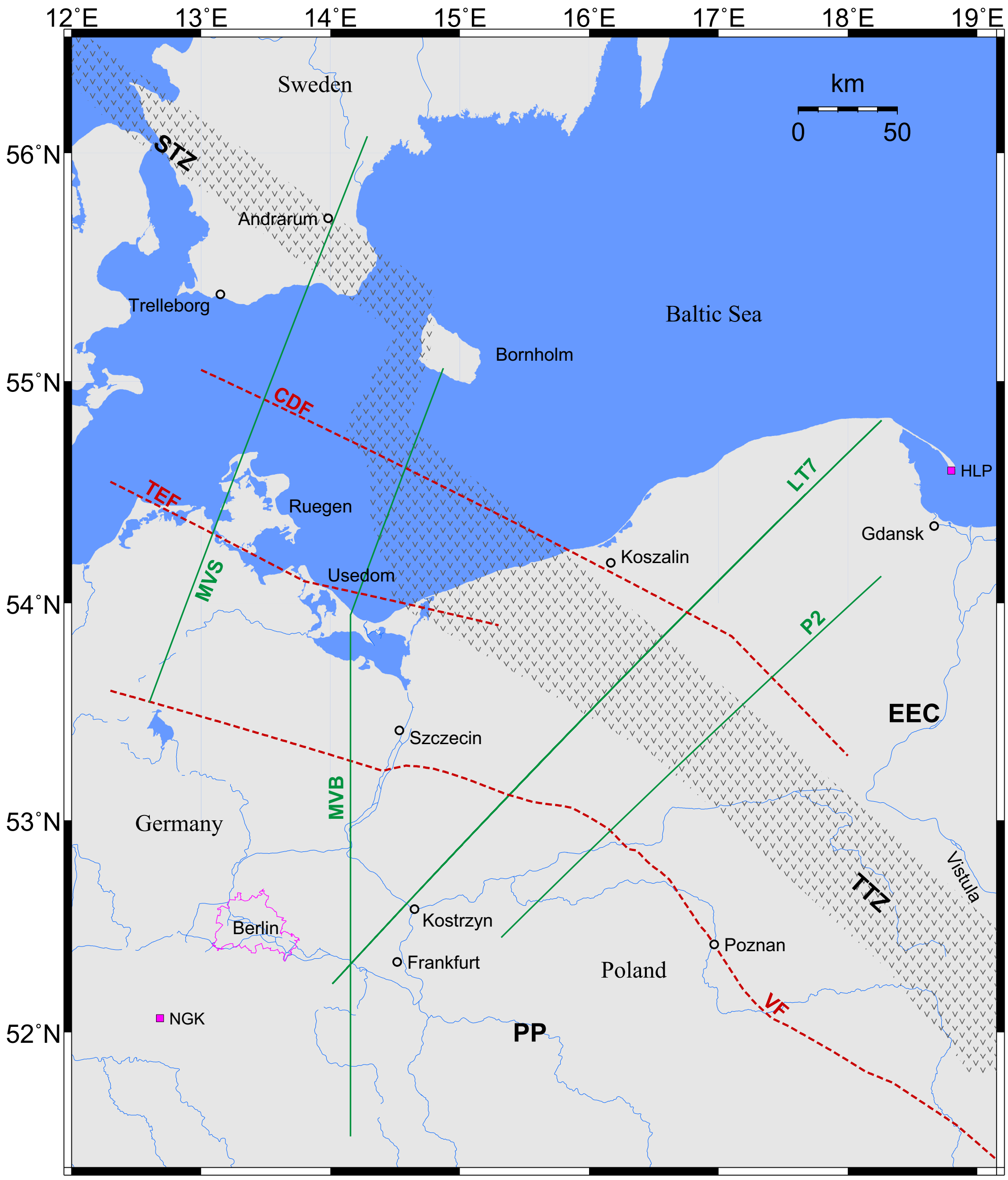

Figure 1: Overview of measurement area with profiles P-2, LT7, MVB, and MVS. Important tectonic elements are the Trans-European Suture Zone (TESZ) consisting of the Sorgenfrei-Tornquist Zone (STZ) and the Teisseyre-Tornquist Zone (TTZ), the Caledonian Deformation Front (CDF), the Trans-European Fault (TEF), the Variscan Front (VF), the Precambrian Platform or East European Craton (EEC), and the Paleozoic Platform (PP).

2 Data examples of new profiles

Most of the earlier EMTESZ measurements have been carried out from 2003 to 2005. Now there are two new profiles, MVB and MVS, mainly measured in summer and autumn 2006 and some new sites in spring 2007 to improve the data quality. The direction of the new profiles was chosen because of the direction of a former BGR profile and effects seen in the Polish EMTESZ-profile (LT-7).

