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Seismic anisotropy and large-scale deformation of the Eastern Alps

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ABSTRACT

Mountain chains at the Earth's surface result from deformation processes within the Earth. Such deformation processes can be observed by seismic anisotropy, via the preferred alignment of elastically anisotropic minerals. The Alps show complex deformation at the Earth's surface. In contrast, we show here that observations of seismic anisotropy suggest a relatively simple pattern of internal deformation. Together with earlier observations from the Western Alps, the SKS shear-wave splitting observations presented here show one of the clearest examples yet of mountain chain-parallel fast orientations worldwide, with a simple pattern nearly parallel to the trend of the mountain chain. In the Eastern Alps, the fast orientations do not connect with neighboring mountain chains, neither the present-day Carpathians, nor the present-day Dinarides. In that region, the lithosphere is thin and the observed anisotropy thus resides within the asthenosphere. The deformation is consistent with the eastward extrusion toward the Pannonian basin that was previously suggested based on seismicity and surface geology.

1. Introduction

Surface geology and tectonic evolution of the Alps appear rather complex (Schmid et al., 2004), and it may be enlightening to study mantle structure in the region. Several geophysical studies have been performed, and they have produced 3D tomographic models (Gebrande et al., 2002; Piromallo and Morelli, 2003; Lippitsch et al., 2003; Brückl et al., 2010; Dando et al., 2011; Mitterbauer et al., 2011; Legendre et al., 2012). Tomographic images show velocity anomalies that can be interpreted in the context of suture zones and the major subduction events. The above-cited studies did not fully clarify the dynamics of the collision however, since they apparently allow opposing views on the structure and evolution of the Eastern Alpine region. More specifically, two recent studies using P-wave velocity tomography for the Eastern Alps come to different conclusions. Lippitsch et al. (2003) interpreted the high velocity anomaly in the Western Alps as dipping southeastward European lower lithosphere beneath the Adriatic microplate while the anomaly in the Eastern Alps is interpreted to represent Adriatic lower lithosphere dipping northeastward beneath the European plate. On the other hand, the more recent ALPASS tomographic model, proposed by Mitterbauer et al. (2011), does not suggest a change of subduction polarity between the Western and Eastern Alps. At the eastern end of the mountain chain, the Alps have been connected in the geological past with the Carpathians and the Dinarides. Nowadays, the Eastern Alps (Gutdeutsch and Aric, 1987; Ratschbacher et al., 1991; Brückl et al., 2010) may be extruding towards the Pannonian basin. Further investigation is needed to provide more reliable evidence, and to study the vertical extent of the eastward extrusion. Many parts of the Eastern Alps have never been studied with respect to seismic anisotropy and deep deformation, due to the sparse coverage of seismic stations in the area.

In this study, we investigate upper mantle anisotropy beneath the Eastern Alps by measuring the splitting of teleseismic SKS/SKKS phases for the Alpine region. These shear waves record large-scale anisotropy produced by lattice-preferred orientation (LPO) of rock-forming minerals and particularly of olivine that represents the major upper mantle volume. The LPO of olivine grains develops in response to tectonic strain (Mainprice et al., 2000; Nicolas and Christensen, 1987; Savage, 1999; Silver and Chan, 1991). We present here our first results from permanent seismic stations in the Eastern Alpine region (their location and network are listed in Table 1) and discuss them in conjunction with earlier measurements from the Western Alps (Barruol et al., 2011) and from the central Alps along the TRANSALP profile (Kummerow and Kind, 2006).

2. Data and method

In this study we focus on large-scale anisotropy in the upper mantle under the Alps, through the splitting of teleseismic SKS/SKKS wave phases. To characterize the nature of anisotropic structures using the shear-wave splitting method, two splitting parameters are defined as the fast orientation azimuth (ϕ, angle between fast axis and radial direction) and delay time between the

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Table 1
Station location and mean splitting parameters, as calculated by transverse energy minimization technique (SC) (Silver and Chan, 1991). The value of errors (95% confidence interval) for the measured mean value of splitting parameters is also listed for each station, together with the number of split events (S-e) and good quality measurement (G-m).

