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Upper mantle structure around the Trans-European Suture Zone obtained by teleseismic tomography

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Abstract

The presented study aims to resolve the upper mantle structure around the Trans-European Suture Zone (TESZ) which is the major tectonic boundary in Europe. The data of 183 temporary and permanent seismic stations operated during the period of the PASsive Seismic Experiment PASSEQ 2006–2008 within the study area from Germany to Lithuania was used to compile the dataset of manually picked 6008 top quality arrivals of *P* waves from teleseismic earthquakes. We used the non-linear teleseismic tomography algorithm TELINV to perform the inversions. As a result, we obtain a model of *P* wave velocity variations up to about ±3 % compared to the IASP91 velocity model in the upper mantle around the TESZ. The higher velocities to the east of the TESZ correspond to the older East European Craton (EEC), while the lower velocities to the west of the TESZ correspond to younger Western Europe. We find that the seismic lithosphere-asthenosphere boundary (LAB) is more distinct beneath the Phanerozoic part of Europe than beneath the Precambrian part. To the west of the TESZ beneath the eastern part of the Bohemian Massif, the Sudetes Mountains and the Eger Rift the negative anomalies are observed from the depth of at least 70 km, while under the Variscides the average depth of the seismic LAB is about 100 km. We do not observe the seismic LAB beneath the EEC, but beneath Lithuania we find the thickest lithosphere of about 300 km or more. Beneath the TESZ the asthenosphere is at a depth of 150–180 km, which is an intermediate value between that of the EEC and Western Europe. The results imply that the seismic LAB in the northern part of the TESZ is of a shape of a ramp dipping to the NE direction. In the southern part of the TESZ the LAB is shallower, most probably due to younger tectonic settings. In the northern part of the TESZ we do not recognize any clear contact between Phanerozoic and Proterozoic Europe, but further to the south we may refer to a sharp and steep contact on the eastern edge of the TESZ. Moreover, beneath Lithuania at the depth of 120–150 km we observe the lower velocity area following the boundary of the proposed palaeosubduction zone.

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1 Introduction

1.1 Tectonic settings

The Trans-European Suture Zone (TESZ) is the most fundamental lithospheric boundary in Europe (Pharao, 1999) which marks a transition between the old Proterozoic lithosphere of the East European Craton (EEC) and the younger Phanerozoic lithosphere of Central and Western Europe. The EEC, the Baltica segment, to the east of the TESZ comprises three palaeocontinents: Sarmatia, Volgo-Uralia and Fennoscandia (Bogdanova et al., 2006) with significant sutures in between them. The territories in the NE part of the EEC consist of several Svecofennian crustal units, such as the Belarus–Podlasie Granulite Domain (BPG), the East Lithuanian Domain (EL) and the West Lithuanian Granulite Domain (WLG), which continue NE–SW direction into Poland and terminate at the TESZ (Bogdanova et al., 2006). The area in between the EL and the WLG is called the Middle Lithuanian Suture Zone (MLSZ) which was interpreted as a palaeosubduction zone along which the EL subducted under the WLG about 1.83 Ga (Motuza, 2004, 2005; Motuza and Staškus, 2009).

To the west of the TESZ the structure of the lithosphere is much more complex compared to the lithosphere of the EEC (Dadlez et al., 2005; Knapmeyer-Endrun et al., 2013a; Babuška and Plomerova, 2001). The territories in Central-Western Europe consist of various continental fragments that were subsequently rifted off the northern margin of Gondwana and accreted to the SW margin of the Precambrian Baltica during the number of orogenic events (Nolet and Zielhuis, 1994; Pharaoh, 1999; Winchester and the PACE TMR Network Team, 2002; Banka et al., 2002). The TESZ contains two pronounced linear segments: the Sorgenfrei–Tornquist Zone (STZ) in the NW part of the TESZ between Sweden and Denmark–Germany, and the Teisseyre–Tornquist Zone (TTZ) stretching from the Baltic Sea in the NW to the Black Sea in the SE (Fig. 1). The territories around the TESZ have formed during four major geological stages: (1) Caledonian collision tectonics, (2) Variscian orogeny, (3) Mesozoic rifting, and (4) Alpine orogenic events (Bogdanova et al., 2007; Thybo, 2000). During the Cambrian period terrains of Lysogory, Malopolska and Bruno-Silesian accreted to Baltica forming Southern Poland and the eastern edge of the Bohemian Massif (Belka et al., 2000). During the Caledonian orogeny the Avalonian segment closing the Tornquist Ocean accreted to the eastern margin of Baltica (Pharaoh, 1999). The Variscan orogeny from the late Silurian to early Carboniferous resulted in a junction of three paleomicrocontinents: Saxothuringian, Moldanubian and Tepla-Barrandian, in the territory of Vogtland and NW Bohemia (Franke and Zelazniewicz, 2000). The Saxothuringian is juxtaposed against the Moldanubian in a broad contact indicating a paleosubduction of the Saxothuringian, possibly with a piece of oceanic lithosphere beneath the Moldanubian (Plomerova et al., 1998). The "triple junction" resulted in the crust and lithosphere thinning as well as the tectono-sedimentary evolution of the Cheb Basin situated above the junction. The basin formed between the late Oligocene and Pliocene by reactivation of the Variscan junction of the three lithospheric blocks (Babuška et al., 2007). During the Cretaceous to Cenozoic periods a number of terrains accreted to Western Europe resulting the Alpine and Carpathian orogenies. During the middle to late Eocene rifting processes took place in Central Europe followed by the quaternary volcanism (Wagner et al., 2002; Babuška et al., 2007) which was possibly related to an upper mantle reservoir (Babuška and Plomerova, 2001; Zhu et al., 2012). The developed Tertiary Eger Rift continues 300 km in ENE–WSW direction and follows the late Variscan mantle transition between the Saxothuringian and the Tepla-Barrandian.

1.2 Review of previous studies

Due to long evolution and complex tectonic structure the TESZ and the surrounding territories have always been a subject of great interest in geosciences. The structure of the crust and uppermost mantle around the TESZ has been studied intensively during the controlled-source seismic experiments – long-range deep seismic sounding (DSS) profiles (e.g. Guterch et al., 1999; Grad et al., 2002; Guterch et al., 2004; Grad et al., 2006; EUROBRIDGE Seismic Working Group, 1999; Pharaoh et al., 2000). The obtained results show large variations of average thickness of the continental crust: the

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Moho depth varies from 28–35 km beneath the Palaeozoic Platform (Guterch and Grad, 1996; Pharaoh et al., 1997; Guterch et al., 1999) to 40–50 km beneath the western part of the EEC adjoining the TESZ and even more further to the NE (Grad et al., 2006; Guterch et al., 2004). The projects provided sufficient information about the crustal structure around the area, which was used to compile some precise 3-D crustal models (e.g. Majdanski, 2012). Using data of the DSS projects the EUROBRIDGE Working Group (1999), Czuba et al. (2001), Yliniemi et al. (2004), Grad et al. (2002) and Thybo et al. (2003) found some reflectors in the upper mantle just beneath the Moho going down to 75 km in the Fennoscandia, which could be related to different crustal units. Similar subhorizontal lithospheric reflectors were observed beneath the TESZ (Grad et al., 2002; Guterch et al., 2004) and the Baltic Sea (Hansen and Balling, 2004). However, the depth of resolution of the DSS profiles is usually limited to about 50–80 km.

Compared to the crust, the structure of the lithosphere and the lithosphere-asthenosphere boundary (LAB) in the TESZ and its surrounding is poorly known. While it was found that the cratonic lithosphere extends much deeper than that of the younger continental regions (e.g. Plomerova et al., 2002; Eaton et al., 2009; Shomali et al., 2006; Gregersen et al., 2010), the studies revealed that the structure of lithosphere and the LAB differs a lot on both sides of the TESZ (e.g. Majorowicz et al., 2003; Artemieva et al., 2006; Koulakov et al., 2009; Wilde-Piórko et al., 2010). Regarding different physical properties and geophysical techniques the LAB has different practical definitions: (1) the seismic LAB defines transition between the solid outer layer of the Earth, which is characterized by higher seismic velocity values, and its low-viscous interior, which is characterized by lower seismic velocity values, (2) the thermal LAB defines transition between outer layer with dominating conductive heat transfer above the convective mantle which usually coincides with a depth of a constant isotherm of about 1300 °C (McKenzie, 1967), (3) the electrical LAB is a transition between generally electrically resistive outer layer of the Earth and conductive layer in the upper mantle.