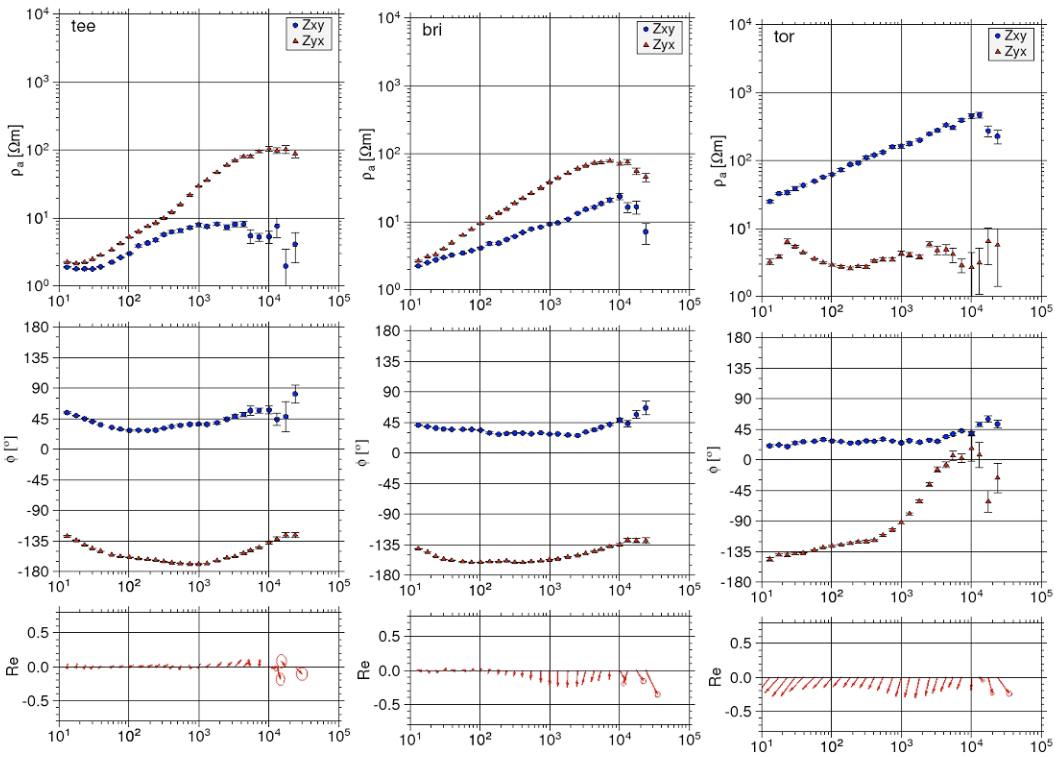

Figure 2: Three sounding examples from the northern, middle and southern part of profile MVB. Station TEE is located on the mainland approximately 20 km from the coast NW of Szczecin. BRI is the next station to the south of the crossing point of two profiles MVB and LT-7 and TOR is the second station from the south. It shows strong 3D-effects in the phase, as they are characteristic for the southern sites. Altogether these three stations have a good data quality and show the characteristics of the profile from the thick, well conducting sedimentary top layer in the north towards the resistive crystalline basement in the south.

Profile MVB (Mecklenburg-Vorpommern – Brandenburg) crosses the Variscan Front (VF) and reaches the Teisseyre-Tornquist Zone (TTZ) at its northern end on Bornholm Island (see fig.1). N-S direction was chosen because of the south-pointing induction arrows at the SW end of the Polish EMTESZ-profiles, cf. fig.4. It has about 260 km length and runs along the 14^{th} degree East meridian. It includes 20 stations with a distance between 6 km and 23 km plus two offshore-stations and one onshore site on Bornholm carried out by the Institute of Geophysics of the Polish Academy of Sciences, Warsaw. In the northern mainland part there are thick sedimentary covers (up to 10 km) penetrated by saline aquifers and/or other well conducting structures like that one beneath Usedom Island, which was identified as alum shales by the BGR (ρ at low periods around 1-3 Ωm), whereas in the southern part the profile reaches a region where the crystalline basement of the Variscides is almost outcropping (ρ_a has higher values even for low periods), see fig.2.

