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## ► To cite this version:

Marco Giovanni Malusà, Stéphane Guillot, Liang Zhao, Anne Paul, Stefano Solarino, et al.. The Deep Structure of the Alps Based on the CIFALPS Seismic Experiment: A Synthesis. *Geochemistry, Geophysics, Geosystems*, 2021, 22 (3), pp.e2020GC009466. 10.1029/2020GC009466 . hal-03196259

**HAL Id: hal-03196259**

**<https://hal.science/hal-03196259v1>**

Submitted on 12 Apr 2021

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## The Deep Structure of the Alps based on the CIFALPS Seismic Experiment: A Synthesis

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### Key Points:

- Summary of the main results of the CIFALPS seismic experiment provides new insights on the deep tectonic structure of the Alpine region
- Application of a wide range of tomographic methods and joint interpretation with geological and petrophysical data
- Interpretive geologic cross sections at the scale of the lithosphere and the upper mantle

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as [doi: 10.1029/2020GC009466](https://doi.org/10.1029/2020GC009466).

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## Abstract

The European Alps are the site where classic geologic concepts such as nappe theory, continental subduction and slab breakoff have been first proposed. However, the deep tectonic structure of the Alps has long been poorly constrained by independent geophysical evidence. This review paper summarizes the main results of the CIFALPS passive seismic experiment, that was launched by Chinese, French and Italian scientists in the 2010s to provide new insights on the deep tectonic structure of the Alpine region. The application of a wide range of tomographic methods to the analysis of a single fossil subduction zone makes the CIFALPS experiment a potential reference case for the analysis of other orogenic belts. Major results include: (i) the first seismic evidence of European continental crust subducted into the Adriatic upper mantle, beneath the place where coesite was first recognized in continental (U)HP rocks in the Alps; (ii) evidence of a major involvement of the mantle wedge during (U)HP rock exhumation; (iii) evidence of a serpentinized plate interface favouring continental subduction; (iv) evidence of a continuous slab beneath the Western and Central Alps, ruling out the classic model of slab breakoff magmatism; (v) evidence of a polyphase development of anisotropic fabrics in the Alpine mantle, either representing active mantle flows or fossil fabrics inherited from previous rifting stages. Detection of these major tectonic features allows to propose interpretive geologic cross sections at the scale of the lithosphere and upper mantle, providing a baseline for future analyses of active continental margins.

## Plain Language Summary

The European Alps are the site where classic geologic concepts such as nappe theory, continental subduction and slab breakoff have been first proposed. However, the deep tectonic structure of the Alps has long been poorly constrained by independent geophysical evidence. This review paper summarizes the main results of the CIFALPS passive seismic experiment, which allows us to propose an updated image of the deep structure of the Alps at the scale of the lithosphere and the upper mantle. The concepts and ideas summarized in this article provide a baseline for further advances in the fields of Alpine tectonics and in the analysis of active continental margins more generally.

## 1 Introduction

The European Alps are one of the best studied orogenic belts in the world, and the site where classic concepts of major relevance for the development of Earth Sciences have been first proposed. Beside the nappe theory (Lugeon 1901; Argand 1911), these include the concept of continental subduction, that was considered as impossible until the discovery of coesite in eclogite-facies rocks of the Dora-Maira massif (Chopin 1984), and the concept of slab breakoff that was first proposed by Davies and von Blanckenburg (1995) to explain the enigmatic Cenozoic magmatism in the Alps and that was subsequently applied to many other orogenic belts worldwide (Garzanti et al. 2018). Despite the relevance of these processes at a broader scale, the deep tectonic structure of the Alps has long been poorly constrained by independent geophysical evidence. The active seismic experiments launched in the 1980s (e.g., Frei et al. 1990; Nicolas et al. 1990b; Roure et al. 1996) even failed to clearly detect the Moho beneath the Internal Alps, and the travel-time tomography models available since the 2000s (e.g., Piromallo and Morelli 2003; Lippitsch et al. 2003) did provide first-order constraints to the deep Alpine structure although they were not invariably consistent.

Within this framework, the aim of the CIFALPS passive seismic experiment, launched in the 2010s through a collaboration among Chinese, French and Italian scientists (Zhao et al. 2016a) was to provide new insights on the deep tectonic structure of the Alpine region, based on recent developments in the fields of seismic data acquisition and tomography model computation, through a full collaboration between geologists and geophysicists. The main geophysical results provided by the CIFALPS experiment have been already published in international journals (Zhao et al. 2015, 2016a, 2020; Lyu et al. 2017; Malusà et al. 2017; Beller et al. 2018; Salimbeni et al. 2018; Solarino et al. 2010; Sun et al. 2019). In this review paper, mainly aimed at a geologic audience, we summarize the main results of the CIFALPS experiment that are discussed within the framework of available geologic and geodynamic constraints to provide an updated image of the deep structure of the Alps at the scale of the lithosphere and the upper mantle. We hope that the concepts and ideas summarized in this article will help provide a baseline for further advances in the fields of Alpine tectonics and in the analysis of active continental margins more generally.

## 2 Tectonic setting

The European Alps are the result of oblique subduction of the Alpine Tethys under the Adriatic microplate since the Late Cretaceous, followed by diachronous continental collision between the Adriatic and European paleomargins during the Cenozoic (e.g., Trümpy 1960; Coward and Dietrich 1989; Dal Piaz 2001; Schmid et al. 2004; Handy et al. 2010; Pfiffner 2014) (Fig. 1a). In the western segment of the orogen, European basement rocks and associated Helvetic-Dauphinois cover sequences that have partly escaped Alpine metamorphism are exposed in the External zone, to the west of the Frontal Pennine Fault (FPF in Fig. 1b) (e.g., Dumont et al. 2011, 2012; Bellahsen et al. 2014). To the east of the Frontal Pennine Fault, the subduction wedge formed atop the European slab is still largely preserved (e.g., Lardeaux et al. 2006; Beltrando et al. 2010) and chiefly includes rocks derived from the Alpine Tethys and the distal European paleomargin (Tricart 1984; Lemoine et al. 1986), the so-called Penninic units (Argand 1911) (shades of blue in Fig. 1b). Rocks derived from the Adriatic paleomargin (brown in Fig. 1b), classically referred to as the Austroalpine-Southalpine units (e.g., Bernoulli et al. 1979; Mohn et al. 2010), are exposed north of the Po Plain on the upper-plate side of the orogen. There, the Ivrea gravity anomaly (Closs and Labrouste 1963) reveals the occurrence of mantle rocks exhumed at shallow depth that may mark the lithospheric necking zone of the southern Tethyan margin (Nicolas et al. 1990a). Eclogitized mantle rocks are exposed in the Lanzo massif to the west of the Insubric Fault (IF in Fig. 1b) (Boudier 1978; Piccardo et al. 2007). South of the Po Plain, the complex transition zone between the Western Alps and the Apennines involves rotated fragments of the Alpine subduction wedge (Maffione et al. 2008; Eva et al. 2015) and is mainly covered by thick Cenozoic sedimentary successions (Rossi et al. 2009; Malusà and Balestrieri 2012).

