Crustal structure of the southern Polish Basin imaged by magnetotelluric surveys

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Abstract

The aim of this study is to provide a continuation to the electromagnetic investigation of the Teisseyre-Tornquist Zone (TTZ). The TTZ is a tectonic boundary crossing Poland in NW-SE direction. Intense research of this zone has taken place in Pomerania (NW Poland) in the past, resulting in spatially coinciding conductivity anomalies and seismic transition zones that are interpreted in terms of a collision zone of ancient continents and micro-plates. Here we present three new two-dimensional magnetotelluric models across the TTZ in central and SE Poland. Signatures of the tectonic border continue to be visible in these models, even if with modifications that increase with distance to the NW Polish models. Furthermore, we observe a not drastic but clear spatial deviation to the tectonic picture derived from seismics that deserves further attention.

1. Introduction: Geological and Geophysical Context

The target of this study, the Polish Teisseyre-Tornquist Zone (Fig. 1), has a scientific history of more than one hundred years. It cannot be recalled here, important aspects of it can be found in Krolikowski (2006) and Dadlez (2013). The key point is the controversy where the margin of the Precambrian East-European Craton (EEC) is and if there is a belt of Caledonian rocks in front of it. The problem is that the basement (presumably an assemblage of terranes accreted to Baltica in the Early Paleozoic) is not accessible to direct observation since it is covered by younger sediments. These sediments form the Polish Basin, the easternmost part of the epicontinental Permian Basin that extends through West and Central Europe (Van Wees et al. 2000). The siliciclastic rocks, carbonates, and thick evaporates are of Mesozoic and mainly Upper Permian (Zechstein) age. The axial and deepest part of the Polish Basin, called the Mid-Polish Trough, was inverted in Late Cretaceous-Paleocene times and is characterized by a complex system of salt structures. Especially (but not only) in this region the sediments reach such thicknesses that even boreholes cannot penetrate them (Fig. 2).

Hence geophysics is the only way to assess the question of ancient tectonic boundaries. Surveying the magnetic anomaly (Tornquist 1908) was the first method, or attempt, to define this border. A glimpse on a modern magnetic map of Poland (Fig. 3, Petecki et al. 2003) suggests that two regions have to be distinguished, one to the NE characterized by positive anomalies and strong heterogeneities, and the other one to the SW that is rather homogeneous and carries a negative anomaly. This division is such fundamental that it can even be seen from space and satellites (cf. Maus et al. 2002). The interpretation that the "positive" side is of Precambrian and the "negative" one of Paleozoic age is hence not surprising and has been pointed out by Petecki (2001a, b, in Krolikowski 2006). However, the tectonic picture shown in Fig. 1 is not based on the magnetic anomaly, but mainly on seismics. This method observes different Moho depths and crustal velocities on both sides of a broad transition zone with rather complicated structure, the course of which roughly follows the magnetic picture, especially in NW Poland (e.g. Janik et al. 2002, Guterch & Grad 2006). It is mainly this seismic transition zone that is referred to and mapped as TTZ today and which is a part of the Trans-European Suture Zone (TESZ) extending from the British Islands to the Black Sea. In NW Poland (Pomerania) as well as more to the west in NE Germany also magnetotelluric investigations gave results that were interpreted in terms of an ancient suture zone (Ernst et al. 2008, Schafer et al. 2011, in Neska 2016, Fig. 4).

Figure 1 Tectonic sketch of Poland after Guterch et al. (2003)