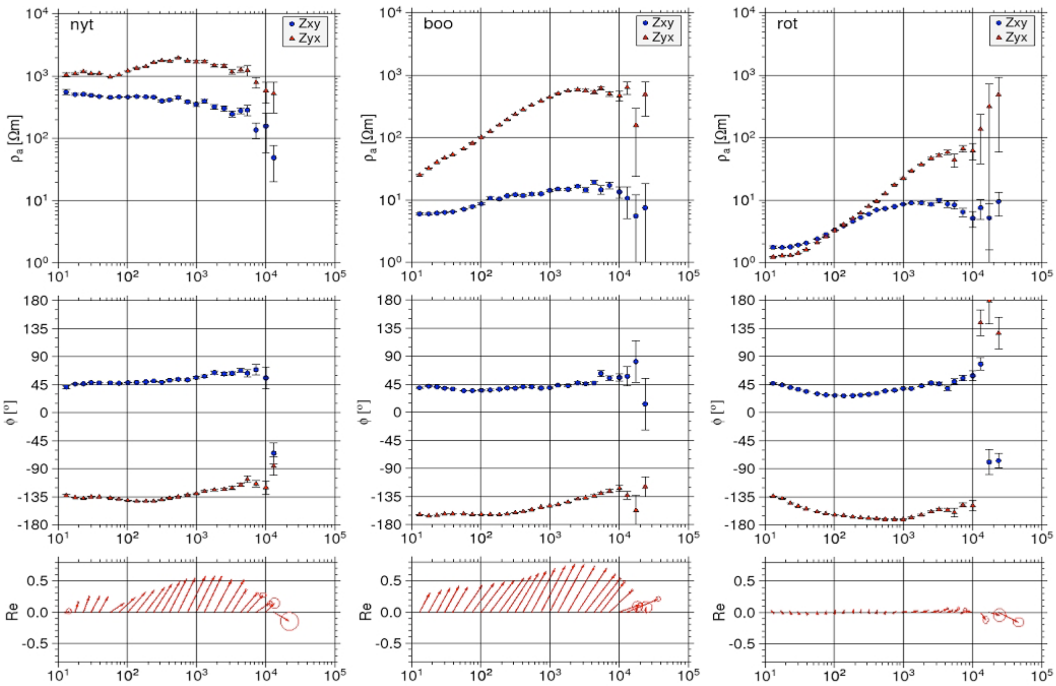

Figure 3: Sounding examples of sites located in profile MVS. From the northern end of the profile there is shown NYT in South Scandinavia, NE of Andrarum (cf. fig.1, a place known for its alum shale outcrops). Site BOO is the southernmost one in Sweden right at the Baltic Sea, and site ROT is at the southern end of the profile in Mecklenburg-Vorpommern.

Profile MVS, meaning Mecklenburg-Vorpommern and Scania, is about 300 km long and runs from north-north-east to south-south-west. It includes 22 stations with a distance between 6 km and 12 km and two offshore-stations from IFM Geomar Kiel that were deployed close to the Rügen and the Swedish coast.

The direction of this profile was chosen because of the induction vectors from former BGR-measurements.

Some transfer functions of MVS are given in fig.3. The ρ_a curves at lower periods show the high apparent resistivity of the Precambrian crystalline basement in the north (station NYT) and at the margin of the sedimentary basin marked by the Baltic Sea (station BOO). Site ROT at the southern part of the profile shows the resistivity of the increasing sedimentary cover (with lower ρ_a at lower periods).

The profile starts in the region of the VF in the south and crosses the TTZ/STZ in South Scandinavia (see fig.1).

Stable transfer functions for all profiles result from magnetotelluric data processing including the remote reference technique according to Egbert et al. [3]. The remote data for MVB and MVS were from the observatories of Belsk and Niemegk.
Strike angles were calculated for single and multi sites after Smith [8], which allows to sort out bad data with a weight matrix. The strike angle for profile MVS has a strong variation especially in the northern part; the average for the profile is around 23°. For profile MVB the strike angle varied from 25° in the South to 1° in the North. The average strike angle for profile MVB is 21°.

3 Wide-area consistency in transfer function map views

The map views of induction arrows and perturbation vectors show a very consistent picture over the measurement area. We present them at a period of ca. 1800 s, since there are maximum real arrows and zero imaginary arrows at most stations.

Considering induction arrows (Wiese convention, fig.4), the whole region is divided into three parts.
There are large (0.7-1.0), NNE pointing arrows in the northern and northeastern part that finds its boundary beginning on Central Rügen Island, then following a line slightly north of Usedom Island and the West Polish coast almost till Koszalin. From there it merges in the known course of the TESZ. Hence, the induction arrows are directed more or less perpendicular to the border of the Precambrian Platform and the Baltic Shield, and their large length is partly caused by the strong conductivity contrast at the edge of the basement.
The middle part is characterized by very short arrows with relatively erratic directions. Only on profiles P-2 and LT7 they eventually suggest some small-scale 3D structures. It becomes clear that the good conductors are located in this part, whose southern boundary is located at 53^{rd} degree North latitude.
In the South, the induction arrows have a moderate length of about 0.3 and they point mainly southwards. This behavior is known for many decades as the North German Conductivity Anomaly.

The perturbation vectors

$$\vec{p} = \begin{pmatrix} h_H \vec{u}_x \\ d_H \vec{u}_y \end{pmatrix}$$

and

$$\vec{q} = \begin{pmatrix} h_D \vec{u}_x \\ d_D \vec{u}_y \end{pmatrix}$$

(with $\vec{u}_x$, $\vec{u}_y$ being unit vectors in the subscripted directions) are a means to visualize the transfer function called perturbation tensor, which correlates the magnetic field components of a local station (B_x, B_y, B_z) with the horizontal magnetic components (B_x^R, B_y^R) measured synchronously at a reference station (Schmucker [7]):