The subduction wedge of the Western Alps includes two main tectono-metamorphic domains (e.g., Malusà et al. 2011, 2015): (i) an Eocene eclogite belt consisting of (ultra) high pressure - (U)HP continental crust domes of European derivation (DM, GP and MR in Fig. 1b) (e.g., Dal Piaz and Lombardo 1986; Henry et al. 1993) tectonically enveloped by (U)HP metaophiolites (e.g., Lombardo et al. 1978; Schwartz et al. 2000); and (ii) a doubly-vergent Frontal wedge consisting of lower-pressure metamorphic units exposed closer to the European mainland (e.g., Caby 1996; Michard et al. 2004). The (U)HP rocks of the Eclogite belt reached the pressure peak in the late Eocene (e.g., Rubatto and Hermann 2001; Gabudianu Radulescu et al. 2009) and were rapidly exhumed to Earth's surface by the early Oligocene, when they were unconformably

covered by syntectonic sediments still preserved in the Tertiary Piedmont Basin (Federico et al. 2004; Malusà et al. 2015) (Fig. 1b). Quartz-eclogite assemblages prevail, but rock slivers with coesite-eclogite assemblages are found in the Dora-Maira dome (Chopin et al. 1991; Groppo et al. 2019) and on top of the Monte Rosa dome (Reinecke 1991; Lapen et al. 2003). The lower-pressure metamorphic units of the Frontal wedge include blueschist-to-(sub)greenschist facies cover sequences and basement slivers that underwent subduction starting from the Paleocene, and were later exhumed in the Eocene - early Oligocene (e.g., Agard et al., 2002; Ganne et al. 2007; Lanari et al. 2014). Different tectonostratigraphic domains are exposed in different segments of the Frontal wedge, likely reflecting the obliquity of the Alpine trench relative to the European paleomargin. In the northern part of the Western Alps, the Frontal wedge includes Valaisan metasediments with minor metaophiolites and upper Paleozoic continental metaclastics (Bertrand et al. 1998; Masson et al. 2008; Polino et al. 2012), juxtaposed against Briançonnais (Br in Fig. 1b) basement units in the rear part of the wedge (Malusà et al. 2005; Bergomi et al. 2017). In the southern part of the Western Alps, the Frontal wedge includes turbidites and Briançonnais cover sequences (Kerckhove 1969; Barfety et al. 1996) juxtaposed against the oceanic metasediments of the Schistes lustrés (SL in Fig. 1b) (Polino and Lemoine 1984; Agard et al. 2002; Schwartz et al. 2009). Progressively more distal facies are thus accreted in the Frontal wedge moving from the North toward the South, but the effects of oblique subduction are also observed in the Eclogite belt, where the relative amount of oceanic crust comprised within the eclogitic tectonic domes increases towards the south and is dominant in the Voltri massif (Forcella et al. 1973; Capponi and Crispini 2002). The well preserved domal shape of the Dora-Maira and Gran Paradiso massifs (Fig. 1b) suggests only minor late-stage indentation of the Adriatic upper plate beneath the southern segments of the Alpine subduction wedge, whereas farther north the Monte Rosa dome is evidently backfolded (Keller et al. 2005), and the Adriatic lower crust has been deeply indented beneath the Lepontine dome during the latest stages of hard continent-continent collision (Pfiffner et al. 2002; Liao et al. 2018a).

### 3 State of knowledge before the CIFALPS experiment

Since the pioneering studies of Dolomieu (1791), Kilian and Revil (1903), Lugeon (1901, 1902) and Argand (1911, 1916), the reconstruction of the deep tectonic structure of the Alps has long been based on field geology data, including the vergence of regional folds (e.g., Ramsay 1963; Milnes 1974) and the polarity of metamorphic field gradients (e.g., Ernst 1971, 1973). Following this approach, the occurrence of higher-pressure rocks towards the Po Plain (e.g., Bocquet 1971; Frey et al. 1974) and the first radiometric constraints to the age of Alpine metamorphism (e.g., Ferrara et al. 1962; Bocquet et al. 1974) have generally suggested an Alpine evolution driven by European subduction beneath Adria, and a progressive deformation propagation towards the European foreland (e.g., Martini 1972; Dewey et al. 1973; Laubscher 1974; Hawkesworth et al. 1975). However, based on the same data sets, alternative interpretations invoking Adriatic subduction were also proposed (e.g., Oxburg 1972; Caby 1975).

Starting from the 1980s, independent constraints to the deep structure of the Alps were provided by active seismic experiments launched in the Western and the Central Alps. They include the joint French-Italian ECORS-CROP experiment across the northern Western Alps (Nicolas et al. 1990b; Roure et al. 1996) and the NFP-20 research program in the Swiss Alps (Frei et al. 1990) (see locations in Fig. 1b). The ECORS-CROP vertical seismic reflection profile (Fig. 2a) has successfully imaged the SE-dipping European lower crust beneath the European foreland (ELC in Fig. 2a), the SE-dipping Frontal Pennine Fault (FPF in Fig. 2a), the top of the Adriatic

mantle beneath the Ivrea gravity anomaly (AM in Fig. 2a) and the Po Plain basin fill (Nicolas et al. 1990b). However, it failed to image the European Moho beneath the Alpine subduction wedge, as underlined by the question mark in Fig. 2a. Additional constraints indicating European subduction beneath Adria were anyway provided by a complementary wide-angle reflection profile (Thouvenot et al. 1990) showing SE-dipping Moho-like surfaces beneath the frontal part of the Alpine metamorphic wedge and beneath the Gran Paradiso dome (Fig. 2b). A migrated ECORS-CROP vertical seismic reflection profile (Fig. 2c) was later reinterpreted by Schmid and Kissling (2000), who suggested that the strong reflectors at ~20 km depth beneath the Gran Paradiso would mark the top of a slice of European lower crust (ELC in Fig. 2c), rather than the top of a mantle slice as originally proposed by Nicolas et al. (1990a) and Polino et al. (1990) (Fig. 2a). According to Schmid and Kissling (2000), the reflectors located at 10-15 km depth beneath the Gran Paradiso would mark the suture zone of the Valaisan ocean, a controversial paleogeographic feature (e.g. Stampfli et al. 2002; Masson et al. 2008) potentially documented only in the Central Alps and in the northernmost Western Alps (Liati and Froitzheim 2006). Information provided by the NFP-20 West profile (Frei et al. 1990) is even more limited. In fact, this profile (in green in Fig. 1b) is limited to the frontal part of the Alpine subduction wedge and to the nearby External zone. The classic geologic cross sections proposed by Schmid et al. (2004) along the ECORS-CROP and NFP-20 traverses, which are shown in Figs. 2d and 2f, are thus constrained only to a limited extent by geophysical data (the masked areas in Figs. 2d and 2f indicate regions not constrained by vertical reflection seismic data). In the absence of further independent constraints, these cross sections have reproduced the nappe structure proposed by Argand (1911) (Fig. 2e), which was conceived well before the advent of plate tectonics.

Since the late 1990s, independent geophysical constraints on the deep Alpine structure were also provided for the southern Western Alps (Tardy et al. 1999) thanks to the GeoFrance 3D project (Groupe de Recherche Géofrance 3D 1997). A local earthquake tomography model (Paul et al. 2001) was able to resolve the deep tectonic structure beneath the Dora-Maira down to depths of 15-20 km (Fig. 2g), leading to the detection of mantle rocks at depths as shallow as ~10 km (AM in Fig. 2g) and to a geologic interpretation (Lardeaux et al. 2006) that was still largely based on field geology data (right panel in Fig. 2g). Geologic cross sections of the southern Western Alps were also presented by Schmid et al. (2017), who suggested an East-vergent backfold at the scale of the entire Eclogite belt and the occurrence, beneath the Dora-Maira massif, of Briançonnais crust slivers down to depths >30 km (see Schmid et al. 2017, their Fig. 2). However, the Dora-Maira dome shows no cartographic evidence for such a backfold (Figs. 1b, 2g), and the Schmid et al. (2017)'s interpretation was not consistent with seismic velocity constraints provided by the GeoFrance 3D experiment (Paul et al. 2001).