Station	Lon (°E)	Lat (°N)	ϕ (°)	ϕ-error	δt (s)	δt-error	S-e	G-m
ABTA	12.5123	46.7474	85	12	1.26	0.28	17	9
ARSA	15.5230	47.2505	116	12	1.30	0.21	63	11
CONA	15.8618	47.9282	124	8	1.00	0.19	33	11
DAVA	9.8803	47.2867	56	5	1.35	0.11	36	20
FETA	10.7291	47.0211	63	33	0.76	0.12	12	5
KBA	13.3447	47.0784	107	16	0.98	0.29	14	6
MOA	14.2659	47.8495	109	5	1.08	0.13	55	32
MYKA	13.6416	46.6299	104	5	1.37	0.22	37	23
OBKA	14.5489	46.5092	119	4	1.47	0.13	76	40
RETA	10.7623	47.4871	50	6	0.82	0.10	19	13
SOKA	15.0327	46.6780	124	6	1.14	0.17	22	16
WTTA	11.6363	47.2638	68	8	1.55	0.27	28	11

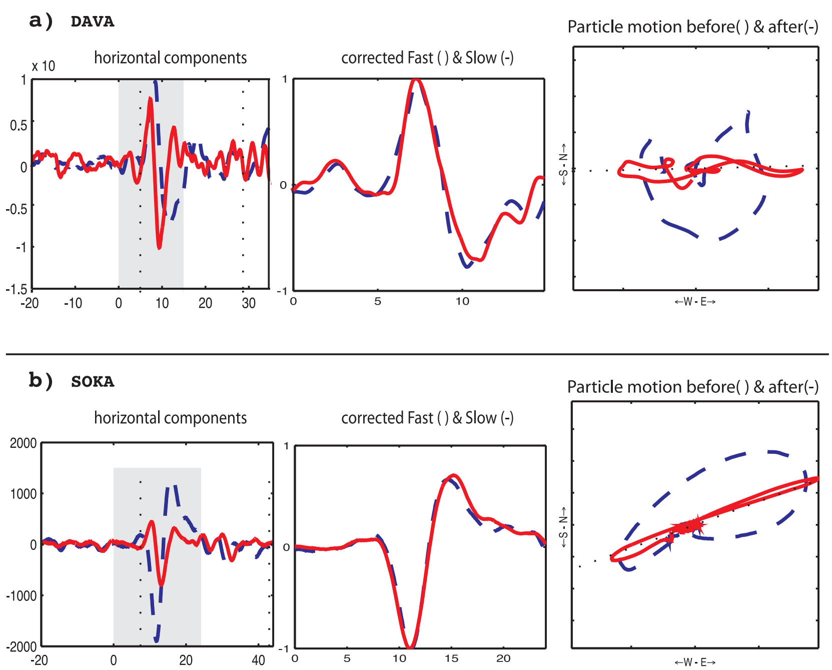

Fig. 1. Two examples of SKS splitting measurements obtained by using the minimum energy (SC) technique at stations (a) DAVA and (b) SOKA from the Eastern Alps. For each event–station pair, the left panel shows the horizontal (radial – dashed, transverse – solid) components, in the middle panel fast and time-matched slow (solid and dashed) components of the SKS wave, and the right panel the horizontal particle motion before (dashed) and after (continuous) anisotropy correction.

fast and slow polarizations (δt). We used the transverse energy minimization technique (SC) (Silver and Chan, 1991) to recover the splitting parameters. In this technique a grid search approach was performed over all possible values of ϕ and δt by rotating the components and correcting the delay time. Thus, the minimum amplitude of the transverse component is achieved corresponding to the best fitting value of splitting parameters. In most cases we applied no filter to include the entire frequency range. To carry out the measurements of anisotropic parameters based on the SC technique, the SplitLab package (Wüstefeld et al., 2008) was used. Fig. 1 shows an example of splitting measurements by SplitLab for two stations, DAVA and SOKA after the application of the SC technique.

