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Mantle lithosphere transition from the East European Craton to the Variscan Bohemian Massif imaged by shear-wave splitting

L. Vecsey, J. Plomerová, V. Babuška, and PASSEQ Working Group

Geophysical Institute, Academy of Sciences of the Czech Republic, Boční II/1401, 141 31 Prague, Czech Republic

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Correspondence to: L. Vecsey (vecsey@ig.cas.cz)

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Abstract

We analyse splitting of teleseismic shear-wave recorded during the PASSEQ passive experiment (2006–2008) focussed on the upper mantle structure across the Trans-European Suture Zone (TESZ). 1009 pairs of the delay times of the slow split-shear waves and orientations of the polarized fast-shear waves exhibit lateral variations across the array, as well as backazimuth dependences of measurements at individual stations. While a distinct regionalization of the splitting parameters exists in the Phanerozoic part of Europe, a correlation with the large-scale tectonics around the TESZ and in the East European Craton (EEC) is less evident. No general and abrupt change in the splitting parameters (anisotropic structure) can be related to the Teisseyre–Tornquist Zone (TTZ), marking the edge of the Precambrian province on the surface. Instead, regional variations of anisotropic structure were found along the TESZ/TTZ. We suggest a south-westward continuation of the Precambrian mantle lithosphere beneath the TESZ and the adjacent Phanerozoic part of Europe, probably as far as towards the Bohemian Massif.

1 Introduction

The Trans-European Suture Zone (TESZ) represents a distinct tectonic feature that can be traced through north-western to south-eastern Europe at a length of ~ 3500 km and manifests the contact zone between the Precambrian and Phanerozoic Europe (Fig. 1). The two parts of Europe differ not only as to their ages, but also in their structure and in several other physical parameters, which can be traced in various geophysical models of the region, e.g., in seismic velocities, anisotropy, and heat flow (e.g., Spakman, 1991; Babuška et al., 1998; Piromallo and Moreli, 2003; Majorowicz et al., 2003; Artemieva et al., 2009; Jones et al., 2010; Debayle and Ricard, 2012). The East European Craton (EEC) appears as a large rigid domain with a thick lithosphere that is bordered in the south-west by a relatively narrow linear Teisseyre–Tornquist fault zone (TTZ). On

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the other hand, the region westward of the TESZ represents a Variscan assemblage of micro-plates with varying lithosphere thickness and fabrics, partly rimmed by rifts and subduction zones reflecting micro-plate collisions (e.g., Plomerová and Babuška, 2010). The central part of the long TESZ, running through the territory of Poland, is a zone of about 150–200 km wide. The term TESZ was introduced for an assemblage of suspect terranes adjoining the EEC edge from the southwest (Berthelsen, 1992) and the TTZ thus marks the north-eastern boundary of the TESZ (Dadlez et al., 2005, see Fig. 1).

Three decades of control-source seismic (CSS) exploration of the TESZ crust (Guterch et al., 1986, 1994; Grad et al., 1999, 2003; Janik et al., 2002, 2005; Środa et al., 2002; Wilde-Piórko et al., 1999; 2010) resulted in detailed, but often different interpretations of its structure. But in general, structure of the crystalline crust of the TESZ, covered by up to 12 km thick sediments, seems to be more complicated than that of the Variscan belt to the west and of the EEC, with sudden structural changes observed laterally along the suture (Dadlez et al., 2005). The authors, as well as Narkiewicz et al. (2011), interpret the complex structure of the broad TESZ as a result of detachment and accretion of lithospheric fragments of Baltica, Avalonia and various Gondvana-derived exotic terranes. To better understand processes that formed this part of Europe, we have to look deeper beneath the crust, i.e., into the lower lithosphere and the upper mantle and probe their velocity structure and fabrics.

The PASSEQ array of seismic stations (Fig. 2 and http://geofon.gfz-potsdam.de/db/station.php, network code PQ) was designed to record during 2006–2008 teleseismic data for studying variations of the upper mantle velocity structure across the TESZ. The array spans across the central part of the TESZ and covers a vast band of ~ 1000 km long and ~ 600 km broad (Wilde-Piórko et al., 2008). Densely spaced broad-band (BB) and short-period (SP) stations are mixed in the central band of the array. Seven parallel lines of SP and of BB stations complement on both sides the central backbone of the array. In combination with other large-scale European passive seismic experiments, particularly with the TOR, which covered the north-western part of the TESZ

(Gregersen et al., 2002), and the SVEKALAPKO, which concentrated on upper mantle structure around the Proterozoic/Archean contact in south-central Fennoscandia (Hjelt et al., 2006), the PASSEQ array complements international data sets needed for high-resolution studies of the European lithosphere and the upper mantle, to help answering questions on structure and evolution of the continent.

In this paper, we present our findings on the mantle structure derived from shear-wave splitting, evaluated from teleseismic data recorded during the PASSEQ array operation. The research aims at detecting changes in anisotropy of the upper mantle beneath the TESZ and surrounding tectonic units. Mapping variations of anisotropic structure of the upper mantle helps to answer questions on how the zone, approximately delimited at the surface, may continue down to the upper mantle, as well as on a possible identification of individual blocks building the lower lithosphere.

2 Data and method

Shear-wave splitting represents nowadays an optics frequently used to measure seismic velocity anisotropy of the upper mantle. Various methods are applied to get splitting parameters and to model anisotropy of the continental upper mantle (e.g., Vinnik et al., 1989; Silver and Chan, 1991; Silver and Savage, 1994; Menke and Levin, 2003), each of them having both advantages and limitations (Vecsey et al., 2008; Wüstefeld and Bokelmann, 2007). To retrieve 3-D orientation of large-scale anisotropic structures in the upper mantle, we have applied a modified version (Vecsey et al., 2008; code SPLITshear, www.ig.cas.cz/en/research-teaching/software-download) of a method introduced by Šílený and Plomerová (1996). The method exploits signals on all three components of the broad-band recordings and analyzes them in the ray-parameter coordinate system (LQT). To study lateral variations of the anisotropic signal in detail, for which we need densely spaced seismic stations, we included also waveforms recorded by medium-period seismographs (Ts ~ 5 s) into the splitting analysis, because the dominant energy of shear waves was in an interval of 8–10 s for most of the broad-band

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recordings. Even some stations, equipped with 2–3 s seismometers, allowed analyzing shear waves as well. However, we always mark anisotropic parameters evaluated at these stations in a different way and consider them as complementary, and only if they are consistent with results of surrounding BB stations. All waveforms were filtered by the 3rd order Butterworth band-pass filter 3–20 s. For details of the method we refer to Vecsey et al. (2008). Here we describe only main principles needed for understanding our figures and results.

Figure 3 shows an example of splitting of the SKS phase recorded at temporary station PA65. Altogether we were able to get 1009 pairs of splitting parameters from the PASSEQ recordings, including null measurements, (Table S1). The shear-wave splitting parameters are evaluated with the use of the method minimizing energy on transverse component T (Vecsey et al., 1998), which is the original method by Silver and Chan (1991) modified into the ray-parameter LQT coordinate system. The broad elliptical particle motion (PM) calculated from the QT components changes to the linear one for the fast (F) and slow (S) components after the coordinate rotation and applying a time shift correcting the splitting. Minimum of a misfit function in the (δt, ψ) space, where δt is a time shift between the fast and slow split shear waves and ψ is orientation of the fast shear-wave in the (Q,T) plane, defines the splitting parameters, with which one can measure the velocity anisotropy. Depth and steepness of the minimum along with the bootstrap diagrams evaluate reliability of the measurement. Orientation of the fast shear-wave given by an angle ψ in the QT plane is defined by two angles – azimuth φ (measured from the north clockwise) and inclination angle θ measured from the vertical axis upwards. Because polarizations often differ for waves coming from opposite directions (i.e., from azimuth φ and from $\varphi + 180°$), in spite of their steep incidences, we always denote the polarization azimuth by an arrow pointing from a station, or from a ray-piercing point, in the down-going direction. This allows us to depict variations of the splitting parameters in full 0–360° backazimuth range (i.e., including different polarizations for opposite directions). Later on, we invert jointly the shear-wave splitting parameters along with *P* wave travel-time deviations, for self-consistent anisotropic models with symmetry axes generally oriented in 3-D (Šílený and Plomerová, 1996).

