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Correlated crustal and mantle deformation in the Tauern Window, Eastern Alps

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Abstract

We study the coupling between crust and mantle in a convergent regime, by comparing measures of upper mantle deformation with indicators of crustal deformation. We use shear-wave splitting parameters, in particular the orientation of fast axes in the upper mantle measured from data recorded at 8 broadband stations located within the Tauern Window. These are compared with kinematic indicators in the Tauern Window region of the eastern Alps at the outcrop scale. Our results show a striking parallelism between the upper mantle and crustal patterns, indicating vertical coherence of deformation all the way between the crust and the mantle lithosphere. The new findings suggest a vertical coherence of deformation of crust and upper mantle, particularly in the western part of the Tauern Window. Similar pattern in our results and indentation models indicate that the effect of the Adriatic indentation acts on the European lithosphere, not only at crustal but also at lithospheric mantle depths. We discuss the implication of this vertical coherence for the question of mechanical coupling.

Wir untersuchen die Kopplung zwischen Erdkruste und Mantel in einem tektonisch konvergenten Regime, indem wir die Deformation des oberen Mantels mit Indikatoren der Krustendeformation vergleichen. Dazu verwenden wir Daten von 8 Breitbandstationen innerhalb des Tauernfensters, um seismische Anisotropie aus der Aufspaltung von teleseismischen Scherwellenphasen zu bestimmen, insbesondere die Orientierung der schnellen seismischen Achsen im oberen Erdmantel. Diese werden mit kinematischen Indikatoren im Tauernfenster (Ostalpen) verglichen. Unsere Ergebnisse zeigen eine auffallende Parallelität zwischen den Deformationsindikatoren des oberen Erdmantels und der Erdkruste. Dieses Muster läßt auf eine vertikale Kohärenz der Verformung schließen, zwischen der oberen Kruste bis in die tiefere Mantellithosphäre. Die neuen Erkenntnisse deuten darauf hin, dass die Wirkung des Adriatischen Indenters auf die gesamte (europäische) Lithosphäre wirkt, d.h. nicht nur in der Kruste, sondern auch im lithosphärischen Mantle. Wir diskutieren die Implikationen der vertikalen Kohärenz für die Frage der mechanischen Kopplung.

1. Introduction

"The extent to which upper crustal deformation is coupled to deformation within the lower crust and mantle ... remains one of the most important and least understood aspects of continental deformation". This was the case, when Leigh Royden wrote this sentence (Royden, 1996), and it is still the case today. However, between now and then new observational constraints, especially seismic anisotropy, have become available. In this study we will use these constraints to address the question of coherence of deformation in crust and mantle. The question has a relation with several other important questions that are open, e.g., is crustal and mantle deformation related? Are they of the same age? To which degree do plate-tectonic driving forces that act in the mantle also act on the crust? Are crust and mantle moving together? Is that the case at all times, and are they coupled in that sense? We approach these questions in this paper by comparing the pattern of deformation in crust and mantle. For this, it seems best to consider a region where rocks from deeper levels within the crust are exposed at the surface. This is the case in the Tauern Window, which is a key area for understanding late Alpine deformation (e.g., Lippitsch et al., 2003; Bokelmann et al., 2013).

The Tauern Window of the Eastern Alps exposes exhumed parts of Europe-derived crust. The southern European margin was accreted to the base of an Adria-derived upper plate, represented today by the Austroalpine nappes (e.g., Schmid et al., 2004, 2013). The Tauern Window is characterized by a complex three-dimensional geometry of tectonic units, including important along-strike changes in its structure (Schmid et al., 2013). This geometry, as described by Schmid et al. (2013) by combining surface geology with the results of deep seismic reflection measurements (Gebrande et al., 2002; Lüschen et al., 2006), basically resulted from crustal-scale collisional accretion in the Alps followed by late-Alpine indentation, crustal-scale folding, orogen-parallel extension and lateral extrusion (Ratschbacher et al., 1991a).

While the surface geological structure of the Tauern Window is well-understood, the structure of the deeper parts of the lithosphere and the mantle below still remains an open problem in the lithosphere-scale geometry of the Alps-Carpathians-Dinarides system (e.g., Brückl et al. 2007, 2010). This also concerns the quantification of kinematic and dynamic interactions between crustal and mantle structures. Anisotropy measurements (shear-wave splitting) around the Tauern Window have been performed along the TRANSALP profile (Kummerow and

Kind, 2006), and for the eastern Alps (Bokelmann et al., 2013; Qorbani et al., 2015). They indicate the geometry of "deep deformation" under the area. For quite a while we`ve noticed the general similarity of those orientations with structures exposed at the surface, as observed in deformational structures in exhumed crustal rocks within the Tauern Window, and we want to study that relation in detail here. A synthetic view of SKS splitting data and structural observations, as presented in this study, should provide an approach to reveal sub-lithospheric deformation beneath the central Eastern Alps. The relation between crustal and mantle deformation has been addressed before, e.g. by comparing mantle anisotropy with orientations of crustal magnetic anomalies for the North American craton (Bokelmann and Wüstefeld, 2009), where a very good agreement has been found, in central Asia (Flesch et al., 2005), and in the north and central Aegean (Brun and Sokoutis, 2010). In comparison, the agreement over different actively-deforming tectonic regions/regimes in Western North America is less clear.

We start this paper by presenting the geological structure of the area, and later present evidence for deformation at mantle depth – eventually overlaying the two, and discussing their relation.

2. Geological setting of the Tauern Window

The Tauern Window exposes a Cenozoic-age nappe pile consisting of crustal slices derived from the distal continental margin of Europe (Subpenninic Units) and a part of the Penninic (or Piemont Ligurian) ocean (Glockner Nappe System), accreted to an upper plate that consists of the Austroalpine Nappe pile that was structured during Cretaceous times. This general structure of the nappe system within the Tauern Window was previously described by Kurz at al. (1996, 1998), and recompiled by Schmid et al. (2013). The present-day architecture of the Tauern Window is primarily characterized by a crustal-scale late Alpine duplex, the Venediger Duplex (or Venediger Nappe System) that formed during the Oligocene. This duplex structure was severely overprinted by doming and lateral extrusion, which was most probably triggered by the indentation of the Southalpine Units east of the Giudicarie Belt. Indentation initiated at around 20 Ma ago and was linked to a lithosphere-scale reorganization of the geometry of the mantle slabs beneath the central Eastern Alps (Schmid et al. 2004, 2013).

