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Electromagnetic images of the deep structure of the Trans-European Suture Zone beneath Polish Pomerania

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[1] A large-scale international electromagnetic experiment has been carried out in northwest Poland and northeast Germany. The main goal was to study the deep conductivity structure across the Trans-European Suture Zone, which is the most prominent tectonic structure of Phanerozoic age in Europe. Electromagnetic measurements were carried out mainly along seismic profiles P2, LT-7, and LT-2 crossing the suture zone and running in the northeastern direction. Strike and dimensionality analyses indicate that a geoelectrical strike of N60°W common to both profiles LT-7 and P2 can be estimated. This strike direction was used to project and rotate all transfer functions and both profiles were subjected to 2D inversion using three different approaches. The results show the presence of highly conductive Cenozoic-Mesozoic sedimentary cover reaching depths up to 3 km. A significant conductivity anomaly beneath the central part of the TESZ, called the Central Polish Anticlinorium, has been well resolved at mid-crustal depths. The upper mantle of the Precambrian East European Craton is more resistive than, adjacent to the West, the younger Paleozoic Platform. **Citation:** Ernst, T., et al. (2008), Electromagnetic images of the deep structure of the Trans-European Suture Zone beneath Polish Pomerania, *Geophys. Res. Lett.*, *35*, L15307, doi:10.1029/2008GL034610.

1. Introduction

[2] Over the last decade, a significant amount of research has focused on studying heterogeneities in the Earth's crust and mantle. These investigations are crucial for understanding the geological processes that shaped the structural units under study. The research methods are mainly seismic, but valuable additional insight into the physical state of the entire lithosphere can be obtained from other geophysical techniques, especially magnetotelluric measurements. As part of several geophysical projects aimed at studying the TESZ (Trans-European Suture Zone) we have carried out the international research project ElectroMagnetic Soundings of TESZ (EMTESZ). This project aims to discover new knowledge about the structure of the TESZ, which is the main boundary separating the Precambrian East European Craton to the East and the Paleozoic Platform to the West. The study has been performed in the eastern segment of TESZ, called Teisseyre-Tornquist Zone (TTZ, see Figure 1).

[3] Electrical conductivity in the Earth's crust is particularly sensitive to conducting phases like saline fluids, partial melts or graphite/sulphides. High temperatures at upper mantle depths also perturbs conductivity substantially, whereas bulk geochemistry has much smaller effects. This project has been carried out by an international working group of researchers from seven countries: Czech Republic, Germany, Finland, Poland, Russia, Sweden, and Ukraine. The complete EMTESZ-Pomerania Working Group list has been published elsewhere [*Brasse et al.*, 2006].

[4] The primary study area along profiles P2 and LT-7 (Figure 1) was chosen because of its interesting tectonics as studies by the international deep seismic sounding project Polonaise'97 recently showed [*Guterch et al.*, 1999], and with the goal to derive a quasi-2D structure to explain the observed EM data sets. Our project resulted in deep electric conductivity models that provide a new foundation for geotectonic interpretation.

2. Geological Background

[5] The Trans European Suture Zone was formed during Paleozoic time [e.g., *Pharaoh*, 1999; *Blundell et al.*, 1992; *Gee and Zeyen*, 1996] in effect of subsequent collisions of Gondwana-derived crustal units, including Avalonia and Armorica (Saxothuringian, Tepla-Barrandian) microplates [e. g., *Tait*, 1999; *Lewandowski*, 2003]. This collage of units forms the basement of the Polish Basin (PB) [see, e.g., *Stephenson et al.*, 2003], which is a first order structure within the TESZ, developed between the Variscan orogen and the East European Craton (EEC) during Mesozoic and Cenozoic time.

[6] The TESZ intersects the European continent from the Black Sea in the southeast to the British Isles in the northwest. It may extend further to the west, entering the Appalachian orogen on the other side of Atlantic Ocean [*Keller and Hatcher*, 1999].

[7] Most of the tectonic units of the Polish segment of TESZ can be related to the Laramian inversion of PB, which formed the Central Polish Anticlinorium, striking NW–SE. The anticlinorium separates two depressions, which are