While processing data of the PASSEQ array, we faced several difficulties. Careful processing of the data mostly allowed to reveal mistakes caused, e.g., by an interchange of the *N*, *E*, *Z* components, or, by polarity flipping, though it was not always straightforward, particularly when both errors occurred simultaneously. Nevertheless, incorrect seismometer orientation to the North proved to be the most difficult obstacle. When a suspicion of a misorientation appeared, we have superimposed all particle motion PM plots at a station (Fig. 4) and searched for a systematic deviation of the PM. Poor linearity of the corrected particle motion patterns is another indication of sensor misalignments (Liu and Gao, 2013). We estimate that with the use of the PM stacking technique only misorientations larger than $\sim 10^{\circ}$ can be identified, because individual PMs can vary due to structure and noise and can form at some stations two different groups in dependence on backazimuths. Figure 4 shows particle motions that clearly identified misoriented seismometers at two stations – PC23 (temporary) and GKP (permanent), in contrast with the particle motions at JAVC with seismometer well-oriented to the North. Our estimates of the deviations attain 28° and 41° at the PC23 and GKP stations, respectively. Cross-check of suspicious misorientations by analyzing the *P* wave particle motions confirms our estimate based on the SKS polarizations (Table 1). We can thus conclude that a distance between stations should be small relative to expected variations in structure, in order to eliminate potential technical errors, which could otherwise be misinterpreted as effects of mantle structure.

We have tested a potential danger of seismometer misorientation by analyzing signals of different quality on well oriented components and then on the horizontal components rotated only by 5° off the correct directions, which simulated a seismometer misalignment. Changes in split-delay times of a waveform classified as "good" lie within the error interval, but azimuths of the fast polarization differ by 15°, if the "minimum *T* energy" method is used (Table 2). The "eigenvalue" method returns well the "new" polarization azimuth. On the other hand, in case of "fair" signals the difference in polarization azimuths, evaluated by the "minimum T energy" method from original recordings and from those rotated by 5°, attains 67°. The "eigenvalue method" returns the fast polarization azimuth that differs by 5° from the original recordings, but it doubles the split delay time regardless of seismometer orientation (Table 2). Vecsey et al. (2008) showed that the "minimum T energy" method is more robust than the "eigenvalue" method in case of noise in a signal. However, as we show here, the "minimum T energy" method appears to be more sensitive to potential errors in seismometer orientation. High accuracy in the northward orientation of seismometers can and should be technically ensured, e.g., with the use of a gyrocompass during station installations, but we can hardly avoid noise completely. Stacking of individual splitting measurements from waves closely propagating through the mantle can help to reveal a distortion of splitting parameters due to noise in signals. Therefore, we consider the "minimum T energy method" as the most robust for analyzing SKS waves, which should exhibit linear polarizations, i.e., no energy on T component, when reaching the bottom of an anisotropic medium.

3 Results

Most papers presenting results of shear-wave splitting analysis search for an azimuth of the fast shear phase and a split-delay time (δt) of the slow shear phase. The azimuth of the fast shear wave is then a priori associated with the horizontal direction of the "fast" olivine axis a of a model mantle peridotite. To summarize all shear-wave splitting parameters evaluated in such "standard" way, we plot average fast shear-wave polarizations (see Table S1 for individual measurements) as bars with their length proportional to the split-delay time (Fig. 5a). Though this presentation shows only azimuthal anisotropy with the π-periodicity, we can identify main large upper mantle provinces with different anisotropic signal: the orientations from W–E prevail in the Bohemian Massif in general (BM, c.f., Babuška et al., 2008), less coherent fast-S orientations occur to the north-west of the BM, while between the Moravian Line and the Carpathians front in the east of the region, the NW–SE average polarizations are very stable and the signal is strong even in close vicinity of the TTZ. This is not the case in the region north of the Elbe–Odra Line. Also further to the east, across the TTZ, the anisotropic signals are less coherent. Beneath the EEC the anisotropic signal is weaker in comparison with that south-west of the TTZ and particularly in the Bohemian Massif.

Location of the PASSEQ array was unfavourable for recording SKS phases, because they do not cover a complete backazimuth range (see inset of Fig. 5a). Earthquakes, which occurred during the recording period of the array at epicentral distance larger than 85° and had a sufficient shear-wave signal/noise ratio, concentrate into two back-azimuth fans: 30–70° and 240–300°. By separating polarizations of SKS waves arriving from western and north-eastern azimuths, one can get a better insight onto geographical variations of the splitting parameters and directional variations at a site (Fig. 5b). We also show individual polarizations as arrows pointing from ray-piercing points at a depth of 80 km with their lengths proportional to the split-delay times (Fig. 6). Null-split measurements are also included (see Table S1).

The splitting parameters evaluated from the PASSEQ recordings of SKS phases depend on back azimuth and exhibit significant lateral variations within the array (Figs. 7–10). Because two directions of SKS shear-wave propagation dominate, we divide the anisotropic signals into two groups comprising nearby events, whose backzimuths are very close and lie towards the NE and the NW. Combining results for nearby events allows us to eliminate incorrectly determined parameters (see also Liu and Gao, 2013) and to recognize reliably geographical changes of mantle structure.

Several provinces, exhibiting their own characteristics of the shear-wave particle motion and apparent splitting parameters, can be delimited around the TESZ. Broad elliptical polarizations within the BM with mostly towards the NW–W oriented fast S polarizations, progressively turn to narrow PMs and null splits at stations north of the BM for waves from the NE (Figs. 7 and 8). In comparison with the lateral extent of the BM, there are only small regions indicating a consistent anisotropic signal in the upper mantle to the north of the massif along the PASSEQ array. Clear and coherent

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anisotropic signals come from shear waveforms at stations in a relatively small region around the 14° E longitude and between 51.5° to 52° N latitude, in the central part of the array crossing the TESZ and at some stations located in the EEC, east of the TTZ (Fig. 7, see also Fig. 1). Waves arriving at stations located along the north-western rim of the array do not split at all, only with the exception of the small region mentioned above.

Three bands of marked PMs evaluated from recordings of the BB stations (Fig. 8) emphasize variations of the anisotropic signal across and along the TESZ for waves arriving from the NE. Width of the bands relates to the width of the PMs. Further off the BM to the NE along lines I and II of the array, the PMs again broaden indicating significant amount of anisotropy in the upper mantle, while along line III the narrow PMs, indicating a small anisotropy or near-symmetry axis propagations, prevail. Besides changes of the PM traced along the lines I–III, i.e., across the TESZ, significant changes in shear-wave polarizations along the TESZ/TTZ are evident as well. Anisotropic signal below the TESZ detected at stations of the central line I almost disappears at stations on lines II and III. Unfortunately, majority of signals at stations located just at the TESZ are contaminated by noise. If well-resolved, directions of the fast shear-wave polarizations at individual stations do not change for waves arriving from the narrow band of the NE backazimuths.