Starting from the 2000s, travel-time tomography studies (e.g., Piromallo and Morelli 2003; Lippitsch et al. 2003; Giacomuzzi et al. 2011) have provided further constraints on the deep structure of the Alpine region, revealing high-velocity anomalies in the Alpine upper mantle (Fig. 3a, b) that were readily interpreted as traces of subducting slabs (e.g., Piromallo and Faccenna 2004; Spakman and Wortel 2004; Kissling et al. 2006). However, some of these models showed high-velocity anomalies in areas where no slab was expected based on geologic evidence (e.g., the Provençal margin of SE France, see Fig. 3a), and different models were not invariably consistent. For example, Piromallo and Morelli (2003) imaged a continuous high-velocity anomaly beneath the Western Alps (cross section A-A' in Fig. 3a) at the very same location where Lippitsch et al. (2003) proposed a shallow slab breakoff (cross section C-C' in Fig. 3b). The identification of a possibly missing section of the Alpine slab beneath the Central Alps (B-B' and D-D' in Fig. 3)

was held to be supportive of the slab-breakoff model first proposed by [Davies and von Blanckenburg \(1995\)](#), which was conceived to explain Alpine magmatism and exhumation of high-pressure rocks. Despite geophysical evidence was not unequivocal, the slab-breakoff model has been applied to the Alps by several studies since then ([Fig. 3c](#)). However, unlike the original formulation of [von Blanckenburg and Davies \(1995\)](#) who suggested an Eocene slab breakoff ([Fig. 3c](#)), most subsequent authors have either proposed an Oligocene slab breakoff (e.g., [Schmid et al. 1996](#); [Bistacchi et al. 2001](#); [Schlunegger and Kissling 2015](#); [Schlunegger and Castellort 2016](#)) or an even younger Pliocene-Quaternary breakoff event (e.g., [Sue et al. 1999](#); [Fox et al. 2015](#); [Kästle et al. 2020](#)), even though no orogenic magmatism and no exhumation event occurred at that time in the Alps.

#### 4 The CIFALPS experiment

The CIFALPS experiment ([Zhao et al. 2016a](#)) is the first passive seismic survey that crosscuts the entire Western Alps across the Dora Maira massif. It involves scientists and institutions from China, Italy and France. Geophysicists and geologists have worked side by side during the project, starting from the early steps of the experiment set up to the final steps of geologic interpretation. The temporary seismic network includes 46 broadband seismic stations operating from July 2012 to September 2013, deployed along a linear WSW-ESE transect from the European foreland to the western Po Plain, and 9 additional stations installed to the north and to the south of the main profile (red yellow-filled dots in [Fig. 1b](#)). Stations located along the main profile, which was chiefly conceived for receiver function analysis ([Zhao et al. 2015](#)), have spacing ranging from ~5 km in the Alpine mountain range to ~10 km in the European foreland and the western Po Plain. Off-profile stations were installed to improve the crossing of seismic rays for local earthquake tomography ([Solarino et al. 2018](#)) and to build mini-arrays for surface wave tomography ([Lyu et al. 2017](#)). Some of the analyses performed during the CIFALPS experiment (e.g., [Zhao et al. 2016b, 2020](#); [Lyu et al. 2017](#); [Sun et al. 2019](#)) also exploited data sets from permanent broadband networks and benefitted from the recent opening of the European seismic databases. A dataset of anomalously deep earthquakes (purple circles in [Fig. 1b](#)) recorded in the western Po Plain during the past 25 years ([Eva et al. 2015](#)) was extremely useful to extend local earthquake tomography analysis towards greater depths and analyze the seismic anisotropy in the crust and the lithospheric mantle.

Most of the analyses presented in this summary work have been published in international journals. The reader is referred to the original publications (see [Table 1](#)) for a more detailed discussion of the procedures followed for the different types of tomography models and for an estimate of their resolution. Different tomographic methods allow to illuminate different levels of the crust and the mantle, and at different locations with respect to the Alpine slab ([Table 1](#)). It should be remembered that a tomographic model is not a true image of the Earth subsurface. It shows the projection of a data set onto a model space controlled by simplifying assumptions. Its accuracy is limited by the seismic data availability and quality, the type of wave used, and the assumptions made. Moreover, solutions are not unique. For example, in teleseismic body wave tomography the ray geometry tends to induce vertical smearing, whereas in surface wave tomography the accuracy of the model degrades with depth. Imaging the Alpine subduction system requires the integration of different tomographic methods through interpretive steps that should avoid any over-interpretations of observed features. A close collaboration between geophysicists and geologists is thus particularly important. The series of independent tomographies presented in this summary paper, despite their numerous limitations, converge towards a coherent geologic

model, which attests to the robustness of our geologic interpretation of the deep structure of the Alps. The application of a wide range of tomographic methods to the analysis of a single fossil subduction zone (Table 1) makes the CIFALPS experiment a reference case that could be exported to other orogenic belts.

## 5 Seismic velocities of rocks involved in the Alpine orogeny

The geologic interpretation of geophysical information provided by the CIFALPS experiment requires independent knowledge of seismic velocities of rocks possibly involved in the Alpine subduction zone. Various proportions of serpentinized mantle, basalts and sedimentary rocks were subducted at the Alpine trench since the Cretaceous during the oceanic subduction stage (Dal Piaz and Ernst 1978; Deville et al. 1992; Agard et al. 2009; Guillot et al. 2009a). Due to the low spreading rates characterizing the Alpine Tethys in the Jurassic, exhumed mantle rocks were dominant on the Tethys seafloor compared to pillow basalts (Lagabrielle and Cannat 1990; Lagabrielle and Lemoine 1997; Manatschal 2004; Piccardo 2003). Rocks from the Tethys seafloor were initially subducted together with slivers of granitic and (meta)sedimentary rocks from the hyperextended Adriatic paleomargin (Rubatto et al. 1998; Thöni 2006; Zanchetta et al. 2012), whereas granitic and (meta)sedimentary rocks from the European paleomargin were later involved in the subduction zone during the main stage of continental subduction in the Paleogene (Rubatto and Hermann 2001; Malusà et al. 2011; Lanari et al. 2012).

P-wave and S-wave velocities for all of these lithologies are provided by several laboratory experiments (e.g., Bezacier et al. 2010, 2013; Ji et al. 2013, 2015; Kern et al. 2002; Khazanehdari et al. 2000; Pera et al. 2003; Reynard 2013; Rudnick and Fountain 1995; Watanabe et al. 2011; Weiss et al. 1999) and are summarized in the diagrams of Fig. 4. The ellipse size in these diagrams is proportional to the maximum and minimum seismic velocities. The ellipse location depends on the pressure-temperature range at equilibrium for each rock type. As shown in Fig. 4, for a given bulk composition, rocks generally display a progressive increase in P and S velocities with depth (i.e., pressure) and metamorphic grade (i.e., temperature). For a specific rock type, the effects of increasing pressure with depth, which would imply an increase in seismic velocity, are partly compensated by the effects of increasing temperature that would conversely imply a seismic velocity decrease. As a result, for a given bulk composition (indicated by ellipses of the same color) major changes in  $V_p$  and  $V_s$  are mainly due to changes in metamorphic mineral assemblages with depth. For example,  $V_p$  values in metapelites (brown in Fig. 4) progressively increase, according to laboratory experiments from 5.6-6.4 km s<sup>-1</sup> in low-grade metapelites to 6.5-6.7 km s<sup>-1</sup> in medium-grade metapelites, reaching values as high as 7.2 km s<sup>-1</sup> in high-grade metapelites with minor variability depending on rock composition (Ji et al. 2015; Khazanehdari et al. 2000; Weiss et al. 1999). In the same rocks,  $V_s$  values progressively increase from 3.3-3.8 km s<sup>-1</sup> in low-grade metapelites (Ji et al. 2015) to 3.8-4.1 km s<sup>-1</sup> in high-grade metapelites (Khazanehdari et al. 2000; Weiss et al. 1999). A similar progressive increase in seismic velocity with depth is also observed in mafic (blue in Fig. 4) and granitic (purple in Fig. 4) rocks.

