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Peeking inside the mantle structure beneath the Italian region through SKS shear wave splitting anisotropy: a review

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Abstract

Over the years, seismic anisotropy characterization has become one of the most popular methods to study and understand the Earth's deep structures. Starting from more than 20 years ago, considerable progress has been made to map the anisotropic structure beneath Italy and the Central Mediterranean area. In particular, several past and current international projects (such as RETREAT, CAT/SCAN, CIFALPS, CIFALPS-2, AlpArray) focused on retrieving the anisotropic structure beneath Italy and surrounding regions, promoting advances in the knowledge of geological and geodynamical setting of this intriguing area. All of these studies aimed at a better understanding the complex and active geodynamic evolution of both the active and remnant subduction systems characterising this region and the associated Apennines, Alps and Dinaric belts, together with the Adriatic and Tyrrhenian basins. The presence of dense high-quality seismic networks, permanently run by INGV and other institutions, and temporary seismic stations deployed in the framework of international projects, the improvements in data processing and the use of several and even more sophisticated methods proposed to quantify the anisotropy, allowed to collect a huge amount of anisotropic parameters. Here a collection of all measurements done on core refracted phases are shown and used as a measure of mantle deformation and interpreted into geodynamic models. Images of anisotropy identify well-developed mantle flows around the sinking European and Adriatic slabs, recognised by tomographic studies. Slab retreat and related mantle flow are interpreted as the main driving mechanism of the Central Mediterranean geodynamics.

Keywords: SKS wave splitting; Central Mediterranean/Italy; Subduction Zones; Upper mantle seismic anisotropy

1. Introduction

The Central Mediterranean is a complex tectonic region where the presence of remnant and active subduction systems is testified by the occurrence of deep seismicity in the Northern Apennines, down to 90 km depth [Selvaggi and Amato, 1992], and in the Southern Tyrrhenian Sea, where it reaches depths well over 300 km inside the mantle [Selvaggi and Chiarabba, 1995]. Moreover, subducting slabs have been mainly traced on the basis of body-wave tomographic models. Indeed, tomographic images show subducted bodies with fast seismic velocities down to 250-300 km beneath the Alps [e.g. Lippitsch et al., 2003; Piromallo and Morelli, 2003; Giacomuzzi et al., 2011; Zhu et al., 2015; Zhao et al., 2016] and down below 440 km beneath the Apennines [Piromallo and Morelli, 2003; Giacomuzzi et al., 2011, 2012] (Figure 1). Notwithstanding the numerous tomographic studies, dealing with different seismic data and techniques, they do not completely answer to the controversial doubts about slab geometry, extent, and orientation [Lippitsch et al., 2003; Mitterbauer et al., 2011; Piromallo and Faccenna, 2004; Giacomuzzi et al., 2012]. Also, a possible change in subduction dipping direction in the Eastern Alps is still debated [Lippitsch et al., 2003; Schmid et al., 2004; Handy et al., 2015].

In this region with various subduction zones, which have been active at the same time, the Adria microplate is a key structure. While it was the lower plate at its eastern subduction, forming the Dinarides in the Cretaceous/Cenozoic and at its western edge forming the Tyrrhenian Sea and Apennines in the Neogene [e.g., Schmid et al., 2008; Handy et al., 2015] (Figure 1), it was the upper plate in the Alpine subduction.

The study of seismic anisotropy at mantle depths can provide important information and constraints to the tectonic evolution of the Italian Peninsula; also it may be really crucial to test and make hypotheses on the mantle deformation and flows controlled by subduction. In particular, SKS-wave splitting is the most unambiguous evidence

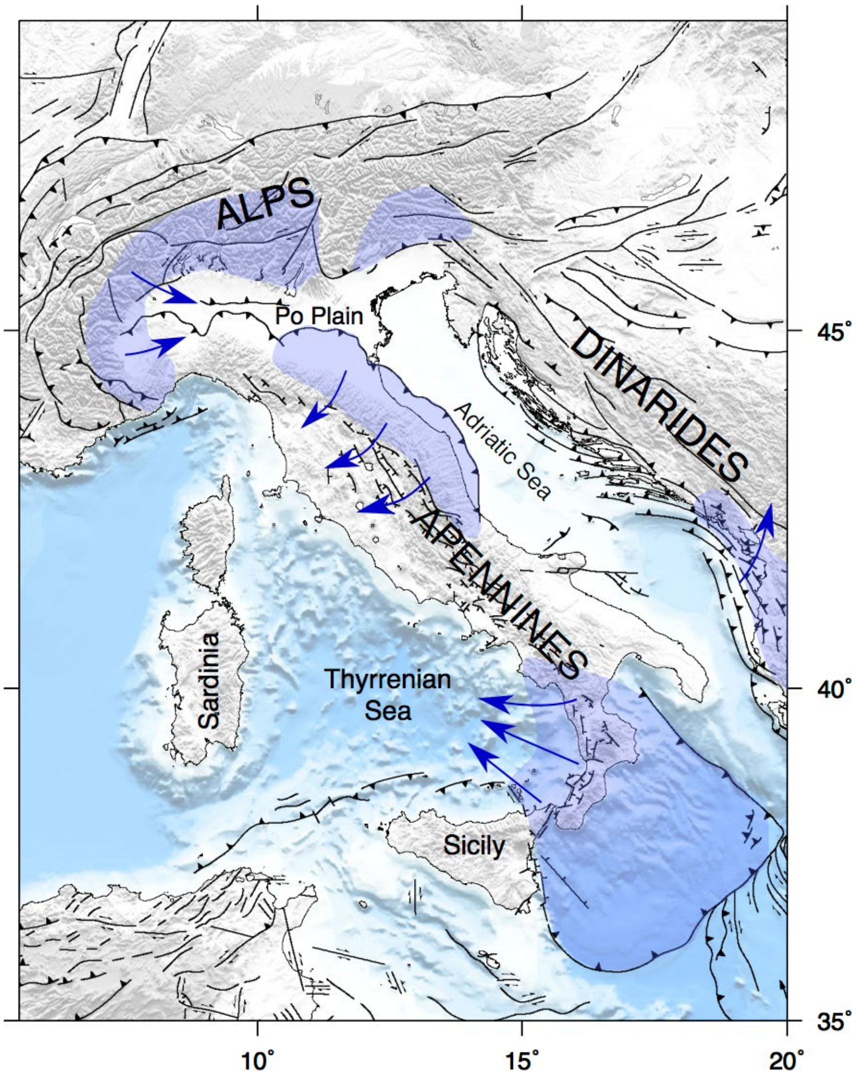

Figure 1. Sketch of the main tectonic and geodynamic features that characterise the Italian region: light blue areas are trench-to-slab parts involved in the subductions and blue arrows represent the main subduction directions [modified from Handy et al 2015].

of the presence of seismic anisotropy. The SKS phase travels as an S-wave in the crust and mantle and as a P-wave through the liquid outer core. At the core-mantle boundary on the receiver side, the P-wave is converted to an S-wave, polarised in the vertical plane of propagation for a spherical symmetric, isotropic Earth, and follows a nearly vertical mantle path. If, along this path, the shear wave passes through anisotropic layers, it splits into two quasi-shear waves with polarisation directions orthogonal to each other and propagating at different velocities, called fast and slow waves, and arriving at the receiver with a certain delay time between each other. The parameters used to describe the seismic anisotropy are the fast direction (phi), that is the direction of polarisation of the fast quasi-shear wave, measured clockwise from the north, and the delay time (dt), representing the travel time difference between the fast and slow quasi-shear waves [Savage, 1999; Margheriti et al., 2020]. The shear wave is split by an anisotropic medium when the wave's propagation direction is not parallel to a symmetry axis of the medium and when its polarisation is not parallel to the fast or slow direction. If the SKS wave does not encounter an anisotropic layer or it is originally polarised in the slow or the fast direction, it does not split and the measurement is classified as null.

The main cause of shear wave splitting in the upper mantle is the lattice preferred orientation (LPO) of crystallographic axes of elastically anisotropic minerals of olivine [Mainprice and Silver, 1993; Mainprice et al., 1998; Savage, 1999]. This phenomena has been documented particularly in subduction zones environments [e.g., Russo and Silver, 1994; Fouch and Fisher, 1996] and can be used to investigate upper mantle flows and deformation in proximity to subducting slabs [e.g., Faccenda and Capitanio, 2013]. The most common pattern in subduction zones is trench-parallel in the forearc region, transitioning to trench-perpendicular in the back-arc region, as observed in New Zealand [Karalliyadda et al., 2015], Japan [Nakajima et al., 2006], Sumatra [Collings et al., 2013], and Marianas [Pozgay et al., 2007]. Hydration from fluid-filled cracks [e.g., Faccenda, 2014] could cause trench-parallel forearc fast-axes, but trench-parallel mantle flow in the forearc [Long and Becker, 2010] and deformation of B-type olivine fabric in the mantle wedge [e.g., Kneller et al., 2005] have been proposed as well. Trench-perpendicular anisotropy in the back-arc region is caused by mantle return flow [e.g., Hall et al., 2000] and extension, which are common for fast retreating slabs. Subduction related anisotropy orientations can also be very complex, as seen at the Hellenic trench due to tears at the western and eastern ends [Paul et al, 2014; Evangelidis, 2017], its curvature, and its strong retreat [Confal et al., 2016]. Tears or break-ups in the slab usually produce some circular anisotropy pattern around the edges due to toroidal mantle flow [e.g. Civello and Margheriti 2004; Faccenna et al., 2005; Faccenda and Capitanio, 2013; Confal et al., 2018; Zhao et al., 2021] and can twist trench-parallel flow [Pondrelli et al., 2022].