Waves propagating from the NW (Figs. 9 and 10) also clearly demonstrate regional variability of the splitting parameters, though for these directions we evaluate a lot of apparent null splits from very narrow PMs in a much larger portion of the PASSEQ array than for waves from the NE. Null splits dominate in the western part of the array beneath the TESZ, between the BM and TESZ and beneath a large part of the BM. On the other hand, strong and coherent fast polarizations are evaluated at most stations of the eastern part of the array, as well as at several stations north of the TTZ in the EEC, the latter with less well coherent polarization orientations.

At some stations (e.g., CLL, Fig. 11), we evaluate splitting parameters which differ significantly even for data from a narrow band of azimuths, yet if only relatively stable

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solutions are considered. We show how sensitive are the results to a width of the elliptical particle motion for a subset of the PASSEQ stations. As expected, the wider PM, the more stable splitting solution we get (cf. results for stations PC21, MOX and CLL, Fig. 11). Split-delay times at the CLL attain values from near null split (i.e., undefined δt) to $\delta t = 1.2$ s, with diffused fast polarization azimuths. In general, we attribute the different polarization azimuths to a signal distortion due to noise, or to a local structure including a shallow one. The CLL station is located at the boundary between the consistently split shear-waves in the BM and null splits north-west of the BM. The complex structure in the rim of the BM affects significantly the splitting parameters evaluated even from waves arriving from very close directions.

Not only the amount of energy content on the T component (see Fig. 3), determining the width of PM ellipse, is decisive for reliability of splitting results. For example, if the Q/T amplitude ratio is $\sim 10:3$ then signal/noise ratio $\sim 4:1$ on the T component is a minimum value indicating a good reliability of the results (Table 2), besides the bootstrap measures (Vecsey et al., 2008) in case of splitting classified as "good" one. Interpreting results at stations, which have only few data and without proper quality checking, could lead to wrong inferences on the upper mantle structure (see also Liu and Gao, 2013).

4 Discussion

Similarly to other continental regions (e.g., Plomerová and Babuška, 2010), anisotropic signals that originate in the upper mantle vary in different provinces covered by the PASSEQ array. Respective mantle regions seem to be delimited by distinct tectonic features. Two types of variations need to be followed: (1) changes of the polarization parameters and/or the PM at individual stations of the array in dependence on direction of wave propagation, and (2) changes of the apparent parameters related to particular directions at all stations across the whole array. The former leads to 3-D modelling of the mantle domain fabrics and the latter sensitively detects changes in the deep

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lithosphere fabrics, especially in cases when ranges of azimuths and incidences of waves, allowing to retrieve 3-D anisotropic models exclusively from the shear-wave splitting, are incomplete.

Complex tectonics of Phanerozic Europe – westward of the TTZ – is reflected in variations of the particle motions and the splitting parameters at stations in this part of the PASSEQ array. The north-south running Variscan Front around the ~ 16° E, paralleling the Moravian Line (Fig. 1), separates the narrow PM beneath the Brunovistulian (BV), Upper Silesian (US), Malopolska (MM) and Lysogory (LU) terranes, from the strong anisotropic signal within the major part of the Bohemian Massif for waves from the NE (Fig. 8). Similarly, this dominant tectonic feature separates weak anisotropic signals in the BM for waves from the NW and the significant anisotropic signal in the Brunovistlulian, US, MM and LU (Fig. 9). This means that anisotropic structures west and east of this part of the Variscan Front (VF) differ and none of them can be approximated by a simple anisotropic model with horizontal symmetry axis. Split-delay times around 1 s locate the main source of the anisotropy into the upper mantle and regional character of the splitting in correlation with large-scale tectonics indicates that major part of anisotropic signal originates in the mantle lithosphere. Simple estimate of a depth interval where the source of anisotropy could be located considering Fresnel zones of rays approaching two nearby stations (e.g., Alsina and Snieder, 1995; Chevrot et al., 2004) can be used only in case of azimuthal anisotropy, i.e., when mantle fabric can be approximated by anisotropic models with horizontal symmetry axis. However, this is not generally valid for complex fabrics of the continental mantle lithosphere (e.g., Babuška and Plomerová, 2006).

Previous studies of the upper mantle structure beneath the BM, based on data of a series of passive seismic experiments from a period of 1998–2009 and with the use of different seismological techniques, model the BM mantle lithosphere as an assemblage of several domains retaining their own fossil fabrics (Plomerová et al., 2000, 2005, 2007, 2012a; Karousová et al., 2012, 2013; Geissler et al., 2012; Babuška and Plomerová, 2013). Joint analysis and inversion of anisotropic parameters of body waves resulted in 3-D self-consistent anisotropic models of the domains with differently oriented and inclined symmetry axes. Processing data from dense networks of the BOHEMA II and III passive seismic experiments identified two domains in the Brunovistulian mantle lithosphere. Its southern part underthrust the eastern edge of the BM up to about 100 km westward beneath the Moldanubian (MD) part of the massif (Babuška and Plomerová, 2013). The northern part of the Brunovistulian mantle lithosphere, covered by the US crustal terrane, steeply collides with the Sudetes in the north-eastern BM (Plomerová et al., 2012a). The authors suggested that the southern and northern fragments of the Brunovistulian micro-plate, separated by the Elbe Fault Zone (EFZ, dashed line in Fig. 1) might have originally belonged to different plates, i.e., Gondvana and Baltica, respectively. Seismic data from the PASSEQ array including directional variations of *P* wave residuals, suggest a continuation of the northern Brunovistulian anisotropic signal without significant changes towards the TTZ (Vecsey et al., 2013), which thus provides additional support to the idea. Moreover, anisotropic signals in *P* spheres in the northern half of the PASSEQ stations (Plomerová et al., 2012b) resemble, in general, to those found beneath the southernmost tip of the Baltic Shield (Plomerová et al., 2002; Eken et al., 2010).

In this paper, we mainly concentrate on the region north and northeast of the BM, where our measurements from PASSEQ data indicate significant changes in mantle fabrics. Null splits or weak anisotropic signals prevail at stations along the Rheic suture and in the easternmost part of the Rhenohercynian domain that parallels the TESZ (Figs. 1 and 7–10). However, within this domain of potential low anisotropy, two relatively small regions with consistent anisotropic signal are detected by waves propagating from the NE. The first one is located between the most bent part of the Variscan Front (VF) and the Rheic Suture, the second one seems to be linked with crossing of the VF and Moravian Line, in a close vicinity of the TTZ. However, apart from the complex tectonics, waveforms at stations in the TESZ suffer from noise due to the thick sedimentary cover of the crystalline basement. Distinct SKS polarizations of waves from the NW in the Brunovistulian domain, as well as delay times between 1 and 2 s, remain almost unchanged across the TESZ towards the EEC (Fig. 9), whereas polarizations of SKS waves arriving from the NE change abruptly at the TTZ (see station line II in Fig. 7).

Regional variations of the splitting parameters, as well as their backazimuth dependences, occur also eastward of the TESZ, but groups of stations with similar anisotropic parameters are less coherent than those in Variscan provinces westward of the TTZ. However, linking these variations with the large-scale tectonics of this Precambrian region is not so straitforward as it is in the Phanerozoic part of Europe, or as it is possible in the northern Fennoscandian lithosphere, where Plomerová et al. (2011) relate, e.g., a significant change in mantle fabrics to the Baltic–Bothnia megashear Zone (BBZ). Nevertheless, the splitting parameters at PASSEQ stations in the EEC and the sensitivity of the splitting parameters on backazimuth of arriving waves indicate a domain-like structure also in this part of the EEC. Unfortunately, not enough shear waveforms, needed for a detailed analysis and modelling of the upper mantle fabrics, were recorded in this part of the PASSEQ array. Both directional and lateral variations in splitting parameters in general confirms our previous inferences (e.g., Vecsey et al., 2007; Babuška et al., 2008; Plomerová et al., 2012a) that fabrics of the continental mantle lithosphere have to be modelled in 3-D with generally oriented symmetry axes.