In fully hydrated ultramafic rocks (green in Fig. 4), measured  $V_p$  values increase from 4.5-6.0 km s<sup>-1</sup> in low-temperature lizardite serpentinite to 6.3-7.0 km s<sup>-1</sup> in high-temperature antigorite serpentinite (Bezacier et al. 2013; Ji et al. 2013). In the same rocks,  $V_s$  values increase from 2.4-3.0 km s<sup>-1</sup> in lizardite serpentinite to 3.4-3.8 km s<sup>-1</sup> in antigorite serpentinite, but  $V_s$  as low as 3.2 km s<sup>-1</sup> can be observed in antigorite mylonites (Watanabe et al. 2011). A sharp change in seismic velocities towards values that are typical of peridotite ( $V_p=7.7-9.0$  km s<sup>-1</sup>,  $V_s = 4.4-5.1$  km s<sup>-1</sup>)



(Bezacier et al. 2010; Khazanehdari et al. 2000; Pera et al. 2003) is expected across the antigorite-out curve (Hilaret et al. 2006). In partly serpentinized peridotites (inset of Fig. 4),  $V_p$  values linearly increase for decreasing volume fractions of antigorite (Reynard 2013). Correlation between seismic velocities and lithology is particularly challenging in subduction wedges, former subduction channels and the nearby upper mantle, because subducted rocks are generally heterogeneous and display anisotropic fabrics and velocity variations as a function of direction (e.g., Bezacier et al. 2013; Rudnick and Fountain 1995; Weiss et al. 1999), and  $V_s$  values are strongly reduced in the presence of fractures, fluids or partial melts. As demonstrated by laboratory studies (e.g., Yoshino et al. 2007), if melt completely wets grain boundaries, even a small amount of melt (e.g., 1%) can produce remarkable velocity drops of 20–30% (Karato 2010; Malusà et al. 2018).

## 6 Seismic evidence of continental subduction in the Western Alps

### 6.1 Moho imaging by receiver function analysis

The first output of the CIFALPS experiment (Zhao et al. 2015) is based on the application of the receiver function (RF) technique (Fig. 5). The RF technique exploits the P-to-S ( $P_s$ ) conversion of seismic waves at velocity interfaces beneath an array of seismic stations (Langston 1979; Ligorria and Ammon 1999). It allows detection of interfaces with downward velocity increase, for example the Moho, and interfaces with downward velocity decrease possibly expected within a subduction wedge, because the polarity of the converted signal depends on the sign of the velocity change. In the Western Alps, application of the RF approach to teleseismic earthquakes (Zhao et al. 2015) has provided the first seismic evidence of European crust subducted into the Adriatic upper mantle, right beneath the place where coesite was first recognized in continental (U)HP rocks by Chopin (1984).

The RF image of Fig. 5a is based on teleseismic events with ENE back-azimuths and magnitude  $M_w \geq 5.5$  (the location of events is shown in Fig. 5c). In order to produce a depth image beneath the CIFALPS transect, Zhao et al. (2015) migrated the time data to depth and stacked the radial receiver functions using the common conversion point method (Zhu 2000). The resulting image shows two main velocity interfaces marked by positive-polarity  $P_s$ -conversions (red-to-yellow regions in Fig. 5a), corresponding to downward velocity increase at the European and Adriatic Mohos (thick dashed lines 1 and 2 in Fig. 5a), and a main blue spot of negative-polarity  $P_s$ -conversions located beneath the Dora-Maira (3 in Fig. 5a).

The eastward-dipping European Moho (1 in Fig. 5a) can be recognized in the RF image from ~40 km depth beneath the Frontal Pennine Fault (FPF in Fig. 5a) to ~75 km depth beneath the Po Plain. In the European foreland, the velocity interface marked by positive-polarity  $P_s$ -conversions is located at ~30–40 km depth and is clearly connected with the European Moho imaged by previous work (e.g., Thouvenot et al. 2007). According to Zhao et al. (2015), the eastward weakening of this converted phase beneath the Alpine subduction wedge, as highlighted by the progressive change in color from red to yellow in Fig. 5a, may be due to eclogitization of the European lower crust at depth >40 km, and consequent reduction of the density (and velocity) contrast with the underlying lithospheric mantle.

The Adriatic Moho (2 in Fig. 5a) can be recognized in the RF image from 10–15 km depth, to the West, to 20–30 km depth to the East, where it is connected with the Adriatic Moho imaged beneath the Po Plain by independent studies (e.g., Molinari et al. 2015). In the westernmost Po

Plain, this velocity interface coincides with the top of the so-called “Ivrea body” (Closs and Labrouste 1963), classically interpreted as a slice of Adriatic upper mantle (Nicolas et al. 1990a; Kissling 1993; Paul et al. 2001; Scafidi et al. 2009) exhumed at shallow crustal depth during Tethyan rifting (Manatschal and Bernoulli 1999; Malusà et al. 2015).

The main spot of negative-polarity Ps-conversions (3 in Fig. 5a) is located between 20 and 40 km depth beneath the Dora-Maira massif. It likely marks a downward velocity decrease from mantle rocks to (U)HP rock slivers and/or associated serpentinites of the suture zone (Zhao et al. 2015; Malusà et al. 2017). The hypothesis of dominant (U)HP continental slivers would be consistent with the predictions of numerical models of synconvergent exhumation (e.g., Jamieson and Beaumont 2013), whereas the hypothesis of dominant serpentinites would be in line with the predictions of numerical models of exhumation triggered by divergence between upper plate and accretionary wedge (e.g., Liao et al. 2018b), which are more consistent with the geologic record available for the Western Alps (Malusà et al. 2011, 2015). Constraints provided by RF allowed to define preliminary two-dimensional models of layer boundaries and velocity contrasts along the CIFALPS profile, which were tested by Zhao et al. (2015) for compatibility with available Bouguer anomaly data by gravity modelling (Fig. 5d). However, Zhao et al. (2015) could not assess the relative proportion of serpentinites and (U)HP rock slivers in the region marked by negative polarity conversions. Such evaluation requires absolute Vp and Vs constraints that were provided, at a later stage of the CIFALPS project, by local earthquake tomography (Solarino et al. 2018) and TransD inversion of surface-wave data (Zhao et al. 2020) as described in Sect. 7.

## 6.2 Moho imaging by other tomographic methods

Breakthroughs provided by RF analysis using teleseismic events have been subsequently confirmed, along the CIFALPS transect, by different seismic data sets and tomographic methods (Fig. 5b). These methods include: (i) tomography from ambient seismic noise (Lu et al. 2018); (ii) local earthquake tomography (Solarino et al. 2018); (iii) tomography from teleseismic full-waveform inversion (Beller et al. 2018); and (iv) tomography from Bayesian transdimensional inversion of Rayleigh wave group velocity dispersion data (Zhao et al. 2020).

Ambient noise tomography (ANT) is particularly efficient to image the velocity structure of the crust and uppermost mantle, provided that continuous noise records are available at dense arrays of seismic stations (Shapiro et al. 2005). Rayleigh waves between stations can be reconstructed from the cross-correlation of recorded seismic noise, basically turning each station to a source of seismic waves (e.g., Campillo and Paul 2003; Larose et al. 2006). In the Alpine region, Lu et al. (2018) used noise correlations to compute Rayleigh wave phase and group velocity and derive a high-resolution 3-D S-wave velocity model. Their dispersion dataset took advantage of the large number of seismic stations in Europe, particularly the great Alpine region with the high-density CIFALPS (Zhao et al. 2016a) and AlpArray (Hetényi et al. 2018) temporary experiments. The depth to the European Moho estimated from ANT beneath the Frontal Pennine Fault and surroundings (green line in Fig. 5b) (Lu et al. 2018) is in good agreement with the Moho depth estimated from RF. At the western end of the profile, the ANT Moho beneath the Southeast Basin is shallower than the RF Moho by 5–8 km, which could be due to an inappropriate velocity model for the migration of RF. Beneath the Po Plain, and on top of the Ivrea body, the Adriatic Moho estimated from ANT correlates well with the RF Moho (Fig. 5b).