The European continent consists of a deeply eroded Variscan (Late Devonian to Carboniferous) metamorphic continental crust, rich in plutonic rocks (north of the Alpine front), covered by Carboniferous to Eocene sedimentary sequences. This crust is still in contact with its lithospheric mantle and dips southwards beneath the Alps (e.g. Kummerow et al., 2004). The Sub-Penninic Nappes within the Tauern Window (Fig. 1) represent the distal European margin, forming ductilely deformed basement and cover nappes, which lost contact with their lithospheric mantle. These form the Venediger Nappe System. This interpretation is based on the conclusion that the crustal material of the Venediger Nappe System was not separated from the European margin by an Oceanic basin (e.g. Froitzheim et al., 1996; Kurz et al., 2001). The eclogitic Sub-Penninic basement units (Eclogite Zone) contain material derived from the Alpine Tethys Ocean and developed in a subduction and accretion channel (Engi et al., 2001; Kurz and Froitzheim, 2002).

The Wolfendorn Nappe is restricted to the northwestern Tauern Window where it structurally overlies two imbricates of the Venediger Duplex. The Eclogite Zone occupies a tectonic position above the Venediger Nappe System but just below the Modereck Nappe System. Eclogite facies conditions of 1.9-2.2 GPa and 600- 630° C (Hoschek, 2001) were reached about 33-32 Ma (Nagel et al., 2013). Subsequent decompression and reheating to amphibolite facies conditions (“Tauernkristallisation”) affected the entire nappe stack including the Venediger Nappe System (Glodny et al. 2008). The onset of subduction is poorly constrained, but available radiometric data suggest an age between 55 and 45 Ma ago (Berger and Bousquet, 2008).

The Modereck Nappe System comprises the units in a similar structural position immediately below the Glockner Nappe. The Seidlwinkl Nappe, an isoclinal fold nappe, is exposed in the central Tauern Window (Frank, 1969) and makes up most of the Modereck Nappe System. Kurz et al. (2008) report that parts of the Modereck Nappe System located in the Grossglockner area are, together with the adjacent Eclogite Zone, affected by eclogite facies metamorphism.

The Penninic Nappes comprise three paleogeographic elements: the Penninic (Piedmont-Ligurian) Ocean, the Brianconnais microcontinent and the Valais Ocean. The Piedmont-Ligurian Ocean opened in Late Jurassic times. Its initial sea-floor formed by exhumation of the sub-continental mantle of the Apulian microplate (Froitzheim & Manatschal, 1996). The Brianconnais microcontinent was a part of the European distal margin until it was cut off by the opening of the Valais Ocean in Cretaceous times. The Valais Oceanic crust comprises Cretaceous ophiolites overlain by Cretaceous to Eocene calcareous turbiditic metasediments. Towards the east the Valais Ocean merged into the Piedmont-Ligurian Ocean, thus forming a single oceanic basin towards the east (e.g. Stampfli, 1994; Froitzheim et al., 1996). This situation therefore makes any subdivision of the Piedmont-Ligurian from the Valais basin somewhat artificial in the area east of the Engadine Window (Kurz, 2005, 2006).

3. Structural evolution and kinematics

A structural and kinematic reconstruction of deformation events within the Tauern Window is provided by Kurz et al. (1996) and was refined by Scharf et al. (2013). Structures related to internal nappe stacking along distinct thrusts (D0 after Kurz et al. 1996) are not developed in mesoscale, but can be derived from the WNW-ESE orientation of branch lines within the Venediger Nappe System. These indicate NNE-to NNW- directed kinematics during nappe detachment (Fig. 1), being related to the formation of the Venediger Duplex (Schmid et al., 2013).

The oldest clearly distinguishable structures resulted from N-directed ductile shearing (D1 after Kurz et al., 1996) (Fig. 1). This deformation is only developed penetratively in the upper structural level of the Venediger Nappe System, parts of the Seidlwinkl-Rote Wand Nappe in the central part of the Tauern Window, and within high-pressure mylonites of the Eclogite Zone (Kurz et al., 1998, 2004). During D1 a first penetrative foliation (s1) parallel to the thrust surfaces and a S- to SSE-dipping apparent stretching lineation (l1) were developed. Deformation conditions within the Venediger Nappe System were close to 500 °C and 6 kbar, and reached eclogite facies metamorphic conditions within the Eclogite Zone and the southern parts of the Seidlwinkl-Rote Wand Nappe. This phase of deformation can therefore be related to the exhumation of units affected by high-pressure metamorphic conditions within a subduction channel (Kurz, 2005; Kurz et al., 2008).

The nappe edifice that formed during D0 and D1 was overprinted by general west-directed shearing (WNW in the eastern, WSW in the western part of the Tauern Window) (Fig. 1). D0,1 structures were obliterated by a penetrative foliation (s2) and a sub-horizontal, NW- to WSW- trending stretching lineation l2 (Kurz et al., 1996). Several units within the Tauern Window were affected by this shearing, that occurred at amphibolite facies metamorphic conditions at about 27 to 29 Ma within the central parts of the Tauern Window (Reddy et al., 1993; Inger and Cliff, 1994) with a continuous decrease to greenschist facies metamorphic conditions towards the margins of the Tauern Window. During this deformational phase the Penninic units are deformed homogeneously within a constrictional strain geometry. The main deformational zone is transferred continuously to deeper structural levels (Kurz et al., 1996). Strain indicators revealed mainly coaxial deformation with subordinate west- directed simple shear (Kurz et al., 1996) (Fig. 1).