In light of the domain-like structure of the continental lithosphere identified in different tectonic provinces (e.g., Babuška and Plomerová, 2006), it is surprising that we do not observe a distinct change of the apparent splitting parameters across the TESZ/TTZ, one of the most prominent tectonic features in the European continent. Instead, we evaluate mainly smooth changes in SKS polarizations, or even a large number of null splits northward of the BM and further across the TESZ towards the ECC. Such observations indicate less coherent fabrics and a transitional change of mantle structure beneath the surface trace of the TESZ/TTZ.

The two sutures in the western part of the TESZ – the Thor suture and Sorgenfrei–Tornquist Zone (STZ, see Fig. 1) sharply delimit domains of the mantle lithosphere of the Baltic Shield, the Danish block (Laurentia), and the North-German Platform (Avalonia, see Pharaoh, 1999). The domains, representing fragments of Fennoscandia, Laurentia and Avalonia, differ in fabrics and lithosphere thickness distinctly (Plomerová et al., 2002; Cotte et al., 2002; Shomali et al., 2002; Babuška and Plomerová, 2004). On the other hand, similar sharp change in lithosphere structure linked with the central part of the TESZ covered by the PASSEQ array, where the TTZ marks the crustal edge of the EEC on the surface, is not evident.

Anisotropic signal can be detected if the SKS propagates through an anisotropic block of a sufficient thickness, i.e., at least of one wavelength thick (Plomerová et al., 2011). Moreover, from lateral changes of anisotropic parameters of body waves we can assess an inclinations and thickness of boundary zones between the anisotropic domains of mantle lithosphere. For example, steep boundaries were retrieved in the MC (Babuška et al., 2002), in the BM (Plomerová et al., 2007), or in northern Fennoscandia (Plomerová et al., 2011), whereas an inclined boundary was modelled in the Proterozoic/Archean contact zone in south-central Finland (Vecsey et al., 2007).

In analogy with previous results, we can deduce that the narrow near-vertical TTZ in the crust, representing the north-eastern boundary of the TESZ (Dadlez et al., 2005), does not have a steep and narrow continuation in the mantle lithosphere. Instead, we suggest a complex transition zone between the Precambrian and Phanerozoic Europe, where various lithospheric fragments, possibly originally belonging to the EEC, underthrust the Phanerozoic domains. Berthelsen (1992) suggested that the TESZ crust was formed by an assemblage of suspect terranes adjoining the EEC edge from the southwest. Our measurements of anisotropy indicate a relatively broad transitional zone in between the two lithospheres of different ages. Depth estimates of the lithosphere-asthenosphere boundary (LAB) situate this important "discontinuity" to ∼ 140 km in the west and down to ∼ 200 km in the east of the TESZ (Plomerová and Babuška, 2010; Knapmeyer-Endrun et al., 2013). Mantle lithosphere thus seems to be thick enough for detecting an anisotropic signal by shear wave splitting analyses. However, considering the SKS wavelength of ∼ 40 km, which corresponds to ∼ 8–10 s dominant periods of teleseismic shear waveforms, crust thickness of ∼ 40 km and wedge-like structure of

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the contact with a transition in between the blocks, we hardly can observe a consistent pattern of anisotropic signals in the split-shear waves and a sharp change of the splitting parameters which would reflect a sharp change of the upper mantle structure.

Dadlez et al. (2005) suggested a scenario of the tectonic development of the TESZ involving detachments of elongated and narrow slivers of the Baltica crust, their north-west wandering along anticlockwise rotated Baltica (Ordovician-Early Silurian, Torsvik et al., 1996) and later their re-accretion to Baltica meeting with docked Avalonia. Nowadays, these pieces are supposed to form the basement of the TESZ crust in the north-western and central Poland. Grad et al. (2008) interpret the high-velocity lower crust extending south-westward of the TESZ as far as beneath the For-Sudetic block, as the edge of Baltica crust. Malinowski et al. (2013) revealed complex pattern of the Paleozoic and Alpine accretion at the EEC margin. But based on a deep seismic reflection profile, they interpret a westward extent of the EEC lower crust only to the TTZ. Further to the south-west they do not associate the reflective horizon with the top of the EEC crystalline basement, but with a different reflective zone in the uppermost part of the lower BM crust towards the Carpathian Fold-and-Thrust belt. Our results on deep lithosphere structure suggest that fragments of the Precambrian mantle lithosphere most probably underthrust the Proterozoic platform west of the TTZ and might penetrate the mantle southward as far as to the EFZ in the eastern BM (northern part of the Brunovistulian). Complex structure of the upper mantle, as well as underthrusting of micro-plate fragments in the TESZ, might contribute to the largest discrepancy in magnetotellutic and seismological LAB depth estimates ever found in the European continent (Jones et al., 2010).

Prevailingly smooth changes of the anisotropic signal (including the nulls) across the TESZ contrast with significant changes in splitting parameters along the TTZ. The notable change occurs around the TTZ intersection with $\sim 18^{\circ}$ E longitude, close to the edge of the LU and MM units (Pharaoh, 1999; see also Fig. 1), which are along with the Brunovistulian domain associated with Baltica (Dadlez et al., 2005). NW of this “triple junction”, a narrow band of the Avalonian fragment is squeezed in between the TTZ

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and the Variscan Front. Narkiewicz et al. (2011) study in details crustal seismic velocity structure and demonstrate preserved memory of a pre-Devonian terrane accretion at the East European Platform margin. The authors took into consideration geological and potential field evidence that allowed them to interpret Upper Silesia, Malopolska and Lysogory blocks as separate crustal units, though without precise marking sutures between the particular exotic terranes identified by sharp lateral gradients in the velocity models. This may also lead to discrepancies in delimiting units in tectonic schemes of different authors (cf. e.g., Pharaoh et al., 1999, Dadlez et al., 2005) and to leaving distinction between some of the units as an open question (Narkiewicz et al., 2011).

Babuška et al. (1998) deduced from depth variations of surface-wave radial and azimuthal anisotropy that lateral extent of the mantle lithosphere of Precambrian units is larger than is extent of mapped crustal terranes. Off-sets between mantle and crust boundaries of tectonic units, attaining several tens of km as a result of lower-crust/mantle decoupling, are often observed (e.g., Babuška et al., 2008). Therefore, based on characteristics of the anisotropy evaluated from shear-wave splitting, we suggest the EEC mantle lithosphere can penetrate into the Phanerozoic part of European plate southwest of the TTZ, beneath the TESZ and probably even farther beneath the Variscan provinces, regardless of which interpretations of the crustal terranes, concerning particularly the Baltica lower-crust extent, is adopted.

5 Conclusions

We have analysed splitting of shear waves (SKS phases) recorded during the PASSEQ passive experiment focussed on a study of the upper mantle structure across the Trans-European Suture Zone (TESZ). 1009 pairs of the delay times of the slow split-shear waves and orientations of the polarized fast-shear waves exhibit lateral variations within the array, if evaluated from the same event. Individual measurements at a station depend on backazimuths as well. Particular attention was paid to tests of the northward orientation of seismometers to avoid misinterpretations of the mantle structure due to

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the instrument misalignment. We identified seismometer misorientations exceeding 10° not only at several portable stations, but also at some observatories.