The studies by Majorowicz et al. (2003) and Artemieva et al. (2006) based on global tomography and heat flow measurements indicate that beneath the EEC the thickness

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of thermal lithosphere is about 180–200 km, while the thickness of the seismic lithosphere is more than 250 km. Even deeper – down to at least 300 km – the positive *P* wave velocity anomaly is found beneath the EEC by Koulakov et al. (2009). Legendre et al. (2012) find no indications for a deep cratonic root below about 330 km for the EEC, while Geissler et al. (2010) do not observe any clear indications of deep seismic LAB beneath the EEC either.

In Central-Western and Northern Europe the passive seismic project TOR 1996–1997, which was carried out across the STZ, provided a detailed model of the upper mantle and the LAB (Gregersen et al., 1999; Plomerova and Babuska, 2002; Shomali et al., 2006; Artlitt, 1999; Cotte et al., 2002). The results show that the average thickness of the seismic lithosphere is about 100 km in Central Europe which coincides with global tomography studies by Artemieva et al. (2006) and the studies of *S* receiver functions by Geissler et al. (2010). The results obtained from the TOR data indicate that beneath the TESZ the thickness of seismic lithosphere is about 120 km, which is an intermediate value between that of the EEC and Western Europe (Shomali et al., 2006; Wilde-Piórko et al., 2010) while the transition beneath the STZ is near-vertical with only a weak tendency to the NE slope (Gregersen et al., 2010). Geissler et al. (2010) indicate the lithosphere thickness of about 115–130 km in the vicinity of the TESZ, while the LAB beneath the SW part of the Variscan Bohemian Massif is estimated at the depth of 115 km, and the thin lithosphere of only about 75 km is reported beneath some parts of the Pannonian Basin. Beneath the Bohemian Massif an extensive low-velocity heterogeneity in the upper mantle is found (Koulakov et al., 2009; Karousova et al., 2013), while the high-resolution tomography studies indicate the most distinct low-velocity perturbations along the Eger Rift down to about 200 km (Karousova et al., 2013). Plomerova et al. (2007) interpret the broad low-velocity anomaly beneath the Eger Rift by an upwelling of the LAB. The authors also find different orientations of seismic anisotropy corresponding to the major tectonic units in the Bohemian Massif (i.e. Saxothuringian, Moldanubian and Tepla-Barrandian), while the studies of shear-wave splitting (e.g. Wüstefeld et al., 2010; Vecsey et al., 2013; Sroda et al., 2014) show that anisotropy in the Bohemian Massif, is higher compared to the anisotropy observed in the TESZ and even smaller, but still noticeable, for the EEC (Plomerova et al., 2008).

Jones et al. (2010) performed comparison between the delineation of the LAB for Europe based on seismological and electromagnetic observations and concluded that the LAB, as an impedance contrast from receiver functions, as a seismic anisotropy change and as an increase in conductivity from magnetotellurics, are consistent with the deeper LAB beneath the EEC and the shallower LAB beneath Central Europe, which coincides with conclusions by Korja (2007) who made a review of previous studies of magnetotelluric imaging of the European lithosphere. Jones et al. (2010) found that the seismic and electric LABs beneath the Phanerozoic Europe are at the depth of about 90–100 km, while for the EEC they differ and the electric LAB is at the depth of about 250 km. The studies also show anomalously thick electrical LAB beneath the TESZ, whereas the seismic LAB should be much shallower. The authors imply that the difference could be caused by increased partial melting or of by hydration beneath the TESZ.

An opportunity to enhance knowledge on the lithosphere structure and the LAB around the TESZ was implemented during the international PASsive Seismic Experiment PASSEQ 2006–2008 (Wilde-Piórko et al., 2008) which aimed to study lithosphere and asthenosphere around the TESZ. The aim of this study is to obtain a model of the upper mantle and the seismic LAB on regional scale around the TESZ using data from the seismic stations operated in the region during the PASSEQ project and the method of teleseismic tomography.

2 Dataset

The PASsive Seismic Experiment PASSEQ 2006–2008 (Wilde-Piórko et al., 2008) was carried out from June 2006 to July 2008 in the territory extending from Germany throughout the Czech Republic and Poland to Lithuania where 139 short-period and 49 broadband temporary seismic stations were deployed (Fig. 2). In this study we use

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data of the PASSEQ project and of some permanent seismic stations operated in the area during the period of the PASSEQ project. Although there were over 200 seismic stations deployed in the region, due to some technical peculiarities in total we used data of 183 seismic stations. From the seismological bulletins of the US Geological Survey (USGS) and the International Seismological Centre (ISC) we selected 101 teleseismic earthquakes (EQs) with magnitude range of 5.5 to 7.2 and epicentral distance of 30° to 92° with respect to the point at the Lithuanian–Polish border at 23° E and 54° N (Appendix Table A1). The majority of the selected EQs are located to the east of the target area (i.e. Sumatra, Japan, Kamchatka and Aleutian regions) due to naturally higher seismicity compared to the regions to the west from the study area, thus, the largest seismic gap of about 45° is for the region of Africa and southern part of the Atlantic Ocean (Fig. 3). Using the Seismic Handler Motif (SHM) (http://www.seismic-handler.org/) program package we analyzed the data and compiled a dataset of 6008 manually picked top quality *P* wave arrivals with evaluated picking error of < 0.2 s.

The calculation of theoretical travel times (TT) of the *P* wave arrivals was performed using the EQ location information from the ISC seismological bulletins and Seismic Handler (SH) program which applies the IASP91 velocity model. The TT residuals were calculated as follows:

$$T_{\text{picked}} - T_{\text{theoretical}} = T_{\text{residual}} \quad (1)$$

where T_{picked} is the observed TT, $T_{\text{theoretical}}$ is the theoretical TT calculated with SH, and T_{residual} is the TT residual. While plotting the values of calculated TT residuals we observe the higher values to the west and the lower ones to the east from the TESZ (Fig. 4) which might be related with different tectonic-geological settings.

3 Teleseismic tomography inversion method

We used the non-linear teleseismic tomography code TELINV (Voss et al., 2006) to perform the inversions. The code is an iterative process where each iteration involves a complete one-step inversion, including both ray tracing and model estimations. Iterations stop when the model ceases to change significantly and the rout-mean-square (RMS) difference between predicted and observed TT residuals is comparable to data variance. The method in details is explained in Thomson and Gubbins (1982), Thurber (1983), Menke (1984), Koch (1985) and Aki et al. (1997).

4 Model parameterization

Our study area is shown in Fig. 2. The spacing between the grid nodes determines resolution of the inversion. Regarding the seismic signal frequency and spacing between the seismic stations, we set spacing of 50 km between the grid nodes in horizontal directions. The 1-D IASP91 velocity model (Kennett and Engdahl, 1991) was used to parameterize the 3-D velocity model with 16 layers of different thicknesses down to 700 km. The inversion was performed for ten layers between 70 and 350 km.

We performed a thorough analysis in order to select optimal inversion parameters for smoothing Θ, damping $\mathbf{D}$ and number of iterations. The smoothing was set to 50. The damping value was determined while running inversions with different values of damping and investigating trade-off between the data variance and model variance (Fig. 5). Here we present results obtained using damping value of 120. We also found that three iterations are enough for inversion, because for higher number of iterations the model and the RMS error change insignificantly.