Generally l2 stretching lineations trend parallel to large-scale folds (Scharf et al. 2013). Accordingly, this deformation phase might be related to crustal scale folding due to north- directed shortening during exhumation of the Tauern Window units and contemporaneous orogen-parallel west-directed stretch within a transpressional regime (Kurz et al., 1996). Strain data from the eastern Tauern Window (Norris et at., 1971; Behrmann,

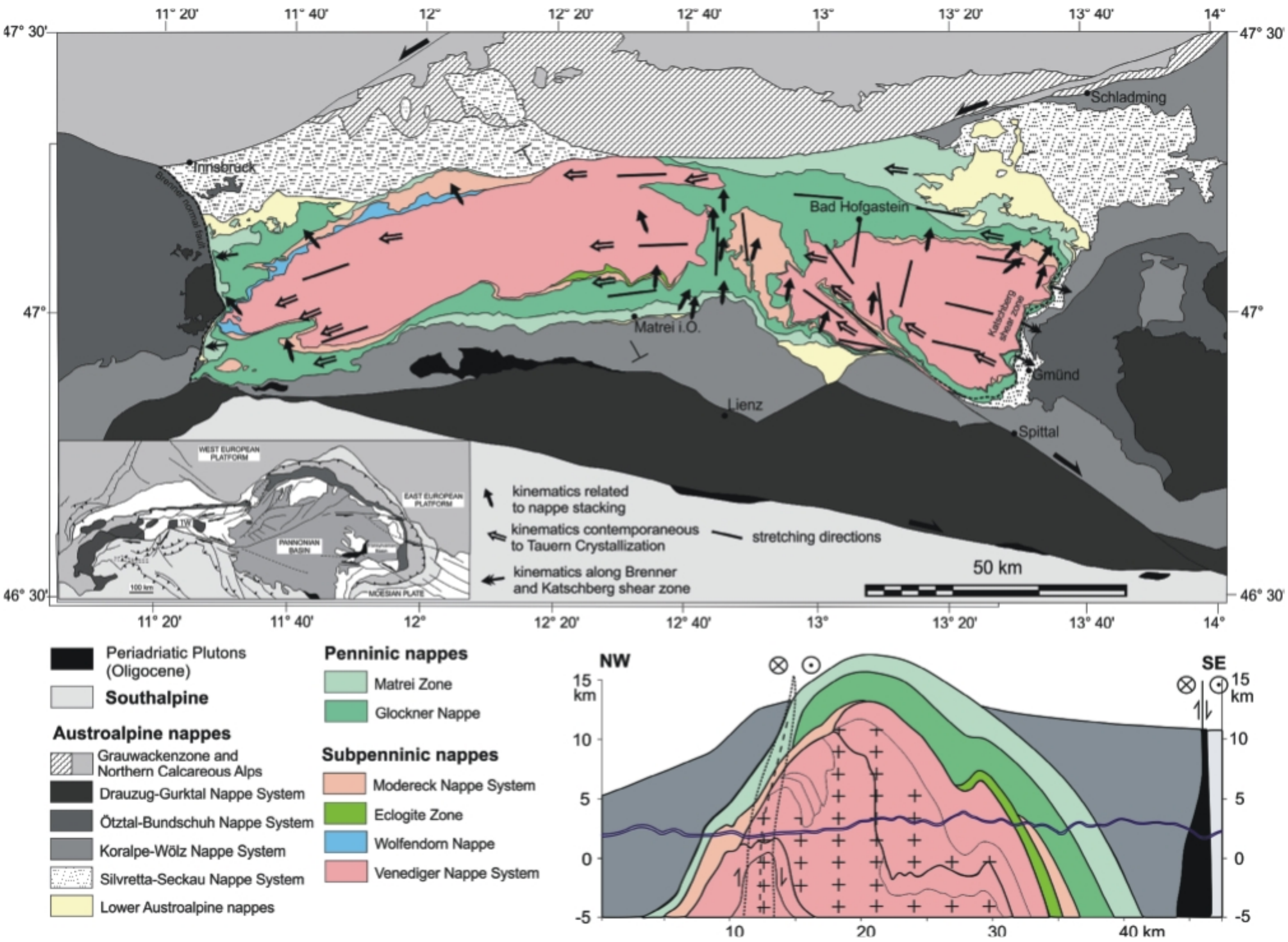

Figure 1: Tectonic map and cross section of the Tauern Window and adjacent Austroalpine units (after Kurz et al., 1998; Schmid et al., 2013), with a general overview of kinematics of nappe stacking and shearing contemporaneous to amphibolite to greenschist facies metamorphism (Tauern crystallization), including kinematic data (after Kurz et al., 1996; Neubauer et al., 1999). Nappe-stacking-related kinematics was reconstructed from maps and field data (for summary, see Kurz et al., 1996, and references therein). Kinematics along the Katschberg shear zone and the Brenner fault refer to Genser and Neubauer (1989), Scharf et al. (2013), and Behrmann (1988), Selverstone (1988), respectively. Stretching directions are derived from Behrmann (1990), Behrmann and Frisch (1990), Kurz et al. (1996), Lammerer and Weger (1998), and Scharf et al. (2013). Inset (after Hausegger et al. 2010) shows tectonic position of Tauern Window (TW) within the Alps-Carpathian-Pannonian system.

1990; Kurz et al., 1996) revealed NW-SE sub-horizontal elongation of approximately 250% and between 50 and 75% NE-SW- directed shortening. Strain generally increases from NE towards SW (Norris et al., 1971; Behrmann, 1990). In the western part of the Tauern Window deformation is more homogenous along a N-S cross section. Data from strain analyses within the Venediger Nappe System revealed subhorizontal WSW-ENE- directed stretch and NNW-SSE- directed shortening (Lammerer and Weger, 1998). Shortening varies between 0.4 and 0.24. D3 as described by Kurz et al. (1996) is related to the formation of the dome structure within the Tauern Window, orogen-parallel extension and lateral extrusion. This led to the final exhumation of the nappe stack beneath the Austroalpine orogenic lid by a combination of tectonic and erosional unroofing (e.g., Ratschbacher et al., 1991; Frisch et al., 1998; Rosenberg et al., 2007). This phase of deformation is characterized by the interference of multiply developed structures, and by deformation partitioning and shear localization along the dome margins (Behrmann and Frisch, 1990; Kurz and Neubauer, 1996). Especially along shear zones bordering the Tauern Window, a new penetrative foliation s3, associated with a stretching lineation l3, was developed. Interior parts of the Tauern Window have been affected by multiple folding, too. Structural and kinematic data documenting this evolution have recently been published by Kurz et al. (1994, 1996, 1998), Kurz and Neubauer (1996), and Scharf et al. (2013).