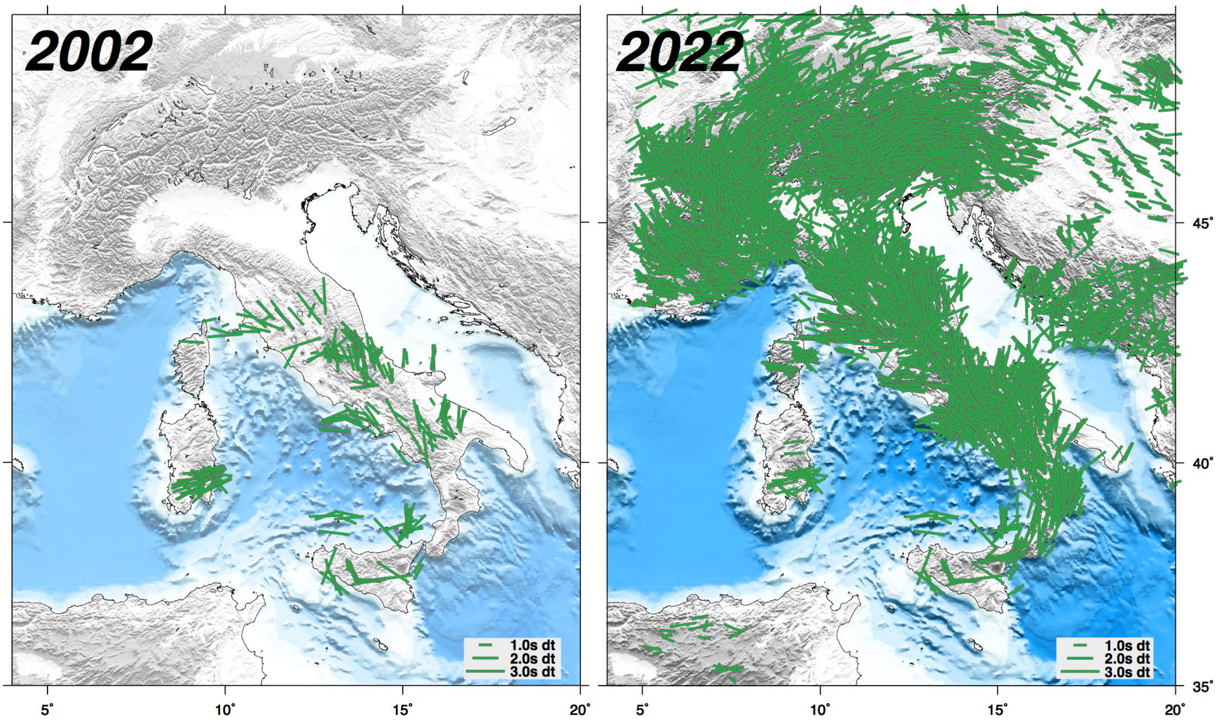

Figure 2. 2002 (left) and 2022 (right) core phases measurements available in Italy. The length of the green bars represent the time delay while the orientation is according to the fast polarisation direction.

"Frozen-in" anisotropy in the actively subducting plate [Zhao et al., 2021] or in remnant slab fragments can leave an imprint on the shear wave splitting measurements.

In this geodynamically complex area, starting from more than 20 years ago considerable progress has been made to map the anisotropic structure beneath Italy and surrounding regions. In Figure 2 we show the first measurements available in 2002 for the region [Margheriti et al., 2003] and the large dataset available at present. However, despite the large amount of information recovered from shear wave splitting databases as SplitLab [Barruol et al., 2009, Wüstefeld et al., 2009] or IRIS DMC Shear wave splitting [IRIS DMC, 2012] or by an individual collection shared on the web [Becker et al., 2012], a coherent and homogeneous dataset of single shear wave splitting measurements for the Italian and surrounding region was lacking.

In this paper we present and describe this dataset, which includes the results of several projects published in tens of papers and that consists of more than 11.000 single core phases measurements, including nulls.

2. Projects contributing to the study of mantle anisotropy in Italy and surrounding regions

Starting from the end of the 90's in Italy, several projects have been developed to improve our knowledge of the deep structure beneath the Italian peninsula. To this epoch belongs the first SKS splitting measurements, done by using data recorded by the *GeoModAp teleseismic transects*, deployed perpendicularly to the Apennines chain in about East-West direction: 1994 (Northern Apennines, NAP), 1995 (Central Apennines, CAP) and 1996 (Southern Apennines, SAP) [Margheriti et al., 1996, 1998]. These measurements first identify the slab parallel direction along the Apennines. Successively, the Italian SKS splitting measurements dataset was expanded, using data from MedNet stations [Margheriti et al., 2003] and with the first measurements done in Sicily [Civello and Margheriti, 2004], enough to hypothesise a mantle flow around the southern Thyrrenian slab.

The great improvement on SKS shear wave splitting measurements has been possible thanks to two NSF Projects: RETREAT (Retreating-TRench, Extension, and Accretion Tectonics) and CAT/SCAN (Calabria-Apennines-Tyrrhenian/Subduction-Collision-Accretion Network). The RETREAT Project [Margheriti et al., 2006], focused in Northern Apennines, consisted in the installation of 50 temporary seismic stations, at which seismic anisotropy was measured together with data from several local permanent stations belonging to the Italian National network [INGV Seismological Data Centre, 2006]. The SKS splitting measurements allowed to identify two different anisotropic domains with different patterns, a Tyrrhenian and an Adriatic one [Plomerová et al., 2006; Salimbeni et al., 2007; 2008], mostly related to different mantle deformation patterns above and below the slab. These findings yielded to interpret the slab-rollback, responsible for the birth of the Apennine belt and the Tyrrhenian Sea, as evolving differently in the northernmost part of Northern Apennines with respect to the other parts of the Apenninic/Calabrian belt. After a first stage during which the retreat was perpendicular to the trench, it became oblique with respect to the strike of the belt and the process continued as a secondary effect of the energetic slab-rollback in the southern edge of the Northern Apennines [Salimbeni et al., 2008].

Successively, benefitting from the wealth of SKS splitting measurements obtained within the CAT/SCAN Project focused on the Southern Tyrrhenian Subduction System [Steckler et al., 2005], this model has been further confirmed [Baccheschi et al., 2007]. The dataset collected in the frame of this Project, together with data of permanent stations of the Italian National Network [INGV Seismological Data Centre, 2006], enabled a detailed study of seismic anisotropy patterns beneath the Calabrian Arc and the Apulian Platform, around the northeastern edge of the southern Tyrrhenian slab [Baccheschi et al., 2007; 2008; 2011]. Shear wave splitting results reveal a distribution strongly controlled by the geometry of the slab, with anisotropy parallel to the mountain chain that would represent the mantle flow below the slab and driven by its retreat motion. Moreover, these measurements support the presence of a toroidal mantle flow around the southwestern edge of the Calabrian slab [Civello and Margheriti, 2004]. At the northeastern edge of the Tyrrhenian slab on the contrary, the absence of trench perpendicular anisotropy measurements speaks against the presence of another mantle toroidal flow beneath southern Apennines [Baccheschi et al., 2007; 2008].

After these NSF projects, the Apennines, from its Northern part up to the Calabrian Arc and Sicily, were really well sampled for seismic anisotropy data. Some other studies recently filled up the few regions with a lower data density. Most of them are related to the Adria microplate, which is truly a leading actor of this region. Salimbeni et al. [2013] identified that the fast polarisation directions detected on the outer part of the Apennines might be attributed to a proper Adria mantle pattern, so to the piece of mantle beneath Adria that the slab did not deform. This feature has been confirmed by subsequent studies [Salimbeni et al., 2014], by the CASE project data [Molinari et al., 2019; Salimbeni et al., 2022] and by other Central Italy measurements [Pondrelli et al., 2022]. However, while the dataset for the Italian peninsula is very rich, only until a few years ago the availability of SKS splitting measurements over the Alpine belt was very scarce.

The first study describing the seismic anisotropy in the upper mantle beneath the Eastern Alps was based on the TRANSALP Project data analysis [Kummerov and Kind, 2006]. At the TRANSALP temporary seismic network North-South profile, SKS shear wave splitting (calculated with stacked technique) revealed fast axis directions consistent along the profile and parallel to the trend of the Eastern Alps, thus suggesting orogen-parallel flow in the upper mantle. After several years, in the Eastern Alps the seismic anisotropy dataset is enriched by measurements made