Moho constraints are also provided by local earthquake tomography (LET). The LET method is based on the analysis of earthquakes within the model volume (Kissling 1988). The maximum

depth of the resolved model is thus limited by the depth of occurrence of the deepest seismic events. The investigated volume needs to be adequately sampled by a dense set of crossing rays, depending on the distribution of both earthquakes and receivers, in order to resolve the inherent trade-off between variations in velocity structure and hypocentre locations. Along the CIFALPS transect, the P-wave velocity structure provided by LET can be locally resolved down to 50-60 km depth (Solarino et al. 2018) using the anomalously deep earthquakes recorded in the western Po Plain (Eva et al. 2015; Malusà et al. 2017). The Adriatic Moho estimated from LET beneath the Po Plain and on top of the Ivrea body (thick grey line in Fig. 5b) confirms the results of RF analysis, providing an even more reliable estimate of Moho depth compared to previous results based on RF alone (see Sect. 7.1 for more details). Only part of the European Moho, i.e., the part located beneath the External Zone, lays within the resolved LET model volume. There, the LET Moho confirms the location of the RF Moho as revealed by analysis of teleseismic events (Solarino et al. 2018).

A further independent image of the European Moho along the CIFALPS transect is based on full-waveform inversion (FWI) of selected teleseismic events recorded during the CIFALPS experiment (Beller et al. 2018). By FWI is meant the inversion of the full seismogram including phase and amplitude effects, within a time window following the first arrival up to a frequency of 0.2 Hz. Based on FWI, Beller et al. (2018) built 3-D models of density and P- and S-wave velocities, and detected the European Moho (blue line in Fig. 5b) at depths ranging from ~30 km beneath the Southeast Basin to ~65 km beneath the Dora-Maira massif, which confirms previous results based on RF.

A more recent Moho image along the CIFALPS transect is based on a Bayesian transdimensional (TransD) inversion of the Rayleigh wave group velocity dispersion data of Lu et al. (2018), as performed by Zhao et al. (2020) according to the procedure described in Bodin et al. (2014) and Yuan and Bodin (2018). TransD inversion provides absolute S-wave velocity information and treats the model parameterization (e.g., the number of velocity layers) as an unknown in the inversion to be determined by the data, thus yielding more robust velocity amplitude estimates (Bodin et al. 2012a, b). The resulting image presented by Zhao et al. (2020) provides compelling evidence of European continental-crust subduction into the Adriatic upper mantle (see Sect. 7.2 for more details), thus confirming the main findings of RF analysis. The eastward-dipping TransD European Moho (red line in Fig. 5b) is located at ~30 km depth beneath the Southeast Basin, getting progressively deeper from ~45 km depth beneath the Frontal Pennine Fault to ~75 km depth beneath the Dora-Maira massif. On the eastern side of the CIFALPS transect, the TransD Moho overlaps with the Adriatic Moho as imaged by RF, ANT and LET (Fig. 5b).

## 7 Absolute velocity structure of the crust and the mantle wedge

A more detailed geologic interpretation of the crustal structure along the CIFALPS transect requires absolute P-wave and S-wave velocity constraints. These constraints are provided by LET (Solarino et al. 2018) and TransD inversion of Rayleigh wave dispersion data (Zhao et al. 2020) and are illustrated below.

### 7.1 Absolute P-wave velocity structure from LET

The absolute P-wave velocity structure revealed by LET in the southern Western Alps (Solarino et al. 2018) is shown in Fig. 6. In order to improve ray crossing (Fig. 6a) and better

constrain the bottom part of the study volume, Solarino et al. (2018) have integrated recordings of the CIFALPS stations with recordings of permanent stations operating during the CIFALPS experiment, and have also considered the intermediate depth earthquakes that occurred before the experiment (Eva et al. 2015). The well-resolved regions of the resulting LET model include the European crust to the west, the Adriatic crust and uppermost Adriatic mantle to the east, and the Alpine subduction wedge (Solarino et al. 2018) (Fig. 6 b, c).

The European upper crust (EUC in Fig. 6c) shows  $V_p$  values  $<6.4 \text{ km s}^{-1}$  and rather constant  $V_p/V_s$  ratios  $\sim 1.70 \pm 0.02$ , consistent with a mainly granitic continental crust (cf. Fig. 4).  $V_p$  values increase in the European lower crust (ELC in Fig. 6c) from  $V_p \sim 6.7 \text{ km s}^{-1}$ , at depth of  $\sim 25 \text{ km}$ , to  $V_p \sim 7.6 \text{ km s}^{-1}$  at depth  $> 40 \text{ km}$  (i.e., beneath the Alpine subduction wedge), under rather constant  $V_p/V_s$  ratios of 1.70-1.72. The observed velocity structure suggests a relatively homogeneous lower crust at the scale of seismic observations along the CIFALPS profile.  $V_p$  values  $\sim 6.7 \text{ km s}^{-1}$  in the lower crust are consistent with granulitic rocks of felsic to intermediate compositions (Rudnick and Fountain 1995; Weiss et al. 1999; Goffé et al. 2003; Wang et al. 2005; Mechie et al. 2012). Major occurrence of granulitic metapelites can be excluded in the light of their higher P-wave velocities (up to  $7.2 \text{ km s}^{-1}$ ; see Fig. 4), which is not observed in the western part of the CIFALPS profile. The progressive increase in P-wave velocities at depth  $> 40 \text{ km}$  may mirror the progressive eclogitization of the European lower crust (Solarino et al. 2018), as eclogitization of a felsic granulite strongly increases the garnet content and consequently the rock density (from  $2.90$  to  $3.30 \cdot 10^3 \text{ kg m}^{-3}$ ) and P-wave velocity (up to  $7.6 \text{ km s}^{-1}$ ) (e.g., Christensen 1989; De Paoli et al. 2012; Hacker et al. 2003, 2015; Hacker and Abers 2004; Hetényi et al. 2007). Alternatively, the increase in P-wave velocity in the European lower crust may indicate an increase in mafic component beneath the Alpine subduction wedge. However,  $V_p$  values provided by LET are far too low for a pure mafic eclogite ( $7.9$  to  $8.7 \text{ km s}^{-1}$ ; Bezacier et al. 2010; Reynard 2013) (Fig. 4). Zhao et al. (2015) and Solarino et al. (2018) have thus favoured the hypothesis of a progressive change in metamorphic assemblages during continental subduction rather than a change in bulk composition from west to east. The progressive P-wave velocity increase in the European lower crust at depth  $> 40 \text{ km}$ , as documented by LET, provides an explanation for the eastward weakening of RF converted phases along the European Moho described by Zhao et al. (2015) (see Fig. 6d).

On the eastern side of the CIFALPS transect, the LET model shows a sharp downward P-wave velocity increase across the Adriatic Moho (thick dashed line 2 in Fig. 6c). Above the Adriatic Moho, the Adriatic upper crust (AUC in Fig. 6c) shows  $V_p$  values  $<6.4 \text{ km s}^{-1}$  and  $V_p/V_s$  ratios  $\sim 1.70$ - $1.74$ . The Adriatic lower crust (ALC in Fig. 6c) shows a more complex velocity structure than the European lower crust, likely reflecting a more heterogeneous composition at the scale of seismic observations. Local spots with  $V_p \sim 7.2 \text{ km s}^{-1}$  and low  $V_p/V_s$  ratios may suggest, according to Solarino et al. (2018), local occurrences of granulite-facies metapelites ( $V_p=6.3$ - $7.2 \text{ km s}^{-1}$ ,  $V_s=3.8$ - $4.1 \text{ km s}^{-1}$ ; Weiss et al. 1999; Khazenedari et al. 2000). North of the Po Plain, similar granulite facies metapelites are also exposed at Earth's surface (e.g., Ewing et al. 2014). In the region labelled as  $ALC_1$  (Fig. 6c), the locally high  $V_p/V_s$  ratios  $>1.8$  associated to  $V_p \sim 7.0$ - $7.3 \text{ km s}^{-1}$  may be interpreted as gabbro underplated at the base of the Adriatic lower crust. Permian gabbros are indeed exposed at Earth's surface north of the Po Plain, and intrude lower crustal rocks belonging to the Adriatic (Southalpine) basement (Quick et al. 1994; Schaltegger and Brack 2007). Below the Adriatic Moho, seismic velocities provided by LET are consistent with dry to partly serpentinized peridotites of the Adriatic lithospheric mantle (AM in Fig. 6c), as indicated by  $V_p$  values  $\sim 7.5$ - $8.0 \text{ km s}^{-1}$  and  $V_p/V_s$  ratios  $\sim 1.70$ - $1.72$ . Peridotites are found at depth  $> 30 \text{ km}$  beneath the Monferrato, and at much shallower depth ( $10$ - $15 \text{ km}$ ) in correspondence with the Ivrea positive

gravity anomaly, in line with results of previous tomography models (Solarino et al. 1997; Paul et al. 2001; Scafidi et al. 2006, 2009; Diehl et al. 2009; Wagner et al. 2012).