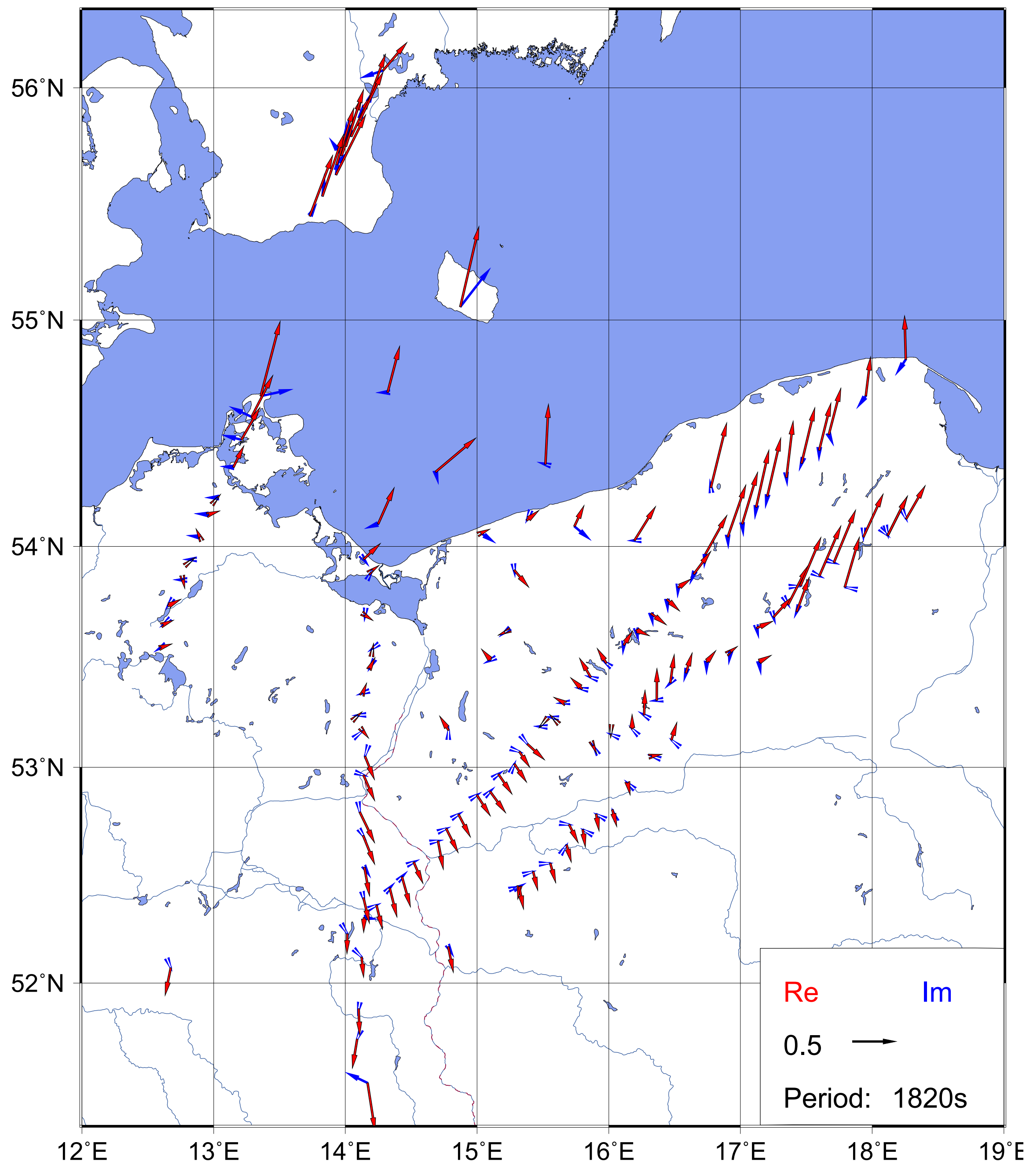

Figure 4: Induction arrows (Wiese convention) at ca. 1800 s indicating a trisection of the measurement area. See text for detailed description.