4. Methods for constraining upper mantle deformation

Seismological studies show that the upper mantle presents significant anisotropic characteristics (e.g., Long and Silver, 2009). Anisotropy is often caused by plastic deformation of rock forming minerals (Karato et al., 2008), which leads to dependence of physical properties according to different trajectories within the rock mass. Seismic anisotropy is observed by differential arrival times of the seismic waves are polarized in different orientations; this characteristics of the anisotropic media is termed birefringence. This phenomenon allows us to recognize anisotropy in the upper mantle and consequently to examine the deformation pattern, which refers to tectonic processes. Anisotropy in the upper mantle can be due to the strain field in the lithosphere and/or asthenospheric flow (Savage, 1999). Laboratory experiments have shown that the upper mantle is dominated by strongly anisotropic minerals (Maupin and Park, 2007). The origin of seismic anisotropy in the upper mantle is assumed to be related to the lattice-preferred orientation (LPO) of olivine due to dislocation creep (Mainprice et al., 2000; Karato et al, 2008).

One of the most useful geophysical methods for constraining upper mantle anisotropy is shear-wave splitting that uses the birefringence or splitting of the shear waves when they pass through an anisotropic medium. Shear-wave splitting is capable to examine the deformation in the upper mantle. As an effect of anisotropy, shear waves are split into two orthogonal phases that arrive at the surface at different time, defining the fast and slow polarization orientations. In the shear-wave splitting method, two splitting parameters are measured: the azimuth of fast axis polarization (Φ), and delay time (δt) between the arrival of fast and slow polarizations. Fast axis azimuth gives useful clues about strain and shear directions (e.g. in the A-type olivine, Φ tends to be aligned in the direction of shear (Savage, 1999; Karato et al., 2008).

Several techniques are developed to derive the splitting parameters. To constrain the upper mantle anisotropy, a frequently used method is the minimum energy technique (SC) (Silver and Chan, 1990), in which splitting parameters are derived by single teleseismic events measured at each seismic station. The best choice to apply the shear wave splitting method is to use teleseismic core phases SKS/SKKS. These phases are the converted shear waves from P waves at the core mantle boundary (CBM) and arrive at the surface almost vertically. The converted S-wave at the CBM is radially polarized; therefore the retrieved anisotropy must lie in the mantle below the seismic station.

Here, we show results of individual SKS splitting measurements (Qorbani et al., 2015) by the SC technique from 8 broadband permanent stations located in the Tauern Window region. Four stations belong to the Austrian broadband seismological network (OE), three stations to the Southern Tyrolia network (SI) operated by ZAMG (Zentralanstalt für Meteorologie und Geodynamik), and one station of the Italian seismic network (IV) operated by INGV (Istituto Nazionale di Geofisica e Vulcanologia). Teleseismic events with magnitude MW greater than 6 within the epicentral distance range of 90° to 130° were used to derive the splitting parameters by means of the SplitLab package (Wüstefeld et al., 2008).

5. Results

Anisotropic fast axis azimuth (Φ), and delay time (δt) measured at the seismic stations are summarized in Figure 2. In the main figure we show the average values of fast axis azimuth and delay times for 12 stations located in the eastern Alps (Bokelmann et al., 2013) as well as 13 stations of the Slovenian network (SL) and 8 stations of Italian networks (IV, NI, SI) (Qorbani et al., 2015) together with previous results for the western Alps (Barruol et al., 2011) and the central Alps along the TRANSALP profile (Kummerow and Kind, 2006). A clear progressive rotation of average fast azimuth orientations was already described by Bokelmann et al. (2013) and is visible in Figure 2. The change of lines orientation occurs between about 12°E and 13°E longitude. This change is located inside the Tauern Window region.

Nearly vertical incidence angles of SKS phases (8°-12°), give a good lateral resolution in the splitting results. Projecting the measurements from their surface location (station position) to depth allows us to assess the regions sampled by the rays. For this purpose, individual measures in the Tauern Window are projected at 120 km depth by using the incidence angle and events back-azimuth. 120 km is the maximum estimated lithospheric thickness in the Tauern Window region (Bianchi et al., 2014; Jones et al., 2010 and references therein). Inserted in Figure 2 is a zoom of the Tauern Window, which shows the individual measurements (Qorbani et al., 2015) projected at 120 km depth. The lines show orientation of fast axis and delay times are scaled by length. Fast axis azimuths are in the range of N45° to N145° (with one exception N18°).

By projecting the measurements on the N-S profiles at the west and the east of the Tauern Window region (Fig. S1), two groups of fast orientations can be observed. In the west, almost all measures show NE-SW orientation while in the eastern part most of measurements are aligned NW-SE, displaying about 45° difference in orientation (Fig. S1). We can therefore consider a separation line at the azimuth of N90° between them, and for an immediate graphical distinction they have been differently colored according to their orientation. Those displaying azimuths less than N90° are shown in blue, and those with azimuth greater than N90° are in red (Fig.3). Stations WTTA, ROSI, ABSI (Fig. 2, inset) display a similar pattern of all individual measures, in which fast axes are oriented about N60°. This similarity can be seen in the average values as well (Fig. 2). On the other hand, anisotropy measurements at the stations located in the eastern part of the region display two fast orientation patterns. In the eastern part, depth projection based on the events backazimuth shows that measurements obtained from events coming from ~N50° and ~N230° back-azimuth show NW-SE orientation of the fast axis (>N90°, red lines) and rays coming from ~N300° back-azimuth result in NE-SW orientation (<N90°, blue lines). The latter is similar to what we observed in the western part where there is no back-azimuthal variation.

Back-azimuthal dependence of SKS splitting measurements is a signature of depth variation of anisotropy, which can be the presence of multiple layers of anisotropy in the upper mantle (Silver and Savage, 1994 and ref therein). Modeling vertical changes of anisotropy based on the back-azimuthal dependence (Qorbani et al., 2015) has presented two anisotropic layers for the upper mantle under the Eastern Alps in which a deeper layer with NE-SW fast orientation and a shallower layer with NW-SE anisotropy on the top are suggested. At the wider scale the latter can be traced to the Carpathian-Panno-