In the central part of the CIFALPS transect, the uppermost part of the Alpine subduction wedge shows  $V_p$  values invariably  $<6.5 \text{ km s}^{-1}$  (Fig. 6c). The structural variability in this region is mirrored by the variability in  $V_p/V_s$  ratios.  $V_p/V_s > 1.75$  in the Briançonnais and Schistes Lustrés units likely reflect low S-wave velocities resulting from a widespread network of mesoscale faults developed in these units during the Neogene (Sue et al. 2007; Malusà et al. 2009). In the western flank of the Dora-Maira massif,  $V_p/V_s < 1.66$  likely reflect high S-wave velocities, possibly due to the presence of poorly fractured granitic gneisses that are also exposed at Earth's surface (Brossasco granite; Paquette et al. 1999; Lenze and Stöckhert 2007). A prominent feature highlighted by the LET model in this part of the transect is the high velocity body ( $V_p \sim 7.5 \text{ km s}^{-1}$ ,  $V_p/V_s = 1.70\text{-}1.72$ ) imaged at depths from  $\sim 10 \text{ km}$  to  $>30 \text{ km}$  (MW in Fig. 6b, c). This body is exclusively found beneath the Dora-Maira massif, as highlighted by the N-S cross-section of Fig. 6b. It was already imaged with similar velocities by previous work ( $V_p \sim 7.4\text{-}7.7 \text{ km s}^{-1}$ ; Paul et al. 2001; Béthoux et al. 2007) but was only resolved down to depths of 15-20 km (cf. Fig. 2g). Its P-wave velocity is not consistent with dry mantle peridotite or imbricated continental crust rocks as suggested for example by Schmid et al. (2017). Instead, it suggests mantle rocks with variable degrees of serpentinization (Reynard 2013) ranging from  $<30\%$ , at depth greater than 30 km, to  $>90\%$  in the uppermost part of the body (see Fig. 4). According to Solarino et al. (2018), this high velocity body may include mantle-wedge rocks exhumed in the late Eocene together with the (U)HP rocks of the Dora-Maira massif, as a result of divergent motion between the Alpine slab and the Adriatic upper plate (Malusà et al. 2011; Liao et al. 2018b). In the southern Western Alps, these mantle-wedge rocks may contribute, together with the Adriatic mantle rocks exhumed during Tethyan rifting, to the positive gravity anomaly classically referred to as the Ivrea gravity anomaly due to the high-density "Ivrea body" (Closs and Labrouste 1963; Nicolas et al. 1990a) (see Fig. 5d).

The bottom part of the LET model of Solarino et al. (2018) provides absolute P-wave velocity constraints to the uppermost part of the Alpine subduction channel (SC in Fig. 6c). At depth  $\sim 50 \text{ km}$ , in the region located beneath the thick blue spot of RF negative polarity conversions (3 in Fig. 6c), P-wave velocity is lower than in the nearby Adriatic upper mantle ( $\sim 7.0\text{-}7.5 \text{ km s}^{-1}$  vs  $\sim 8.0 \text{ km s}^{-1}$ ). This region may include serpentinites or other lithologies possibly found in a high-pressure mélange zone (Marschall and Schumacher 2012), such as eclogitic metasediments and mafic eclogites. However, the observed velocities ( $V_p \sim 7.0\text{-}7.5 \text{ km s}^{-1}$ ;  $V_p/V_s < 1.70$ ) are consistent with ultramafic rocks with a degree of serpentinization ranging between 50% and 75% (according to Reynard 2013), but they are neither consistent with eclogitic metasediments ( $V_p \sim 7.0 \text{ km s}^{-1}$ ;  $V_p/V_s \sim 1.75$ ) nor with mafic eclogite ( $V_p > 7.9$ ;  $V_p/V_s \sim 1.73$ ) (Weiss et al. 1999; Reynard 2013).  $V_p/V_s$  ratios  $\sim 1.74$  indicate that slivers of eclogitic metasediments could be present instead at  $\sim 40 \text{ km}$  depth beneath the western flank of the Dora-Maira massif.

In general terms, velocity changes evidenced by LET (Solarino et al. 2018) match with those highlighted by RF analysis (Zhao et al. 2015), despite the different techniques and datasets used (i.e., local vs teleseismic events). Not only do the European and Adriatic Mohos detected by these different techniques show a remarkable fit (see Sect. 6.2), but also the downward velocity decrease revealed by LET from the exhumed mantle wedge to the underlying subduction channel is consistent with the spot of negative-polarity Ps-conversions provided by RF (3 in 6c). A good match is also observed for local anomalies, e.g., the high  $V_p/V_s$  ratios in region ALC<sub>1</sub> (Fig. 6c)

corresponding to a major break in the alignment of positive-polarity Ps-conversions in the RF image (Fig. 6d).

The shape of the high-velocity region corresponding to the exhumed mantle wedge is mirrored by the distribution of seismic events (Fig. 6d) (Eva et al. 2015; Malusà et al. 2017). The exhumed mantle wedge is virtually aseismic, consistent with the fact that serpentinization promotes aseismic deformation (Peacock and Hyndman 1999; Hilairet et al. 2007). Earthquakes are mainly located in the surrounding regions. To the east, the anomalously deep earthquakes ( $30 < Z < 75$  km) recorded beneath the western Po Plain (Cattaneo et al. 1999; Eva et al. 2015) are aligned along an active lithospheric strike-slip fault referred to as the Rivoli-Marene deep fault (RMF in Fig. 6d). Results provided by LET confirm that this left-lateral fault (see focal mechanisms in Fig. 6d) is located in the mantle beneath the Adriatic Moho, as first proposed by Malusà et al. (2017) based on RF results.  $V_p/V_s$  values  $>1.74$ , beside  $V_p \sim 8.0$  km s<sup>-1</sup> at depth around 25-35 km (Fig. 6c) may reflect low S-wave velocities due to the impact of the Rivoli-Marene deep fault on the fabric of Adriatic-mantle peridotite (Solarino et al. 2018). In the same region, the azimuthal harmonic decomposition of RF reveals the occurrence of anisotropic rocks (Piana Agostinetti et al. 2017) (Fig. 6d). High-amplitude anisotropic components of RF are observed in places also within the Adriatic crust and along the Adriatic Moho.

### 7.2 Absolute S-wave velocity structure from TransD inversion

The shear wave velocity model of the Western Alps based on TransD inversion of Rayleigh wave group velocity dispersion data (Zhao et al. 2020) is shown in Fig. 7. It provides absolute  $V_s$  constraints to the European and Adriatic crust, and a high-resolution image of the velocity structure of the Alpine subduction zone. Figure 7c-e shows three cross-sections of the inverted velocity model down to 90 km depth, in different sites of the Western Alps corresponding to the NFP-20 West, ECORS-CROP and CIFALPS profiles. Along these cross-sections, the European lithospheric mantle (in blue on the left) is clearly underthrust beneath the Adriatic mantle on the eastern part of each profile (in blue on the right). A major Moho step of  $\sim 8$  km, first highlighted by Lu et al. (2018), is detected along the ECORS-CROP profile beneath the Belledonne massif (Fig. 7d). A similar Moho step is observed along the NFP-20 West profile (Fig. 7c) north of the Frontal Pennine Fault. No Moho step is observed along the CIFALPS profile (Fig. 7e).