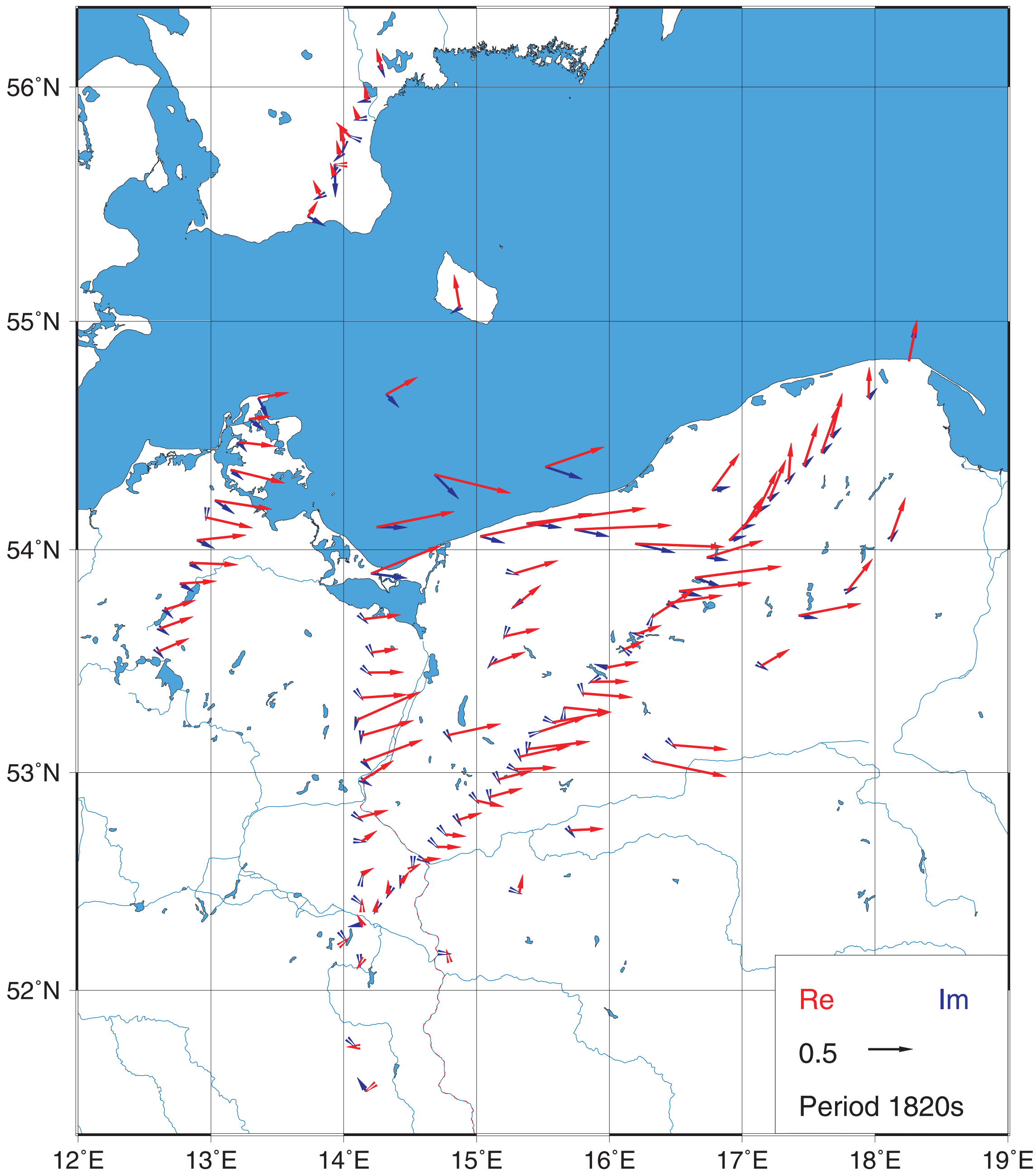

Figure 5: Perturbation vectors (only $\vec{p}$) at ca. 1800 s with respect to Niemegk Geomagnetic Observatory and rotated by 90°. Two prominent conductors emerge in this presentation, one slightly north of 53°N and another one along the Baltic coast between Rügen and Koszalin. See text for more details.

$$\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \begin{pmatrix} h_H + 1 & h_D \\ d_H & d_D + 1 \\ z_H & z_D \end{pmatrix} \begin{pmatrix} B_x^R \\ B_y^R \end{pmatrix}$$

If the reference station is situated on a relatively one-dimensional subsurface, the perturbation vectors reflect nicely the direction and strength of the anomalous (i.e. caused by lateral conductivity contrasts) magnetic field at the local station and thereby eventually the run of well-conducting anomalies.
In our case, Niemegk observatory (NGK) served as reference site. Fig.5 shows the so-called $\vec{p}$-vectors that are connected to the North component of the reference field variations. Due to the mainly E-W striking geological structures and corresponding induced currents, anomalous magnetic fields are rather observed in North direction and therefore, $\vec{p}$-vectors are more illustrative than the remaining $\vec{q}$-vectors.
In fig.5, the vectors are rotated by 90° to visualize the strike of well-conducting anomalies instead of the direction of the anomalous magnetic field itself. Contemplating the region referred to as "middle part"in terms of induction arrows, we can see that perturbation vectors give a more differentiated picture of that generally well conducting region. There can be distinguished two conductivity anomalies. One is obviously identical with the classical North German Conductivity Anomaly, of course extending far into Poland, slightly north of 53°N and striking E-W. The second one is much stronger and runs along the Baltic coast. Its maximum can be described by a line from South Rügen Island over Usedom and the West Polish Baltic coast, then bending to SE and following the Craton edge.

4 2D-modeling

Being aware that some data, particularly tippers, display 3-D characteristics or different strike directions in several areas of Pomerania and NE Germany, we employed 2-D inversion of various transfer functions on all four profiles to obtain a first-order overview on structures of the subsurface. For LT7 and P-2, the data were rotated into the coordinate frame assuming an electrical strike direction of N60°W, which is roughly coinciding with the trend of the TTZ, but problematic in the region of the German-Polish border as mentioned in section 1. The data of MVB and MVS were rotated according to an electric strike direction of N69°W, or N67°W, respectively.