While a distinct regionalization according to anisotropic structure of the mantle lithosphere exists in the Phanerozoic part of Europe, a correlation with the large-scale tectonics around the TESZ and in the East European Craton (EEC) is less evident. No general and abrupt change in the splitting parameters can be related to the Teisseyre–Tornquist Zone (TTZ), marking the edge of the Precambrian province on the surface. Significant change of the mantle lithosphere structure appears at the northern edge of the Variscan Bohemain Massif (BM). Distinct regional variations of anisotropic structure can also be followed along the TESZ/TTZ, while changes across the zone are gradual. Based on geographical variations of shear-wave splitting, we suggest a southwestward continuation of the Precambrian mantle lithosphere beneath the TESZ, and probably even further southwest.

Supplementary material related to this article is available online at http://www.solid-earth-discuss.net/6/229/2014/sed-6-229-2014-supplement.pdf.

Acknowledgements. Contributions of all members of the PASSEQ working group are greatly appreciated. The field works and research of the Czech team was supported by grant No. IAA300120709 of the Grant Agency of the Academy of Sciences and grant No. 210/12/2381 of the Grant Agency of the Czech Republic.

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Table 1. Estimated deviations of misaligned seismometers.

Station	permanent/ temporary	Latitude [°]	Longitude [°]	Misorientation [°]	Number of PMs
BFO	perm	48.3301	8.3296	−12	1
BSEG	perm	53.9353	10.3169	12	15
FUR	perm	48.1629	11.2752	−12	15
GKP	perm	53.2697	17.2367	41	15
KOLS	perm	48.9333	22.2731	−15	2
JAC	temp	50.3718	12.9132	−49	14
PA10	temp	50.4903	13.1355	−10	15
PA69	temp	53.2387	19.8420	24	11
PA70	temp	53.4720	20.5229	−10	10
PC21	temp	49.6700	12.6780	10	13
PC23	temp	49.9774	13.1686	28	14
PC32	temp	50.7915	15.1957	13	13
PG41	temp	50.7510	17.3330	−22	11
PG42	temp	51.0980	18.0640	−22	14
PG01	temp	48.4204	12.0779	56	1
PR04	temp	52.4098	12.9744	26	3

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Table 2. Synthetic tests of seismometer misorientation.

Signal Quality	Splitting Method	Signal			
		original		5° misoriented	
		δt [s]	φ [°]	δt [s]	φ [°]
good	transverse	0.6	77	0.7	92
	eigenvalue	0.6	86	0.6	81
fair	transverse	0.6	200	0.8	133
	eigenvalue	1.2	208	1.2	213

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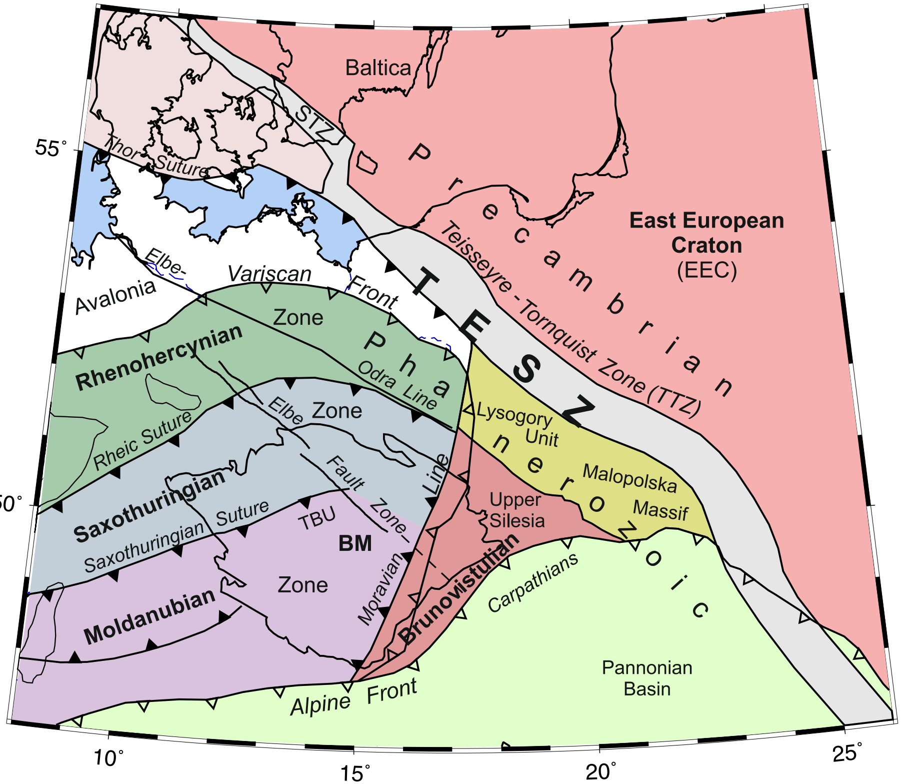

Fig. 1. Simplified tectonic sketch of the Trans-European Suture Zone (TESZ) and adjacent areas according to Pharaoh (1999). STS stands for the Sorgenfrei–Tornquist Zone, TBU for the Teplá–Barrandian Unit included in the Moldanubian Zone of the Bohemian Massif (BM).

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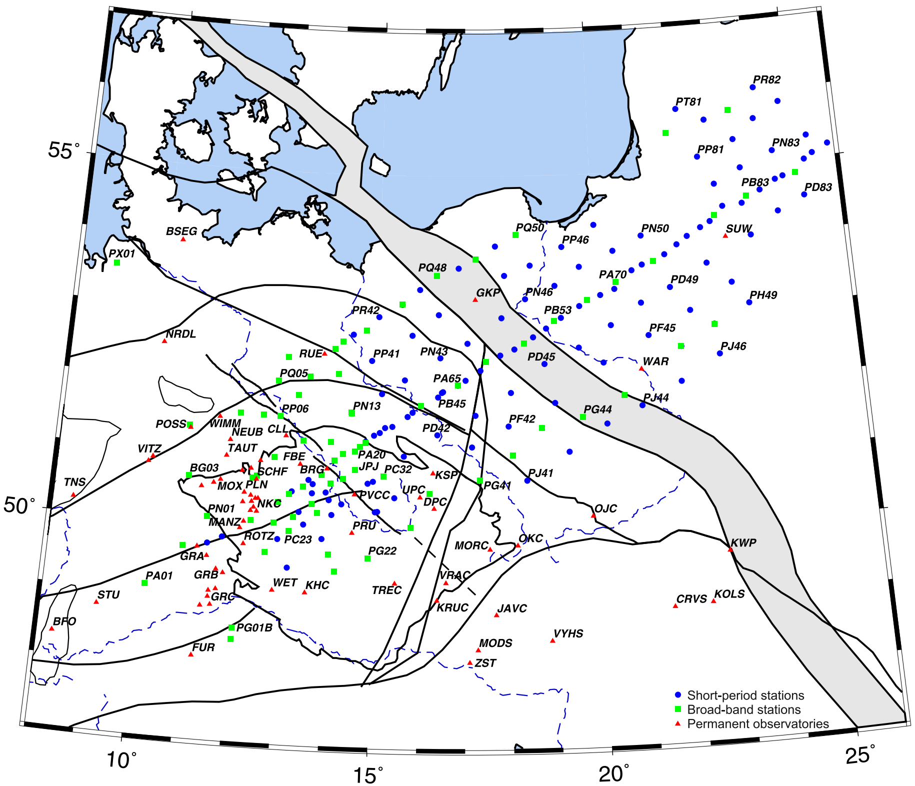

Fig. 2. Seismic stations of the passive experiment PASSEQ (2006–2008) designed to study upper mantle structure of the Trans-European Suture zone (TESZ). Labels are assigned to some of stations for easier orientation.