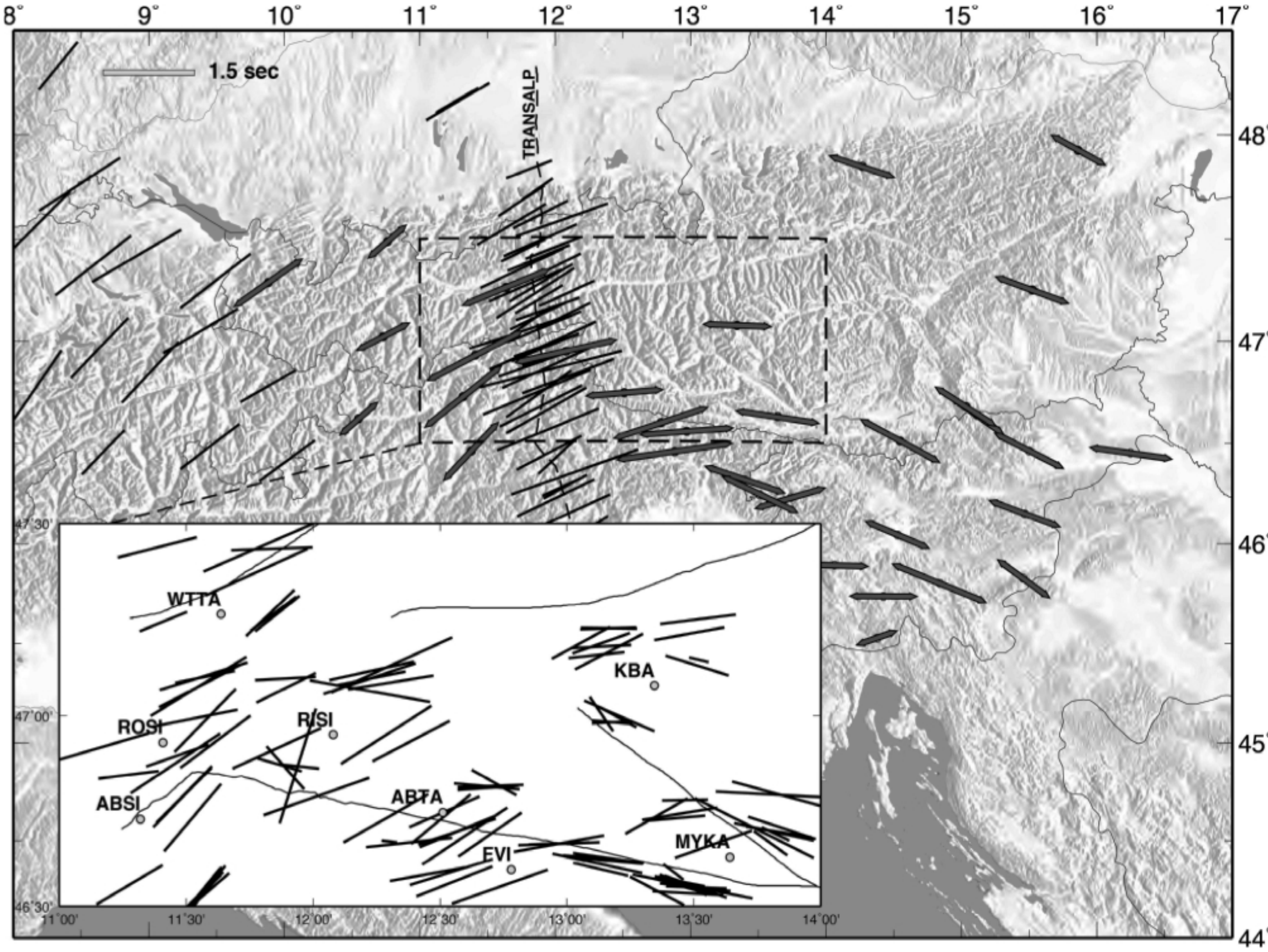

Figure 2: Background, average shear-wave splitting results (arrows) at broadband stations in the eastern Alps (Bokelmann et al., 2013; Qorbani et al., 2015). The orientation of the lines represents fast axis azimuth (°N) and the length indicates the amount of delay time in seconds. SKS splitting measures from former studies (Barruol et al., 2011; Kummerow and Kind, 2006) are shown in black thin lines. The progressively rotating pattern of average anisotropic fast axes is noticeable. The inset is a zoom of the area included in the dashed perimeter, showing the projection at 120 km depth of individual splitting measurements (Qorbani et al., 2015), which were obtained from different teleseismic events at each station in the Tauern Window area. Black thin lines in the insert indicate the main strike slip faults.

nian region. In the central part of the TW area, measures obtained for station ABTA mostly display E-W fast orientation, and measurements obtained from RISI are scattered in a wider range of azimuth and delay times.

Kinematic data deduced from exhumed lower crustal rocks, and anisotropic measurements obtained from seismological observations are two independent data sets that provide deformation patterns in the crust and in the upper mantle respectively. A principal difference is though that for the mantle, we have only constraints on the shear orientations (not the sense of direction), while for the crust, we also know the sense of shear. We have plotted these two data sets together for the