In the shear wave velocity model of Zhao et al. (2020), the Alpine subduction wedge exhibits a “normal” velocity structure in all three profiles, from Earth’s surface to regions 4 and 5 (Fig. 7c-e).  $V_s$  values progressively increase with depth from  $\sim 3.3$  km s<sup>-1</sup> (red to orange colors) in the uppermost levels of the subduction wedge, to  $>3.6$  km s<sup>-1</sup> (yellow to green colors) at depth  $> 40$  km. This normal velocity structure is consistent with expected  $V_s$  values in metapelites and gneisses exposed in the Alpine belt, and with a progressive  $V_s$  increase with depth. Very low  $V_s$  regions (dark red) correspond to the main sedimentary basins formed atop the European and Adriatic crusts (Southeast basin and Po Plain, respectively). The lateral extent of the low  $V_s$  material ascribed to the subduction wedge can be evaluated in the horizontal slices of the tomography model at 50 and 60 km depth (Fig. 7a, b). The region with  $V_s < 3.8$  km s<sup>-1</sup> (green to yellow colors), detected all along the arc of the Western Alps at 60 km depth (Fig. 7b), is apparently thicker in the northern Western Alps compared to the southern Western Alps.

On the eastern side of each cross-section, the culmination of the region with  $V_s > 4.0$  km s<sup>-1</sup> (marked by blue colors) invariably matches with the location of the Ivrea gravity anomaly shown in Fig. 1b. A region with  $V_s > 3.8$  km s<sup>-1</sup> is imaged beneath the Dora-Maira starting from  $\sim 10$  km

depth. This region has a similar shape, with a near-vertical western boundary, as the high  $V_p$  anomaly imaged beneath the Dora-Maira by LET along the same profile (Fig. 6c). A similar high-velocity region is not observed beneath the eclogitic domes farther north (Fig. 7c, d), in line with results provided by LET (Solarino et al. 2018). At 50-70 km depth along the CIFALPS profile, the inverted model also shows a region with  $V_s < 3.7$  km s<sup>-1</sup> (green to yellow colors) that is interposed between the European lithospheric mantle and the overlying Adriatic mantle (6 in Fig. 7e). This low-velocity region, which reverts a trend of progressively increasing  $V_s$  with depth, is not observed along the ECORS-CROP and NFP-20 West profiles (cf. Fig. 7c, d). It has been interpreted by Zhao et al. (2020) as the evidence of serpentinites preserved along the Alpine subduction channel. In fact, the decreasing  $V_s$  values from region 5 to region 6 cannot be explained by metamorphic phase changes in metapelites and gneisses. The only rock characterized by  $V_s$  values of  $\sim 3.6$  km s<sup>-1</sup> in the 55-70 km depth range is serpentinite (Fig. 4). Alternatively, the low  $V_s$  values in region 6 may be due to high pore-fluid pressures, which would in turn promote serpentinization. A sharp  $V_s$  increase, observed at depth  $> 70$  km along the Alpine subduction channel, may reflect destabilization of antigorite and transformation of subduction-channel serpentinite into peridotite (e.g., Reynard 2013).

## 8 Velocity structure in the upper mantle along the CIFALPS profile

For a reliable geologic interpretation of the upper mantle structure along the CIFALPS profile, seismic velocity constraints of the slab structure and the mantle flow in the surrounding asthenosphere are required. Crucial for the interpretation of seismic velocities in the Alpine upper mantle is also the location of the lithosphere-asthenosphere boundary beneath the European foreland and the Alpine subduction wedge. Within the framework of the CIFALPS experiment, this information is provided by array analysis of seismic surface waves (Lyu et al. 2017). Information concerning the deeper slab structure is provided by teleseismic P-wave tomography (Zhao et al. 2016b), whereas clues on asthenospheric mantle flow are provided by the analysis of seismic anisotropy (Salimbeni et al. 2018).

### 8.1 The lithosphere-asthenosphere boundary beneath the Alpine foreland areas

The depth of the lithosphere-asthenosphere boundary beneath the Alpine region has been investigated by Lyu et al. (2017) using a combination of CIFALPS and permanent seismic station data. Lyu et al. (2017) inverted the fundamental mode Rayleigh wave dispersion curves for  $V_s$  using the crustal interfaces imposed from RF (Zhao et al. 2015). The resulting  $V_s$  values, derived from independent measurements in each mini-array, are shown in Fig. 8a.  $V_s$  values vary smoothly across the profile length. The decrease in S-wave velocity below  $\sim 110$  km depth in the western part of the profile (Fig. 8a) has been interpreted by Lyu et al. (2017) as the lithosphere-asthenosphere boundary beneath the European foreland. The top of this low-velocity layer, marked by a thick dashed line in Fig. 8a, is approximately parallel to the eastward dipping European Moho as detected by RF and other methods, which suggests a  $\sim 110$  km thick and eastward-dipping European lithosphere. These findings are consistent with the lithospheric thickness generally observed in Phanerozoic Europe using surface waves (e.g., Dost 1990; Cotte et al. 2002) and S-receiver functions (Geissler et al. 2010). S-wave velocities retrieved by Lyu et al. (2017) in the European upper mantle are overall low, at least when compared with velocities of the AK135 model (Kennett et al. 1995). S-wave velocities are much higher in the Adriatic lithosphere ( $\sim 5$  km s<sup>-1</sup>, dark blue colors in Fig. 8a), and consistent with a lithosphere-asthenosphere boundary located

at ~100 km depth beneath the Po Plain, as proposed by Brandmayr et al. (2010) and Malusà et al. (2018).

## 8.2 Velocity structure beneath the Alpine subduction wedge

According to Lyu et al. (2017), very low  $V_s$  values  $< 4 \text{ km s}^{-1}$  are found at the base of the European lithosphere in the central part of the CIFALPS profile, at depth ~120 km beneath the Alpine subduction wedge (7 in Fig. 8a). In that region, the high-velocity anomaly imaged by teleseismic P-wave tomography is strongly attenuated (Lippitsch et al. 2003; Zhao et al. 2016b; see Sect. 8.3), and a low- $V_s$  anomaly has been also detected by FWI (Beller et al. 2018) (7 in Fig. 8b). This is illustrated in the composite cross-section of Fig. 8b, which combines in the upper panel the results of TransD inversion of surface-wave dispersion data (Zhao et al. 2020), and in the lower panel the  $V_p$  perturbations based on teleseismic P-wave tomography (Zhao et al. 2016b). The  $V_s$  anomaly derived from FWI and described by Beller et al. (2018) is shown as purple isolines (Fig. 8b). Note that these different models are based on different data, obtained by means of different techniques and their resolving power is also different. Beller et al. (2018) have suggested that the low- $V_s$  anomaly detected in their S-wave velocity model may be supportive of a slab detachment beneath the Western Alps, an interpretation recently reintroduced by Dal Zilio et al. (2020) and Kästle et al. (2020). However, when the low- $V_s$  anomaly detected by Beller et al. (2018) is analysed in more detail and compared with information provided by independent tomographic methods along the CIFALPS profile (Fig. 8b), a different scenario emerges. The anomaly shows in fact two peaks, a weaker one at the base of the European lithosphere (7 in Fig. 8b) and a stronger one at ~75-95 km depth along the subduction channel above the European slab (8 in Fig. 8b). The anomaly 8 is not present in the TransD inversion model of Zhao et al. (2020) because it lays in a region where the model is not well resolved (cf. Zhao et al. 2020, their Fig. S9). Along the subduction channel, low  $V_s$  values in the 55-70 km depth range (6 in Fig. 8b) likely mark the occurrence of serpentinite (see Sect. 7.2). Given the sharp  $V_s$  increase at depth  $>70$  km along the subduction channel (Fig. 8b), interpreted by Zhao et al. (2020) as due to transformation of serpentinite into peridotite after destabilization of antigorite (cf. Fig. 4), the low  $V_s$  anomaly detected by Beller et al. (2018) at 75-95 km depth (8 in Fig. 8b) may also indicate a metasomatized mantle peridotite due to infiltration of slab fluids. We conclude that comparison among different techniques underlines that the results provided by Beller et al. (2018) are not supportive of European slab detachment. Instead, they are consistent with the results provided by other tomography approaches that have been applied during the CIFALPS experiment (e.g., Lyu et al. 2017; Zhao et al. 2020).