We inverted the classical MT transfer functions (apparent resistivities and phases for both TE and TM modes) and the tipper. Exceptions are the MVS profile and two single offshore sites on MVB, where only the tipper was inverted. The non-linear conjugate gradient algorithm of Rodi & Mackie [6] as an implementation of Tikhonov's regularization approach allows for a variety of settings which all influence the resulting model space. The most important parameter is the regularization quantity itself; it determines the trade-off between model roughness and data fit. It has been chosen between 5 and 30 leading to RMS fitting values between 1.5 (MVS) and 2.5 (MVB).

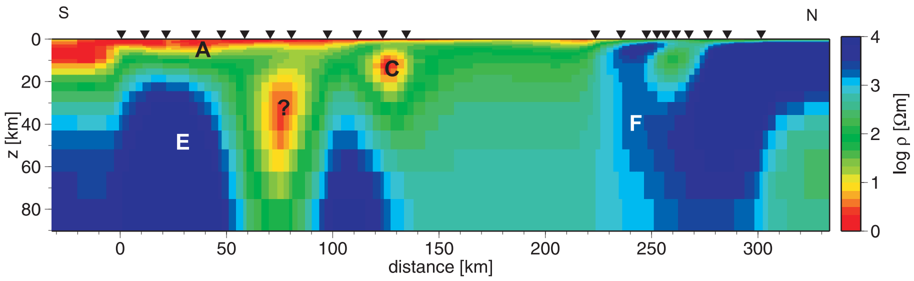

Figure 6: 2D resistivity model of profile MVS. See text for details.

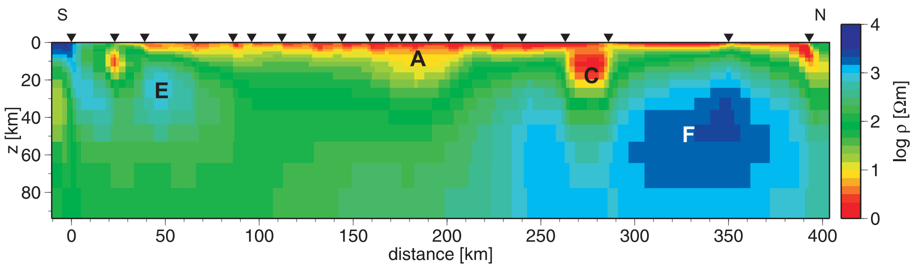

Figure 7: 2D resistivity model of profile MVB. See text for details.

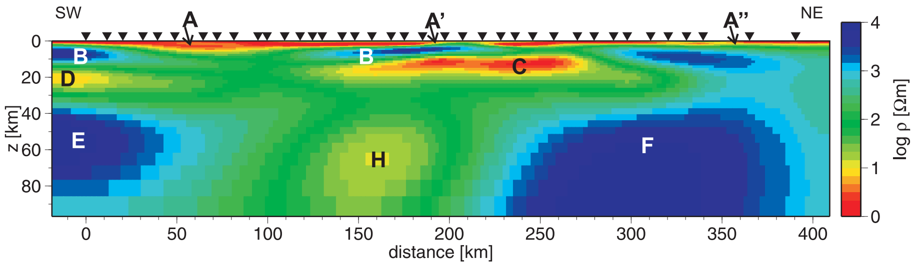

Figure 8: 2D resistivity model of profile LT7. See text for details.

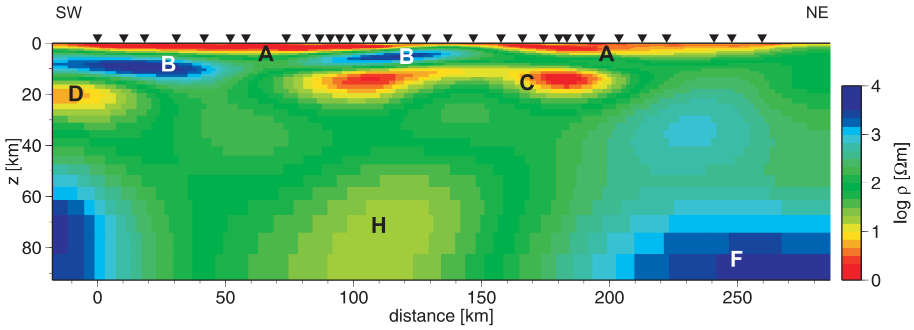

Figure 9: 2D resistivity model of profile P-2. See text for details.

The algorithm further includes the option of penalizing vertical or horizontal structures, inversion for static shift and the assignment of minimum errors (error floors) which may be set in a way that importance of phases is higher than statics-prone apparent resistivities. This large number of settings requires in turn a large number of experiments in order to find a best or best-suited model that explains the data.

The models obtained are shown in figs. 6 - 9. They display several distinct conductive and also resistive features, which are marked by upper-case letters.