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5 Crustal travel time corrections

As discussed previously (see Sect. 1.2), the structure of the crust in the study area varies significantly, as well as the thickness of the sedimentary cover, which is up to about 20 km in the Polish Basin. In order to obtain the upper mantle structure it is important to remove the effects which are created by the Earth's crust from the inversion results. The crustal TT corrections for individual seismic stations were compiled as following:

$$TT_{\text{model}} - TT_{\text{iasp}} = TT_{\text{diff}} \tag{2}$$

where TT_{model} is TT through the crustal velocity model, TT_{iasp} is TT through the IASP91 velocity model, and TT_{diff} is TT difference. We used two sets of the crustal TT corrections: (1) the first set was compiled using the EuCRUST-07 (Tesauro et al., 2008) 3-D crustal model for Europe with model grid of $1^\circ \times 1^\circ$, (2) the second set was compiled using the precise 3-D crustal model for Poland (Majdański, 2012) with model grid of 0.3° of latitude and 0.5° of longitude, and results of some DSS profiles. The territories not covered by the model by Majdański (2012) were assigned with constant values that were estimated using the interpreted results (full velocity profiles) below the shot point SP9 in the EUROBRIDGE'95 profile and the shot point SP2 in the CELEBRATION09 profile. The value obtained from the EUROBRIDGE'95 profile was used for the stations deployed in Lithuania, and value obtained from the CELEBRATION09 profile was used for the stations deployed in Germany and the Czech Republic (the constant depths of the Moho boundary of 50 km and 32 km, respectively, were assigned as well) (Fig. 6a). The crustal TT corrections were calculated assuming the vertical ray propagation in the crust. Regarding the incidence angles in our dataset, the assumed vertical propagation in the crust causes $< 2\,\%$ shortening of the raypaths, thus, the effect in the results on velocity amplitudes is negligible.

In order to estimate the effect of the crustal TT corrections on the velocity amplitudes we performed inversion with the field dataset without and with the crustal corrections

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applied (Fig. 7). The inversion results with the EuCRUST-07 model show artificially high signal amplitudes, especially around the TESZ where thickness of the sediments is significantly larger compared to the surroundings (Fig. 7b), thus, we concluded that this set of the crustal corrections is not applicable in our study. The inversion results obtained with the second set of crustal TT corrections based on the crustal model by Majdański (2012) (Fig. 7c) do not reproduce the shape of the thick sediments in the TESZ like it is obvious in Fig. 7b, but shows two distinct structures on both sides of the TESZ. Compared to the results obtained without (Fig. 7a) and with (Fig. 7c) the crustal TT corrections we indicate a major difference, as expected, beneath the northern and central part of the TESZ due to large sedimentary basin, while we observe no obvious artifacts in the results. Thus, we concluded that this set of the crustal TT corrections is reasonable for our study.

6 Resolution and synthetic tests

To estimate resolution of the inversion results we use the hit matrix and the checkerboard test. The hit matrix is based on calculation of the number of rays which transverse a particular cell. The inversion with the synthetic checkerboard model shows which parts of the target area can be and cannot be resolved with the same configuration as the observed dataset. In our study we compiled the synthetic velocity model of checkerboard structure with blocks of 200 km in horizontal directions and four layers thick with ±4 % velocity difference compared to the IASP91 velocity model (Fig. 8a). The synthetic dataset was compiled by adding small random perturbations to each observed TT. The inversion results obtained with the synthetic dataset show reasonably well resolved checkerboard-type structure (Fig. 8b). However, in the vertical slices in Fig. 8b we observe the vertical smearing dipping to the east which is most likely due to the majority of rays coming from the regions located to the east of the study area (Fig. 3). Moreover, the synthetic structure in the western part is better resolved than in the eastern part (Fig. 8b) due to the larger number of top quality picked *P* wave arrivals in the data of the stations deployed to the west from the TESZ. A further estimate of the resolution is derived from the diagonal elements of the resolution matrix (Fig. 9) which provides a relative measure of the resolution: the low values show areas of low resolution and the high values show areas of high resolution. The horizontal slice at the depth of 90 km (Fig. 9) shows that areas directly below the seismic array are better resolved compared to the areas which are not underneath the array. The horizontal slice (Fig. 9) indicates that the values of higher resolution coincide with areas of the better station coverage (i.e. the larger number of picks in the dataset) in the southwestern part of the study area. The vertical slice along the main transect (Fig. 9) shows the highest resolution in this area as well down to 300 km, while the high resolution observed at the bottom along the entire transect is an artifact from the inversion and should be ignored.

Based on the previous geophysical and petrophysical studies (Wilde-Piórko et al., 2010; Griffin et al., 2003), we compiled a synthetic 3-D velocity model with geologically possible structure. The main features of our synthetic "geological" velocity model (Fig. 10a) are: (1) the lower and the higher seismic velocities to the west and to the east from the TESZ, respectively, (2) the shape of the LAB of a ramp type dipping to the NE direction, and (3) the deep cratonic roots for the EEC (in the NE part of the study area). Small random TT perturbations were added to the synthetic TT. The inversion result obtained with the synthetic dataset (Fig. 10b) shows the lower and the higher velocity areas to the west and to the east from the TESZ, respectively. In the results we also observe the clear ramp shape of the LAB and the higher velocity anomaly at the bottom of the velocity model in the NE part of the study area (Fig. 10b).

7 Results and discussion

As shown by numerous seismic studies (e.g. Knapmeyer-Endrun et al., 2013b), the LAB in Precambrian cratonic areas is not easily detected by seismic methods and can be misinterpreted with the so-called Mid-Lithospheric Boundary (MLB). The nature of the latter is still not completely understood. However, the seismic LAB can be detected

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beneath the younger areas and traced across boundaries of the cratons in the passive seismic experiments that sample both cratonic and non-cratonic lithospheres. In our study we used the data of such passive seismic experiment and performed inversions with the compiled dataset of top quality *P* wave arrivals, and resolved structure of the upper mantle from 70 km down to 350 km in the study area. The obtained model of *P* wave velocity variations can be used to estimate the LAB and the lithosphere thickness around the TESZ.

In teleseismic tomography many factors contribute to the observed signal (velocity) amplitudes, such as damping value, implementation of the crustal TT corrections (about 1 % of the observed velocity contrast), temperature variations (up to 1 %) and anisotropy (about 0.5 %) in the study area, and distortions on the full raypaths outside the velocity model. Moreover, the used TELINV code implements the "flat-Earth" transformation which affects the apparent velocities. Regarding the size of our velocity model and the incidence angles in our dataset, the discrepancy due to the "flat-Earth" transformation is about 1.5 % of the observed amplitudes of velocity variations. In our results we observe amplitudes of velocity variations up to ±6.5 % compared to the IASP91 velocity model, however, taking into account all the above mentioned causes we should consider the signal amplitudes up to about ±3 %.

The inversion results with our field dataset show the higher *P* wave velocity values compared to the IASP91 velocity model beneath the EEC and lower ones beneath Western Europe, while the TESZ appears as a transitional complex tectonic structure with significant velocity perturbations in longitudinal and transversal directions (Fig. 10c). This general finding coincides with results by Koulakov et al. (2009) who reported on a sharp transition along the TESZ from the negative amplitudes, characterizing the young tectonic features of Central Western Europe, to positive ones beneath the old EEC. Moreover, we indicate that the LAB is more distinct beneath the Phanerozoic part of Europe than beneath the Precambrian part, which coincides with the results by Plomerova et al. (2010) and Knapmeyer-Endrun et al. (2013b).