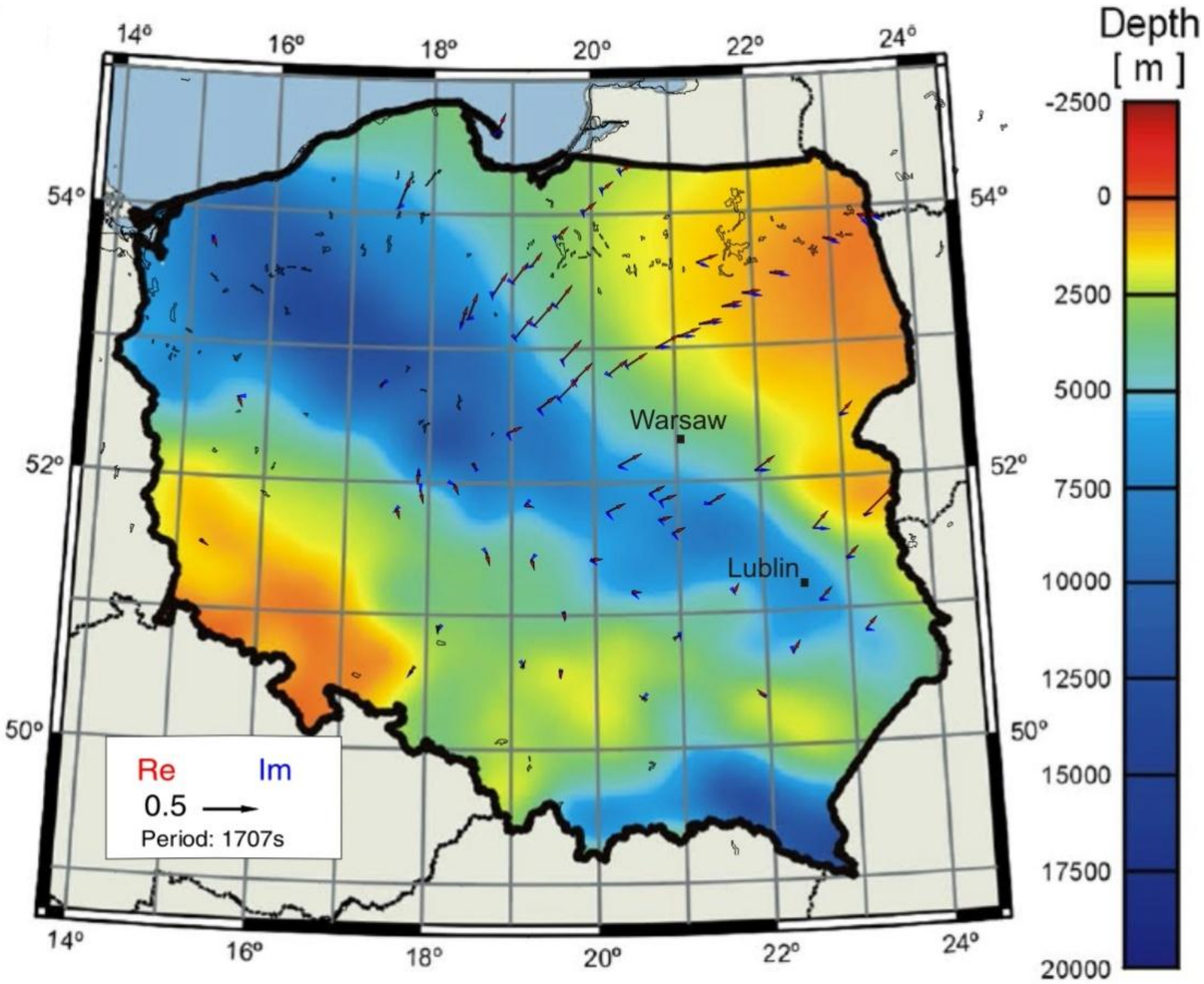

Figure 2 Map of sediment thickness to basement in Poland (Grad & Polkowski 2015) with induction arrows at 1700s superimposed on it. Note that for most regions real (red) arrows point away from greater depths and are perpendicular to isolines, but not for the Lublin Basin south of Warsaw.

2. Resistivity models for central and south-east Poland

New resistivity models (Fig. 4) have been obtained from three profiles in central and SE Poland that are described in the following. The first profile (no. 3 on Fig. 4) lies on a line running diagonally through Poland from SW to NE. It has a length of just under 300 km, consists of 13 stations, and coincides roughly with a seismic profile referred to in the literature as P4 (e.g., Guterch et al. 2006). Stations were measured partly in 1999 (NE part of profile) and partly in 2013/14 (in the SW). Data were processed with Egbert's code (Egbert & Booker 1986) and the remote-reference technique resulting in a consistent set of transfer functions covering almost the whole LMT range (10-10,000 s). The average strike direction has been determined to N15°W and transfer functions were rotated accordingly. A two-dimensional inversion of TE and TM mode and tipper has been performed by