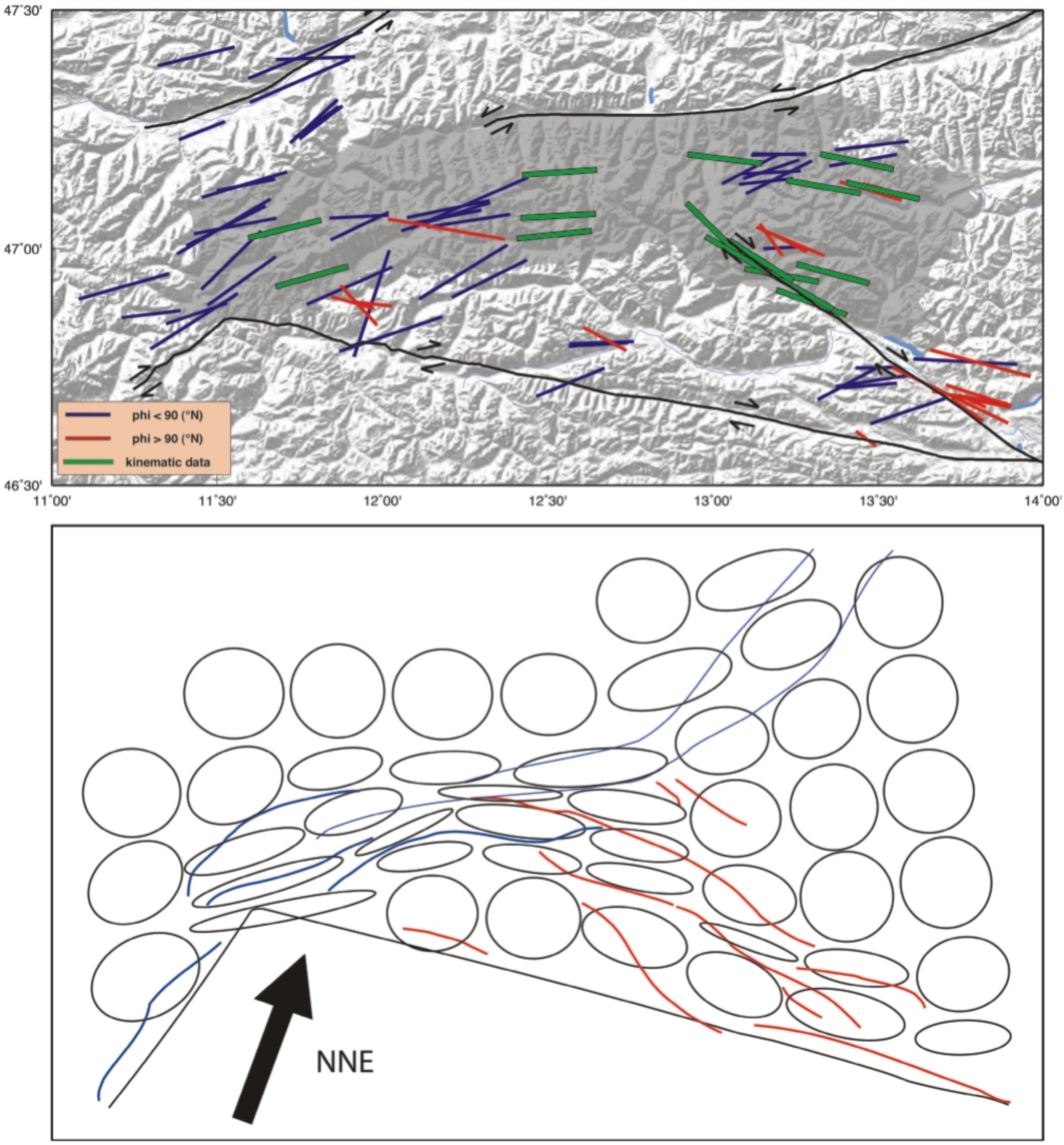

Figure 3: Top: Map showing correlation between crustal (kinematic data) and upper mantle deformation (the anisotropic fast orientations). Fast azimuths displaying an angle smaller than 90° with respect to the North are shown in blue and those at azimuth greater than 90° are shown in red (see Fig. S1). Green lines show the stretching directions related to D2,3 within the Tauern Window. Bottom: The distribution of deformation resulting from the experimental indentation model of Rosenberg et al. (2007). Ellipses represent the strain orientation at the surface of the model. In the west there is good correlation between the strain orientations and the deformation pattern in the upper mantle detected by SKS splitting measurements. In the east, the NW-SE fast orientation (red lines in the top panel) is in the same orientation as the strain pattern (ellipses). Lines show the major faults after the experiment. They are colored based on the similarity to the upper mantle anisotropy. Straight lines are the indenter edges and the black arrow shows the best fitting indentation direction (NNE) in the experiments.

Tauern Window region (Fig. 3). The anisotropy measurements located north of the Periadriatic line have been selected. As seen in Figure 3, the D2,3 stretching directions appear to correlate with the orientation of the anisotropic fast axes in the western and the eastern Tauern Window (TW). As mentioned before, the dominant anisotropic fast orientation NE-SW in the western part of the TW gradually changes to E-W orientation in the longitudes of the middle part of the study area (Fig. 3). In the same fashion, shear orientations (kinematic data) show an ENE-WSW trend in the west and turn to E-W in the center of the TW region (green lines in Fig. 3). In the eastern part of the TW, anisotropic measurements present two main patterns. In this part, NW-SE oriented fast axis (red lines) coincide with the kinematic data. This suggests that this group of fast orientations, which correlate with the surface deformation geometry, is related to the shallower anisotropic structures (as suggested by two-layer modeling, Qorbani et al., 2015) rather than the second group of orientations (blue lines) in this part of TW.

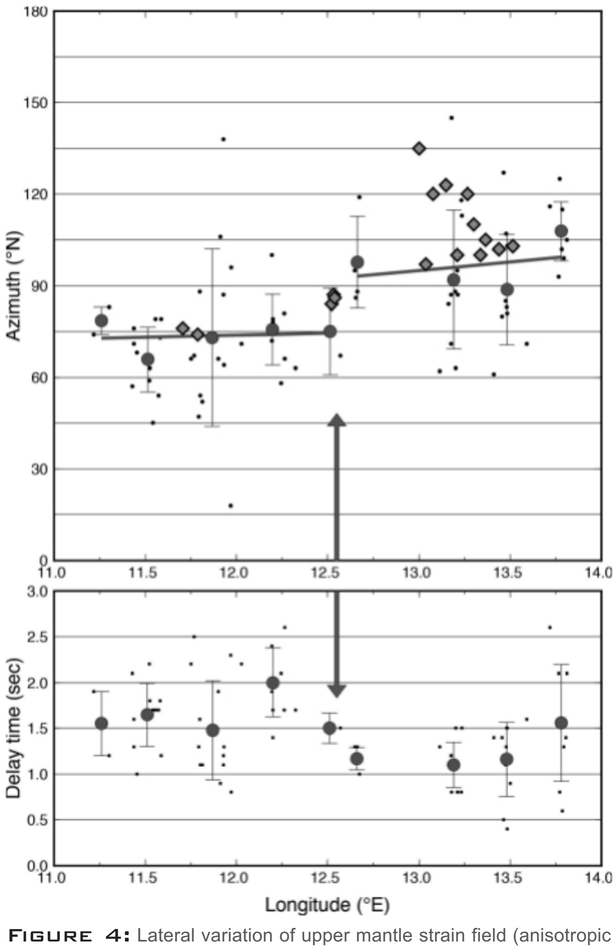

Figure 4: Lateral variation of upper mantle strain field (anisotropic fast orientation) together with the D2,3- related crustal shear direction as a function of longitude in the Tauern window region (top panel). Small points are individual measurements projected at 120 km depth. Circles present the average value of fast axis azimuth at longitude intervals of 20 min and diamonds show (crustal) shear orientation. Upper mantle and crustal deformation pattern change at the longitude of 12.5°E. Lines fit anisotropy data on the right and left of 12.5°E and indicate the change in deformation geometry of the upper mantle (as well as the crust). Bottom panel shows the variation of splitting delay times as function of longitude. Small points are individual measurements projected at 120 km depth, while Circles are the average value at longitude intervals of 20 min.