The data set comprised the teleseismic events in the epicentral distance range 90° to 130° and magnitudes greater than 6 Mw, recorded by the Austrian broadband seismological network (OE) between 2002 and 2011. The OE network includes 12 permanent stations (see Table 1) with three-component broadband STS-2 sensors. We inspected teleseismic events at the stations on average 197 per station. Altogether 2371 SKS/SKKS phases have been investigated for all stations; out of this number of events, we measured the individual splitting parameters for 418 SKS/SKKS phases and obtained between 12 and 76 clear split phases per station. All results were classified as “good”, “fair”, and “poor” quality (Barruol et al., 1997; Wüstefeld and Bokelmann, 2007). That way, at least 9 good quality measurements were achieved for most stations, ABTA, ARSA, CONA, DAVA, MOA, MYKA, OBKA, RETA and SOKA (except for FETA with 5, and KBA with 6). A circular mean was calculated only over the good quality fast axis azimuths to obtain an average value of splitting parameters for each station.

3. Results and discussion

Mean values of the measured splitting parameters are summarized in Fig. 2. Vectors present the orientations of fast azimuths where their length corresponds to the mean value of delay times (δt) for each station. Table 1 provides the mean values of measured fast axis azimuth, together with 95% confidence intervals (CI). This value is less than ±8° for 8 stations, smaller than ±12° for ABTA and ARSA, and ±16° and ±33° for KBA and FETA, respectively. Since the measured fast orientations for each station show tightly grouped distributions, we will discuss only the calculated mean