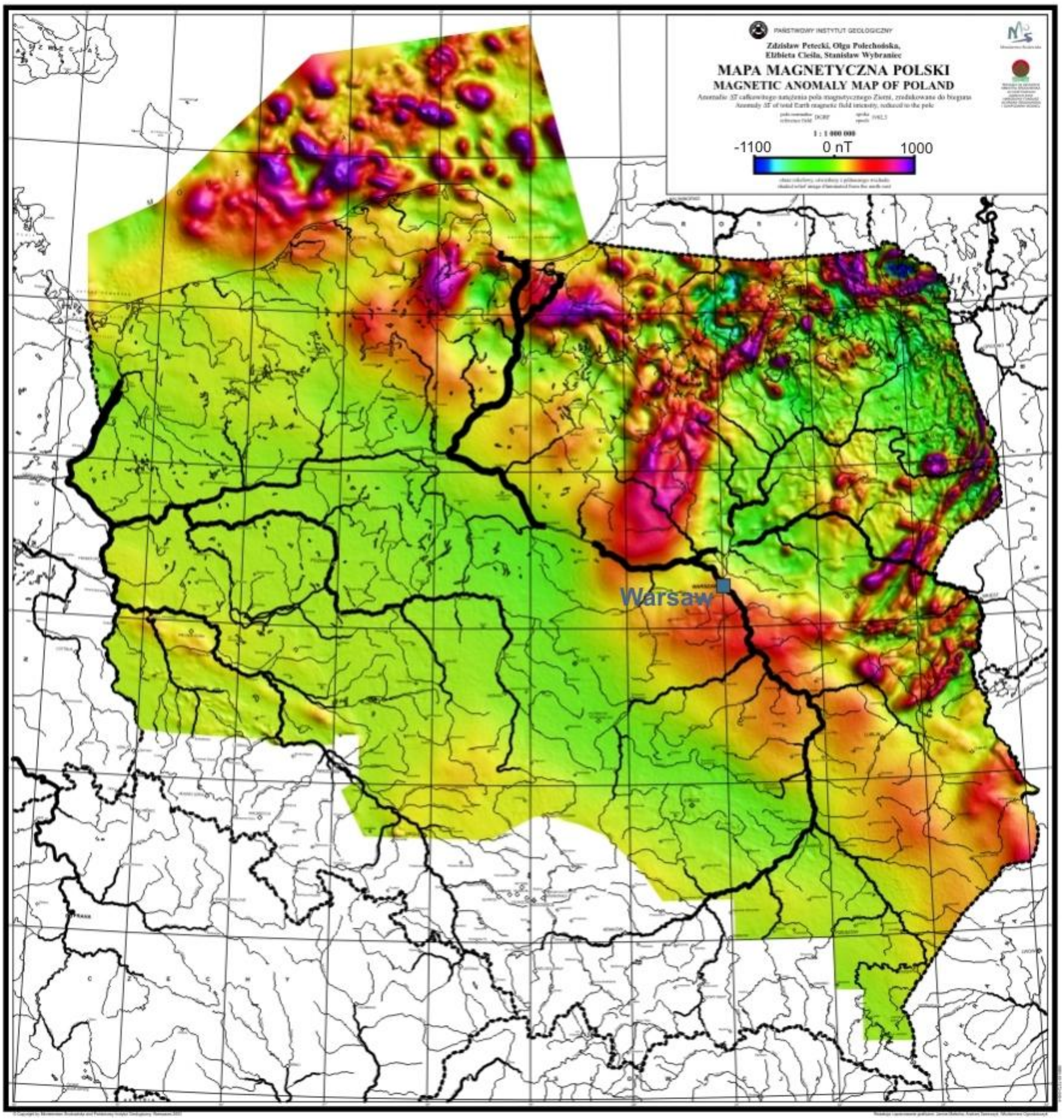

Figure 3 Magnetic map of Poland (Petecki et al. 2003, modified)

means of the REBOCC code (Siripunvaraporn & Egbert 2000). The final model has an RMS value of 2.19. The influence of the TE mode had to be somewhat limited by means of an enlarged error floor of 50 per cent for apparent resistivities and 5° for phases (while 20 per cent and 2° where used for the TM mode and 0.04 for both real and imaginary tippers) and by using an inversion result of only TM mode and tipper as starting model for the final joint inversion of all three transfer functions.