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To the east of the TESZ a pronounced high velocity structure in the upper mantle is observed beneath Poland (Fig. 10c). The observed velocity perturbations down to about 120 km beneath Poland are about 2 to 3 % higher compared to the IASP91 velocity model, while going deeper the variations are slightly smaller which most likely indicates some effects due to the applied crustal TT corrections. The higher velocity values in this area are observed down to about 200 km, which coincides well with the studies by Wilde-Piórko et al. (2010), Majorowicz et al. (2003) and Koulakov et al. (2009). Legendre et al. (2012) found the highest velocity values in the mantle of the EEC at about 150 km depth. Further to the NE from the TESZ the high velocity area goes deeper, and beneath the territory of Lithuania we find the thickest lithosphere of about 300 km or more (Fig. 10c). Due to vertical smearing (Fig. 8), which is intrinsic to all tomography inversions, the observed higher velocity area associated with the deep cratonic roots could be extended to the layers deeper than it really is, however, our result is in a good agreement with other observations – the obtained value of thickness of lithosphere beneath the EEC is about 50 km larger compared to the global tomography results obtained by Artemieva et al. (2006), but coincides well with results obtained from *P* and *S* wave tomography by Koulakov et al. (2009) who find the *P* wave velocities up to 2 % higher extending to at least 300 km beneath Lithuania. Thick lithosphere extending to at least 250 km depth is also found beneath the central part of the Fennoscandian Shield (Sandoval et al., 2004), but they find no indications of the LAB anywhere within 300 km beneath the EEC (Bruneton et al., 2004; Geissler et al., 2010; Legendre et al., 2012). Our study does not show the seismic LAB beneath the EEC either. The study of the *S* receiver functions by Knapmeyer-Endrun et al. (2013b) indicate a negative conversion that could be related to a velocity decrease at 190 km to 230 km depth which is in agreement with the depth estimates for the cratonic LAB, however, the conversion was observed not in all analyzed seismic stations in the EEC, thus, the authors suggest that the stations might imply spatial variations in the sharpness of the corresponding velocity change.

In the NE part of the study area beneath Lithuania at the depth of 120–150 km we find the lower velocities compared to the surroundings following the MLSZ (Fig. 10c) – the predicted paleosubduction zone between the WLG and EL (Motuza, 2004, 2005; Motuza and Staškus, 2009). Our results (Fig. 11b) also indicates a slope of higher velocities dipping to the north which agrees with the model proposed by Motuza and Staškus (2009), that the EL subducted under the WLG. We infer that this feature indicates a slab of "frozen" palaeosubduction. The lower velocities observed below the slab along the predicted palaeosubduction edge could be related to increase in temperature.

We find an area of higher velocities in the lithospheric mantle down to about 210 km in the northern part of the TESZ (northern Poland) (Fig. 10c). Knapmeyer-Endrun et al. (2013a) observe an increase in TT of Ps-conversions across the mantle transition zone which could be caused either by a temperature reduction or an increase in water content in this mantle region. As we observe the higher velocities we propose that this anomaly could be related to thermal regime and temperature reduction. In general, the upper mantle of the northern TESZ is more of cratonic type, while going to the south the seismic velocities are lower.

Our results indicate the dominating negative velocity amplitudes to the west of the TESZ almost everywhere down to 350 km except in the territory of Northern Poland–Germany along the Rheic Suture where we find the higher velocity anomaly down to about 90–100 km, while closer to the TESZ the LAB is observed at the depth of about 120 km (Fig. 10c). The result is consistent with results obtained by Knapmeyer-Endrun et al. (2013b) and Wilde-Piórko et al. (2010) who indicate the average seismic lithosphere thickness of about 90 km, and associate the uplift of the LAB beneath Western Europe and the TESZ with partial melting of the upper mantle due to thermal conditions (Wilde-Piórko et al., 2010). Moreover, the studies of Shomali et al. (2006) and Gregersen et al. (2010) carried out using data of the TOR 1996–1997 passive seismic project indicate lithosphere thickness of about 100 km in Northern Germany, which coincides well with our results for this territory. The depth of the LAB of about 100 km is a common characteristic to the Phanerozoic regions (Plomerova et al., 2002).

The observation of the lower velocity values (Fig. 10c) compared to the IASP91 velocity model to the west of the TESZ coincides with results by Koulakov et al. (2009) who report the negative anomalies up to 4 % for this area. In our results the large lower velocity area of about −2 to −3 % compared to the IASP91 velocity model is observed beneath the Bohemian Massif and the rift systems in Central Europe (Fig. 10c). The lithosphere thinning of 80–90 km beneath the Armorican terrains of Saxothuringian, Tepla-Barrandian and Moldanubian is reported in studies by Babuška and Plomerova (2001). Karousova et al. (2013) find an extensive low-velocity heterogeneity in the upper mantle beneath the Bohemian Massif, while Koulakov et al. (2009) report a broad negative zone (−1 to −3 %) beneath the Central Rift System and the Bohemian Massif at the depth from 100 to 200 km. In our results we find the largest negative signal amplitudes under the NE part of the Bohemian Massif and the Sudetes Mountains from the depth of at least 70 km (Fig. 10c, 11a). Moreover, our results indicate lower velocity anomaly under the Eger Rift (Fig. 10c). Although the Eger Rift is a relatively small structure, our dataset is sufficient to resolve it, thus, we indicate the lower velocities from 70 km down to at least 180 km beneath it. This result is in a good agreement with results by Karousova et al. (2013) who indicate the most distinct low-velocity perturbations along the Eger Rift down to about 200 km, and Koulakov et al. (2009) who observe a low velocity zone (−2 %) in this area between about 80 and 250 km. Plomerova et al. (2007) interpreted the broad low-velocity anomaly beneath the Eger Rift as an uplift of the LAB.

The asthenosphere on the western edge and on the eastern edge of the TESZ is at the depth of about 150 km and 180 km, respectively. Moreover, the structure of the TESZ varies significantly going from the north to south (Fig. 10c). In the studies of Legendre et al. (2012) it is found that the mantle lithosphere beneath the TESZ shows moderately high velocities and is of an intermediate character between that of the cratonic lithosphere and the thin lithosphere of Central Europe. The studies carried out around the TESZ indicated a sharp discontinuity along the TESZ, but provided no strong evidence on the shape of the LAB beneath it due to lack of resolution (discussed in details in Knapmeyer-Endrun et al., 2013a). As we used a dense network of seismic stations (Fig. 2) (with average spacing of 60 km and spacing of 20 km along the main PASSEQ transect) we are able to resolve the shape of the LAB with higher precision. In the results (Fig. 11c) we indicate that in the northern part of the study area the higher velocities (which are associated with the seismic LAB) are observed deeper going to the NE direction, which shows the ramp-shape of the LAB. The angle of the deepening of the LAB is about 30° (Fig. 11c). In the northern part of the TESZ we do not recognize any separate structures or clear contact which could be related to the different tectonic settings of Phanerozoic and Proterozoic Europe, but further to the south we may refer to a sharp and steep contact on the eastern edge of the TESZ (Fig. 11c). In our "geological" synthetic model we introduced and reasonably resolved the ramp type LAB dipping to the NE direction as well (Fig. 10a and b) which is somehow similar to the results obtained with the field dataset (Fig. 10c). Gregersen et al. (2010) compared results of different studies performed using the data of the TOR project and concluded that the transition between the two tectonic settings on both sides of the STZ, is sharp and steep with a weak tendency to the NE slope. We indicate from our results (Fig. 11c) that further to the south the LAB is shallower and its shape changes most probably due to younger tectonic settings (i.e. Carpathian Mountains) in the region.

8 Conclusions

- The observed higher P wave velocity values to the east of the TESZ correspond to the older EEC and the lower ones to the west of the TESZ correspond to younger Western Europe. The TESZ is resolved as a complex structure with intermediate characteristics between those of the EEC and Western Europe.

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- We indicate that the LAB is more distinct beneath the Phanerozoic part of Europe than beneath the Precambrian part. The lower velocity anomalies from 70 km are observed under the Bohemian Massif, the Sudetes Mountains and the Eger Rift, while further north beneath the Variscides the depth of the LAB is about 100–120 km. Our study does not show the seismic LAB beneath the EEC, but beneath Lithuania we find the thickest lithosphere of about 300 km or more. In the TESZ the asthenosphere is at a depth of 150–180 km which is an intermediate value between that of the EEC and Western Europe.