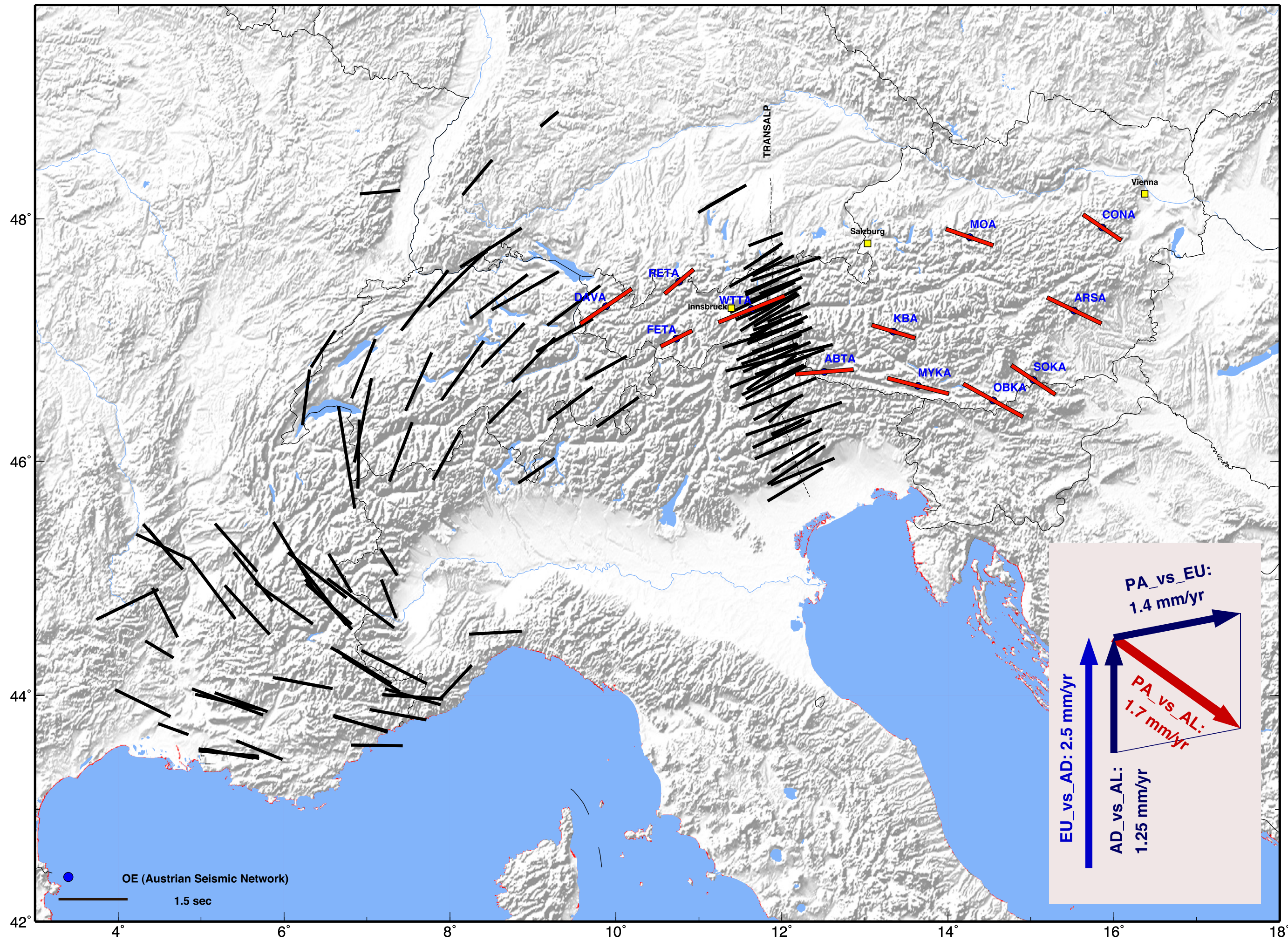

Fig. 2. Shear-wave splitting results for stations in the Alps. New results from 12 permanent stations in the Eastern Alps are shown with red bars. Black bars for results from previous studies (Barruol et al., 2011; Kummerow and Kind, 2006). The bars show fast orientation (ϕ) and delay time (δt) scaled by length. Note the changing fast axes orientations along the Alps. The insert shows the construction of the relative motion of the Eastern Alps (red arrow) relative to the deeper part of the Alps, from the convergence of the Adriatic plate toward stable Europe, and the extrusion of the Eastern Alps, to explain the fast orientations in the Easternmost Alps (see text). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

values of fast azimuth in the following, instead of the individual measurements. Measured splitting delay times (δt) (Silver and Chan, 1991) scatter considerably, with mean values between 0.76 and 1.55 s (Table 1). These values are generally in line with earlier measurements (Barruol et al., 2011), and would be interpreted as a layer thickness on the order of 85 to 170 km, assuming a velocity difference of 4% between the two shear-wave phases. The larger splitting values would be difficult to accommodate all within the lithosphere. Kovács et al. (2012a) have also found values around 4% from mantle xenoliths from the nearby Pannonian basin, with some samples giving 6.4%. The latter samples pertain to the lower part of the lithosphere only. An asthenospheric contribution is apparently required for explaining the anisotropy. This is especially the case for the easternmost stations.

Measured fast orientations fall into two groups: Stations in the West show SW–NE fast orientations, and stations in the East NW–SE. In between, station ABTA has an intermediate fast orientation azimuth of N85°, nearly E–W. Stations in the western part of this study closely agree with results from Switzerland (Barruol et al., 2011). In the center, the North–South TRANSALP profile (Kummerow and Kind, 2006) at longitude ∼12°E, has provided fast orientations of 60°–70°N, very similar to station WTTA, as well as Western Austria and Switzerland. On the other hand, stations in the easternmost part of the Alps show fast orientations that are rather different, NW–SE, yet they again show a very good spatial consistency among that group. Barruol et al. (2011) had found fast axes azimuths that rotate along with the Alpine Arc in the Western Alps. This has raised much interest in how anisotropic fast axes would be oriented in the rest of the Alps. Fig. 2 shows that the pattern continues, but in Central Austria there is an abrupt change, and fast orientations jump to a NW–SE pattern.

To study this in more detail, we have projected the stations from Fig. 2 onto the centerline of the Alps that we have determined by connecting the centers of gravity of the mountain chain (assuming constant density in the Alps for simplicity). This projection allows inspecting fast orientation as a function of distance along the Alps, from the Southwest to the Northeast (Fig. 3). We note that, within the progressive rotation along the Alps, there are two zones in the Alps where fast orientations remain constant. These are (a) Central Switzerland to about Innsbruck (between points 1 and 2 in Fig. 3), and (b) to the East of Salzburg (point 3). No significant spatial change of fast orientation is detected within these two zones. All of the progressive changes along the Alps occur in the Western Alps and at longitudes between Innsbruck and Salzburg. The latter zone agrees well with the Tauern Window in which exhumed deep structural units are exposed. The pattern of fast orientation in these two zones appears to be similar, as far as one can tell with the stations available at the moment. On