- A signifies the very conductive Cenozoic-Mesozoic overburden; its very low resistivity of approx. 1 Ωm is due to the saline aquifer which is commonly encountered throughout the North German-Polish Basin (e.g., Magri et al. [4]) in a depth of several hundred m. It reaches maximum thicknesses of almost 15 km in the middle of profile MVB, forming a typical basin structure and causing thereby the induction arrow pattern known as North German Conductivity Anomaly (cf. fig.4). This layer vanishes almost completely in the central regions of the Mid-Polish Trough (A' on fig.8, continuing also on fig.9), where older, more resistive sediments are encountered close to the surface due to a partly eroded anticline structure. Note that this layer overlies also the EEC (A", fig.8) and the Baltic Sea (fig.7). The latter is less clearly visible in fig.6 where a possibly thicker sediment cover remained unresolved due to the lack of stations in the central part of the sea. The upper limit of this layer is not well resolved due to the period range investigated here, but seems to undulate somewhat along LT-7 according to the sealing, Mid-Oligocene clay layer (called "Rupel clay" in the NE German Basin) above.

- B (visible on figs. 8 and 9) is interpreted as the resistive Zechstein layer. It is apparently broken (or less resistive) in westernmost Poland close to the German border.

- The most obvious and pronounced conductor C – with resistivities as low as 2 Ωm and an integrated conductivity (conductance or conductivity-thickness product) between 1000 and 1500 S – is underlying the whole TTZ at a depth of 10-12 km (figs. 8 and 9). In a more concentrated, less layer-like form (which can be a question of regularization) it is encountered beneath Usedom and Rügen Islands (figs. 7 and 6). It correlates with the Pre-Variscan consolidated crust as deduced for the TTZ region from the analysis of seismic refraction data (Dadlez [2]) with relatively low P-wave velocities of about 5.85 km/s. We may thus infer that the conductor is located in Silurian-Cambrian, pre-Variscan (Caledonian) meta-sediments. From the models alone it is not possible to uniquely deduce the cause of the enhanced conductivities; they may either be due to saline fluids (crustal brines) or electronic conductors like graphite or alum shale. The latter is frequently encountered in boreholes in the northernmost basin areas in NE Germany (e.g., at well G14 close to Rügen island in the Baltic Sea) and crops out in the southernmost Swedish province of Scania. Note that in electromagnetic methods only conductance is resolved within certain limits, not the individual quantities themselves. This layer could thus be thinner than shown in figs. 6 - 9 with an increased conductivity or vice versa.

- D is a mid-deep crustal conductor at approx. 20 km depth (figs. 8 and 9).

Although it lies at the margin of the profiles and may thus not be resolved, data of profile MVB confirm the existence of a conductive lower crust.

- E and F are the very resistive deeper sections corresponding to the Paleozoic Platform in the SW and the East European Craton in the NE. Again, E is at the margin of the profile and poorly resolved.

- H appears to be the most controversial structure in figs. 8 and 9. It may not be well resolved due to its depth and 3-D effects in the central parts of the TTZ, but note that it is modeled in all 3 different inversion schemes on both profiles (*pers. comm.* M. Smirnov, I. Varentsov). However, if the resistivities in this "anomaly" are set equal to the surrounding (i.e., 50 Ωm), the resulting rms is 1.7585 (instead of 1.7450 for the original LT7 model) or 1.2389 instead of 1.2293 at central site POM just above. This is an insignificant change and we may safely assume more normal resistivities here.

The most suspicious and immediately obvious overall appearance of the models in figs. 7 - 9 is that they resemble the picture of a subduction zone. This is not as clearly expressed in the images of P-2 and MVB as beneath LT7, but all three models indicate a rise of the moderately conductive zone associated with the upper mantle towards the NE and on top of the roots of the EEC. Although being aware that resolution detoriates at large depths, this image may not be completely arbitrary. The idea of the TTZ being the location of an ancient subduction zone was introduced by Zielhuis & Nolet [9], based on anomalously low S-wave velocities at great depth beneath the TTZ. The ancient subduction setting of East Avalonia and Baltica together with the asthenospheric high in the domain of the Polish Trough is accordingly visualized by Mazur & Jarosinski [5]. The "anomaly" H may thus be regarded as a relict of Caledonian subduction.

5 A regional synopsis of resistivity structure

Fig.10 shows an attempt to combine the four models in a map in order to get an overview of the regional resistivity structure. The models extend to a depth of 90 km. The view is directed on the area from Northeast.

The resistive, massive block of the Precambrian Platform can be seen in all models in the foreground. On the German-Polish mainland as well as partly in the Baltic Sea, very well conducting sediments cover the surface. They seem to deepen on the MVB profile where the North German Conductivity Anomaly is expected according to the perturbation vector map view (section 3), a fact suggesting that this anomaly is just caused by the geometry of the sediment-filled North-German-Polish Basin. The other big anomaly indicated by perturbation vectors is represented on every profile by a prominent, rather compact mid-crustal conductor of only a few Ωm (letter C in figs. 6 - 9). Since their locations coincide with the edge of the Precambrian Platform, it is plausible that the development of well-conducting material, e.g. black shales, took place in the frame of the continental plate collision of Baltica and Avalonia. The southern ends of the profiles show rather heterogeneous structures,