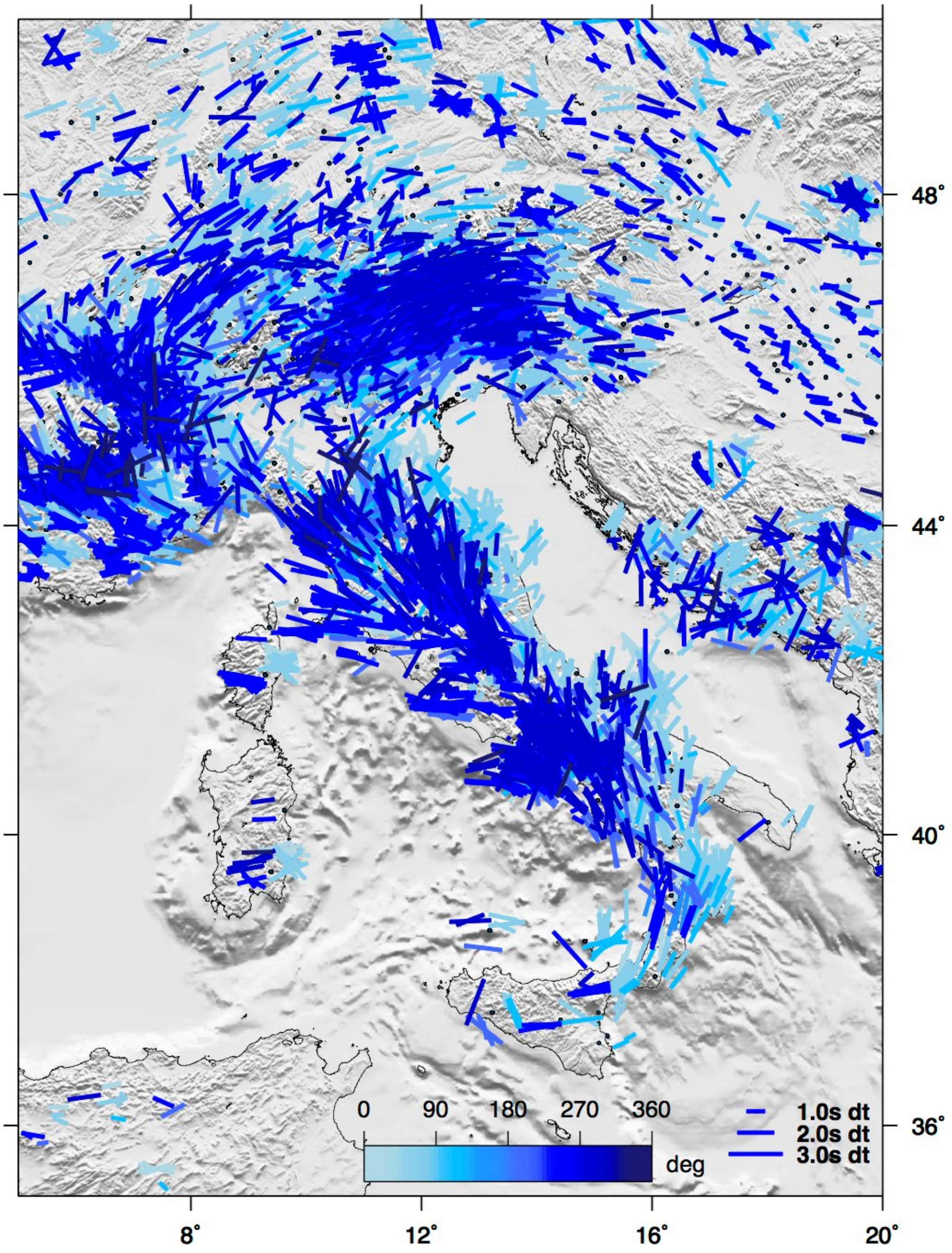

Figure 3. All SKS measurements available for the Italian region and surrounding areas, plotted at 150 km depth piercing point, following a colour scale related to the back azimuths and the length of bars depending on the time delay (bottom right).

by Bokelman et al. [2013] and Qorbani et al. [2015], even if these studies mainly implemented the use and analysis of seismic anisotropy patterns to find clarifications of complex structures. The SKS shear wave splitting observations along most of the Alps showed (also confirmed from more recent data) one of the clearest examples worldwide of fast orientation parallel to the mountain belt. On the contrary, in the Eastern Alps the anisotropy orientation does not agree with the Carpathians or the Dinarides belt directions [Qorbani et al., 2016]. This discrepancy induced the authors to model the splitting observations taking into account the back azimuthal variation of the measurements related to a vertical change of anisotropy [Qorbani et al., 2015]. Thus, beneath the eastern part of Eastern Alps two layers of anisotropy have been identified and the deeper one is interpreted as a piece of the detached slab of the European plate. The new results of shear wave splitting analysis done by Link and Rumpker [2021] using the data of the SWATH-D experiment [Heit et al., 2017] confirm this complexity.

In the meanwhile also in the Western Alps shear wave splitting measurements are produced by Barruol et al. [2002, 2004, 2011], mapping a regular rotation of fast anisotropy direction that follows the belt arc and has been again interpreted as mantle deformation due to the retreat of the subducting european slab. This anisotropy distribution is in continuity with SKS measurements taken in the southern Massif Central and may be all together representative of a large asthenospheric flow towards the Tyrrhenian Sea [Barruol et al., 2011]. This pattern has been confirmed also by CIFALPS shear wave splitting measurements [Salimbeni et al., 2018], that also added a set of data for the Po Plain, certainly less easy to be interpreted with respect to Alpine measurements. The regularity of the rotation of mantle anisotropy beneath the Alps finds another support in the shear wave splitting measurements performed over the central part of AlpArray network [Hetényi et al., 2018; Petrescu et al., 2020a], in a large stripe starting from the Po Plain at south and reaching Germany at north. SKS directions parallel the strike of the belt, rotating clockwise from West to East over ~ 700 km distance. No significant change is visible in the Central Alps at the location of the putative switch in subduction polarity. More recent measurements done using data recorded by the transect CIFALPS2 [Liu et al., 2022; Paul et al., 2022] filled the last gap left in the Alps and confirmed the pattern already described.

Out of the proper Italian territory, the study of seismic anisotropy was carried out also on surrounding regions mainly related to the Adria microplate. For instance, CASE (Central Adriatic Seismic Experiment; Molinari et al., 2019], an AlpArray complementary project, produced recently a set of shear wave splitting measurements for a transect crossing the Adriatic Sea and that possibly describes both sides of this intriguing double slab system [Salimbeni et al., 2022]. This is the most recent study on easternmost regions, where our dataset extends including measurements from previous works [Qorbani et al., 2016; Subasic et al., 2017; Song et al., 2019; Petrescu et al., 2020b] for the Carpathian-Pannonian areas.

3. SKS measurements in Italy and surrounding regions

The dataset we describe in this paper is a collection of single shear wave splitting and null measurements taken from several papers already published. The measurements listed in each of that works have been obtained with different softwares, as for instance the more recent SplitLab [Wüstefeld et al., 2008] and SplitRacer codes [Reiss and Rumpker, 2017], but share the same principles and methods, that point to the recovery of the anisotropy that minimizes the energy on the tangential component. The most frequently used is Silver and Chan [1991], but also the methods of Vinnik et al. [1992] and Šílený and Plomerova [1996] are diffused; the few differences between all of them are in the reference system or in the way uncertainty is computed. A common approach is the assumption taken to obtain phi and dt, i.e., that the detected anisotropy consists of a single layer of horizontal symmetry axis anisotropy. If the anisotropy at depth is more complex, such as double anisotropic layers or dipping anisotropy, we must take into account that the obtained anisotropy parameters are apparent and the analyses of their variation with respect to back-azimuth or angle of incidence allow to recognise real patterns. The use of different codes, then, imply that also the quality of the listed results is reported differently as well as the amount of information to reproduce the measurements, i.e. the event/station information list, used filter, time window, etc. The result of an harmonisation process is included in the Supplementary Material Table S1 (downloadable at the link: https://osf.io/nqxk4). In addition, in the Table 2 of the Supplementary Material, the list of all papers that contributed to the dataset is reported (downloadable at the link https://osf.io/7qwdx).

The dataset we present here covers completely the Italian territory and most of the surrounding regions. The highest density of data are along the belts, Alps and Apennines. In Figure 3 all available SKS measurements are mapped at the 150 km depth piercing points and colour-scaled with respect to back azimuths. We commonly use this plotting technique because it allows us to better identify the eventual presence of local lateral changes in anisotropy direction at depth. Indeed, different fast polarisation directions for different back azimuths means that beneath the station, the anisotropy direction changes and this variation is clearly visible when data is mapped at the piercing point, thus avoiding the overlap of all measures on the station site.

Usually, we select the 150 km depth for piercing points because it is the mantle depth at which we assume, based on observations of parameter variations and Fresnel zone analysis, that most detected anisotropy is located. In Figure 3 it is possible to observe that SKS data in Sardinia, Corsica and western Sicily have a very similar direction independently from back azimuth, while moving in the Apennines along the Adriatic Sea coasts, examples of different directions for different back azimuths are present: often measurements from NE (lightest blue) have different directions with respect to those coming from NW or SW back azimuths (darker blues). In several studies