- In the northern part of the TESZ the upper mantle is more of cratonic type. We infer that the LAB in the northern part of the study area is of a ramp type dipping to the NE direction at an angle of about 30°. Under the nothern part of the TESZ we do not recognize any contact between the Phanerozoic and the Proterozoic parts of Europe, but further to the south we may refer to a sharp and steep contact on the eastern edge of the TESZ. Going to the south the shape of a LAB beneath TESZ is changing and its depth is shallower most likely due to younger tectonic settings.

- Beneath Lithuania at the depth of 120–150 km we observe the low velocity area which follows the boundary of the proposed palaeosubduction zone between the EL and the WLG tectonic units.

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Table A1. List of 101 teleseismic EQs used in this study.

Year	Month	Day	Time UTC	Lat	Long	Depth	*M*
2006	6	18	18:28:00	32.9995	−39.7009	8.6	6.0
2006	6	22	10:53:11	45.3023	149.4132	104.3	6.0
2006	6	27	18:07:21	6.4781	92.7356	25.8	6.3
2006	6	27	2:39:33	52.1552	176.1572	28.3	6.2
2006	6	28	21:02:09	26.8361	55.806	15.1	5.8
2006	7	6	3:57:52	39.0233	71.7719	23.7	5.8
2006	7	8	20:39:57	51.1889	−179.264	3.2	6.6
2006	7	10	7:21:36	−11.5727	−13.4176	10	5.5
2006	7	12	14:44:44	−8.5692	67.8158	10	5.7
2006	7	27	11:16:40	1.7244	97.1295	30	6.3
2006	7	29	19:53:41	23.5288	−63.876	8.5	5.8
2006	8	6	14:26:17	37.4091	74.7119	4.9	5.6
2006	8	6	18:16:39	26.2558	143.9864	23	5.9
2006	8	11	14:30:39	18.4706	−101.135	58.4	6.1
2006	8	16	18:38:58	−28.8283	61.7726	10	5.9
2006	8	24	21:50:36	51.0679	157.5354	53.5	6.5
2006	9	1	12:04:21	53.9609	−166.361	75.6	5.9
2006	9	10	14:56:06	26.39	−86.5804	10	5.9
2006	9	24	22:56:21	−17.6967	41.8104	17.2	5.7
2006	9	29	13:08:24	10.8486	−61.7653	53.4	6.1
2006	9	30	17:50:22	46.189	153.1761	19.4	6.6
2006	10	1	9:06:00	46.3193	153.3046	19.5	6.5
2006	10	9	10:01:47	20.7054	120.0645	17.3	6.3
2006	10	10	23:58:06	37.1616	142.8023	32.2	6.0
2006	10	21	18:23:20	13.3641	121.4278	18	5.9
2006	10	23	21:17:22	29.411	140.3506	29.9	6.4
2006	11	17	18:03:11	28.5876	129.8655	23.1	6.2
2006	11	29	15:38:43	53.8157	−35.435	10	5.6
2006	12	1	3:58:20	3.4573	99.103	204.2	6.3
2006	12	25	20:00:59	42.0738	76.0856	15.2	5.8
2006	12	26	12:26:20	21.8354	120.533	6.3	7.1
2006	12	30	8:30:47	13.205	51.3376	10	6.6
2007	1	9	15:49:32	59.4467	−137.138	10	5.7
2007	1	17	23:18:48	10.0815	58.7013	10	6.2
2007	2	4	20:56:57	19.3369	−78.3947	10	6.2
2007	2	19	2:33:42	1.6404	30.6974	27.3	5.6
2007	3	1	23:11:50	26.6058	−44.647	10	6.0
2007	3	6	3:49:38	−0.506	100.4824	21.2	6.4
2007	3	9	7:27:29	−11.4284	66.2758	10	5.7
2007	3	9	3:22:42	43.2206	133.5123	439.5	6.0
2007	3	13	2:59:00	26.1733	−110.697	10	6.0
2007	3	18	2:11:03	4.6505	−78.5033	1.1	6.2
2007	3	22	6:10:43	−3.342	86.7202	26.9	5.9
2007	3	25	0:41:56	37.3209	136.5686	4	6.7
2007	3	28	21:17:10	−6.2242	29.619	13.4	5.8
2007	4	3	3:35:06	36.4738	70.6405	215.5	6.2
2007	4	4	19:58:02	−17.1836	66.875	10	5.9
2007	4	5	3:56:49	37.3659	−24.6358	16.2	6.3
2007	4	10	13:56:50	13.0113	92.5102	15.3	5.5
2007	4	13	5:42:21	17.2469	−100.241	33.4	6.0
2007	4	20	1:45:55	25.6879	125.0772	9.2	6.3
2007	5	4	12:06:51	−1.3273	−15.0009	10	6.2
2007	5	5	8:51:38	34.3079	81.9875	13.4	6.1
2007	5	7	11:59:46	31.3215	97.6605	12	5.5
2007	5	16	8:56:13	20.5565	100.7342	10	6.3
2007	5	23	19:09:13	21.9055	−96.3184	1.7	5.6
2007	5	30	20:22:11	52.0987	157.2889	120.4	6.4

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Table A1. Continued.

Year	Month	Day	Time UTC	Lat	Long	Depth	M
2007	6	2	21:34:58	23.0785	101.0073	11	6.1
2007	6	13	19:29:44	13.7024	−90.6465	64	6.7
2007	6	15	18:49:51	1.7332	30.7452	20.1	5.9
2007	6	18	14:29:48	34.4568	50.8578	11.4	5.5
2007	7	3	8:25:59	0.7697	−30.1971	10	6.3
2007	7	6	1:09:18	16.5781	−93.6161	120	6.1
2007	7	13	21:54:43	51.8785	−176.246	44.1	6.0
2007	7	15	13:08:00	52.4899	−168.032	12.5	6.1
2007	7	16	14:17:36	36.866	134.7943	347.1	6.8
2007	7	17	14:10:41	−2.826	36.267	14.8	5.9
2007	7	20	10:06:52	42.9111	82.2962	19.1	5.6
2007	7	29	4:54:35	53.6067	169.7092	28	5.9
2007	7	30	22:42:05	19.3104	95.541	15.9	5.6
2007	7	31	22:55:28	−0.1482	−17.7189	2.7	6.2
2007	8	2	13:37:27	12.447	47.4593	10	5.7
2007	8	2	2:37:42	46.9248	141.8324	19.9	6.2
2007	8	2	5:22:16	46.7681	141.7716	6.9	5.8
2007	8	2	3:21:44	51.3075	−179.975	37.8	6.7
2007	8	7	0:02:21	27.3494	126.7991	4.4	6.0
2007	8	13	22:23:03	−30.9737	−13.4479	10	5.5
2007	8	15	20:22:11	50.2629	−177.554	17.8	6.5
2007	8	16	14:18:25	−3.4566	−12.1013	20.9	5.5
2007	8	20	22:42:28	8.1332	−39.2186	10	6.5
2007	9	1	19:14:22	25.0103	−109.64	11.9	6.1
2007	9	3	16:14:52	45.7243	150.1509	98.6	6.2
2007	9	6	17:51:26	24.3526	122.237	56.2	6.2
2007	9	10	1:49:12	3.0475	−77.9501	27.6	6.8
2007	9	13	3:35:27	−2.156	99.5994	18.8	7.0
2007	9	13	2:30:01	−1.6595	99.61	24	6.5
2007	9	20	8:31:13	−2.0015	100.064	29.1	6.7
2007	9	26	18:39:33	−7.0062	−11.6291	10	5.6
2007	10	2	18:00:07	54.5033	−161.735	42.9	6.3
2007	10	4	12:40:29	2.5719	92.9055	34.7	6.2
2007	10	18	16:13:13	30.1823	−42.6211	12.3	5.7
2007	10	24	21:02:50	−3.9271	101.0147	28.2	6.8
2007	10	31	3:04:54	37.372	−121.798	10	5.6
2007	11	7	7:10:20	22.1583	92.3702	29.7	5.5
2007	11	27	4:26:59	16.2324	119.824	45.3	5.9
2007	12	6	17:12:03	22.7483	−45.1418	15.9	5.8
2007	12	8	19:55:18	−7.5221	37.6041	10	5.6
2007	12	12	23:39:58	52.1242	−131.437	10	5.8
2007	12	19	9:30:26	51.3295	−179.509	34.2	7.2
2007	12	25	14:04:33	38.4955	142.0641	48.1	6.1
2007	12	26	22:04:55	52.5351	−168.221	34.1	6.4

