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Slab detachment under the Eastern Alps seen by seismic anisotropy

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ABSTRACT

We analyze seismic anisotropy for the Eastern Alpine region by inspecting shear-wave splitting from SKS and SKKS phases. The Eastern Alpine region is characterized by a breakdown of the clear mountain-chain-parallel fast orientation pattern that has been previously documented for the Western Alps and for the western part of the Eastern Alps. The main interest of this paper is a more detailed analysis of the anisotropic character of the Eastern Alps, and the transition to the Carpathian–Pannonian region. SK(K)S splitting measurements reveal a rather remarkable lateral change in the anisotropy pattern from the west to the east of the Eastern Alps with a transition area at about 12°E. We also model the backazimuthal variation of the measurements by a vertical change of anisotropy. We find that the eastern part of the study area is characterized by the presence of two layers of anisotropy, where the deeper layer has characteristics similar to those of the Central Alps, in particular SW–NE fast orientations of anisotropic axes. We attribute the deeper layer to a detached slab from the European plate. Comparison with tomographic studies of the area indicates that the detached slab might possibly connect with the lithosphere that is still in place to the west of our study area, and may also connect with the slab graveyard to the East, at the depth of the upper mantle transition zone. On the other hand, the upper layer has NW–SE fast orientations coinciding with a low-velocity layer which is found above a more-or-less eastward dipping high-velocity body. The anisotropy of the upper layer shows large-scale NW–SE fast orientation, which is consistent with the presence of asthenospheric flow above the detached slab foundering into the deeper mantle.

1. Introduction

Seismic anisotropy is defined as a directional dependence of seismic velocity. It is assumed that the upper mantle presents significant anisotropy (Maupin and Park, 2007). This anisotropy is most probably due to a non-random distribution of crystallographic orientation of minerals in the olivine-rich ultramafic upper mantle rocks. The non-random distribution is known as lattice-preferred-orientation (LPO). The relation between the typical intrinsic anisotropy in the upper mantle and LPO, which is a result of the deformation, has been well-documented (Babuška and Cara, 1991; Silver and Chan, 1991; Mainprice et al., 2000). It is generally accepted that the anisotropy is due to deformation that either occurred at earlier times ("fossil deformation") or due to present tectonic activities (Savage, 1999, and references therein). In either case, the anisotropy can indicate the geometry of the flow. Therefore mapping seismic anisotropy can resolve the pattern of mantle flow in the asthenosphere as well as the fossil deformation pattern within the lithosphere, which has great importance for understanding the upper mantle geodynamics.

The simplest measure of upper mantle anisotropy is the shear-wave splitting, particularly using SKS core phases (e.g. Vinnik et al., 1984; Silver and Chan, 1988; Long and Silver, 2009) which have been studied extensively in recent years. Near-vertical incidence angles of SKS phases give good lateral resolution (i.e. 50 km, the radius of Fresnel zone at 150 km depth), since anisotropy is to be attributed to a steep ray path. However, the depth where the splitting occurs is less well-determined. Although the measuring procedure of shear-wave splitting is straightforward, the practical interpretation of measurements can be quite challenging.

In this study we first present the overall pattern of anisotropy, based on the average values of SKS splitting parameters, then we focus on the spatial changes of the individual measurements and we show striking lateral variations of anisotropy within the region. Later the backazimuthal variation of fast orientations is modeled by means of two anisotropic layers. Finally, using the results of two anisotropic layers modeling, together with some constraints from velocity tomography studies and the analysis of lithospheric

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thickness, we present a possible lithospheric and asthenospheric upper mantle structure for the Eastern Alps.

2. Tectonic setting

The Alps are an arc-shaped double-verging mountain chain developed at the boundary between the Eurasian plate (to the North) and the Adriatic microplate (to the South). They are geographically divided into Southern, Eastern, Central, and Western Alps. Alpine tectonic history is deeply linked to that of the adjacent mountain chains as the Dinarides, the Carpathians and the Apennines. Palaeogeographic reconstructions suggest that in the area where the Alps are located today there was the Meliata Ocean in Triassic time, a marginal ocean basin of the neo-Thetis. In Late Triassic-Early Jurassic this ocean initiated subduction towards SE (Kozur, 1991); in the late Jurassic the opening of the Vardar Ocean took place in its backarc, and at the same time occurred the opening of the Piemont–Ligurian Ocean. During Cretaceous time, another ocean, the Valais, opened on top of the Piemont–Ligurian Ocean, in association with the opening of the Atlantic further to the West (Frisch, 1979; Stampfli, 1994). About 80 Ma ago the Piemont–Ligurian Ocean started subducting below the Adriatic continental margin following the SE directed subduction initiated by Meliata. The contact between the Adriatic continental crust and the Piemont–Ligurian oceanic crust coincide with the geological boundary observed today between the Austroalpine units (in the Eastern Alps) and Penninic Units.

The continental collision between Europe and Adria started ∼35 Ma ago (Froitzheim et al., 2008; Handy et al., 2010). The image we have today of the deep structure of the Alps is derived by the interpretation of tomographic images. The different regional models (i.e. Lippitsch et al., 2003; Koulakov et al., 2009; Mitterbauer et al., 2011) agree in identifying two lithospheric roots, one located below the Eastern Alps, and one located below the Central–Western Alps, separated between 12° and 13°E.