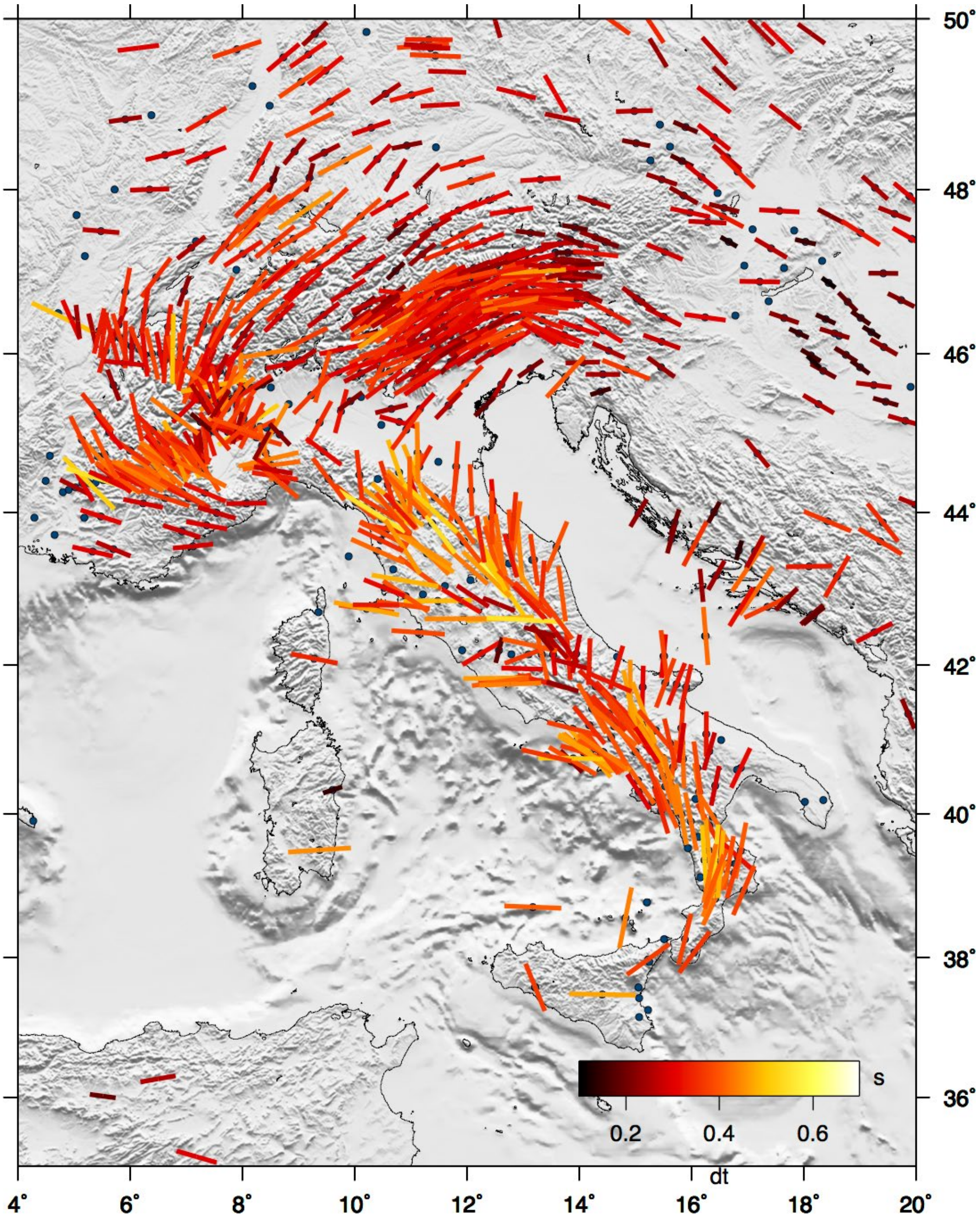

Figure 4. Average values at each station, mapped only when obtained with at least three measurements. Length of symbols is proportional to dt and coloured as a function of the dt value (Table S3 of the Supplementary Material downloadable at the link https://osf.io/uxc4f).

using these simple mapping techniques, different domains have been identified, helping a lot the interpretations. An early example is the definition of the Apennines, Thyrrenian and Adria domains [Salimbeni et al., 2007, 2008, 2013], obtained following lateral changes in the anisotropy direction.

In this case, when the data availability is as rich as for the Italian region, the results obtained are the main mantle flow patterns. In addition, mapping symbols colour-scaled with the delay time dt allows to identify trends in the amount of anisotropy, not only in its direction.

In Figure 4 main trends are indeed evident, as the anisotropy parallel to both the main mountain belts, Alps and Apennines, or the EW trend diffused in most of the Tyrrhenian Sea. Moreover, highest delay time values (light orange to yellow) are along the Apennines, from the northern part of the belt to Sicily, passing through the Calabrian Arc. It is worth noting that this is the part of the italian peninsula interested in the youngest tectonics. In the Alpine region the fast direction parallel to the mountain strike is present also in the European foreland and in a portion of the Po plain, at least on its eastern part.

Average values at stations are clearly a good instrument to enhance large scale variations. It is not however the guarantee to have an homogeneous image of the seismic anisotropy pattern. When data availability is adequate, a process of smoothing may be applied over the entire dataset to get an homogeneous view of the anisotropy distribution. The final product is a picture that may have different resolution on the basis of the density of the input

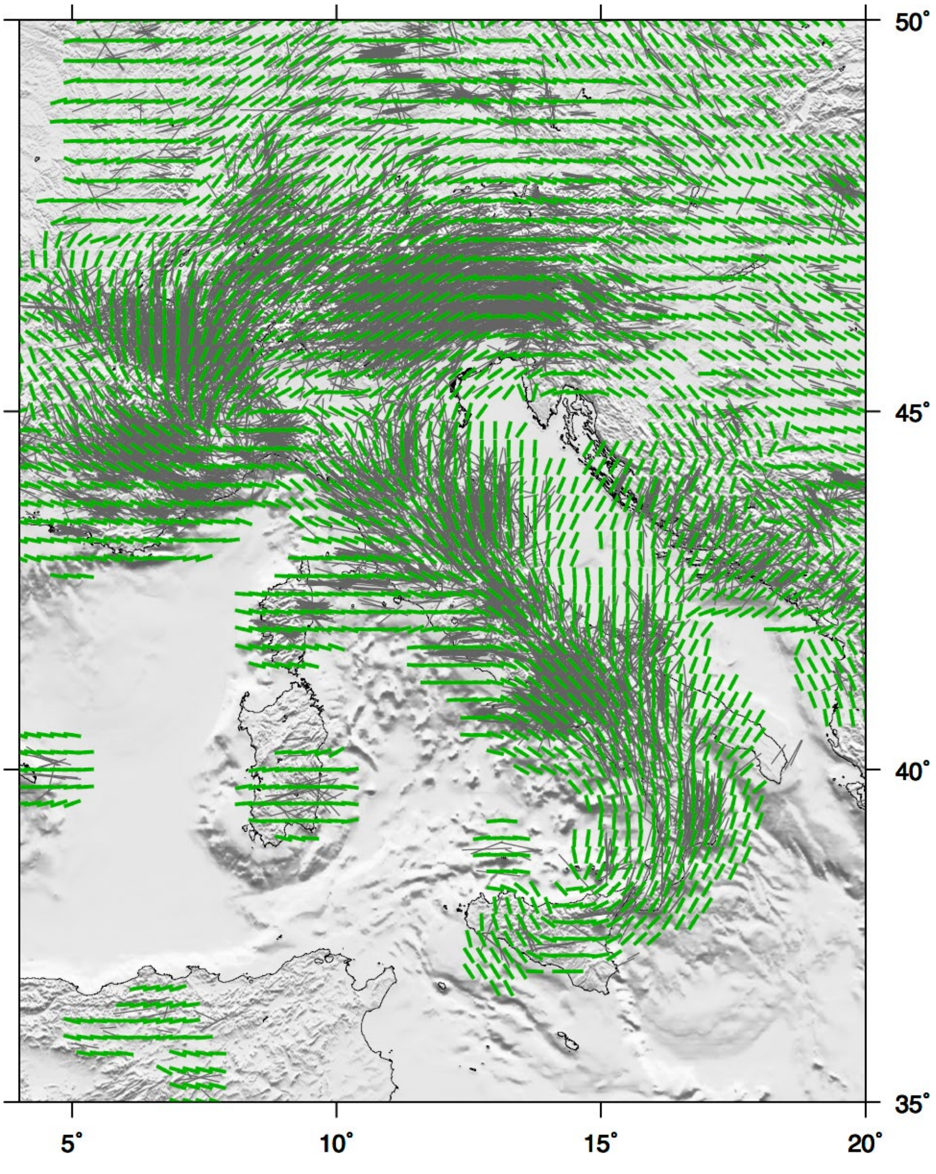

Figure 5. Smoothed seismic anisotropy distribution (in green) for Italy and surrounding region. The single shear wave splitting measurements of the database, used to obtain this map, are the black symbols in background.

dataset and the choice of smoothing parameters. In Figure 5 the result of the smoothing of all single shear wave splitting measurements located at the 150 km depth piercing point is shown. The smoothing process is obtained using the techniques described in Müller et al. [2003] over a 0.25°x0.25° grid cell, with 70 km of search radius for the nearest neighbours containing at least 5 measurements and using a normalised tricubic weight function based on the quality of the single measurements. According to the indication for local investigation given by Müller et al. [2003], we used a smoothing parameter of $\lambda = 1$ to keep fidelity to the interpolated data.

Except for studies where the large scale image is the focus, it is however extremely interesting to understand small scale features. To do so, we go back to the use of single measurements, back azimuthal coverage, and plotting at piercing points, trying therefore to have a map more informative than Figure 3, with the intention to better distinguish smaller trends. In Figure 6, the entire available dataset has been used to compute at each station the average value for each quarter of back azimuth, then plotted in its middle, at 150 km depth piercing point. That