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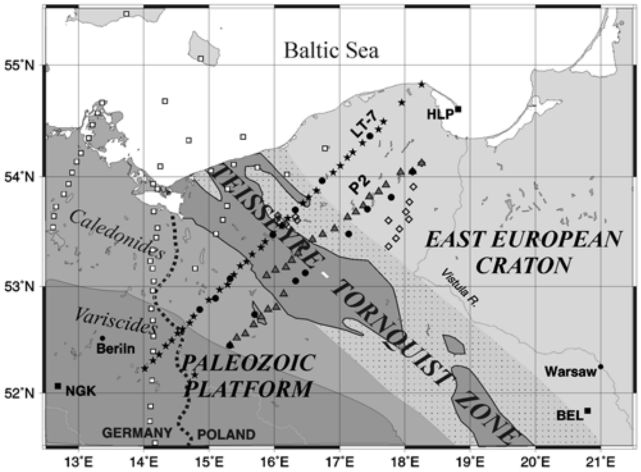

Figure 1. Site map of the EMTESZ Pomerania Project in the eastern sector of the TESZ (Teisseyre-Tornquist Zone): Long-period magnetotelluric (LMT) soundings using instruments from Poland (circles), Sweden (triangles), and Germany (stars); Czech Broadband magnetotelluric (BMT) soundings (diamonds); and geomagnetic observatories (BEL, HLP, NGK). White squares denote more recent LMT soundings that are not treated in this work.

composed of smaller tectonic units, separated by transverse faults [*Kutek*, 2001]. At the surface, the boundary between EEC and the Paleozoic Platform is seen as the Teisseyre-Tornquist lineament, which splits toward northwest into various tectonic lines and structural elements [*Berthelsen*, 1984; *Pharaoh et al.*, 1997]. Profiles P2 and LT-7 (Figure 1) are situated close to each other in northwestern Poland, so they intersect the same main tectonic units of the TESZ.

[8] On both profiles, three separate parts are clearly distinguishable. The northeastern one located on the Precambrian Platform, is clearly recognizable by means of reflection seismics and drilling, indicating a relatively simple geological structure composed of sedimentary rocks a few kilometers thick (with thickness decreasing towards the northeast) and a high-resistivity crystalline basement. The southwestern part lies already on the Paleozoic Platform and is also characterized by "quiet" tectonics, but with thicker sedimentary sequences and a less consolidated crystalline basement. The central parts of the profiles cross the above-mentioned TESZ zone and possess the most complex geological structures. A large sedimentary basin formed in the Permian and Mesozoic periods, called the Polish Basin, reaches a thickness of 7000 m of post-Zechstein sediments as shown by results of seismic reflection studies [*Krzywiec et al.*, 2006]. The main limitation for reflection seismic methods is the very strong reflectivity of Zechstein formations. Our current knowledge about deeper structures comes solely from interpretation of refraction and wide angle seismic experiments like the Polonaise'97 project. The seismic reflection technique and drilling are effective at recognizing the upper part of the structure. The seismic experiments show the presence of relatively low-velocity rocks (V_p = 6.1 km/s) down to a depth of 20 km beneath the PB and a high-velocity lower crust (V_p = 6.8–7.3 km/s). The crustal thickness in the TESZ is intermediate between that of the East European Craton (EEC) to the northeast (40–45 km) and that of the Variscan crust (VB) to the southwest ($\sim$30 km). Velocities in the uppermost mantle are relatively high (V_p = 8.25–8.45 km/s).

3. Data Acquisition

[9] The magnetotelluric data were collected in 2001–2005 using instruments from four institutions: PAS Warsaw (LMT), FU Berlin (LMT), Uppsala University (BMT and LMT), and CAS Prague (BMT), where BMT stands for broadband ($T \approx 0.003 - 1.000$ s) and LMT for long-period ($T \approx 10 - 20000$ s) magnetotellurics. All the teams of the EMTESZ-Pomerania Working Group took part in the field work. The stations were deployed along seismic transects LT-7 and P2 with some additional sites surrounding these profiles. The data set therefore covers the whole transition zone from the East European Craton over the TESZ to the Paleozoic Platform (Figure 1). At all sites, horizontal electric and magnetic variations, as well as vertical magnetic variations, were recorded with GPS synchronization. This allowed multi-site remote-reference processing and, in particular, the estimation of inter-station transfer functions. The geomagnetic observatories Niemegk (NGK), Hel (HLP), and Belsk (BEL), located at the margins of the actual study area, as well as two repeated field points (WIA and P8) served as base sites. Later in 2005–2007, the EMTESZ-Pomerania sounding array was extended to the northwest with stations in and near the Baltic Sea in Poland and at two additional profiles in northeast Germany and southeast Sweden (Figure 1). However, data from these new sites are not analysed in this paper.

[10] The participating institutions employed different sensors and recording systems; for example, FU Berlin used University of Göttingen loggers and Magson fluxgate magnetometers; PAS Warsaw used Belsk observatory loggers, Bobrov's quartz, and LEMI fluxgate magnetometers; CAS Prague operated Metronix loggers and induction coils; while the Uppsala team used EDL loggers with Metronix coils and LEMI fluxgates. After taking into account specific system responses and sampling rates for all stations, a final time-series data set was constructed.