6. Discussion

6.1 Anisotropy and deformation regimes

Anisotropic structures observed in the mantle below orogens related to continental subduction and subsequent collision (e.g. the Variscan, Apennines, Pyrenees, Himalaya/Tibet, etc.), are commonly aligned perpendicular to the convergence direction (Bormann et al., 1993; Lave et al., 1996; Barruol et al., 1997). This anisotropy can be originating from subduction-related fossil alignment or upper mantle flow that is currently active.

Along the Alpine chain, mountain belt-parallel anisotropy has been already observed (Vinnik et al., 1994; Smith and Ekström, 1999; Barruol et al., 2011; Bokelmann et al., 2013, Bianchi and Bokelmann, 2014). However, the average fast axis of SKS splitting showed ~10° (counterclockwise) deviation from the Alps trend in the eastern Alps, along the TRANSALP (Kummerow and Kind, 2006). This difference is about ~20° in the Central Alps (see Barruol et al., 2011) and further to the east from the TRANSALP profile (~12°E, in the middle of TW region), this deviation reaches up to ~45° (see Bokelmann et al., 2013, Qorbani et al., 2015).

In the TW area, beside the average fast axes, we observe orientations both at the upper mantle level (individual SKS measurements) and crustal tectonic kinematics that are oblique to the general trend of the Alpine mountain chain. Both the crustal and upper mantle deformation patterns (Fig. 3) expose a change of orientation in the middle of the TW. To evaluate the location of this change of orientation (or bending), we have compared anisotropic and kinematic data together as a function of longitude (Figure 4). In Figure 4, the overall trend of the anisotropic pattern is shown by spatial averages, computed at longitude intervals of 20 min along the TW. The point of change in the orientation of upper mantle deformation patterns occurs at the same longitude as the change of stretching directions in the crust (12.50°E, indicated by the arrow in Fig. 4). This bending therefore appears to indicate a correlation between the crust and upper mantle, probably related to a common cause of deformation at the crustal depth and in the deeper lithosphere/asthenosphere.

The average anisotropic delay times in the TW (filled circles in the bottom panel, Fig. 4) are greater than 1.0 sec. These values cannot be created by the anisotropic structures in the crust, which may have effect on delay times of 0.1 second per 10 km thickness; this suggests that the observed splitting signal can not be explained by shear-wave splitting in the crust alone (Barruol and Mainprice, 1993; Barruol and Kern, 1996), on kinematic grounds. Moreover, SKS phases used in this study are associated with a dominant period of 10 seconds, and it should also for that reason be not very sensitive with respect to relatively small features such as the crust (Barruol et al., 2011). The major part of splitting delay time is therefore due to the anisotropy in the upper mantle under the TW as has been widely suggested before (Silver and Chan, 1991, Vinnik et al., 1992).

Considering SKS splitting measures together with the D2,3-related crustal kinematics data shows that crustal and upper mantle deformation is coherent in the TW region. The question that arises is at which time was the deformation (in crust and mantle) created? For the crust, age information is given by D2-related shearing that was widely contemporaneous to amphibolite to upper greenschist facies metamorphism ("Tauern Crystallization"). It affected the entire nappe pile within the Tauern Window. This metamorphic event is dated around 23 to 29 Ma (for summary, see Kurz et al.,1996; Scharf et al., 2013). A deformation acting over 20-30 Ma is indeed enough to create the observed anisotropy assuming typical strain rates (Vinnik et al., 1994; Savage, 1999). Thus, the SKS splitting results may be associated with these relatively recent tectonic events. Under the circumstances, in which the parallelism of crustal and upper mantle deformation is observed, crustal deformation may be a direct response to the motion in the upper mantle (e.g., Flesh et al., 2005). Therefore it is reasonable to infer that what caused the arcuate shape of TW is still active in the upper mantle.

Bending and exhumation of the TW area, which started from late Oligocene to early Miocene (28 – 20 Ma) (e.g., Prosser, 1998; Schmid et al., 2004) is suggested to be the main consequence of nearly northward movement of the South Alpine block, acting as a rigid indenter (Ratschbacher et al., 1991; Rosenberg et al., 2004). Experimental results focusing on the indentation effect in the Eastern Alps (Rosenberg et al., 2004, 2007) have suggested that the oblique indentation N20°E shows the most similarity to the deformation pattern in this region.

To evaluate the degree of crustal-upper mantle parallelism as a response to deformation regimes within the upper mantle, we compare our dataset with the distribution of deformation pattern resulting from an indentation experiment (Fig. 3, bottom). In this figure, ellipses illustrate the strain orientation at the surface of the model and curvy lines are the major faults after exerting the oblique indenter in the experiment (Rosenberg et al., 2007). On the left, these lines and anisotropic fast axes are oriented in a similar pattern as the kinematic data which all show N50°-N70° azimuth. These lines (on the left) are colored according to the pattern of upper mantle anisotropy derived from SKS splitting in the west of TW (blue lines). Dominant NW-SE fast anisotropy orientation and kinematic data in the East is comparable with the major faults in this part of the model (lower part of Figure 3) which are shown in the same color as the fast anisotropic orientations (red).

The similarity between upper mantle anisotropy and the experimental deformation pattern can be discussed in terms of indentation effect. Regardless whatever caused the indenter movement, the indentation has affected not only the crust but also the lithospheric mantle as well as the sub-lithospheric structures, resulting in the vertical coherence of deformation from the upper mantle to the crust. This coherence probably initiated in the same age as the indentation started, and exists as long as the indentation lasts.

6.2 Vertical coherence of deformation and mechanical coupling

We have seen that the geometry of deformation in crust and mantle is vertically coherent, and it is natural to try to explain this by the depth range in which the indenter acts, coupled with rheology in the different layers in the lithosphere. Results of experimental models (Rosenberg et al., 2007) have tested several rheological models for the area, and have suggested that the fault geometry in the Eastern Alps is best explained by a rheological model that consists of a brittle upper crust, a ductile lower crust, and a ductile lithospheric mantle on the top of viscous asthenosphere (Fig. 5). The vertical coherence that we observe, is between lower crust (from crustal kinematics) on one hand, and the deeper lithosphere-asthenosphere system (from the splitting measurements) on the other.

