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# Upper mantle structure across the Trans-European Suture Zone imaged by S-receiver functions

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A B S T R A C T

We present a high-resolution study of the upper mantle structure of Central Europe, including the western part of the East European Platform, based on S-receiver functions of 345 stations. A distinct contrast is found between Phanerozoic Europe and the East European Craton across the Trans-European Suture Zone. To the west, a pronounced velocity reduction with depth interpreted as lithosphere–asthenosphere boundary (LAB) is found at an average depth of 90 km. Beneath the craton, no strong and continuous LAB conversion is observed. Instead we find a distinct velocity reduction within the lithosphere, at 80–120 km depth. This mid-lithospheric discontinuity (MLD) is attributed to a compositional boundary between depleted and more fertile lithosphere created by late Proterozoic metasomatism. A potential LAB phase beneath the craton is very weak and varies in depth between 180 and 250 km, consistent with a reduced velocity contrast between the lower lithosphere and the asthenosphere. Within the Trans-European Suture Zone, lithospheric structure is characterized by strong heterogeneity. A dipping or step-wise increase to LAB depth of 150 km is imaged from Phanerozoic Europe to 20–22° E, whereas no direct connection to the cratonic LAB or MLD to the east is apparent. At larger depths, a positive conversion associated with the lower boundary of the asthenosphere is imaged at 210–250 km depth beneath Phanerozoic Europe, continuing down to 300 km depth beneath the craton. Conversions from both 410 km and 660 km discontinuities are found at their nominal depth beneath Phanerozoic Europe, and the discontinuity at 410 km depth can also be traced into the craton. A potential negative conversion on top of the 410 km discontinuity found in migrated images is analyzed by modeling and attributed to interference with other converted phases.



## 1. Introduction

### 1.1. Overview

Variations in the depth of the LAB are of fundamental interest in plate tectonics and studies of the Earth's evolution as the LAB separates the rigid outer shell of the Earth that translates coherently from the mechanically weak, more ductile asthenosphere below. Gutenberg (1926) was the first to identify the LAB seismically as a drop in velocity with depth, creating an asthenospheric low-velocity layer below a faster lid. Subsequently, the velocity structure of the upper mantle has been investigated both globally and on a regional scale with body waves (e.g. Kárason and van der Hilst, 2000), surface waves (e.g. Pasyanos et al., 2014), or combinations of both (e.g. Kustowski et al., 2008; Legendre et al., 2012; Zhu et al., 2012). Vertical changes in surface wave anisotropy have also been used to indicate LAB depth, assuming it represents the change from frozen-in anisotropic structures in the lithosphere to anisotropy related to present-day mantle flow (e.g. Plomerová and Babuška, 2010). In addition, ScS reverberations or SS precursors (e.g. Schmerr, 2012) originating at the LAB have been used to derive its depth.

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In recent years, the use of S-receiver functions (S-RFs, Farra and Vinnik, 2000) to image the LAB has gained increasing popularity (for an overview, see Kind et al., 2012). This technique avoids both the vertical resolution issues inherent to body wave tomography (Priestley and Tilmann, 2009) and the limitations in distinguishing sharp discontinuities from gradual velocity variations with surface waves (Eaton et al., 2009). The LAB has been mapped with S-RFs in a variety of tectonics settings, including oceanic plates (e.g. Kawakatsu et al., 2009), rifts (e.g. Lekic et al., 2011), and orogenic belts (Kumar et al., 2005). Results from these studies generally agree with LAB depth estimates from tomography.

Continental cratons are characterized by thick and cold lithospheric keels extending to 200–250 km depth (Eaton et al., 2009) based on seismic tomography (e.g. Priestley and Tilmann, 2009), heat flow measurements (e.g. Artemieva, 2006), mantle xenoliths (e.g. Griffin et al., 1999), and electrical conductivity data (e.g. Korja, 2007). However, LAB conversions from corresponding depths have not universally been observed in S-RFs (Fischer et al., 2010). Instead, shallower discontinuities, at 60–150 km depth, have been imaged with no trace of a deeper LAB conversion, e.g. beneath cratonic North America (e.g. Abt et al., 2010), Australian cratons (Ford et al., 2010), and the Kalahari Craton (e.g. Savage and Silver, 2008). Abt et al. (2010) interpret these observations as caused by a discontinuity internal to the lithosphere, the MLD. A comparable discontinuous velocity reduction at ∼100 km depth beneath cratons had previously been found in long-range, active-source seismic profiles and termed 8° discontinuity (Thybo and Perchuć, 1997).

Recent work indicates lithospheric stratification beneath cratons, imaging both MLD(s) and LAB beneath Scandinavia (e.g. Kind et al., 2013), the Canadian Shield (Miller and Eaton, 2010), the Kalahari Craton (Sodoudi et al., 2013), and the West African Craton (Cooper and Miller, 2014).

Other discontinuities in the upper mantle imaged by S-RFs include the bottom of the asthenosphere (e.g. Hansen et al., 2009; Kind et al., 2013) and a low-velocity layer on top of the 410 km discontinuity (e.g. Vinnik and Farra, 2007).