The next profile CZ-SI (after the towns Czestochowa and Siedlce, no. 4 on Fig. 4) comprises five stations distributed over a length of 200 km on a line running roughly 60 km south of Lodz and Warsaw. The LMT data were measured in 2012 and processed, again, with Egbert & Booker (1986). One station had serious problems with data quality. For the complete dataset, transfer functions below a few hundred seconds hint at another strike direction than longer periods, where it amounts, again, to N15°W. Hence only transfer functions (TE mode and tipper) >300s were subjected to a two-dimensional inversion by means of the REBOCC code after appropriate rotation. The final model had an RMS of 7.39 per cent which sounds much but is partly a result of the rather strict error floor (10 per cent for apparent resistivities, 3° for phases, 0.03 for tippers), and bad fitting concerns apparent resistivities much more than phases and tippers. The large station distance, the missing short-period range, and the data quality problems led to a model that is less informative than the other ones presented here (note that the uppermost 10 km are not resolved and not shown here), but the difference to the previous model (see next section) is constrained.

The last profile named C05 (no. 5 in Fig. 4) was measured in 2006. Five LMT stations were distributed over 180 km along a line some dozens of km off the Polish-Ukrainian border. The data were processed with a code described in Korepanov et al. (2014) and checked with Egbert & Booker (1986) and Egbert (1997), transfer functions were rotated accordingly to the strike direction of N30°W. Two-dimensional inversion of all three transfer functions was carried out with the REBOCC code and converged well with a final RMS of 1.07 after operations to down-weight the influence of the TE mode similarly as described for the first model.

All models shown in Fig. 4 (with the exception of CZ-SI) show shallow, high-conductive surface layers that can be assigned to the sediments. These contain a known aquifer of high salinity that extends through the whole North-German-Polish Basin (cf. Neska 2016 and citations therein). In lower crustal to upper mantle depth we find high (several hundred Ωm) to very high (up to 10,000 Ωm) resistivity values. Their lateral differences and their interruptions by deep-reaching areas of moderate resistivity deserve further consideration which, however, exceeds the scope of this work. Most interesting in terms of the question whether Pomeranian structures do continue in the new models are mid-crustal conductors with resistivity values not higher than about 2 Ωm. Such low resistivities are most likely due to a combination of ionic and electronic conduction. The latter is (if of larger scale) bound to an interconnected network of graphite or pyrrhotite which can develop from an original material rich in alum or black shale under metamorphic conditions of a collision zone and in the middle crust (Schafer 2011 and citations therein). Such a high-conducting structure that is indicative of a tectonic collision is undoubtedly present in the diagonal profile, it is (at most) slightly indicated in CZ-SI, and it is absent in C05. Implications are discussed in the next section.

3. Discussion, Conclusions, and Outlook

The prominent high-conductive anomaly in mid-crustal depth associated with the TESZ in Pomerania remains visible on the mid-Polish profile with very similar depth (10-20 km) and resistivity values (< 2 Ωm). This suggests that the underlying tectonic structure is of the same nature