Coherent crustal and upper mantle deformation, as it has been observed in many continental settings, e.g. the Canadian Shield (Bokelmann and Wüstefeld, 2009), the Sao Francisco Craton (Vauchez et al., 1994), and in other settings suggests a lithospheric origin of anisotropy in those areas. Alternatively correlated lithosphere-asthenosphere anisotropy (Fouch and Rondenay, 2006) was recently suggested to be the cause of belt-parallel deformation in the western Alps (Barruol et al., 2011) meaning frozen-in alignments within the lithospheric mantle are oriented in the direction of upper mantle flow in the asthenosphere. This suggestion can explain well-correlated kinematic data and anisotropy measures in the western TW region (Fig. 3). For this region, Willingshofer and Cloetingh (2003) presented a lithospheric strength model along the TRANSALP profile in which strong coupling between crust and mantle for the Eastern Alps has been suggested. Our dataset is consistent with this, suggesting that lower crust and lithospheric mantle are mechanically coupled.

Compared with the western TW, the eastern TW shows a

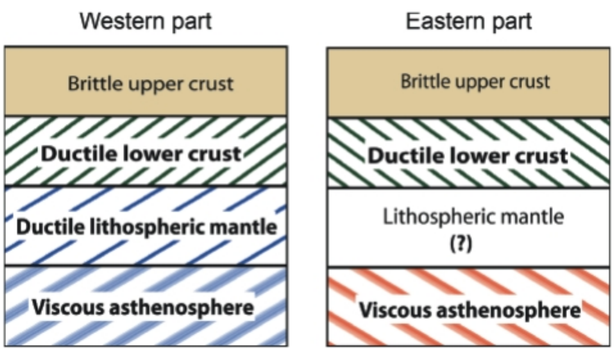

Figure 5: Demonstration of rheological layering in the Tauern Window region (after Rosenberg et al., 2007). Hatchings are colored same as Figure 3. Blue hatching represents the depth of observed seismic anisotropy (NE-SW) in the western part of TW that is correlated well with the kinematic data from the lower crust (green hatching) suggesting crust-upper mantle coupling in this area. In the eastern part, red hatching illustrates the depth of NW-SE anisotropy pattern in the asthenosphere that is correlated with the kinematic data. The lithospheric mantle in this area is an invisible layer (see text).

different pattern of upper mantle deformation. The kinematic data correlates with the NW-SE anisotropic orientation. This anisotropy orientation has also been observed much further to the east, in the Carpathian-Pannonian region (Stuart et al., 2007, Kovacs et al., 2012). Furthermore, the crustal and lithospheric thickness in the eastern Alps shows an eastward decrease (Ratschbacher et al., 1991; Frisch et al., 1998; Bianchi et al., 2014), to on average ~70 km lithospheric thickness; that is not thick enough to create the observed SKS splitting (Qorbani et al., 2015). Therefore, the associated fabric is most probably located in the asthenosphere.

On the other hand, we observed NE-SW anisotropic orientation in the eastern part (blue lines in Fig. 3). The back-azimuthal dependence of the SKS measurements can be considered as a signature of vertical change of anisotropic sources. In a separate paper (Qorbani et al., 2015) we have studied this in detail, and have presented parameters of the seismic anisotropy in the two layers. Hence, the NE-SW anisotropic orientation originates from a structure located deeper than the asthenospheric flow.

Deformation within the ductile lower crust is correlated with the orientation of the flow within the viscous asthenosphere in the eastern TW (Fig. 3 and 5). By the employed methodology (SKS splitting) we are not able to address the anisotropic structure of the lithospheric mantle in this area, as explained above. This “invisible” lithospheric mantle might very well be aligned in the same orientation as the asthenospheric flow (NW-SE), especially if the deeper lithosphere in the eastern Alps is weak, as has been suggested by (Genser et al., 1996; Okaya, 1996; Willingshofer and Cloetingh, 2003). In that case, deformation in that layer might very well follow the motion in neighbouring layers. It will be interesting to devise observational strategies for observing deformation in that layer specifically. This is particular interesting since other regions (e.g., Fry et al., 2010) seem to be associated with a different kind of fast orientation. Those authors presented an orogen-parallel anisotropy within the shallow structures (less than 30 km depth), and orogen-perpendicular alignments for the sub-crustal materials (30 km < depth < 70 km), which is the direction of subduction of EU under the AD slab. That study is done for the central Alpine region to the West of the TW area. We cannot rule out that such a fossil-anisotropy layer also exists in the Eastern TW.

7. Conclusion

SKS splitting measurements and kinematic data deduced from exhumed crustal rocks reveal striking similar deformation patterns in the Tauern Window. Parallelism between crustal shear directions and anisotropic fast orientations exposes vertical coherence of deformation from the upper mantle to the crust. The similar geometry of crustal and upper mantle deformation confirms the earlier notion of Selverstone (1988) and Royden (1996) that mantle and crust in the Eastern Alps are (mechanically) coupled. Their inference was based on the shape of the deforming zone at the Earth’s surface. This is particularly clear for the western part of the Tauern Window where NE-SW orientations of fast anisotropy axes correlate well with the kinematic data of orogen-parallel stretch. The strong crust-upper mantle coupling had been already suggested using data from the TRANSALP profile (Willingshofer and Cloetingh, 2003).

In the eastern part of the Tauern Window, NW-SE oriented anisotropy possibly reveals the orientation of flow in the asthenosphere and is in agreement with the kinematic data. In this area, similar deformation geometry between the ductile lower crust and the viscous asthenosphere is observed. NW-SE fast orientations in the asthenosphere can be seen as a signature of shearing that has been initiated after European plate break off in ~29 Ma (Schmid et al., 2013) and is still active within the whole lithosphere beneath the Tauern Window area and the Eastern Alps. On the crustal scale, the general structure within the Tauern window indicates that exhumation of the lower crust can be related to crustal scale folding due to north-directed shortening contemporaneous to orogen-parallel west-directed stretch within a transpressional regime, starting in a times range of 29 to 23 Ma which is consisted with the flow regime that initiated within the above mentioned time frame.

The correlation of deformation in crust and mantle indicates that the indentation effect in the area of the Tauern Window is not restricted to the crust, but shows its effect also at deeper levels in the lithosphere-asthenosphere system. In that sense, it constitutes a “crust-mantle coupling”. The synchronizing factor in this coupling is the lateral boundary condition imposed by the indenter. The coupling thus exists as long as the indenter acts. This however does not necessarily imply that the crust and mantle portion of the lithosphere move coherently at all times.

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