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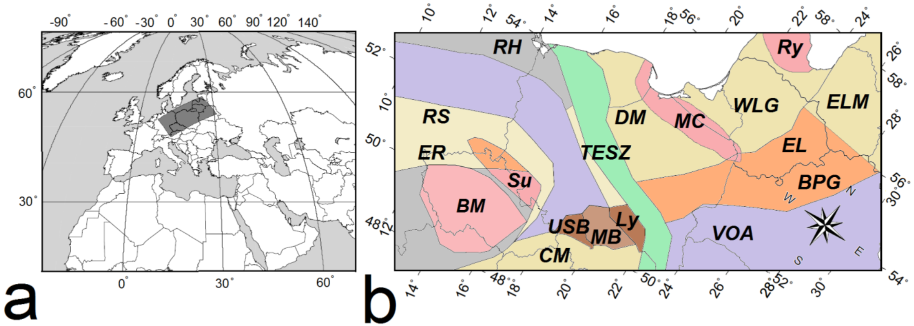

Figure 1. (a) Geographical location of the study area (grey rectangle). **(b)** Tectonic sketch of the study area compiled from Skridlaite and Motuza (1999), Malinowski et al. (2008), Guterch et al. (1999), Bogdanova et al. (2001), and Gee and Stephenson (2006). Units: BM, Bohemian Massif; BPG, Belarus–Podlasie Granulite Belt; CM, Carpathian Mountains; DM, Dobrzyn Massif; EL, East Lithuanian Domain; ELM, East Latvian Massif; ER, Eger Rift; Ly, Lysogory; MB, Malopolska Block; MC, Mazury Complex; RH, Rhenoherzynian Front; RS, Rheic Suture; Ry, Riga batholith; Su, Sudetes Mountains; TESZ, Trans-European Suture Zone; USB, Upper Silesian Coal Basin; VOA, Volyn–Orsha aulacogen; WLG, West Lithuanian Granulite Domain.

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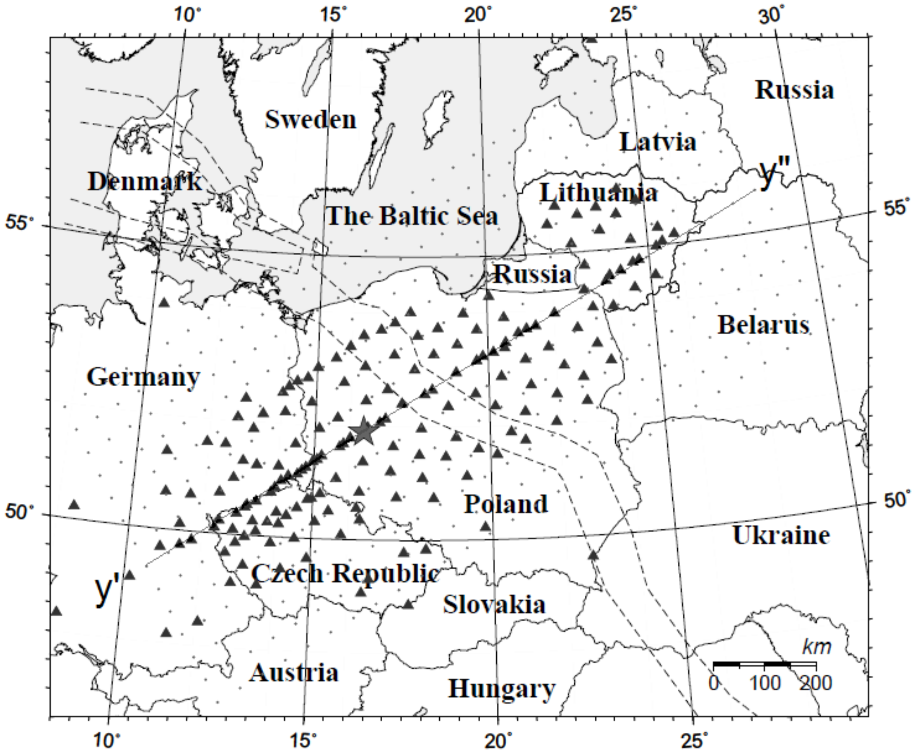

Figure 2. Seismic stations used in this study marked as triangles. Dots indicate nodes of the model grid. Star indicates origin of the local Cartesian coordinate system used. Dashed lines indicate the TESZ. Solid line $y'y''$ marks the main PASSEQ transect at $y = 0$ in the local Cartesian coordinate system.

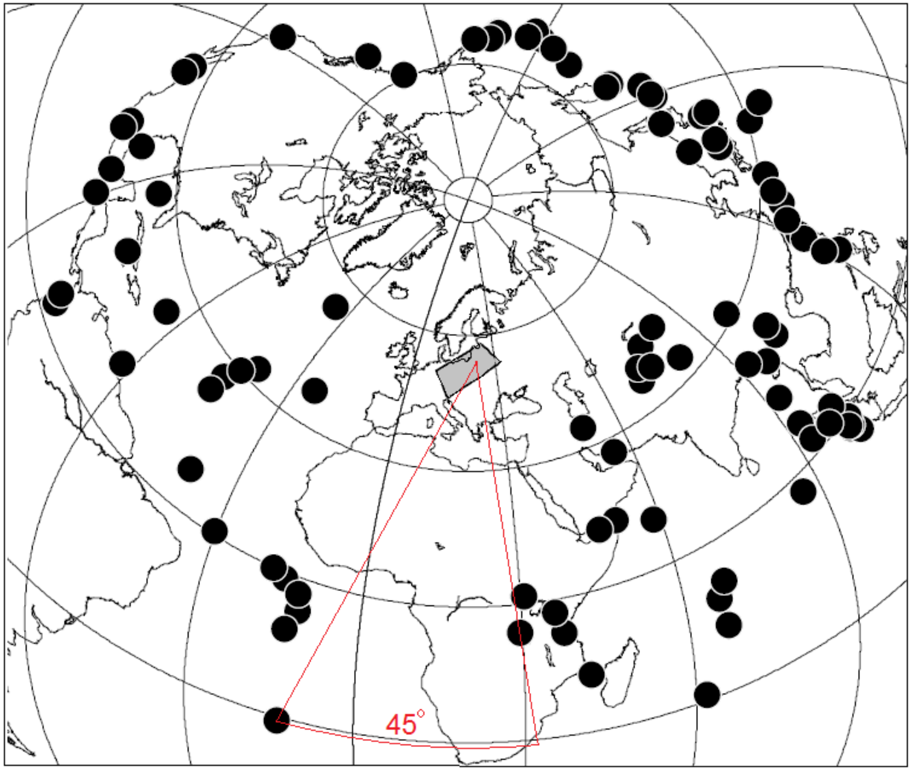

Figure 3. Map of epicenters of EQs (black circles) used in our study. Grey rectangle indicates the study area. Red lines show the largest seismic gap.