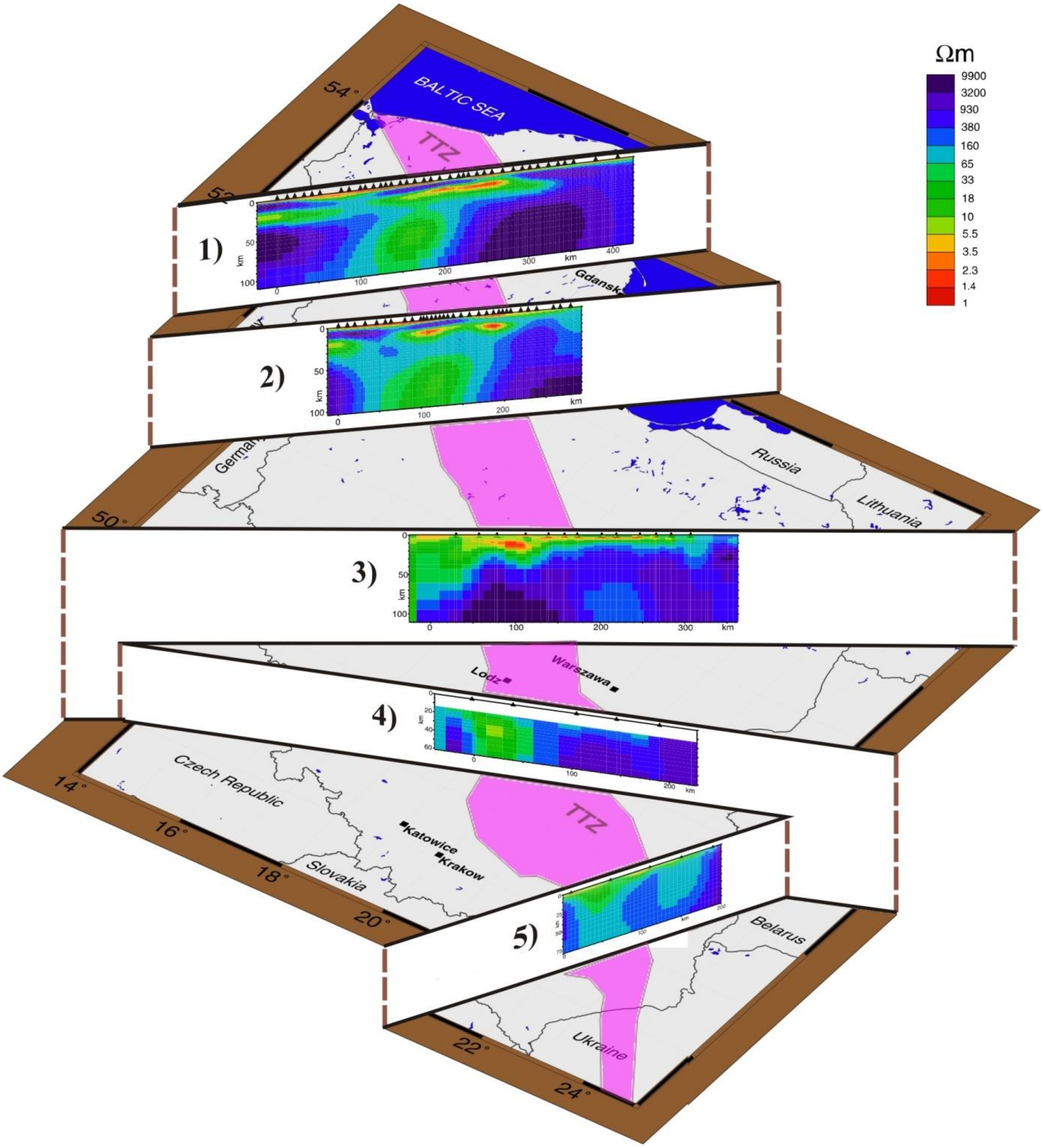

Figure 4 Two-dimensional models of electrical resistivity related to their location in Poland and to the Teisseyre-Tornquist-Zone (TTZ, in pink color) according to Fig. 1. The models LT7 (1) and P2 (2, both after Ernst et al. 2008), mid- or diagonal Polish one (3), CZ-SI (4), C05 (5) have equal resistivity and vertical scales. Note the spatial coincidence of the NE boundary of the TTZ with conductive mid-crustal zones for (1) and (2) and the slight deviation between them for (3), (4), and (5).

in both places, which is what one would expect from the known tectonic picture. In central Poland the anomaly appears relatively focused, whereas it has a laterally relatively extended, even bimodal, structure in Pomerania (where, however, a model regularization that promotes horizontal smoothing has been used, Ernst et al. 2008). This double anomaly can be interpreted as connected to two orogenic events or their remnants, the NE one to the Caledonian Deformation Front and the southern one to the Variscan Deformation Front following Jozwiak (2012) and Narkiewicz & Dadlez (2008). The convergence of both deformation lines in central Poland suggested by the singular anomaly is in accordance with expectations from the general tectonic picture. Another interesting point is that above the anomaly, resistivity is enhanced in comparison to the horizontal surrounding. This can be explained as a consequence of salt tectonics, which is characteristic of this part of the Polish Basin, during a later geologic epoch. Details will be treated in a separate work.
The next profile to the SE referred to as CZ-SI shows another picture. A zone of enhanced conductivity is present in a location (to the W of the model) not conflicting with an interpretation as a continuation of the previously discussed anomalies. On the other hand, its depth (~30 km) and resistivity (5-10 Ωm) characteristics is too different to reflect just the same 2D structure intersected in another place. Comparison with the mapped conductivity anomaly pattern (Fig. 5) rather suggests that this conductive zone could be the end of the anomaly (or anomalies) encountered to the NW. To settle this and to overcome the problems about the deviating strike direction at short periods a three-dimensional study of this area is necessary. This remains a task for the near future.