Here we use S-RFs from the densest station network yet available to map upper mantle discontinuities, in particular the LAB, across the Trans-European Suture Zone (TESZ) in central Europe. Whereas S-RFs from dense local networks have been used to investigate the LAB structure in specific parts of Phanerozoic Europe (PE) west of the TESZ in detail (e.g. Heuer et al., 2006, 2007; Seiberlich et al., 2013), only limited S-RFs results from isolated stations were available across and east of the TESZ so far (Geissler et al., 2010).

### 1.2. Tectonic setting

Central Europe is divided by a major lithospheric boundary, the TESZ (Pharao, 1999), which extends over 2000 km from the North Sea to the Black Sea (Fig. 1). This boundary separates Phanerozoic Europe from the Precambrian East European Craton (EEC), and is clearly identified in various geophysical data sets, e.g. the gravity field (Yegorova and Starostenko, 1999), heat flow (Artemieva, 2003), magnetotellurics (Korja, 2007), and seismic tomography (Kustowski et al., 2008; Legendre et al., 2012; Zhu et al., 2012; Janutyte et al., 2015). While the lithosphere of the EEC east of the TESZ has been stable for at least 1.45 Ga as paleo-contintent Baltica (Bogdanova et al., 2006), PE developed by successive accretion of terranes rifted from the paleocontinent Gondwana. These accretions took place during three main orogenic phases from the late Ordovician to the Cenozoic: the Caledonian (450–425 Ma), the Variscan (400–300 Ma), and the Alpine–Carpathian (100–35 Ma) orogeny. During the Variscan orogeny, the Armorican Terrane Assemblage, subdivided into the Saxothuringian, Teplá-Barrandian, and Moldanubian zones, collided with Baltica. A prominent outcrop of Variscan crystalline basement is preserved today in the Bohemian Massif (BM). In addition to the mentioned units, the BM encompasses the Sudetes Mountains and the Moravo-Silesian terrane at its eastern margin (Fig. 1). The European Variscides have mostly been overprinted by the European Cenozoic Rift System (ERCS) and associated volcanism, e.g. in the Rhine Graben, Rhenish Massif, and the Eger Rift within the BM (Dézes et al., 2004).

The TESZ itself is a 150–200 km wide region of suspect terranes to the southwest of the Sorgenfrei–Tornquist Zone (STZ) and Teisseyre–Tornquist Zone (TTZ).

The EEC consists of three major segments: Fennoscandia, including the Baltic Shield, in the north, and Sarmatia, including the Ukrainian Shield, and Volgo–Uralia to the south-west and south–east, respectively. Terranes related to Sarmatia and Fennoscandia, which abut the TESZ to the east, evolved separately until a major collision at 1.84–1.80 Ga (Bogdanova et al., 2006). Whereas the terranes belonging to Fennoscandia have ages between 1.9 and 1.8 Ga, the ones belonging to Sarmatia are older than 1.95 Ga. Post-collisional Mesoproterozoic lithospheric deformation and magmatism, indicated by the development of numerous crustal shear zones and the emplacement of the Riga pluton and Mazury complex, affected the craton at 1.6–1.45 Ga. The Fennoscandian-Sarmatian Suture (FSS) to the south–east of our measurement region is approximately outlined by the intracratonic Central Russian Rift System, which formed at 1.3–1.0 Ga and was affected by intraplate volcanism between 1.0 and 0.65 Ga (Artemieva, 2003).

### 1.3. Previous geophysical work

The global lithospheric model LITHO1.0 (Pasyanos et al., 2014, Fig. 1) clearly images the TESZ as a sharp transition in lithospheric thickness from 70–90 km in the west to more than 200 km in the east. Global and continental-scale tomographies have likewise found distinct contrasts in upper-mantle velocity anomalies in the 80 to 250 km depth range, but could not uniquely resolve the shape of the LAB across the TESZ: an east-ward dipping ramp (Kárason and van der Hilst, 2000) as well as a west-ward dipping ramp (Kustowski et al., 2008) has been suggested. In a regional study using adjoint tomography, Zhu et al. (2012) image a sharp TTZ and high velocities beneath at least parts of the EEC down to the mantle transition zone. However, Legendre et al. (2012), combining S-wave and surface wave information, find high velocities beneath the EEC only to 200 km depth, with a distinct decrease in perturbations below. Besides, they resolve a region with intermediate mantle velocities between PE and the EEC, bounded by the Elbe Line and the TTZ.

Along a transect across the STZ between northern Germany and Sweden, Gregersen et al. (2002) picture a distinct two-step increase in lithospheric thickness in P-wave tomography, with an intermediate LAB depth around 120 km beneath the TESZ. No velocity reduction that could be associated with a LAB was found beneath the EEC down to the lower limit of the models at 300 km. The most recent regional P-wave travel-time tomography finds variations in LAB shape along the strike of the TESZ (Janutyte et al., 2015). While resolving a ramp with a 30° eastward dip in northern Poland, a sharper and steeper contact between Phanerozoic and Proterozoic upper mantle is imaged in southeastern Poland. Due to depth limitations in ray coverage, this study likewise could not image deeper parts of the mantle beneath the EEC.

Plomerová and Babuška (2010) and Wilde-Piórko et al. (2010) estimate LAB thickness from lateral variations of static terms of relative P wave residuals. Across the TESZ in northern Poland, Wilde-Piórko et al. (2010) find a stepwise increase in LAB depth, similar to the observations across the STZ, from 93 km in PE via 119 km beneath the TESZ to 193 km beneath the EEC.