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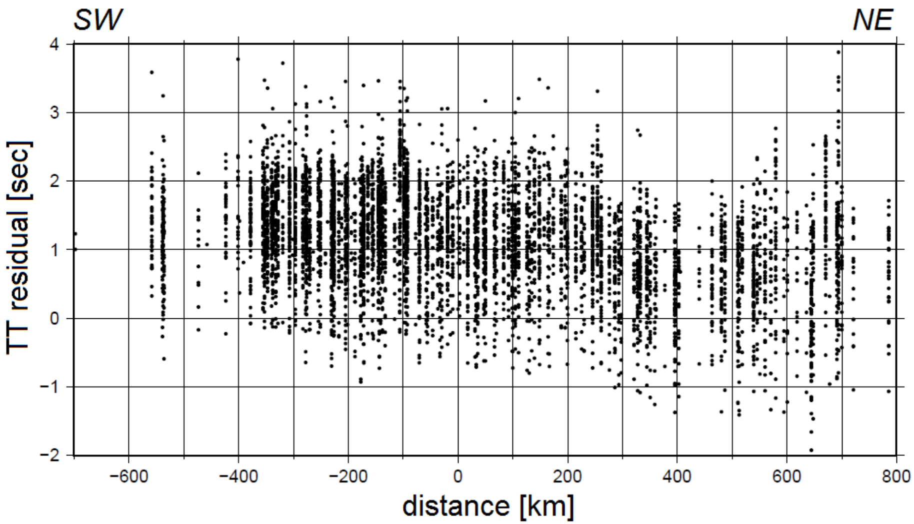

Figure 4. Distribution of the TT residuals observed in individual seismic stations along the main transect of the study area.

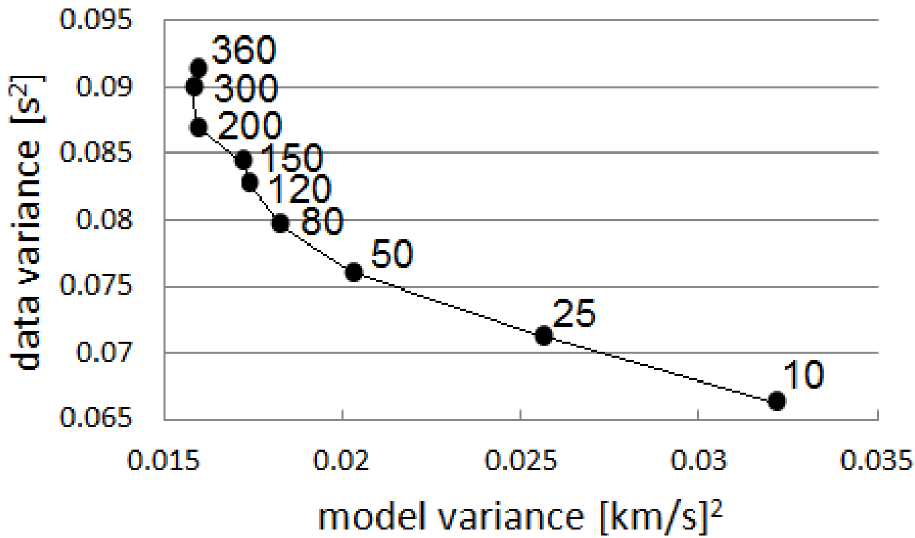

Figure 5. Trade-off between the data variance and model variance obtained with different damping values from 10 to 360. The presented results were obtained using damping value of 120.

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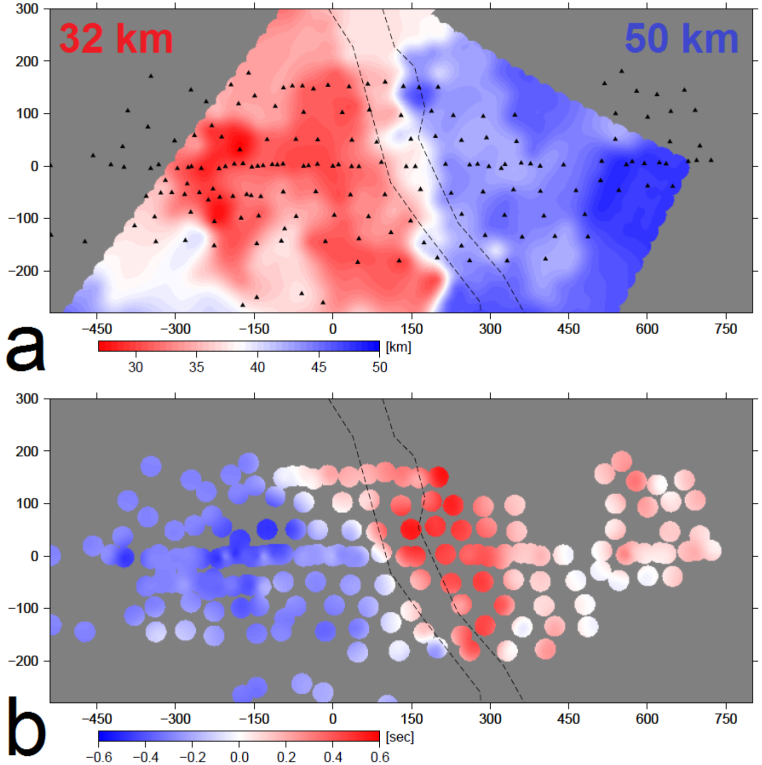

Figure 6. (a) Moho map of the precise 3-D crustal model by Majdański (2012) which was used to estimate the crustal TT corrections. The Moho depth for the areas outside the model was defined using results of some DSS projects: the area to the east was assigned with 50 km and to the west with 32 km. **(b)** Estimated crustal TT corrections in the individual seismic stations. The values are expressed in seconds in respect to the IASP91 velocity model.

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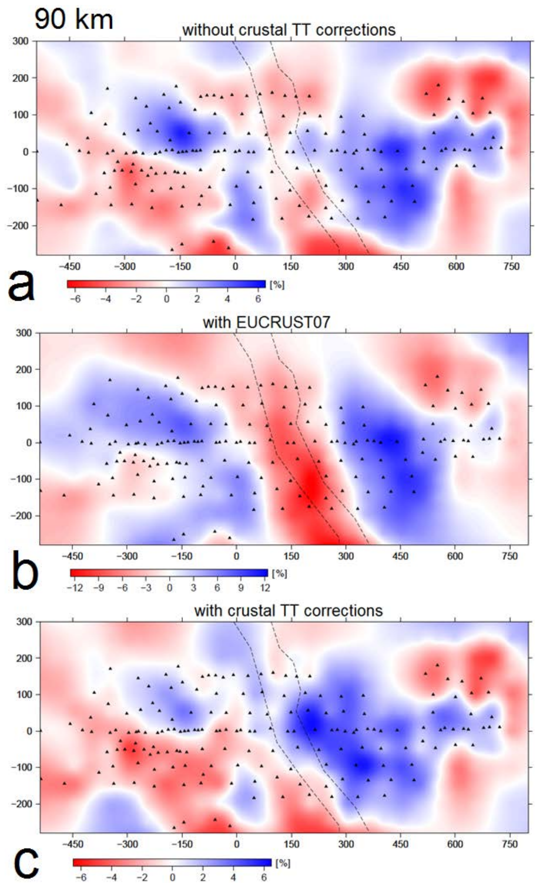

Figure 7. Horizontal slices at the depth of 90 km of the inversion results **(a)** without crustal TT corrections, **(b)** with EuCRUST-07 model, and **(c)** with crustal TT corrections compiled using model by Majdański (2012) and result of some DSS projects. Triangles indicate seismic stations. Dashed lines indicate the TESZ.