The model to the SE (C05) is characterized by a trough-like structure with ~30 km depth and moderate resistivities of a few tens of Ωm. High-conductive layers are found only very close to surface. Thereby this model confirms the results of older, adjacent profiles on both sides of it (Adam et al. 1997, Pushkarev et al. 2007). According to this, very low resistivities of ~1 Ωm at mid-crustal depths as in NW and central Poland can be ruled out for this region.

Hence in NW to central Poland the TESZ is accompanied by prominent mid-crustal conductivity anomalies and in the SW only by moderate ones. A further difference between both regions comprises the relation to the tectonic model that is based on seismics. The TESZ according to seismic models (e.g., Blundell et al. 1992, Guterch et al. 2003 and citations therein) and the TESZ indicated by the position of conductivity anomalies coincide spatially very well in Pomerania (Fig. 4). In central and SW Poland there is a slight but systematic deviation between both zones. The zones of enhanced conductivity lie within the "seismic" TESZ, but not directly in front of the presumed EEC boundary as in the NW. The distance between both patterns amounts to ~80 km on the mid-Polish profile (for comparison, the maximal difference between this border after various authors is just under 50 km, in Grad & Polkowski 2015) and it does not decrease to the SE. Generally speaking, the slight sinistral turn that the seismic TTZ performs between Warsaw and the Holy Cross Mountains (the latter are marked with brown color in Fig. 1) is not observed in the running of mid-crustal conductive zones. Interestingly, this area is in gravity (Malopolska High, Krolikowski 2006) and magnetic maps (Petecki et al. 2003) characterized by strong positive anomalies which are indicative of a magmatic intrusion. Similar anomalies visible on the EEC in NW Poland are interpreted as caused by Vendian (i.e. Precambrian) rifting magmatism (Krolikowski 2006). On the other hand, seismic authors describe this area as a sedimentary basin filled with up to 10 km thick sediments and sometimes refer to it as the Lublin Basin[1] (in Grad & Polkowski 2015) which, astonishingly, does not influence the resistivity pattern imaged by induction arrows (Fig. 2) and the HMT (Fig. 5). This means that the pleasant situation of Pomerania, where various geophysical results allow for a consistent tectonic interpretation, does not simply continue. Rather the pictures delivered by various geophysical methods in central to SW Poland demand another way of tectonically relevant integration than in the NW. Another light is shed on the tectonic interpretation of the TTZ by Berthelsen (1998) and Mazur et al. (2015) who suggest that the (seismic) TTZ is a Precambrian intra-EEC suture and the proper Caledonian suture between EEC and Paleozoic Europe is situated much more to the west and not as evident in seismic sections due to thick younger sediments.

From a magnetotelluric point of view we can say that, if the TTZ was marked in accordance with the resistivity pattern instead of seismic velocities, the resulting picture in central and SE Poland would be different and much more similar to the division suggested by the magnetic map (Fig. 3).