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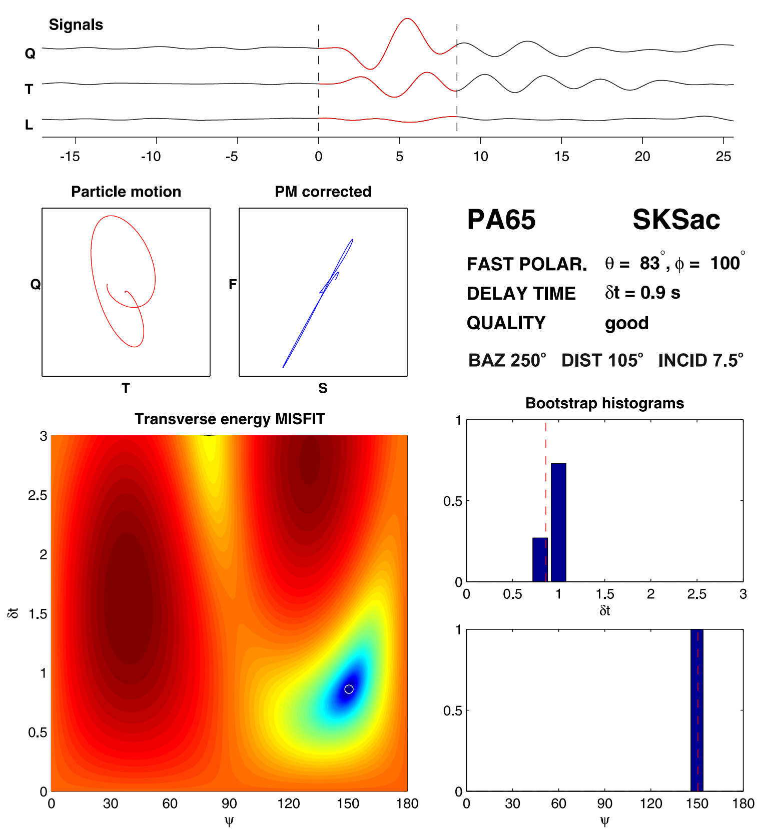

Fig. 3. Example of evaluation of SKSac phase splitting at station PA65 in the central part of the PASSEQ array (see Fig. 2) for an earthquake in Chile–Argentina border region: 25 August 2006, 00:44 UTC, 24.34° S 67.01° W, 185 km deep, 5.8 Mw. Epicentral distance to the station is 105.2°, backazimuth 250.0° and incidence angle 7.5°. For more details on the method we refer to Vecsey et al. (2008).

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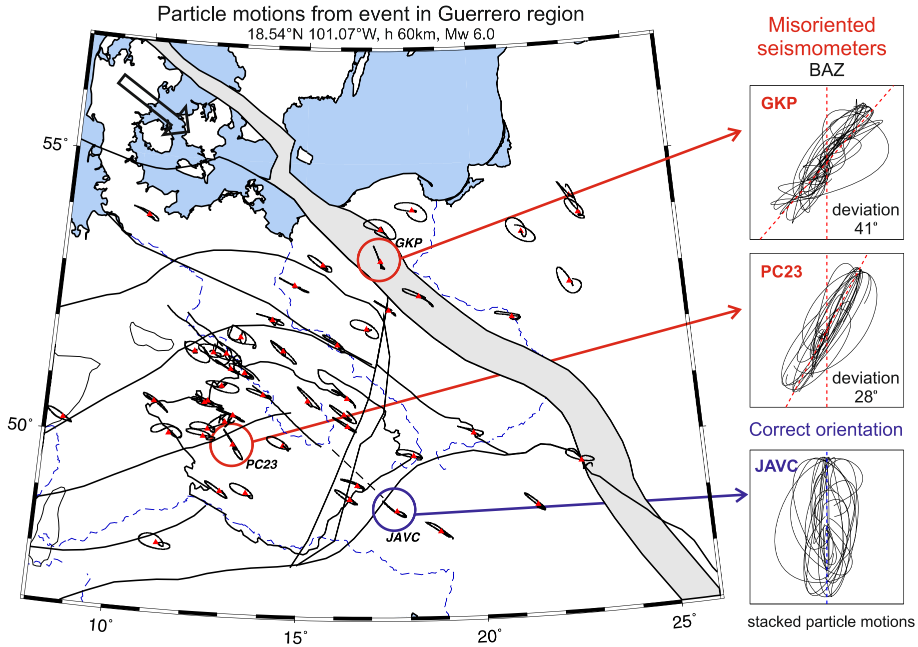

Fig. 4. Horizontal shear-wave particle motion (PM) across the PASSEQ array for an event from the NW (left), located in Guerrero region, documenting incorrect northward orientation of seismometers at stations GKP and PC23. PMs rotated to the backazimuths and stacked for all events evaluated at stations PC23 and GKP with misoriented seismometers, and correctly aligned seismometer at JAVC (right). Only sufficiently large errors (∼> 10°) in seismometer misorientation can be revealed by this method. Smaller deviations of the PM can be caused by a weak anisotropy in the upper mantle.

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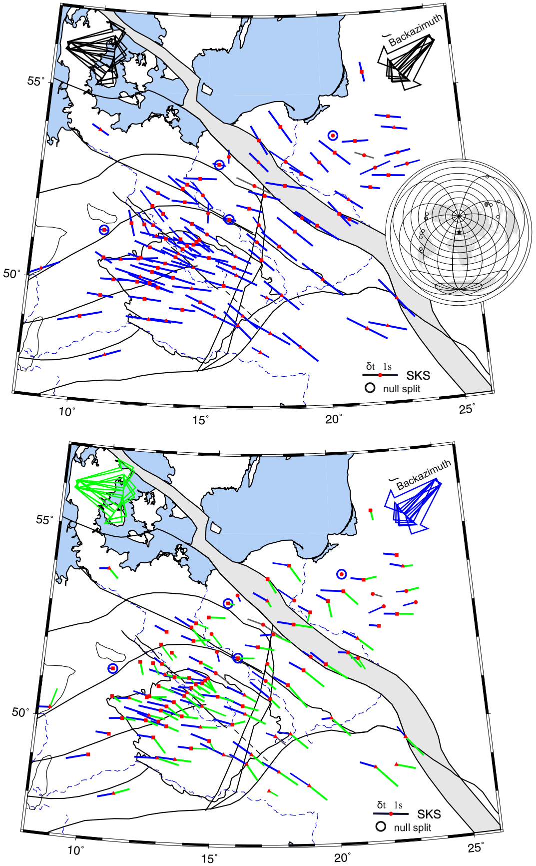

Fig. 5. Shear-wave splitting presented in a standard way, i.e., the fast shear-wave polarization azimuths (Table S1) as bars with length proportional to the split delay time: **(a)** averages calculated from all measurements regardless of wave backazimuth and **(b)** averages calculated separately for waves arriving from the west and from the north-east. Inset shows epicentre distribution of 15 events used in this study relative to the PASSEQ array (star).