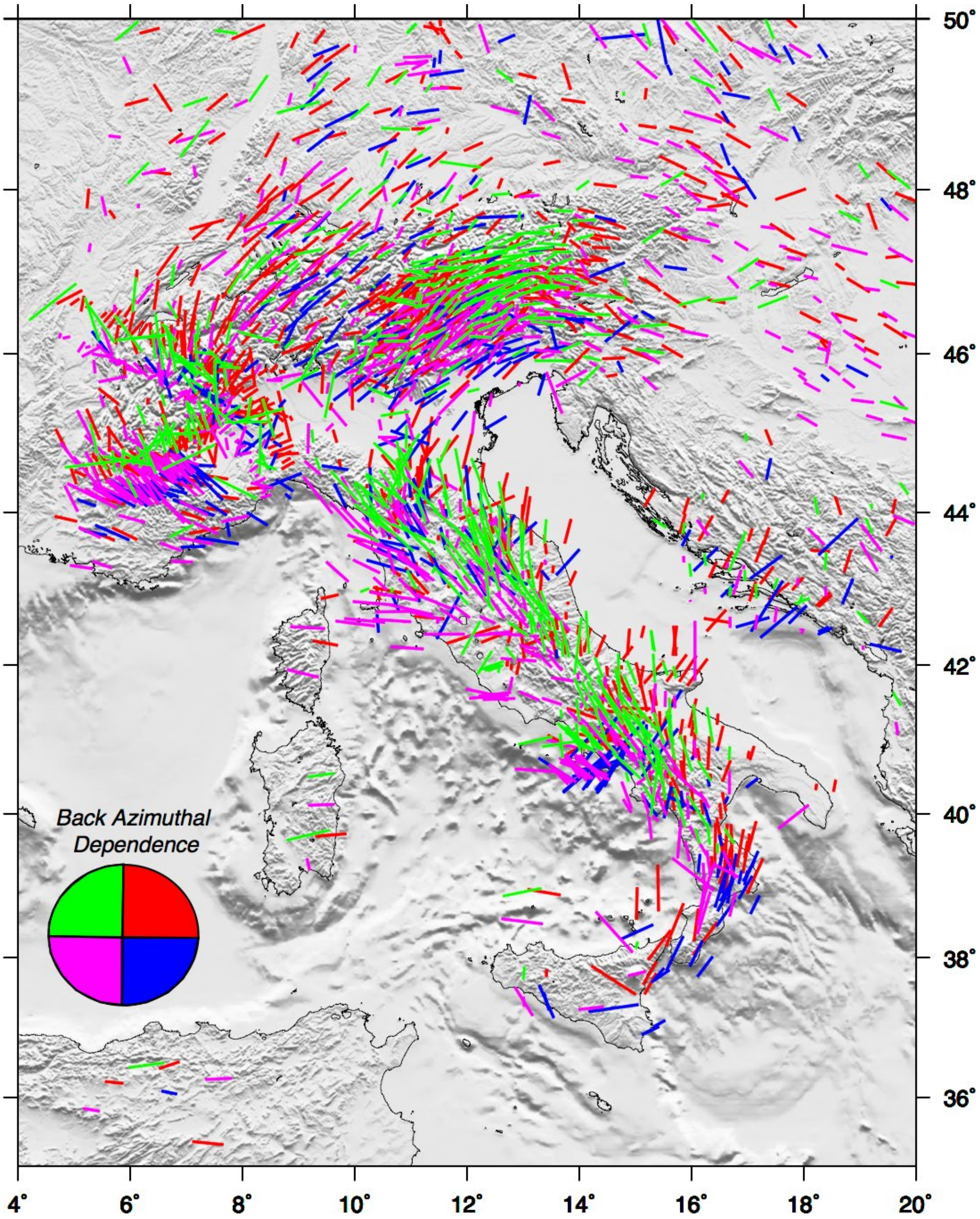

Figure 6. Quarter average values at each station for the Italian region. Symbols are colour coded following the legend values: red is the average value for 0°-90° back azimuth; blue for 90°-180° back azimuth; pink for 180°-270° back azimuth and green for 270°-360°.

means we split at each station all measurements between the four back azimuth quarters and we compute the average value. The result is, when data availability is good, to have four symbols around each station, each one in correspondence of the quarter bisector (Figure 6). If the four values show a similarity, it is correct to think that at depth the detected seismic anisotropy is homogeneous in direction and amount, as for instance in Sardinia and Corsica and in central Tyrrhenian.

On the contrary, if quarter average values show variations it is reliable to consider that the station is located over a more complex and heterogeneous anisotropic volume. Using this technique, in Salimbeni et al. [2013] a boundary between different anisotropic domains has been identified for stations located in the outer part of the Northern Apennines, along the Adriatic Sea side. The western quarter average values detect the typical NW-SE Apenninic mantle flow pattern, while eastern back azimuths record the proper Adria mantle NNE-SSW directions, interpreted as the undeformed mantle by the Apenninic slab retreat.

4. Conclusive remarks on the relevance of SKS measurements

4.1 Relation with other anisotropy data and coherence of lithospheric and asthenospheric deformation

One of the well known limits of shear wave splitting measurements is the scarce definition of the depth distribution of anisotropy. Indeed, the anisotropy parameters obtained with a SKS splitting measure represents the summary of all possible anisotropy crossed by the seismic ray. It is however known that most of anisotropy is supposed to be in the upper mantle, being the place where mantle circulation mainly develops, while the contributions of crust and lower mantle is negligible, less than 0.3 s and less than 0.7 s respectively [Savage, 1999]. Moreover, as we describe in previous paragraphs, the azimuthal variation of shear wave splitting parameters at each single station gave us clues about the lateral and vertical gradients in the anisotropic pattern observed below this very complex region. In some regional studies, i.e. Salimbeni et al. (2008, 2018), the use of Fresnel zones of teleseimic events analysed to obtain SKS measurements helped to discriminate also depth distribution of the anisotropy.

However, locating the anisotropy with depth is as difficult as well as important when we try to understand the degree of coupling or decoupling between shallow and deep phenomena. The solution is the comparison of seismic anisotropy detected with different phases (Figure 7), as for instance the Pn anisotropy that is certainly located immediately below the Moho and SKS shear wave splitting [e.g. Diaz et al. (2013) for the Mediterranean area]. When the two different data show an agreement, as it is the case along most of the Apennines, the Calabrian Arc, the Tyrrhenian Sea, and the Eastern Alps (Figure 7), we could conclude that a coherency of the anisotropy with depth, interpreted as a coherency in the deformation, may be tentatively correlated with a coupling. On the contrary, a difference between the two anisotropies supports a variation with depth and that their source is due to different deformation phenomena, sometimes it is possible to refer to a decoupling. This kind of reasoning may be also done through the comparison of shear wave splitting results with surface wave azimuthal anisotropy, shown in Fig. 7 [Zhu et al., 2015]. However in this last case, often the recovered azimuthal anisotropy has a very low definition with respect to the dataset as the one described in this work and it is better used in greater scale contexts instead of the small but clearly complex region of the central Mediterranean.

4.2 Support to geodynamic models

The dataset of seismic anisotropy data for the Italian peninsula, obtained through core phase shear wave splitting measurements, is clearly rich, with some regions characterised by a greater density (i.e. Alps and Apennines), but with a complete coverage of the interesting zones.

Seismic anisotropy distribution is controlled by the geodynamic structure, that in this region includes at least 3 main slabs, the Alpine one, where Eurasia subducted under Adria plate, and the two Adria slabs, one dipping toward the west beneath the Apennines and toward the Thyrrenian, and the other toward the east beneath the Dinarides. As already described, complexities, discontinuities and heterogeneities of these slabs, including flipping dip directions, have been discussed and still are open questions (Supplementary Figure S2). However, seismic anisotropy studies gave several indications and answers to these geodynamic doubts.

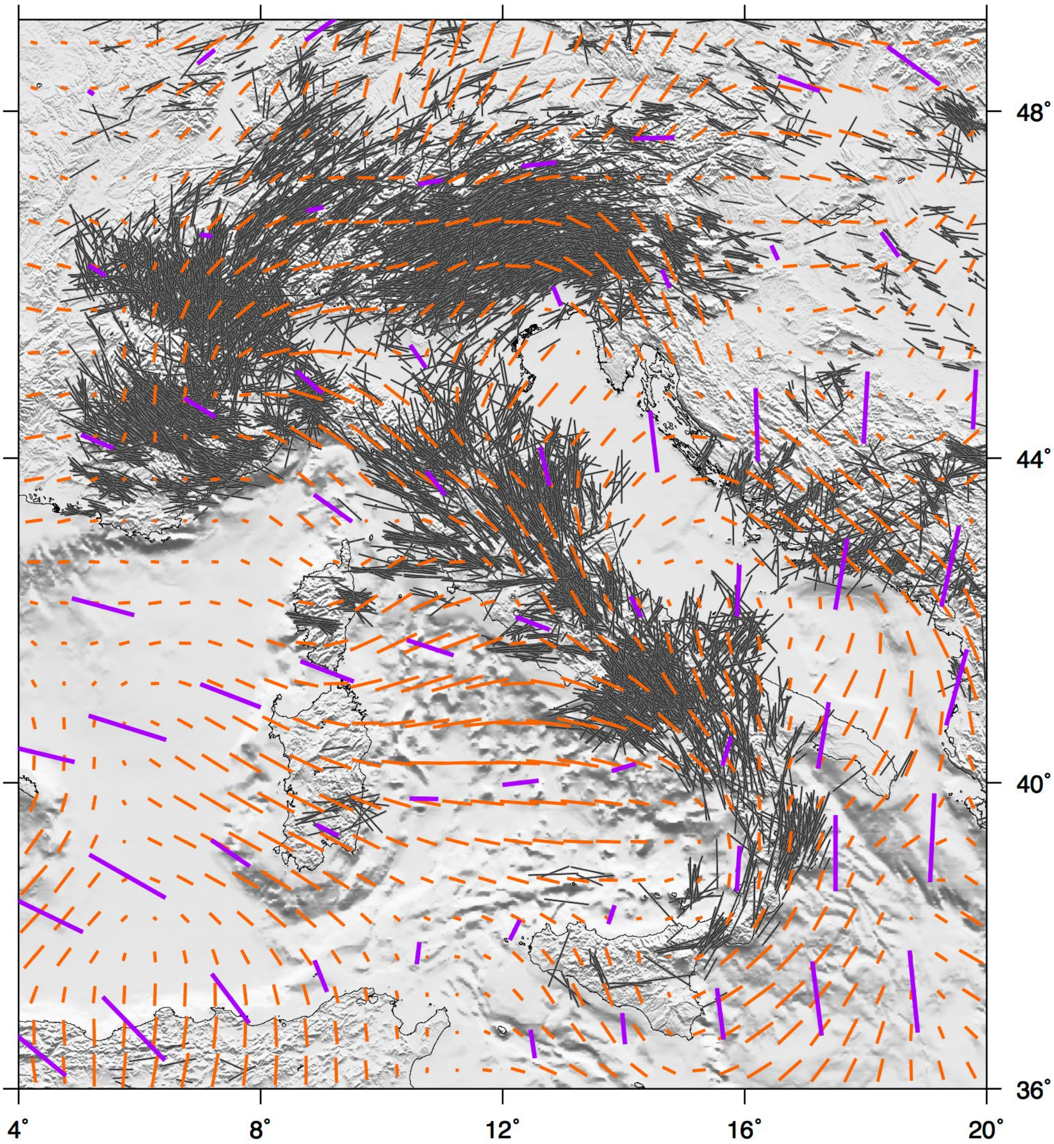

Figure 7. Map of different anisotropy measurements. In the background, in grey all the single shear wave splitting data from the collection presented in this work. In orange the Pn anisotropy [Diaz et al., 2013] and in red the azimuthal anisotropy from surface waves at 100 km of depth [Zhu et al., 2015].