On the surface, geodetic data generally agree with a counterclockwise rotation of the Adriatic plate with respect to stable Europe around a pole in the western Alps (e.g. Calais et al., 2002; Nocquet and Calais, 2004). The CCW rotation of Adria leads to different deformation regimes along the Alpine arc, such as: compression in the Eastern Alps, dextral shear in the Central Alps and transtension or very slow deformation in the western Alps. This suggests that active deformation in the Alps (and in the neighboring Apennines and Dinarides) is controlled, and possibly dynamically driven, by the motion of the Adriatic microplate rather than by the convergence between Africa and Eurasia (Nocquet and Calais, 2003). Vertical GPS ground motions show that the most elevated areas are uplifting while the adjacent sedimentary basins undergo subsidence (Serpelloni et al., 2013). Similar evidence is given by measured erosion rates along the Alpine arc. First of all there is a crucial difference between the European plate (undergoing erosion) and the Adriatic plate (undergoing deposition), suggesting a decoupling between the two plates (Baran et al., 2014). Concerning the European side, the western Alps are characterized by high levels of erosion (>0.6 km/My), while the Eastern Alps show lower erosion rates (∼0.06 km/My), with the exception of the Tauern Window area, where a rate of 0.3 km/My is reached (Baran et al., 2014). The difference in erosion rate supports the hypothesis of slab brake-off below the western part of the Alps (von Blanckenburg and Davies, 1995).

3. Data and method

The most frequently used method for constraining the anisotropy within the upper mantle is the shear-wave splitting method, which is based on birefringence, or splitting of the core shear-waves (SKS) into two orthogonally polarized quasi-phases. The splitting of teleseismic SKS phases has been largely used in order to constrain upper mantle anisotropy (e.g. Vinnik et al., 1984; Silver and Chan, 1991; Margheriti et al., 2003; Buontempo et al., 2008; Barruol et al., 2011). Two fundamental parameters can be measured through this method: the fast orientation azimuth (ϕ, angle between fast axis and radial direction) and the splitting delay between fast and slow polarizations (δt). Assuming that the upper mantle anisotropy is confined in one laterally uniform layer, the horizontal components of SKS phases can be analyzed in order to estimate the amount and symmetry orientations of the azimuthal anisotropy (Vecsey et al., 2008). Several techniques are used to measure splitting parameters. The one used in this study is the transverse component minimization technique (SC) illustrated by Silver and Chan (1991). The application of this technique was performed by the use of the SplitLab package (Wüstefeld et al., 2008).

The splitting parameters are retrieved by applying a grid-search over all possible values of ϕ and δt. The azimuth and delay that better remove the effect of splitting on the T component are those that describe the anisotropic parameters of the mantle beneath the recording station (Wüstefeld et al., 2008). One example of splitting parameters measurement by the SC technique is illustrated in supplementary Figs. S1a, S1b. In most measurements we applied no filter to keep the complete frequency range in order to not loose part of the waveform energy and to prevent the dependence of measured splitting parameters on filtering.

Data collection for this study consisted of the teleseismic events with magnitude *Mw* greater than 6 occurring in epicentral distance range from 90° to 130° recorded by 33 stations of 5 permanent networks (see Table 1 and Fig. 1). We used data recorded by the Austrian broadband seismological network (OE) between 2002 and 2013. This network includes 12 permanent stations maintained by the Zentralanstalt für Meteorologie und Geodynamik (ZAMG, http://www.zamg.ac.at). Data from 13 broadband stations of the Slovenian seismic network (SL) recorded between 2005 and 2013 were included in this study, and accessed through the Observatories and Research Facilities for EUropean Seismology (ORFEUS) database (http://www.orfeus-eu.org). Data recorded between 2008 and 2012 were retrieved from one station of the Italian seismic network (IV) maintained by INGV (Istituto Nazionale di Geofisica e Vulcanologia). From the NE-Italian broadband network (NI, operated by OGS, Istituto Nazionale di Oceanografia e di Geofisica Sperimentale), events occurred between 2010 and 2011 recorded by at least two stations have been included. Events occurring between 2006 and 2011 and recorded by 5 stations of the South-Tyrol network (SI) have been included. Altogether 5845 SKS/SKKS phases recorded at all stations have been visually selected. Among these phases, we observed and measured the individual splitting parameters for 868 SKS/SKKS phases. All measurements were classified as "good", "fair", and "poor" splitting quality (Barruol et al., 1997; Wüstefeld and Bokelmann, 2007). When no significant energy on transverse components was recorded, the event was considered as displaying a "Null" orientation. 642 Null measurements were observed; out of this number of Nulls, we labeled 372 Null measurements as "good Null". Supplementary Fig. S1c shows an example of good Null measures.

4. Results

4.1. Splitting parameters; average values

Among 868 measured splitting parameter pairs (fast orientation and splitting delay) showing clear splitting of SKS phases, we selected 470 individual good quality pairs (supplementary Table S2). The calculated average value for each station over the good