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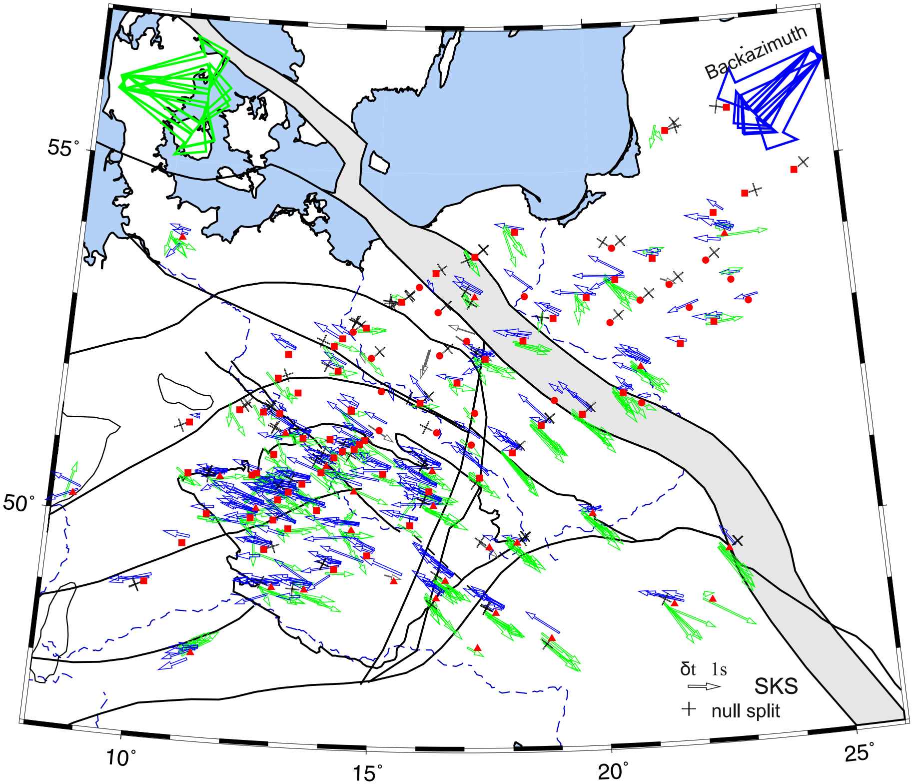

Fig. 6. Fast shear-wave polarizations (ψ, δt) evaluated in the LQT coordinate system presented at ray-piercing points at depth of 80 km. The arrows mark azimuths φ of the polarized fast split-shear waves and point in down-dip directions. See also Fig. 3 and related text.

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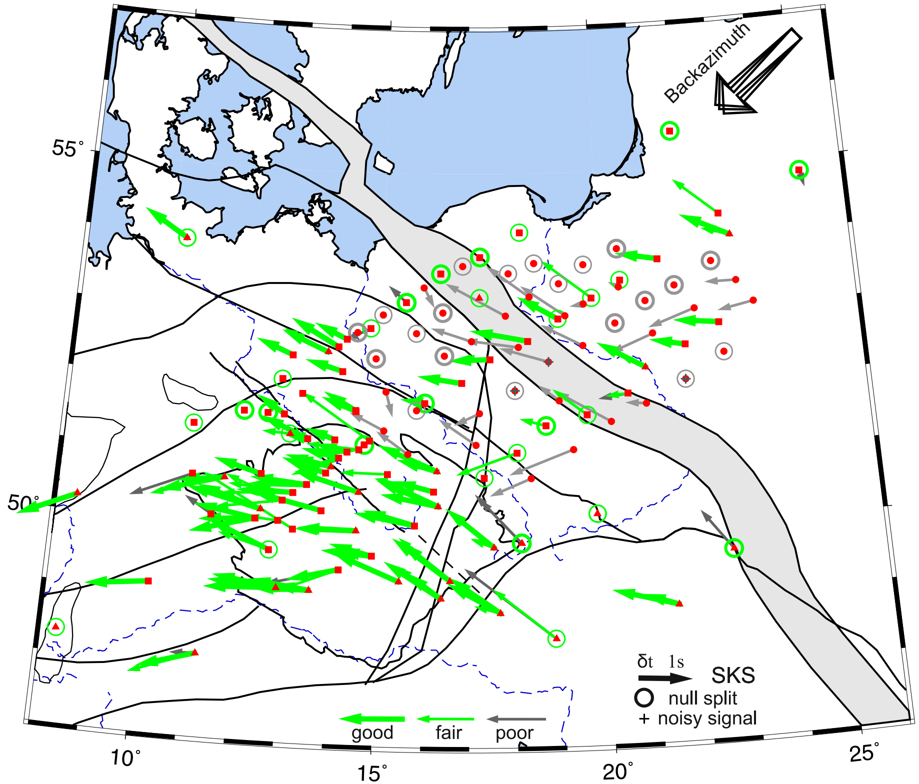

Fig. 7. Azimuths φ of the fast shear-wave polarizations and the split-delay times δt evaluated for three events from the NE backazimuths. Anisotropic signal dominate in the Bohemian Massif, null splits or small provinces with coherent polarizations exist west and north of the Bohemian massif. Complementary measurements at stations equipped with 2–3 s seismometers are shown in light-grey colour.

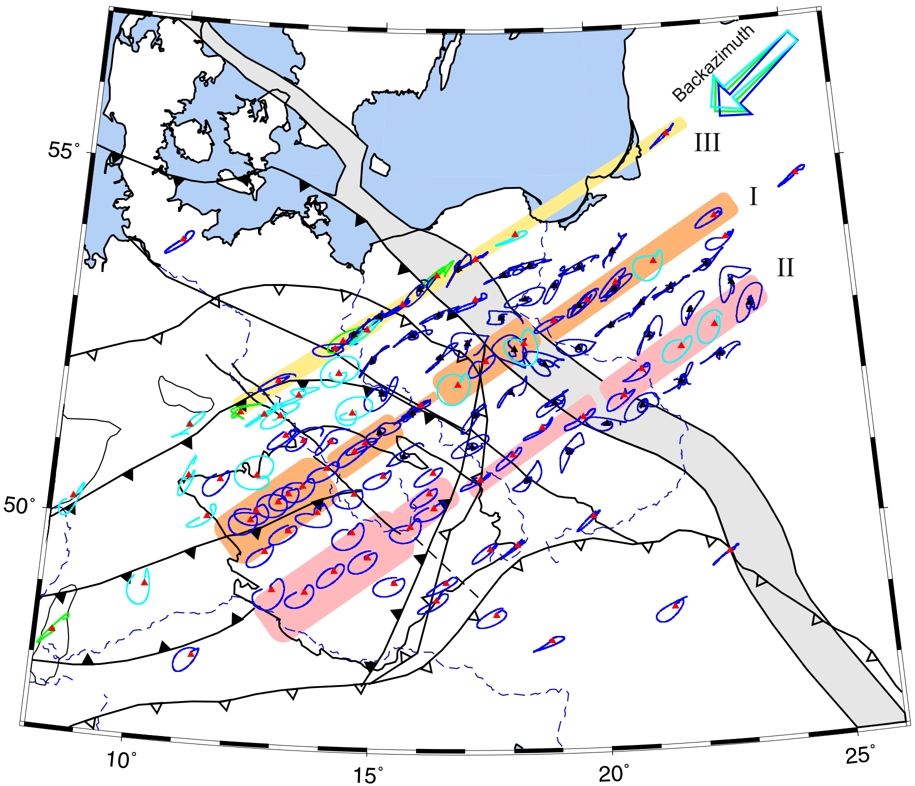

Fig. 8. Particle motions (PM) for three events from the NE (the same as in Fig. 7). To emphasize variations of the PM across and along the TESZ three profiles of the BB stations are marked by coloured bands, whose widths are in relation to the width of the PM ellipses: orange – three areas of broad PMs (in the BM, TESZ/TTZ and EEC) along the Profile I; red – broad PMs in the BM, followed by narrow PMs, which is getting gradually broader in the EEC along the Profile II; yellow – mostly linear PMs along Profile III.