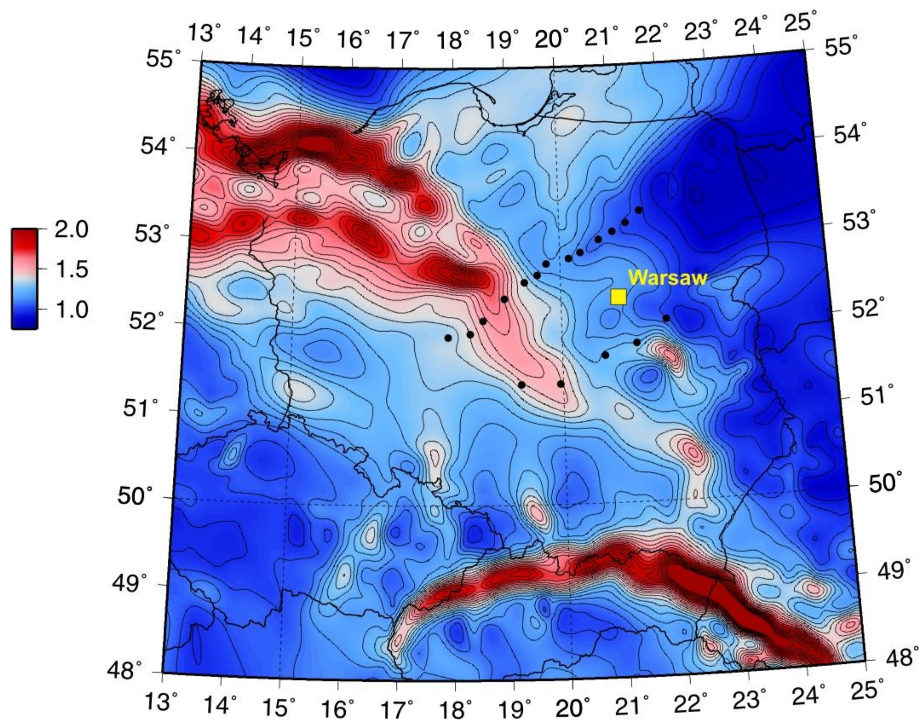

Figure 5 Amplitude of the maximum eigenvalue of the Horizontal Magnetic Tensor (HMT, Jozwiak 2012) at 1800s for Poland. Black points are stations of the diagonal and CZ-SI profiles (3 and 4 in Fig. 4). Note that the running of the well-conducting anomaly that extends from NW to central and SE Poland (red and light-red colors) differs from the northern margin of the TTZ (cf. Fig. 1) at latitudes of both profiles.

[1] Note that the according to our knowledge original, or underlying, tectonic outline of Central Europe by Berthelsen (http://www.oberrheingraben.de/Tektonik/Karte%20Gebirgsbildungen%20Europa.htm) does not interpret this region south of Warsaw as either Precambrian or Paleozoic basement, but describes it only in terms of seismics (i.e., greater Moho depth) and later tectonic events (Upper Cretaceous-Paleocene basin uplift).

Acknowledgements

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References

Ádám, A., Ernst, T., Jankowski, J., Jozwiak, W., Hvozdara, M., Szarka, L., Wesztergom, V, Logvinov, I., and Kulik, S. (1997), Electromagnetic induction profile (PREPAN95) from the East European Platform (EEP) to the Pannonian Basin, *Acta Geodaetica et Geophysica Hungarica* **32**, 203-223.

Berthelsen, A. (1998), The Tornquist Zone northwest of the Carpathians: an intraplate pseudosuture, *GFF* **120**, 223-230, doi: 10.1080/11035899801202223.

Blundell, D. J., Freeman, R., Mueller, S., and Button, S., eds. (1992), A Continent Revealed: The European Geotraverse, Structure and Dynamic Evolution. Cambridge University Press.

Dadlez, R. (2000), Pomeranian Caledonides (NW Poland), fifty years of controversies: a review and a new concept, *Geol Quart* **44 (3)**, 221-236.

Egbert, G.D. and Booker, J.R. (1986), Robust estimation of geomagnetic transfer functions, *Geophysical Journal of the Royal Astronomical Society* **87**, 173-194.

Egbert, G.D. (1997), Robust multiple-station magnetotelluric data processing, *Geophys J Int* **130**, 475–496.

Ernst, T., Brasse, H., Cerv, V., Hoffmann, N., Jankowski, J., Jozwiak, W., Kreutzmann, A., Neska, A., Palshin, N., Pedersen, L. B., Smirnov, M., Sokolova, E., and Varentsov, I. M. (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.

Grad, M. and Polkowski, M. (2015), Seismic basement in Poland, *Int J Earth Sci (Geol Rundsch)*, doi: 10.1007/s00531-015-1233-8.

Guterch, A., Grad, M., Spicak, A., Bruckl, E., Hegedus, E., Keller, G.R., Thybo, H., and CELEBRATION 2000, ALP 2002, SUDETES 2003 Working Groups (2003), An Overview of Recent Seismic Refraction Experiments in Central Europe , *Stud. Geophys. Geodet.* **47**, 651-657.