Our compilation of SKS splitting measurements over the Italian peninsula and surrounding areas shows an orientation of the anisotropy with main patterns of fast-axis mainly parallel to the mountain belts and the strike of the Apennines and Alps slabs, interpreted as trench-parallel mantle flow beneath the slabs induced by their retreat (Figure 8). Another main pattern is in the Western Alps, where the rotation of anisotropy direction around the Alpine (European) slab enters the Thyrrenian domain [Salimbeni et al., 2018 and references therein]. This pattern has been interpreted as an asthenospheric flow from below the Alpine slab, feeding the Thyrrenian mantle above the Apennines slab and encouraging its rollback (Figure 8). This asthenospheric mantle flow has been described for the first time by Barruol et al. [2004] and confirmed by successive works. This flow pattern follows the route of the slab from the initial rifting phase along the Gulf of Lion (30-22 Ma) to the drifting of the Corsica-Sardinia lithospheric block with the opening of the Liguro-Provençal basin first (22-17 Ma) and then the Tyrrhenian Sea later [Lucente et al., 2006].

In the same region, precisely at the transition between Western Alps and Apennines, another possible toroidal mantle flow was hypothesised in several geodynamic models [Vignaroli et al., 2008; Salimbeni et al., 2013; Király et al., 2018] as an escape point for the NW-SE mantle flow below the Apennines towards the NW, from below the northern edge of the Apennines slab toward the Thyrrenian, through a possible separation between the Alpine and Apennines

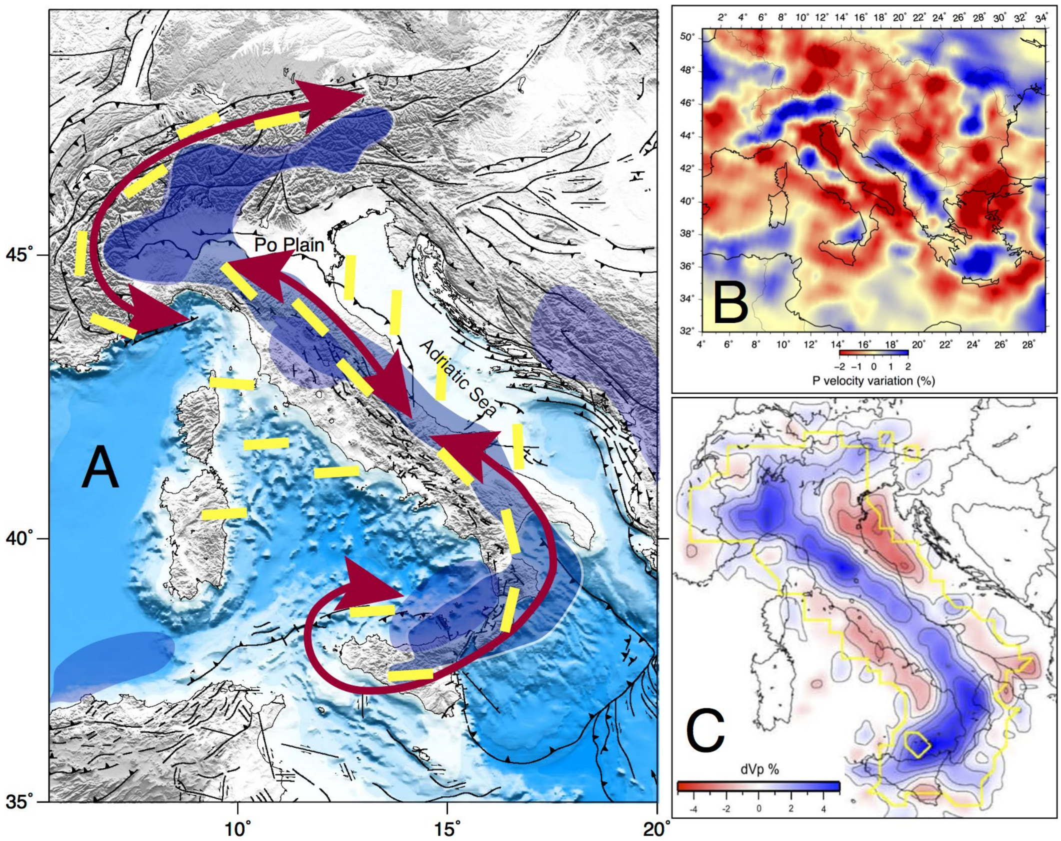

Figure 8. A) Map where light and dark blue regions are the contour of the slabs at about 150 km depth as seen by seismic tomography studies of Piromallo and Morelli [2003] and Giacomuzzi et al. [2011] respectively. Yellow symbols are a sketch of seismic anisotropy. Red arrows represent the possible mantle flow identified starting from detected seismic anisotropy and the presence of slabs. B) and C) slices at 150 km depth of tomographies by Piromallo and Morelli [2003] and Giacomuzzi et al. [2011].

slab. More recent measurements did not find any anisotropy N-S directed in correspondence of the Alps-Apennines transition, excluding the idea that below slab Apenninic mantle may escape into Thyrrenian domain.

Going on in the description of examples, where seismic anisotropy data supported or ruled out hypotheses done on the basis of tomographic images or geodynamic modelling about the deep structure beneath the Italian peninsula, seismic anisotropy data supports the assumption of the existence of a slab tear beneath Sicily, reported in tomographic images [Piromallo and Morelli, 2003], through which mantle flows [Civello and Margheriti, 2004]. On the contrary, shear wave splitting measurements showed a different pattern in Central Italy with respect to the one expected for the toroidal mantle flow that numerical and analytical models and interpretations of tomographic images of seismic velocity variations had drawn there [Giacomuzzi et al., 2012; Király et al., 2018]. Here the pattern of seismic anisotropy shows just a very small interruption in the NW-SE Apenninic typical pattern, too small with respect to the slab window imaged by tomographies. The little mantle flow that shear wave splittings may represent is enough for a young step tear, recently developed and probably not enough evolved to be related to a greater toroidal mantle flow [Pondrelli et al., 2022].

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References

Baccheschi, P., L. Margheriti and M. Steckler (2007). Seismic anisotropy reveals focused mantle flow around the Calabrian slab (Southern Italy), Geophys. Res. Lett., 37, L05302, doi:10.1029/2006GL028899.

Baccheschi, P., L. Margheriti, M. Steckler and CAT/SCAN Seismology Team (2008). SKS splitting in Southern Italy: Anisotropy variations in a fragmented subduction zone, Tectonophys., 462, 49-67.

Baccheschi, P., L. Margheriti, M. Steckler and E. Boschi (2011). Anisotropy patterns in the subducting lithosphere and in the mantle wedge: A case study—The southern Italy subduction system. J. Geophys. Res., 116, B08306, doi.org/10.1029/2010JB007961.

Barruol, G. and M. Granet (2002). A Tertiary asthenospheric flow beneath the southern French Massif Central indicated by upper mantle seismic anisotropy and related to the west Mediterranean extension, Earth Planet. Sci. Lett., 202, 1, 31-47.

Barruol, G., A. Deschamps and O. Coutant (2004). Mapping upper mantle anisotropy beneath SE France by SKS splitting indicates Neogene asthenospheric flow induced by Apenninic slab roll-back and deflected by the deep Alpine roots, Tectonophys., 394, 1-2, 125-138, doi:10.1016/j.tecto.2004.08.002.

Barruol, G., A. Wuestefeld and G. Bokelmann (2009). SKS-Splitting-database. Université de Montpellier, Laboratoire Géosciences, https://doi.org/10.18715/sks_splitting_database.

Barruol, G., M. Bonnin, H. Pedersen, G. Bokelmann and C. Tiberi (2011). Belt-parallel mantle flow beneath a halted continental collision: the Western Alps, Earth Planet. Sci. Lett., 302, 429-438, doi:10.1016/j.epsl.2010.12.040

Becker, T. W., S. Lebedev and M.D. Long (2012). On the relationship between azimuthal anisotropy from shear wave splitting and tomographic models, J. Geophys. Res., 117, B01306, doi:10.1029/2011JB008705.

Bokelmann, G., E. Qorbani and I. Bianchi (2013). Seismic anisotropy and large-scale deformation of the Eastern Alps, Earth Plan. Sci. Lett., 383, 1-6.