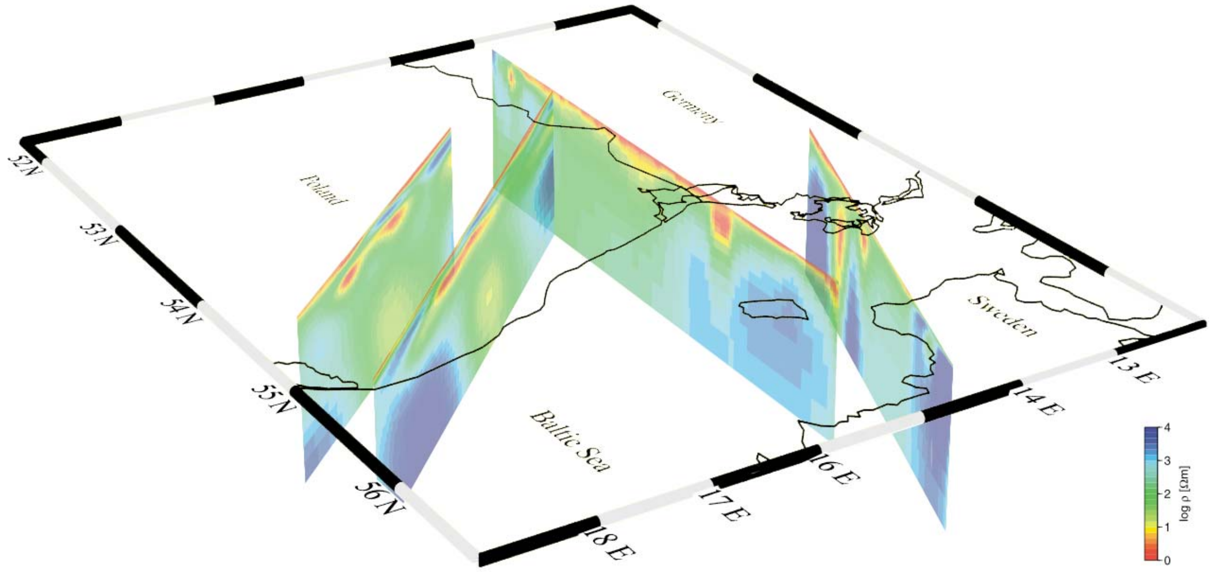

Figure 10: View from NE on four 2D resistivity models introduced in section 4 and arranged according to their geographic position. Depth extend of models 90km. The continuity of structures throughout profiles and the accord with information given by induction arrows (conf. fig.4) and perturbation vectors (fig.5) is significant.

although a rising resistivity towards the Variscan basement can be generally stated. The big differences in ρ values can have their reason in large distances between the profile ends (in case of P-2 and MVS) as well as in different assumed strike angles of the profiles although they have a common cross-over point (in case of LT7 and MVB).

Comparing figs. 1 and 10 one has to state the following: The main anomaly (C in figs. 6 - 9) coincides with the Teisseyre-Tornquist Zone on the Polish mainland, but obviously does not continue to the NW with the Sorgenfrei-Tornquist Zone (but note that good quality sites are missing in the Baltic Sea close to the Swedish coast). It bends to W at the Baltic coast, instead, thereby coinciding with the Trans-European Fault. This fact is certainly worthwhile considering in the discussion about the tectonic development of this region.

References

[1] H. Brasse, V. Červ, T. Ernst, W. Jóźwiak, L.B.B. Pedersen, I. Varentsov, and EMTESZ Pomerania working group. Probing the electrical conductivity structure of the Trans-European Suture Zone. *EOS Trans. AGU*, 2006ES001383, 2006.

[2] R. Dadlez. The Polish Basin – relationship between the crystalline, consolidated and sedimentary crust. *Geological Quarterly*, 50(1):43–58, 2006.

[3] G. D. Egbert and J. R. Booker. Robust estimation of geomagnetic transfer functions. *Geophysical Journal of the Royal Astronomical Society*, 87:173–194, 1986.

[4] F. Magri, U. Bayer, M. Tesmer, P. Möller, and A. Pekdeger. Salinization problems in the NEGB: results from thermohaline simulations. *Int J Earth Sci (Geol Rundsch)*, DOI 10.1007/s00531-007-0209-8, 2007.

[5] S. Mazur and M. Jarosiński. Deep basement structure of the paleozoic platform in sw poland in the light of polonaise-97 seismic experiment. *Pr. Państw. Inst. Geol.*, 2006. (in print).

[6] W. Rodi and R. L. Mackie. Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversions. *Geophysics*, 66:174–187, 2001.

[7] U. Schmucker. *Anomalies of Geomagnetic Variations in the Southwestern United States*. Univ. of California Press, Berkeley, 1970.

[8] J. T. Smith. Understanding telluric distortion matrices. *Geophysical Journal International*, 122:219–226, 1995.

[9] A. Zielhuis and G. Nolet. Shear-wave velocity variations in the upper mantle beneath central europe. *Geophysical Journal International*, 117(3):695–715, 1994.