4. Data Processing and Analysis of Transfer Functions

[11] The set of transfer functions (TF) estimated for the EMTESZ-Pomerania array includes impedances, tippers, and horizontal magnetic inter-station responses. Several modern robust data processing codes were applied to parts of this data array. The FU Berlin team employed *Egbert*'s [1997] code, CAS Prague used Metronix-supplied software, the Uppsala team developed original code [*Smirnov*, 2003], and PAS Warsaw used original time-domain schemes [*Ernst et al.*, 2001; *Nowożyński*, 2004]. Finally, all the data were homogeneously analysed by the Troitsk team using a new multi-site scheme [*Sokolova et al.*, 2005].

[12] Although data quality was quite good at many sites, problems arose due to EM noise originating from direct current (DC) trains operating in Poland and in the Berlin area. Usually, a single remote-reference (RR) analysis was sufficient to estimate transfer functions of acceptable quality.

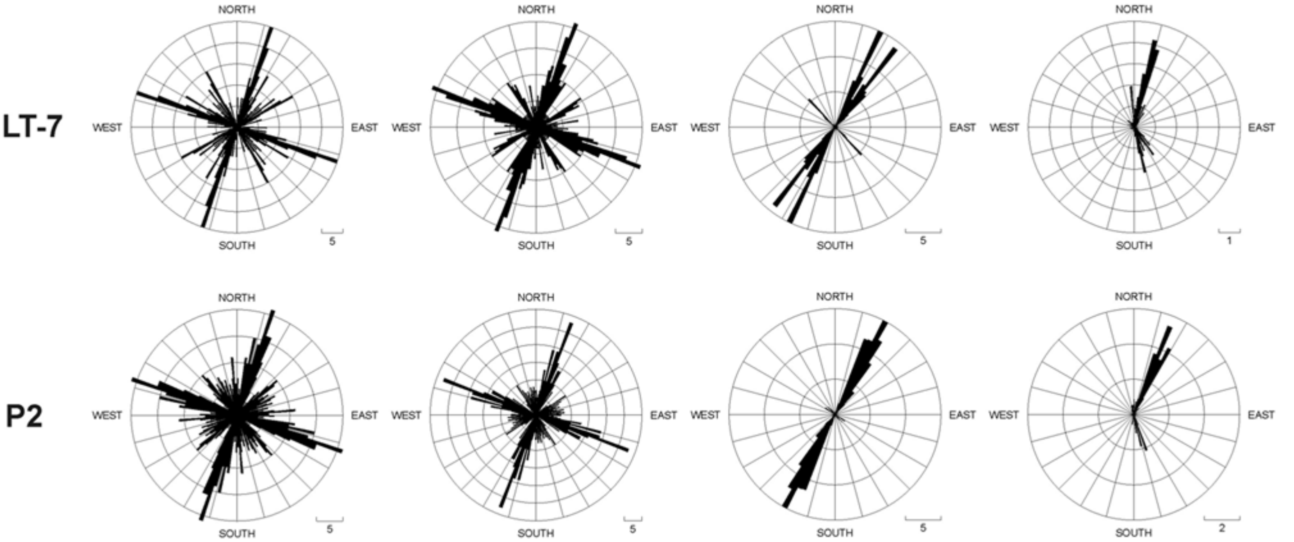

Figure 2. Rose diagrams of principal direction azimuths at long periods; (left to right) for impedance, using Swift's and CBB [*Caldwell et al.*, 2004] schemes; for anomalous horizontal magnetic tensor [*Varentsov and EMTESZ-Pomerania Working Group*, 2005; *Varentsov*, 2007a], and for real induction arrows. Note the 90°-ambiguity inherent to impedances.

The data processing technique known as extended multi-RR with magnetic control (mRRMC) was used to exploit the variety of remote sites and analyse the homogeneity of the horizontal magnetic field [*Sokolova et al.*, 2005; *Varentsov*, 2007a]. This minimized distortions due to the DC trains and improved the general quality of the TF data set.

[13] Finally, impedances have been estimated reliably at almost all LMT sites in the period range of 10–15 000 s (0.003–2 000 s at BMT sites). Tippers are reliable up to periods of about 10 000 s, but their quality suffers at longer periods. Horizontal magnetic responses seem to be stable for periods up to 20 000 s [*Varentsov et al.*, 2005].