Civello, S. and L. Margheriti (2004). Toroidal mantle flow around the Calabrian slab (Italy) from SKS splitting, Geophys. Res. Lett., 31, L10601, doi:10.1029/2004GL019607.

Collings, R., A. Rietbrock, D. Lange, F. Tilmann, S. Nippress and D. Natawidjaja D. (2013). Seismic anisotropy in the Sumatra subduction zone, J. Geophys. Res. Solid Earth, 118,10, 5372-5390.

Confal, J. M., T. Eken, F. Tilmann, S. Yolsal-Çevikbilen, Y. Çubuk-Sabuncu, E. Saygin and T. Taymaz (2016). Investigation of mantle kinematics beneath the Hellenic-subduction zone with teleseismic direct shear waves. Phys. Earth Plan. Int., 261, 141-151.

Confal, J. M., M. Faccenda, T. Eken and T. Taymaz (2018). Numerical simulation of 3-D mantle flow evolution in subduction zone environments in relation to seismic anisotropy beneath the eastern Mediterranean region, Earth Plan. Sci. Lett., 497, 50-61.

Davis, J. C. (2002). Statistics and Data Analysis in Geology, 3rd ed., 656, Wiley, New York.

Díaz J., A. Gil and J. Gallart (2013). Uppermost mantle seismic velocity and anisotropy in the Euro-Mediterranean region from Pn and Sn tomography, Geophys. J. Int., 192, 1, 310-325, https://doi.org/10.1093/gji/ggs016.

Evangelidis, C. P. (2017). Seismic anisotropy in the Hellenic subduction zone: Effects of slab segmentation and subslab mantle flow. Earth Plan. Sci. Lett., 480, 97-106.

Faccenda, M. and F. A. Capitanio (2013). Seismic anisotropy around subduction zones: Insights from three-dimensional modeling of upper mantle deformation and SKS splitting calculations. Geochem., Geophys., Geosys, 14, 1, 243-262.

Faccenda, M. (2014). Water in the slab: A trilogy. Tectonophysics, 614, 1-30.

Faccenna, C., L. Civetta, M. D'Antonio, F. Funiciello, L. Margheriti and C. Piromallo (2005). Constraints on mantle circulation around the deforming Calabrian slab, Geophys. Res. Lett., 32, L06311, doi:10.1029/2004GL021874.

Fouch, M. J. and K. M. Fischer (1996). Mantle anisotropy beneath northwest Pacific subduction zones. J. Geophys. Res. Solid Earth, 101, B7, 15987-16002.

Giacomuzzi, G., C. Chiarabba and P. De Gori (2011). Linking the Alps and Apennines subduction systems: new constraints revealed by high-resolution teleseismic tomography. Earth Plan. Sci. Lett., 301, 3-4, 531-543.

Giacomuzzi, G., M. Civalleri, P. De Gori and C. Chiarabba (2012). A 3D Vs model of the upper mantle beneath Italy: Insight on the geodynamics of central Mediterranean. Earth Plan. Sci. Lett., 335, 105-120.

Hall, C. E., K. M. Fischer, E. M. Parmentier and D. K. Blackman (2000). The influence of plate motions on three-dimensional back arc mantle flow and shear wave splitting. J. Geophys. Res.: Solid Earth, 105, B12, 28009-28033.

Handy, M. R., K. Ustaszewski and E. Kissling (2015) Reconstructing the Alps-Carpathians-Dinarides as a key to understanding switches in subduction polarity, slab gaps and surface motion, Int. J. Earth. Sci. (Geol. Rundsch), 104, 1-26, doi:10.1007/s00531-014-1060-3.

Heit, B., M. Weber, F. Tilmann, C. Haberland, Y. Jia and D. Pesaresi (2017). The Swath-D Seismic Network in Italy and Austria, GFZ Data Services. Other/Seismic Network.

Hetényi G., I. Molinari, J. Clinton et al. (2018). The AlpArray Seismic Network: a large-scale European experiment to image the Alpine orogeny, Surv. Geophys., 39, 1009-1033. doi:10.1007/s10712-018-9472-4.

Karalliyadda, S. C., M. K. Savage, A. Sheehan, J. Collins, D. Zietlow and A. Shelley (2015). S-wave splitting in the offshore South Island, New Zealand: Insights into plate-boundary deformation, Geochem., Geophys., Geosys., 16, 9, 2829-2847.

Király, Á., C. Faccenna and F. Funiciello (2018). Subduction zones interaction around the Adria microplate and the origin of the Apenninic arc, Tectonics, 37, 3941-3953. https://doi.org/10.1029/2018TC005211.

Kneller, E. A., P. E. Van Keken, S. I. Karato and J. Park (2005). B-type olivine fabric in the mantle wedge: Insights from high-resolution non-Newtonian subduction zone models, Earth Plan. Sci. Lett., 237, 3-4, 781-797.

Kummerow, J., R. Kind and TRANSALP Working Group (2006). Shear wave splitting in the Eastern Alps observed at the TRANSALP network, Tectonophysics, 414, 1-4, 117-125.

INGV Seismological Data Centre (2006). Rete Sismica Nazionale (RSN), Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy. https://doi.org/10.13127/SD/X0FXnH7QfY

IRIS DMC (2012). Data Services Products: SWS-DBs Shear-wave splitting databases, https://doi.org/10.17611/DP/SWS.1.

Link F. and G. Rumpker (2021). Resolving seismic anisotropy in the lithosphere-asthenosphere in the Central/Eastern Alps beneath the dense SWATH-D network, Front. Earth Sci., doi: 10.3389/feart.2021.679887.

Lippitsch, R., E. Kissling and J. Ansorge (2003). Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography, J. Geophys. Res.: Solid Earth, 108, B8.

Liu, D., L. Zhao, A. Paul, H. Yuan, S. Solarino, C. Aubert, S. Pondrelli, S. Salimbeni, E. Eva and M. Malusà (2022). Receiver function mapping of the mantle transition zone beneath the Western Alps: New constraints on slab subduction and mantle upwelling. Earth Planet. Sc. Lett., 577, 117267. doi: 10.1016/j.epsl.2021.117267.

Long, M. D., and T. W. Becker (2010). Mantle dynamics and seismic anisotropy, Earth Plan. Sci. Lett., 297, 3-4, 341-354.

Lucente F.P., L. Margheriti, C. Piromallo and G. Barruol (2006). Seismic anisotropy reveals the long route of the slab through the western-central Mediterranean mantle, Earth Plan. Sci. Lett., 241, 517-529, doi:10.1016/j.epsl.2005.10.041.

Mainprice, D., and P. G. Silver (1993). Interpretation of SKS-waves using samples from the subcontinental lithosphere, Phys. Earth Planet. Inter., 78, 257-280, doi.org/10.1016/0031-9201(93)90160-B.

Mainprice, D., W. Ben Ismaìl and F. Wagner (1998). The relationship between olivine textures and seismic anisotropy in a database of upper mantle rocks, Materials Science Forum 273-275, 681-686.

Margheriti L., C. Nostro, M. Cocco and A. Amato (1996). Seismic anisotropy beneath the Northern Apennines (Italy) and its tectonic implications, Geophys. Res. Lett, 23, 20, https://doi.org/10.1029/96GL02519.

Margheriti L. (1998). SKS-wave splitting and upper mantle structure: results in Southern Apennines, Annali di Geofisica, 41, 4, 607-616.

Margheriti, L., F. P. Lucente and S. Pondrelli (2003). SKS splitting measurements in the Apenninic-Tyrrhenian domain (Italy) and their relation with lithospheric subduction and mantle convection, J. Geophys. Res., 108(B4), 2218, doi:10.1029/2002JB001793.

Margheriti, L., S. Pondrelli, D. Piccinini, N. Piana Agostinetti, F.P. Lucente, A. Amato, P. Baccheschi, L. Giovani, S. Salimbeni, J. Park, M. Brandon, V. Levin, J. Plomerova, P. Jedlicka, L. Vecsey, V. Babuska, A. Fiaschi, B Carpani and P. Ulbricht (2006). The Subduction Structure of the Northern Apennines: Results from the RETREAT Seismic Deployment, Ann. Geophys., 49, 4/5, 1119-1131, doi: 10.4401/ag-3107.

Margheriti L., P. Baccheschi and J. Park J. (2020). Seismic Anisotropy, Encyclopedia of Geology, 2nd edition https://doi.org/10.1016/B978-0-08-102908-4.00156-9.

Mitterbauer, U., M. Behm, E. Brückl, R. Lippitsch, A. Guterch, G. R. Keller, E. Koslovskaya, E. M. Rumpfhuber and F. Šumanovac (2011). Shape and origin of the East-Alpine slab constrained by the ALPASS teleseismic model, Tectonophysics, 510, 1-2, 195-206.

Molinari I., I. Dasović, J. Stipčević, V. Šipka, E. Kissling, J. Clinton, S. Salimbeni, S. Prevolnik, D. Giardini, S. Wiemer, the AlpArray-CASE Field Team and the AlpArray-CASE Working Group (2019). Probing the Central Adriatic Lithosphere structure: the AlpArray-CASE seismic experiment, Geofizika Journal, doi:10.15233/gfz.2018.35.6.

Müller, B., V. Wehrle, S. Hettel, B. Sperner and K. Fuchs (2003). A new method for smoothing oriented data and its application to stress data, in Fracture and In-Situ Stress Characterization of Hydrocarbon Reservoirs, M. S. Ameen (editor), Geol. Soc. Spec. Publ., 209, 107-126.

Nakajima, J., J. Shimizu, S. Hori and A. Hasegawa A. (2006). Shear-wave splitting beneath the southwestern Kurile arc and northeastern Japan arc: A new insight into mantle return flow, Geophys. Res. Lett., 33, 5.