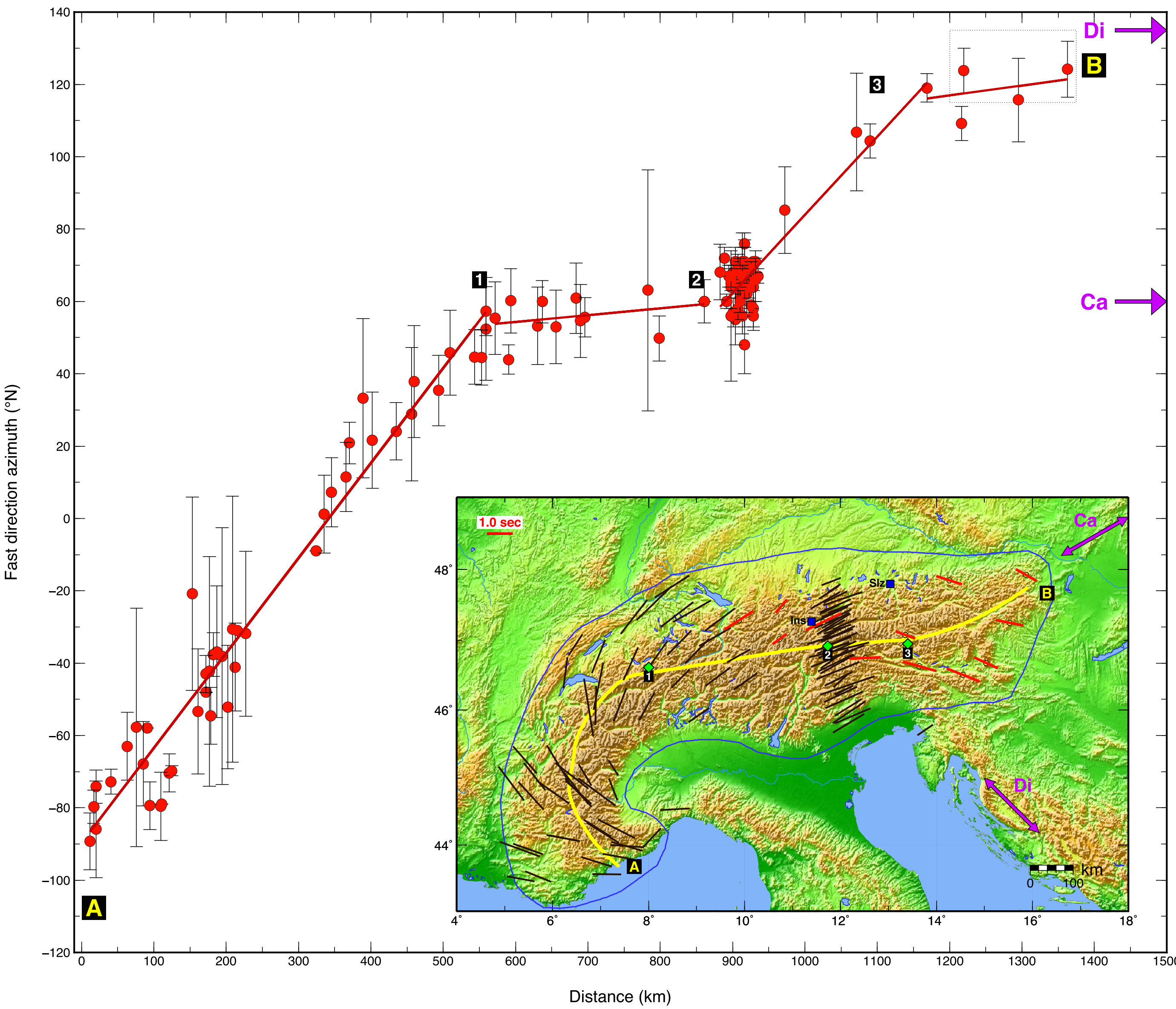

Fig. 3. Rotation of fast orientations with distance along the Alps. Red circles give the fast azimuth for station locations projected onto the central line along the Alps. Note the regions of constant fast azimuths around Switzerland and the Eastern Alps, and the region of fast spatial rotation in between (see text). For the Eastern part of the Alps, starting at point 3, the topographic trend rotates toward the North, while the fast azimuths rotate toward the South. The easternmost stations (box) are located on thin lithosphere (see text). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the other hand, splitting delays do not show clear spatial variations.