[14] Rose diagrams as a visualization of dimensionality were constructed for the whole variety of estimated transfer functions (Figure 2). Estimated strike directions and related 3D (skew) factors show that the 2D approach is sufficient to interpret data at both the P2 and LT-7 profiles. A common strike direction of N60W was selected from this analysis to project and rotate all transfer functions for further inversion studies.

5. Two-Dimensional Inversion Studies

[15] As in the time series analysis different techniques were applied at this stage: FU Berlin used NLCG code [*Rodi and Mackie*, 2001], the Uppsala team applied the REBOCC procedure [*Siripunvaraporn and Egbert*, 2000], and the Troitsk team exploited *Varentsov's* [2002, 2007b] scheme. The Uppsala team inverted the impedance determinant plus tipper data, the FU Berlin team made a classic bi-modal impedance and tipper inversion, and the Troitsk team considered the most comprehensive joint analysis of bi-model impedance, tipper, and horizontal magnetic responses. In all studies, apparent resistivities were down-weighted to overcome static distortions.

[16] The inversion results obtained by different algorithms look similar though not identical [*EMTESZ Working Group*, 2006]. The REBOCC results enhanced local conductors and subvertical conductivity structures. Models produced by NLCG and Varentsov codes showed the best agreement especially in subhorizontal upper crustal conductors. Although the latter code fitted more data and outlined finer crustal details, we present the NLCG geoelectric sections since they are more conservative (Figure 3).

[17] The RMS fit for the models shown is ~1.7 at both profiles, where an error floor of 20 % for apparent resistivities, 1.5° for phases and 0.02 for tipper has been assumed during the inversion. The models in Figure 3 display several different and common conductive and resistive structures, which are marked by upper-case letters as follows:

[18] **A** signifies the highly conductive Cenozoic-Mesozoic overburden with resistivity as low as 1 Ωm due to the saline aquifer commonly encountered throughout the North German-Polish Basin at a depth of several hundred metres with an average conductance of ~1000 S. It reaches maximum thicknesses of 3–5 km in southwest Poland near the German border and at the EEC edge, but almost vanishes at the centre of the Polish Through (**A′**). This undulation reproduces the known structure of the Central Polish Anticlinorium, where older, more compacted and therefore more resistive sediments are situated close to the surface, with the adjacent depressions.

[19] **B** is interpreted to be the resistive layer related mainly to the Zechstein and Pre-Zechstein formations. It is less resistive (or apparently broken) in westernmost Poland and at the EEC edge.

[20] Underlying almost the entire TESZ at a depth range of ~10–20 km is the most obvious and pronounced sub-horizontal conductor **C,** which has a resistivity as low as 2 Ωm and a conductance that rises above 10 000 S in some places. It correlates well with the Caledonian consolidated crust of relatively low P-wave velocities (~5.85 km/s), which were deduced from seismic refraction data [*Dadlez*, 2006]. We may infer that this conductor relates to the Silurian-Cambrian meta-sediments. Its enhanced conductivity may be caused either by electronic conductors (graphite, alum shale) within Caledonian forma-