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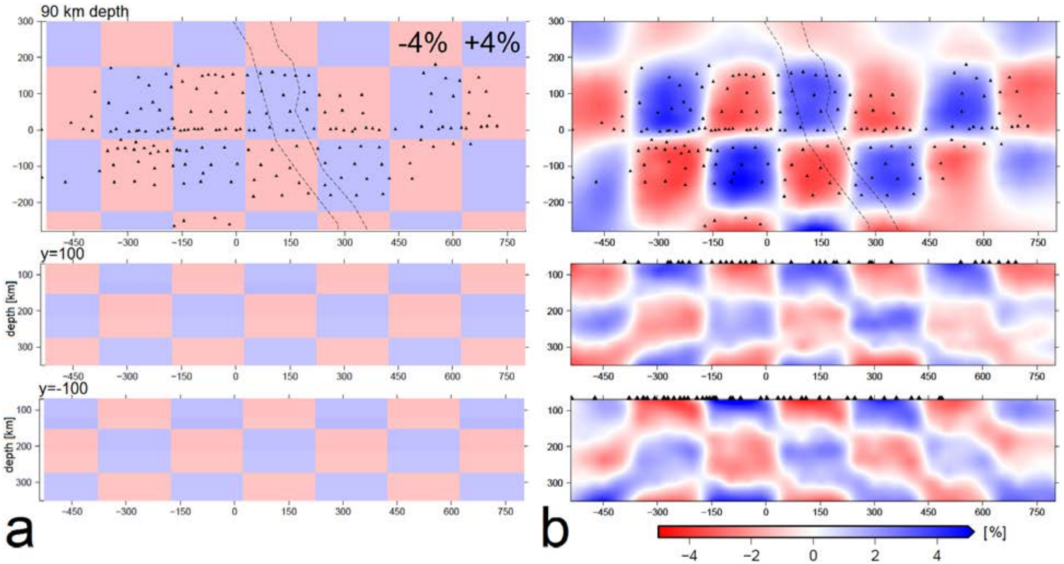

Figure 8. Checkerboard test. Horizontal slice at a depth of 90 km and two vertical slices. **(a)** Initial velocity model. **(b)** Inversion results with the synthetic dataset. Triangles mark the seismic stations. Dashed lines indicate the TESZ.

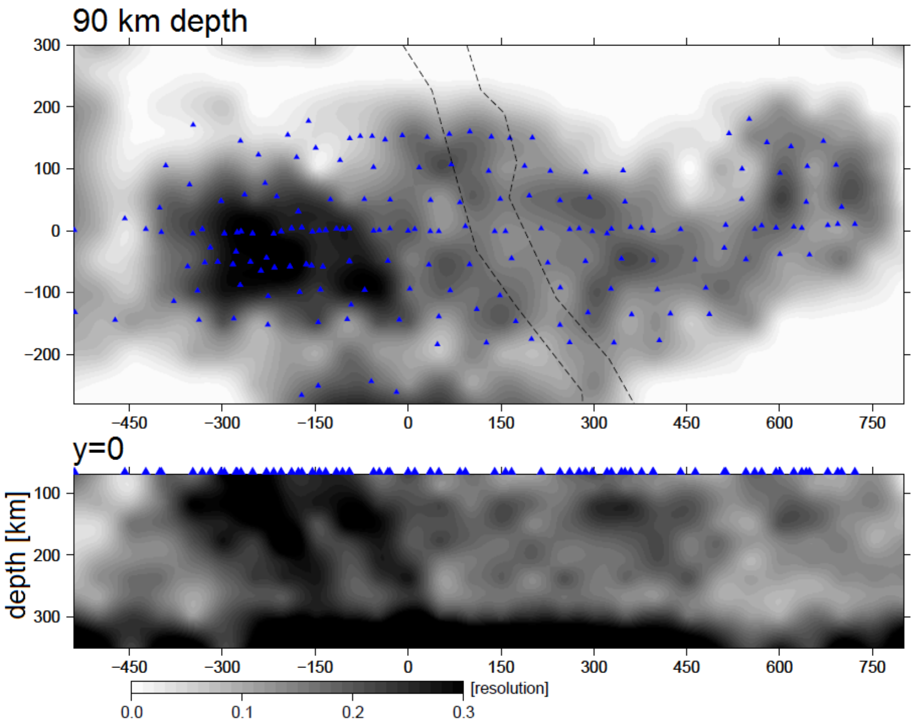

Figure 9. Horizontal and vertical slices of resolution matrix. The low and the high values of resolution indicate poorly and well resolved areas, respectively. Triangles mark seismic stations. Dashed lines indicate the TESZ.

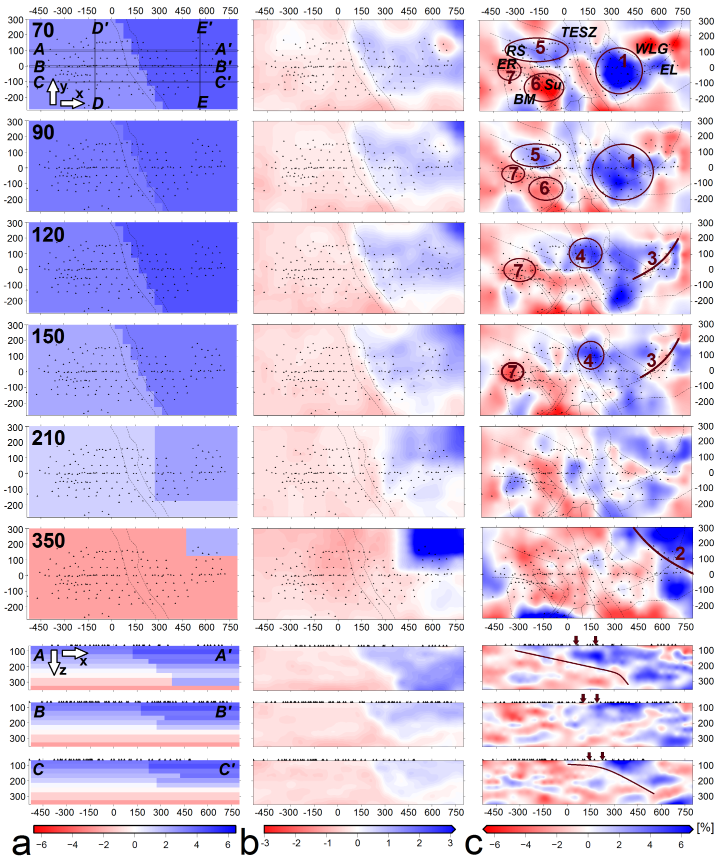

Figure 10. Caption on next page.

Scheme 1. *P* wave velocity perturbations in horizontal slices at indicated depths (km) and vertical slices parallel to the main transect of the study area. Results obtained with the synthetic "geological" model: **(a)** input velocity model, and **(b)** inversion results. **(c)** Results obtained with the field dataset. Triangles mark seismic stations. x, y and z indicate longitude, latitude and depth (in km), respectively, in a local Cartesian coordinate system. Dashed lines on horizontal slices indicate boundaries of tectonic units (see Fig. 2). Numbered areas mark the discussed interpreted structures: 1 – high velocity area beneath Poland (craton); 2 – deep cratonic roots extending to at least 300 km or more beneath Lithuania; 3 – palaeosubduction boundary between the WLG and the EL; 4 – high velocity area beneath Northern Poland; 5 – higher velocity area along the Rheic Suture; 6 – lower velocity area beneath the Sudetes mountains and the Bohemian Massif; 7 – low velocity area beneath the Eger Rift. Solid lines on vertical slices show the interpreted seismic LAB; and brown arrows indicate the TESZ.

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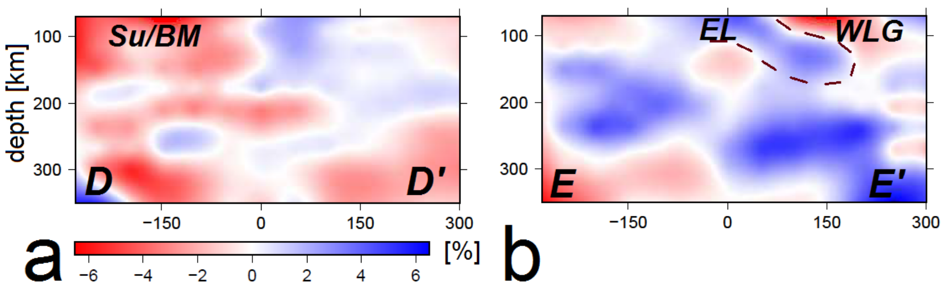

Figure 2. *P* wave velocity perturbations in vertical slices DD′ and EE′ transverse to the main transect (see Fig. 10). **(a)** Low velocities are observed in the western part of the Bohemian Massif (BM) and the Sudetes Mountains (Su) from 70 km. **(b)** Dashed line indicated resolved palaeosubduction zone under Lithuania between the WLG and the EL.

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