The effect of the Alpine orogenic events is manifest in the clear rotation of seismic anisotropy along the Alps, similar to that of the mountain chain. Such mountain chain-parallel fast orientations have been found beneath many other mountain ranges, e.g., the Hercynian (Bormann et al., 1993), Apennines, the Pyrenees, the Himalaya/Tibet (Lave et al., 1996), the Appalachians (Barruol et al., 1997), the Carpathian arc (Ivan et al., 2008), and the Western Alps (Barruol et al., 2011). Except for Tibet, the pattern for the Alps is the clearest example of this phenomenon. Since all of these mountains chains have been associated with subduction, it is interesting to compare this trend in seismic anisotropy with active subduction zones. Several of those show similar behavior, with fast axes parallel to the trench, e.g., the Calabrian arc (Baccheschi et al., 2007), and the Gibraltar arc (Buontempo et al., 2008; Diaz et al., 2010), but not all; some show different splitting characteristics, usually with trench-parallel orientations close to the trench, but trench-normal toward the back-arc. Fry et al. (2010) show orogen-parallel fast orientations for the crust in Switzerland, from ambient noise, while the depth region just below the Moho may be characterized by orogen-normal orientations. The latter may possibly be a thin layer, thinner than resolvable in SKS shear-wave splitting observations. Surface waves (e.g., Marone et al., 2004) suggest layering for the wider region around the Alps with Love waves requiring higher shear velocities than Rayleigh waves. One key suggested recently for explaining the spatial variation of splitting behavior within the wedge was the effect of water that might cause different slip systems in olivine grains to be activated during large-scale deformation, either in nominally anhydrous minerals (Karato et al., 2008), or through free fluids (Kovács et al., 2012b). In the Alps and similar (older) settings in the last stage of orogeny, most of the water may have left the upper mantle, and the dominant slip system may be the classical A-type (Nicolas and Christensen, 1987; Nicolas, 1993). This may perhaps be the reason why we have not found any indication of orogen-perpendicular fast orientation in the Alpine upper mantle so far. In the following we will therefore only consider A-type fabric. Another guiding model for the internal deformation of mountain ranges is transpression (Nicolas, 1993), where part of the material (e.g., layers) undergoes pure shear, and other parts simple shear with a horizontal flow direction, and orogen-parallel flow (Barruol et al., 2011).

We have noted the relatively good agreement between fast directions and the trend of the mountain chain. Given the high quality of the observations, we can go a step beyond, and address this pattern in more detail, and especially the region where the similarity with the topographic trend actually breaks down, e.g., in the Eastern Alps. In this, we need to keep in mind that our shear-wave splitting observations are associated with a finite Fresnel zone, with a width (diameter) of about 100 km at a depth of 150 km. This may smooth the observed spatial variation somewhat, but it does not cause the overall smooth rotation of fast orientation along the Alps.

The abrupt change of fast orientation occurs across the Tauern Window, which is also the area where the Adriatic indenter acts (Robl and Stüwe, 2005). Its effect may be to bend the colliding block around its edge, which may explain the banana-shape of the Tauern window through the effect of a clockwise block rotation of the zone to the East relative to that in the West; such a difference in orientation across the Tauern Window longitude range is also observed in paleomagnetic data (Mauritsch and Frisch, 1980). To the east of the Tauern Window, fast azimuths point toward the Southeast, in between the orientations which Carpathians (Ca) and Dinarides (Di) have nowadays. In principle, that orientation is not far from the ancient orientation of the Carpathians, before the opening of the Pannonian basin (Royden and Baldi, 1988), which had been around 110° from North, with a relatively large uncertainty from the reconstruction though. If pre-Alpine deformation played an important role, then this would predict that seismic anisotropy in the Dinarides would also follow the trend of the Dinarides. This is to be seen. A difficulty in this view, however, is that the three easternmost stations are located on a thin lithosphere of about 60–80 km thickness (Artemieva et al., 2006; Bianchi et al., 2013), and the lithosphere can therefore not explain the major portion of the splitting signal there. The three stations in the East thus may be recording mainly asthenospheric anisotropy that would be younger compared with frozen-in anisotropy within the lithosphere, and probably even related with ongoing deformation. The anisotropy at the easternmost stations is not much different from the four stations further to the west, except that the fast orientation is slightly more southerly.