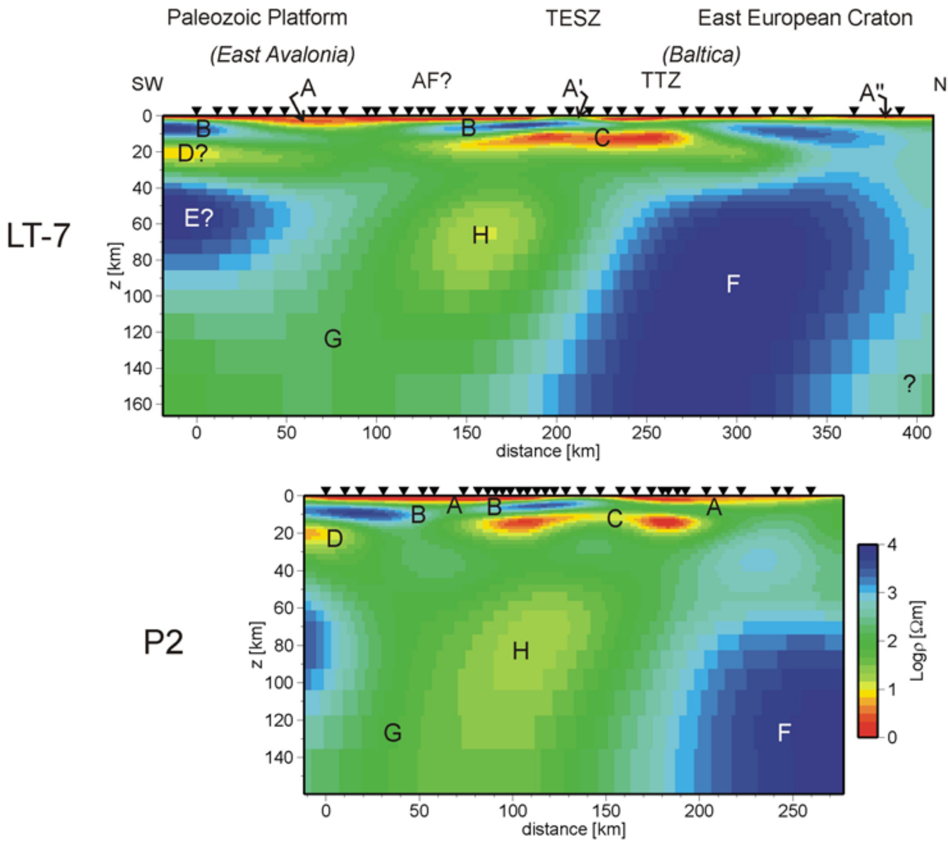

Figure 3. Two-dimensional models of the deep conductivity distribution for the LT-7 and P2 profiles (capital letters outline the principle geo-electric structures correlated in both profiles).

tions initially rich in coal facies, or by saline fluids (crustal brines) located most likely in the vicinity of deep fault systems. Additional information from other methods is needed to decide which of these options explains the observed conductivity better. This layer may be thinner than that shown in Figure 3 with an increased conductivity or vice versa, because layer conductances are the most stable parameters estimated within the resolution limits of magnetotelluric sounding techniques.

[21] **D** looks like another crustal conductor at the same depth of 10–20 km as **C**, and they may both have a similar petrology and/or origin. This conductor lies at the profile margins and is therefore less resolved. However, new data along the 14°E-profile (Figure 1) confirm its existence [*Neska et al.*, 2008].

[22] **E** and **F** are deeper, very resistive ($\gg$1 000 Ωm) crustal blocks corresponding to the Paleozoic Platform in the southwest and the East European Craton in the northeast. **E** is less covered by the data and is therefore less resolved.

[23] **G** reflects the less-resistive Paleozoic upper mantle starting at a depth of ~100 km, which fits in with the "asthenospheric" structures identified below Northern Germany based on seismological and geothermal studies [e.g., *TOR Working Group et al.*, 2002]. In models produced using the Varentsov code, this zone ends at approximately the Polish-German border, while the upper mantle in the TESZ seems to be more resistive and it resembles the normal structure for Precambrian cratons below the EEC. Enhanced conductivity zone **H** appears to be the most controversial structure and looks less pronounced in models produced by Varentsov's code. It may be poorly resolved because of its location below two prominent conducting structures; in fact, it may be an artifact caused by 3D data distortions in parts of the southwest profile, especially in tippers, as a result of the influence of the North-German conductivity anomaly.

[24] It should be noted that appreciable 3D data distortions also appear in the TESZ centre around the Czaplinek block and at northeast profile edges due to the complicated patterns in the distribution of subsurface conductance. Models generated using the Varentsov code account for 3D effects in the 2D inversion procedure, but such a complex issue is beyond the scope of this paper.

6. Geological Implications

[25] It is possible to distinguish three separate parts along both profiles. In the first region to the northeast, the presence of highly resistive crust is clearly marked, which undoubtedly corresponds to the EEC. The craton seems to be quite uniform in the geo-electric sense. In the second, central region corresponding to TTZ, formations of higher electrical conductivity are observed at the meta-sediment and crustal levels. The complex structure of this region, in particular in the upper crust, testifies its complicated geotectonic history. However, the models in Figure 3 do not show separate terranes within the TTZ, but rather vertical

conductivity contrasts at large depths. The third region at the southeast profile side is undoubtedly the Paleozoic Platform. It is not as homogeneous as the EEC, and its crust is more conductive. The suture between the EEC and the Paleozoic Platform is clearly seen on both profiles. This suture is very deep-rooted, and at first glance its geometry resembles that of the subduction zone. However, it is not a typical subduction zone pattern, in which the thin plate thrusts under the thicker one, although in the upper mantle one can notice some traits of such a model. A more likely hypothesis is that the structures we imaged were formed as the result of a developing rift zone. We speculate that this structure may be attributed to the early Paleozoic formation of the Tornquist Sea [*Pisarevsky et al.*, 2008]. It seems likely that the development of rift and closure episodes (extension/compression sequences) that affected present-day TTZ during Phanerozoic time [e.g., *Kutek*, 2001; *Dadlez et al.*, 2005], may explain the observed asymmetry in the geo-electric images of this zone.

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