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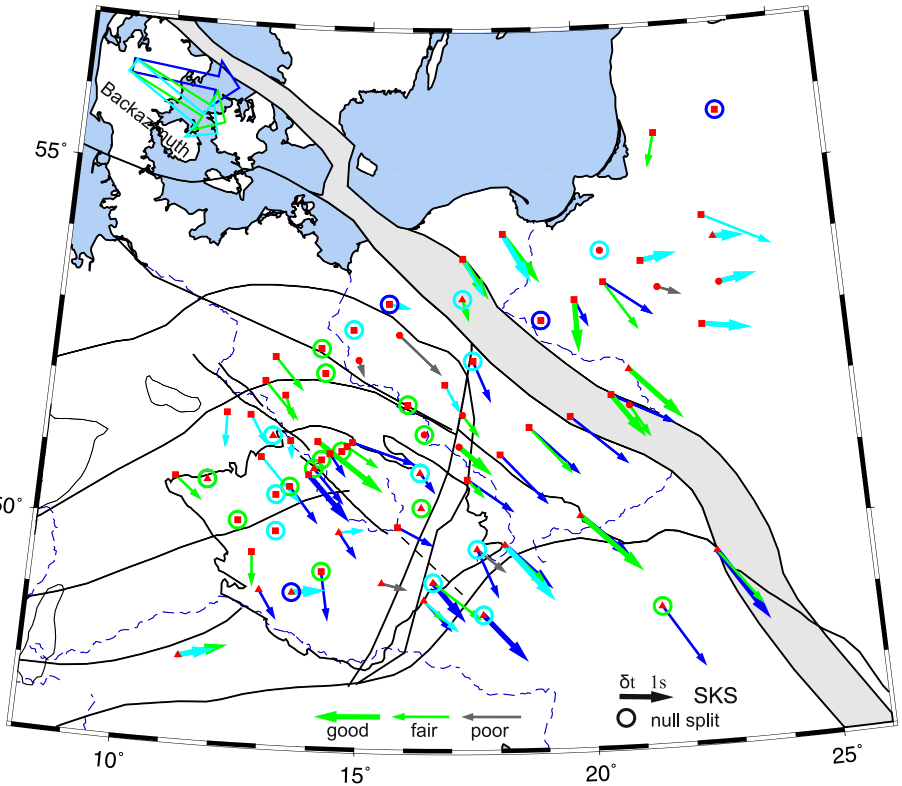

Fig. 9. Azimuth φ of the fast shear-wave polarizations and delay times δt evaluated for four events from the NW backazimuths. Green arrows represent results stacked for two events. Nulls or near-null splitting prevail in the BM and in the western part of the array, whereas stations east of the Moravian Line show strong anisotropic signal for this backazimuth interval.

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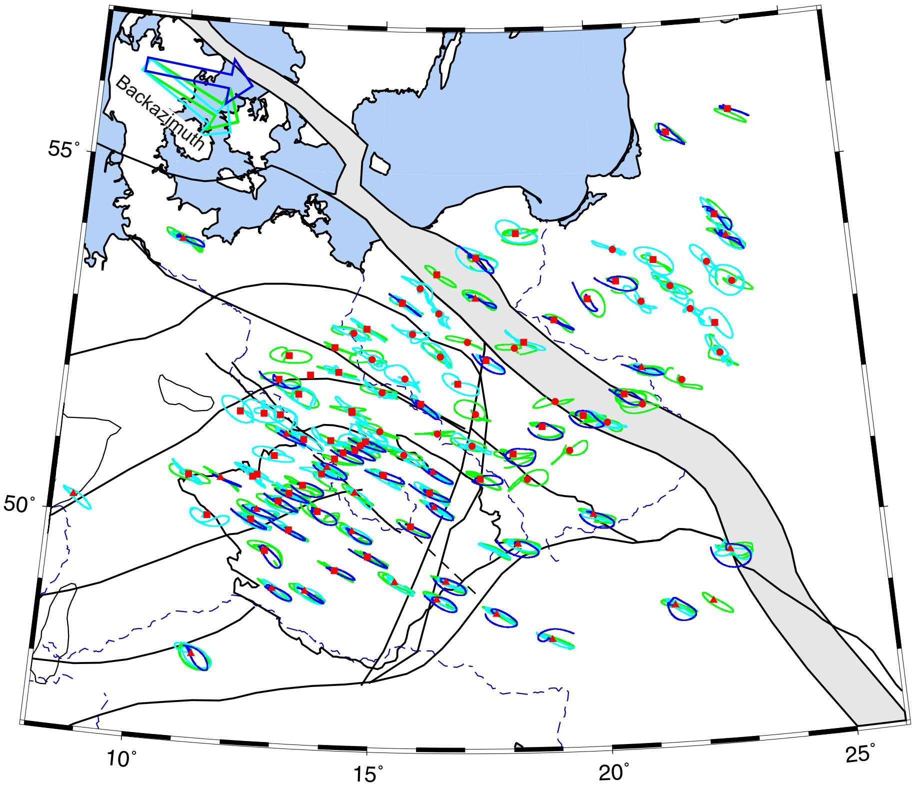

Fig. 10. Particle motions (PM) for the same events from the NW as in Fig. 9.

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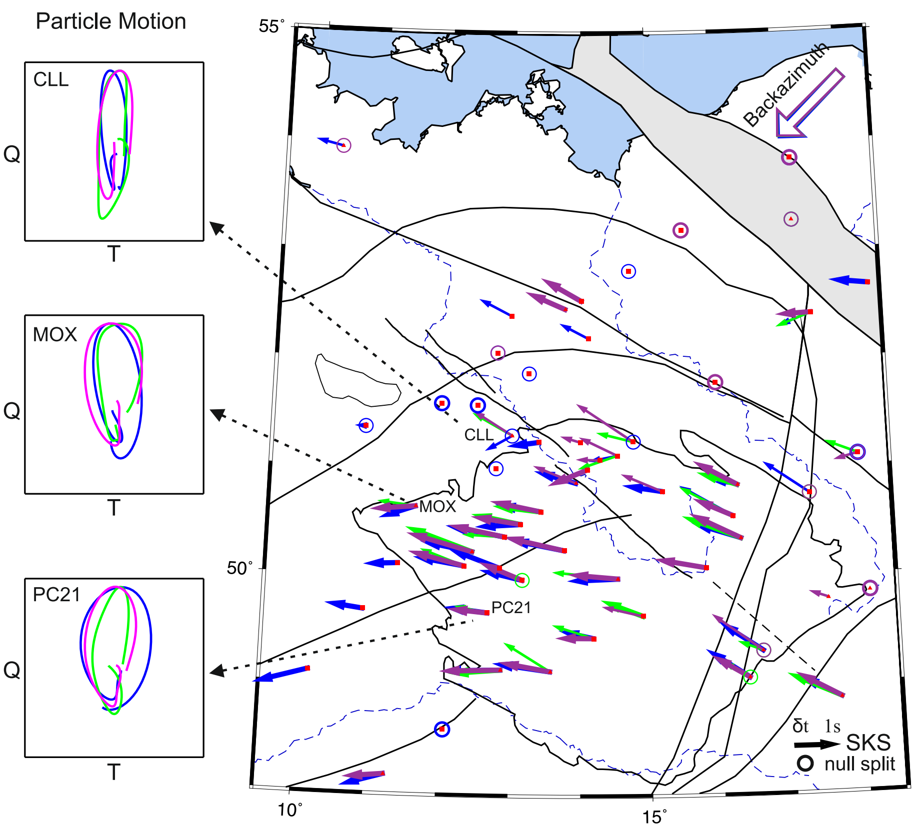

Fig. 11. Shear-wave polarizations evaluated at a part of the PASSEQ array from recordings of three events. Splitting parameters evaluated from narrow particle motion (PM) of waves arriving from very close directions differ at station CLL, while we get identical splitting parameters from the broad PM at, e.g., station PC21. Complex structures can affect significantly the splitting parameters of waves arriving even from very close directions.

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