An important tectonic feature of the area is the extrusion of the central part of the Alps toward the Pannonian basin in the East. There is good evidence that this occurs, at least at the Earth's surface, from seismicity (Brückl et al., 2010; Gutdeutsch and Aric, 1987), structural geology (Frisch et al., 1998; Ratschbacher et al., 1991), and geodesy (Bus et al., 2009). Recent GPS velocities from the European geodetic networks have given motions approximately toward the east for the Eastern Alps (Bus et al., 2009), relative to stable Europe, although individual stations scatter somewhat around that direction, and the different studies performed so far do not agree very well.

To relate surface motion to the shear-wave splitting observations, we need to consider that seismic anisotropy records internal deformation rather than displacement. Plate-motion-related deformation with a horizontal flow plane would attain a fast orientation parallel to the relative motion of the deeper mantle relative to the surface. We assume that the mantle is stationary with respect to the central Alps. If the convergence across the Alps is taken up by roughly constant strain, the Central Alps would move toward stable Europe with approximately half the velocity of the Adriatic Indenter. The latter is 2.5 mm per yr (Bus et al., 2009) relative to stable Europe (AD versus EU in the insert of Fig. 2). The direction of motion of the Pannonian unit relative to stable Europe (PA versus EU) is 1.4 mm per yr with an azimuth of 79° from North (Bus et al., 2009). The motion of the Pannonian unit with respect to the Central Alps (PA vs AL) is then 1.7 mm/yr with an azimuth of 126°. This is in the range of the fast directions that are between 110° and 125° (Table 1), showing that the observed anisotropy for the easternmost stations is consistent with the eastward escape proposed by earlier authors. Our observations for the easternmost stations are thus consistent with deformation associated with the eastward escape. This deformation would occur in the asthenosphere then, which would suggest that not only the crust, but also the entire lithosphere escapes toward the Pannonian basin. The splitting directions generally agree also with predicted escape motions from thin viscous sheet modeling (Robl and Stüwe, 2005) of the effect of the indenter on the lateral escape. Deformation in the asthenosphere does not exclude that some of the deformation is taken up within the lower crust though. Perhaps high-resolution techniques such as anisotropic receiver functions will be able to contribute that component of lithospheric deformation independently. Known faults in the area (Mur-Mürz fault, SEMP fault) do not seem to dominate the deformation in the upper mantle, since they are striking in ENE direction, except the Periadriatic line which strikes ESE. At smaller scale this deformation might become visible.

4. Conclusions

We constrain upper mantle anisotropy beneath the Eastern Alps by measuring shear-wave splitting parameters. Fast orientation measurements indicate the presence of a more-or-less mountain chain-parallel seismic anisotropy in the upper mantle under all of the Alps, showing a clear rotation of fast axis azimuths along the Alps, in accordance with the topographic pattern. This indicates a simple pattern of mantle deformation that is all the more remarkable, since geological structure at the surface of the Alps shows a very complicated pattern. In the Eastern Alps, fast orientations jump by about 45° across the Tauern Window area. For the easternmost stations, which are located on thin lithosphere, yet record a shear-wave splitting of similar size, we find that fast directions agree closely with those predicted by the relative motion of the surface (GPS) with respect to the central Alps. This suggests that we may be observing a mantle deformation signal of the eastward extrusion. In that case, the entire lithosphere takes part in the lateral escape toward the Pannonian basin. The measured splitting parameters show a remarkably simple spatial pattern of fast orientations, given the complex surface geology of the Alpine orogen.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2013.09.019.

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