Paul, A., H. Karabulut, A. K. Mutlu and G. Salaün (2014). A comprehensive and densely sampled map of shear-wave azimuthal anisotropy in the Aegean-Anatolia region, Earth Plan. Sci. Lett., 389, 14-22.

Petrescu, L., S. Pondrelli, S. Salimbeni, M. Faccenda and the AlpArray Working Group, (2020a). Mantle flow below the central and greater Alpine region: insights from SKS anisotropy analysis at AlpArray and permanent stations, Solid Earth, 11, 1275-1290, doi:10.5194/se-11-1275-2020.

Petrescu, L., G. Stuart, G. Houseman and I. Bastow (2020b). Upper mantle deformation signatures of craton-orogen interaction in the Carpathian-Pannonian region from SKS anisotropy analysis, Geoph. J. Int., 220, 2105-2118,DOI:10.1093/gji/ggz573.

Piromallo, C. and A. Morelli (2003). P wave tomography of the mantle under the Alpine-Mediterranean area, J. Geophys. Res.: Solid Earth, 108, B2.

Piromallo, C. and C. Faccenna (2004). How deep can we find the traces of Alpine subduction?, Geophys. Res. Lett., 31, 6.

Plomerova, J., L. Margheriti, J. Park, V. Babuska, S. Pondrelli, L. Vecsey, D. Piccinini, V. Levin, P. Baccheschi and S. Salimbeni (2006). Seismic anisotropy beneath the northern Apennines (Italy): mantle flow or lithospheric fabric?, Earth Planet. Sci. Lett., 247, DOI:10.1016/j.epsl.2006.1004.1023.

Pondrelli S., J. M. Confal and P. Baccheschi (2022). New SKS splitting anisotropy measurements point to recent tearing beneath Central Italy, Tectonophysics, 840, 229549, https://doi.org/10.1016/j.tecto.2022.229549.

Pozgay, S. H., D. A. Wiens, J. A. Conder, H. Shiobara and H. Sugioka (2007). Complex mantle flow in the Mariana subduction system: Evidence from shear wave splitting, Geophys. J. Int., 170, 1, 371-386.

Qorbani, E., I. Bianchi and G. Bokelmann (2015). Slab detachment under the Eastern Alps seen by seismic anisotropy, Earth Planet. Sci. Lett., 409, 96-108, doi:10.1016/j.epsl.2014.10.049.

Qorbani, E., G.H.R. Bokelmann, I. Kovacs, F. Horvath and G. Falus (2016). Deformation in the asthenospheric mantle beneath the Carpathian-Pannonian Region, J. Geophys. Res., 121, doi:10.1002/2015JB012604.

Reiss, M. C. and G. Rümpker (2017). SplitRacer: MATLAB Code and GUI for Semiautomated Analysis and Interpretation of Teleseismic Shear-Wave Splitting, Seism. Res. Lett., 88, 2A, 392-409, doi: https://doi.org/10.1785/0220160191.

Russo, R. M. and P. G. Silver (1994). Trench-parallel flow beneath the Nazca plate from seismic anisotropy, Science, 263, 5150, 1105-1111.

Salimbeni, S., S. Pondrelli, L. Margheriti, V. Levin, J. Park, J. Plomerova and V. Babuska (2007). Abrupt change in mantle fabric across northern Apennines detected using seismic anisotropy, Geophys. Res. Lett., 34, L07308, doi:10.1029/2007GL029302.

Salimbeni, S., S. Pondrelli, L. Margheriti, J. Park and V. Levin (2008). SKS splitting measurements beneath Northern Apennines region: A case of oblique trench-retreat, Tectonophys., 462, 68-82, doi:10.1016/j.tecto.2007.11.075.

Salimbeni, S., S. Pondrelli and L. Margheriti (2013). Hints on the deformation penetration induced by subductions and collision processes: Seismic anisotropy beneath the Adria region (Central Mediterranean), J. Geophys. Res., 118(11), 2013JB010253, doi:10.1002/2013jb010253.

Salimbeni S., S. Pondrelli, L. Margheriti, V. Levin and J. Park (2014). Looking for layered anisotropic structures in the mantle beneath the northern Apennines. J. Geodynamics, 82, 39-51, DOI: 10.1016/j.jog.2014.09.001.

Salimbeni, S., M. G. Malusà, L. Zhao, S. Guillot, S. Pondrelli, L. Margheriti, A. Paul, S. Solarino, C. Aubert, T. Dumont, S. Schwartz, Q. Wang, X. Xu, T. Zheng and R. Zhu (2018). Active and fossil mantle flows in the western Alpine region unravelled by seismic anisotropy analysis and high-resolution P wave tomography, Tectonophysics, 731-732, 35-47, doi:10.1016/j.tecto.2018.03.002.

Salimbeni, S., S. Pondrelli, I. Molinari, J. Stipčević, S. Prevolnik, I. Dasović and the AlpArray-CASE working group (2022). Seismic anisotropy across Adria plate, from the Apennines to the Dinarides, Front. Earth Sci., Sec. Solid Earth Geophys., https://doi.org/10.3389/feart.2022.881138.

Savage M. K. (1999). Seismic anisotropy and mantle deformation: What have we learned from shear wave splitting? Rev. Geophys., 37, 1, 65-106, https://doi.org/10.1029/98RG02075.

Schmid, S. M., B. Fügenschuh, E. Kissling and R. Schuster (2004). Tectonic map and overall architecture of the Alpine orogen, Eclogae Geologicae Helvetiae, 97, 1, 93-117.

Schmid, S.M., D. Bernoulli, B. Fügenschuh, L. Matenco, S. Schefer, R. Schuster, M. Tischler and K. Ustaszewski (2008). The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units, Swiss J. Geosci., 101, 139-183.

Selvaggi, G. and A. Amato (1992). Subcrustal earthquakes in the Northern Apennines (Italy): evidence for a still active subduction?, Geophys. Res. Lett., 19, 21, 2127-2130.

Selvaggi, G. and C. Chiarabba (1995). Seismicity and P-wave velocity image of the Southern Tyrrhenian subduction zone, Geophys. J. Int., 121(3), 818-826.

Silver, P. G. and W. W. Chan (1991). Shear wave splitting and subcontinental mantle deformation, J. Geophys. Res.: Solid Earth, 96, B10, 16429-16454.

Song, W., Y. Yu, C. Shen, F. Lu and F. Kong (2019). Asthenospheric flow beneath the Carpathian-Pannonian region: Constraints from shear wave splitting analysis, Earth Planet. Sci. Lett., 520, 231-240, doi:10.1016/j.epsl.2019.05.045.

Steckler, M., A. Amato, I. Guerra, J. Armbruster, P. Baccheschi, F. Di Luccio, A. Gervasi, P. Harabaglia, W. Kim, A. Lerner-Lam, L. Margheriti and L. Seeber (2005). Results from CAT/SCAN, the Calabria-Apennine-Tyrrhenian/Subduction-Accretion-Collision Network, AGU Fall Meeting Abstracts.

Subasic, S., S. Prevolnik, D. Herak and M. Herak (2017). Observations of SKS splitting beneath the Central and Southern External Dinarides in the Adria-Eurasia convergence zone, Tectonophysics, 705, 93-100, doi:10.1016/j.tecto.2017.03.027.

Vignaroli, G., C. Faccenna, L. Jolivet, C. Piromallo and F. Rossetti (2008). Subduction polarity reversal at the junction between the Western Alps and the Northern Apennines, Italy, Tectonophys., 450(1-4), 34-50.

Vinnik, L.P., L. I. Makeyeva, A. Milev and Y. Usenko (1992). Global patterns of azimuthal anisotropy and deformation in the continental mantle, Geophys. J. Int., 111, 433-473.

Walther, M., T. Plenefisch and G. Ruempker (2014). Automated analysis of SKS splitting to infer upper mantle anisotropy beneath Germany using more than 20 yr of GRSN and GRF data, Geoph. J. Int., 196, 1207-1236, doi:10.1093/gji/ggt456.

Wüstefeld, A., G. Bokelmann, C. Zaroli and G. Barruol (2008). SplitLab: A shear-wave splitting environment in Matlab, Comput. Geosci. UK, 34(5), 515-528, doi:10.1016/j.cageo.2007.08.002.

Wüstefeld, A., G. H. R. Bokelmann, G. Barruol and J.-P. Montagner (2009). Identifying global seismic anisotropy patterns by correlating shear-wave splitting and surface waves data, Phys. Earth Planet. Int., 176 (3-4), 198-212, doi:10.1016/j.pepi.2009.05.006 (database available online at http://splitting.gm.univ-montp2.fr/).

Zhao, L., A. Paul, M. G. Malusà, X. Xu, T. Zheng, S. Solarino, S. Guillot, S. Schwarz, T. Dumont, S. Salimbeni, C. Aubert, S. Pondrelli, Q. Wang and R. Zhu (2016). Continuity of the Alpine slab unraveled by high-resolution P wave tomography. J. Geophys. Res.: Solid Earth, 121(12), 8720-8737.

Zhao, L., X. Liu, D. Zhao, X. Wang and Q. Qiao (2021). Mapping the Pacific slab edge and toroidal mantle flow beneath Kamchatka, J. Geophys. Res.: Solid Earth, 126(11), e2021JB022518.

Zhu, H., E. Bozdağ and J. Tromp, (2015). Seismic structure of the European upper mantle based on adjoint tomography, Geophys. J. Int., 201, 1, 18-52, https://doi.org/10.1093/gji/ggu492.

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