Guterch, A. and Grad, M. (2006), Lithospheric structure of the TESZ in Poland based on modern seismic experiments, *Geol Quart* **50(1)**, 23-32.

Janik, T., Yliniemi, J., Grad, M., Thybo, H., and Tiira, T. (2002), Crustal structure across the TESZ along POLONAISE'97 seismic profile P2 in NW Poland, *Tectonophysics* **360**, 129-152, doi: 10.1016/S0040-1951(02)00353-0.

Jankowski, J., Ernst, T., and Jóźwiak, W. (2004), Effect of thin near-surface layer on the geomagnetic induction arrows: An example from the East European Platform, *Acta Geophysica Polonica* **52 (3)**, 349-361.

Jozwiak, W. (2012), Large-Scale Crustal Conductivity Pattern in Central Europe and Its Correlation to Deep Tectonic Structures, *Pure and Applied Geophysics* **169**, 1737-1747.

Korepanov, V., Ladanivskyy, B., and Leonov, S. (2014), New user-friendly program for field data processing, Extended Abstract, 22nd Electromagnetic Induction Workshop, Weimar, Germany, 24 – 30 August 2014.

Królikowski, C. (2006), Crustal-scale complexity of the contact zone between the Palaeozoic platform and the East-European Craton in the NW Poland, *Geol Quart* **50**, 33–42.

Maus, S., Rother, M., Holme, R., Luhr, H., Olsen, N., and Haak, V. (2002), First scalar magnetic anomaly map from CHAMP satellite data indicates weak lithospheric field, *Geophys Res Lett* **29(14)**, doi: 10.1029/2001GL013685.

Mazur, S., Mikolajczak, M., Krzywiec, P., Malinowski, M., Buffenmyer, V., and Lewandowski, M. (2015), Is the Teisseyre-Tornquist Zone an ancient plate boundary of Baltica?, *Tectonics* **34 (12)**, 2465–2477, doi: 10.1002/2015TC003934.

Narkiewicz, M., and Dadlez, R. (2008), Geological regional subdivision of Poland: general guidelines and proposed schemes of sub-Cenozoic and sub-Permian units, *Prz. Geol.* **56**, 391–397, in Polish with English abstract.

Neska, A. (2016), Conductivity Anomalies in Central Europe, *Surveys in Geophysics* **37 (1)**, 5-26, doi: 10.1007/s10712-015-9349-8

Petecki, Z. (2001a), Magnetic evidence for deeply buried crystalline basement southwest of the Teisseyre-Tornquist Line in NW Poland, *Acta Geoph Pol.* **4**, 509–515.

Petecki, Z. (2001b), Charakter i geometria podloza magnetycznego NW Polski, Panstw. Inst. Geol., Centr. Arch. Geol. Warszawa.

Petecki, Z., Polechonska, O., Ciesla, E., and Wybraniec, S. (2003), Magnetic map of Poland, scale 1:500,000, Pol Geol Ins, Warsaw.

Pushkarev, P. Yu., Ernst, T., Jankowski, J., Jozwiak, W., Lewandowski, M., Nowozynski, K., and Semenov, V.Yu. (2007), Deep resistivity structure of the Trans-European Suture Zone in Central Poland, *Geophys J Int* **169**, 926-940.

Schäfer, A., Houpt, L., Brasse, H., Hoffmann, N., and EMTESZ Working Group (2011), The North German Conductivity Anomaly revisited, *Geophys J Int* **187**, 85-98, doi: 10.1111/j.1365-246X.2011.05145.x.

Siripunvaraporn, W. and Egbert, G. (2000), An efficient data-subspace inversion method for 2-D magnetotelluric data. *Geophysics* **65(3)**, 791-803.

Tornquist, A. (1908), Die Feststellung des Südwestrandes des baltisch-russischen Schildes und die geotektonische Zugehörigkeit der ostpreussischen Scholle, *Schriften der Phys.-Ökonomischen Gesellschaft* **49 (1)**, 1–12, Königsberg.

Van Wees, J.D., Stephenson, R.A., Ziegler, P.A., Bayer, U., McCann, T., Dadlez, R., Gaupp, R., Narkiewicz, M., Bitzer, F., and Scheck, M. (2000), On the origin of the southern Permian Basin, Central Europe, *Marine Pet Geol* **17(1)**, 43-59.