## 8.3 Slab structure from teleseismic P-wave tomography

Previous seismic tomography models of the Alpine upper mantle have revealed more or less discontinuous P-wave velocity anomalies interpreted as the seismic signature of subducted lithospheric slabs (e.g., Wortel and Spakman 2000; Lippitsch et al. 2003; Piromallo and Faccenna 2004). However, interpretations in terms of slab length and lateral or vertical slab continuities strongly depend on the resolution of seismic tomography models. The Zhao et al. (2016b)'s tomography study performed within the framework of the CIFALPS experiment first benefited from the recent opening of the European seismic databases and improvement of the permanent broadband network. It is based on a much denser station coverage than any previous work, especially in the Western Alps. Data were recorded by 527 broadband seismic stations: 449 from permanent networks, 23 from the PYROPE temporary experiment (Chevrot et al. 2014) and 55 from the CIFALPS experiment. In order to avoid interference of upper mantle tomography by crustal anomalies, Zhao et al. (2016b) used the EPcrust reference model to correct for traveltimes



residuals within the crust (Molinari and Morelli 2011). Although the EPcrust model does not include all the details of the most recent Moho maps (e.g., Spada et al. 2013; Lu et al. 2020), and the approach chosen by Zhao et al. (2016b) does not include the effects of 3-D propagation of nonvertical rays from different azimuths in the heterogeneous crust (e.g., Waldhauser et al. 2002), synthetic tests performed by Zhao et al. (2016b) indicate that their tomography model of Vp perturbations is not significantly affected by smearing of crustal anomalies to mantle depth.

Teleseismic tomography models of Vp perturbations display lateral P-wave velocity changes with respect to the horizontally averaged Vp in the region crossed by incident P waves. They are not associated to a reference model. The lower panel of Fig. 8b shows a cross-section of the Zhao et al. (2016b)'s model along the CIFALPS profile down to 400 km depth. The cross-section includes strong low-velocity anomalies (9 in Fig. 8b) at 100–250 km depth beneath the Frontal wedge and the European foreland, and an E-dipping high-velocity anomaly (blue in Fig. 8b) beneath the Eclogite belt and the western Po Plain. This high-velocity anomaly, likely marking the European slab beneath the Western Alps, is continuous from the uppermost mantle where it links with the lithosphere-asthenosphere boundary detected by array analysis of seismic surface waves (Lyu et al. 2017) and with the European Moho recognized by RF and TransD inversion (Zhao et al. 2015, 2020). Specific resolution tests suggest that any major slab gap should be revealed by the model, if present. According to the tomography model, the inferred length of the Western Alps slab may reach ~300 km (cf. Malusà et al. 2015, their Fig. 6), but such estimate should be taken with caution due to the potential vertical smearing typical of teleseismic body-wave tomography images. The Zhao et al. (2016b)'s model also shows a weakening of the high-velocity anomaly at the base of the European lithosphere (7 in Fig. 8b), supported by the results of subsequent work by Lyu et al. (2017) and Beller et al. (2018) discussed in Sect. 8.1-8.2. Such weakening affects part, but not the entire thickness of the Western Alps slab.

#### 8.4 Comparison with other tomography models

The continuity of the high-velocity anomaly in the Zhao et al. (2016b)'s model along the CIFALPS profile contrasts with those interpretations (e.g., Fox et al. 2015; Kissling and Schlunegger 2018; Kästle et al. 2020) based on the Lippitsch et al. (2003)'s model that have suggested slab breakoff beneath the Western Alps (see also Fig. 3c). Kissling and Schlunegger (2018) rejected the Zhao et al. (2016b)'s interpretation of a continuous slab in the Western Alps using the arguments that the Zhao et al. (2016b)'s model would be mainly based on 2-D information and poor quality data, which is incorrect as it is based on data from >500 stations distributed in the entire Alpine region (grey triangles in Fig. 1a), including 29 months of data at 449 high-quality broadband permanent stations. Cross-sections of these different tomographic models are compared in Fig. 9: the Lippitsch et al. (2003)'s ray-based model (on the left in Fig. 9) has a horizontal grid size of 50 km, it is based on ~4,200 traveltimes measurements and it was the first to suggest a slab breakoff beneath the Western Alps; the Zhao et al. (2016b)'s kernel-based model (on the right in Fig. 9) has a denser horizontal grid size of 25 km, it is based on ~42,000 traveltimes measurements and was the first to explicitly propose a continuous slab under the Western Alps, although similar evidence is also provided by teleseismic tomography models from other working groups (e.g., Piromallo and Morelli 2003; Koulakov et al. 2009; Giacomuzzi et al. 2011; Hua et al. 2017; Paffrath et al. 2020). As shown in Fig. 9, the first-order features of the Lippitsch et al. (2003)'s and Zhao et al. (2016b)'s models are remarkably similar, despite interpretations that are quite different (for the sake of clarity, the contours of equal Vp anomaly in the Lippitsch et al. (2003)'s model are also plotted onto the Zhao et al. (2016b)'s model to the

right). Both models show low-Vp anomalies located beneath the European foreland and a high-Vp anomaly under the western Po Plain that becomes weaker at ~120 km depth (7 in Fig. 9). The 0% anomaly isoline in the Lippitsch et al. (2003)'s model largely matches the boundary between high-Vp and low-Vp perturbations in the Zhao et al. (2016b)'s model. The observed differences in the amplitudes of Vp perturbations between models are not informative, because the kernel-based models (e.g., the finite frequency method used in Zhao et al. 2016b) generally yield higher root-mean square amplitudes for Vp perturbations than the ray-based method (e.g., Lippitsch et al. 2003).

Evidence of potential slab breakoff and associated passive asthenospheric upwelling along the breakoff gap should include, in a teleseismic P-wave tomography model, a low-velocity anomaly cutting across the high-velocity anomaly representing the broken slab. However, the shape of the anomaly is generally retrieved much better than its amplitude. Within the framework of the CIFALPS experiment, Zhao et al. (2016b) performed a series of tests, e.g., by replacing part of the high-velocity slab with a low-velocity body extending from 80 to 140 km depth, in order to mimic a possible slab breakoff beneath the CIFALPS profile. They found that the shape of a low-velocity body, if present, would be well recovered as a low-velocity anomaly by the inversion, albeit with attenuated amplitude (see Zhao et al. 2016b, their Fig. 5). They also demonstrated that a strong high-velocity anomaly in the crust like the Ivrea body does not smear to mantle depth and could by no way erase or attenuate a possible low-velocity anomaly in the mantle related to slab breakoff (see Zhao et al. 2016b, their Fig. 6). Within this framework, it is worth noting that the small low-velocity anomaly at ~120 km depth detected by Lippitsch et al. (2003) under the Dora-Maira is not connected, in their model, with the main low-velocity anomaly beneath the European foreland (see the left panel in Fig. 9). In fact, the two regions are separated by a region with  $V_p$  (%) > 0. Based on these considerations, the Lippitsch et al. (2003)'s model may provide no clear support to the hypothesis of a slab detachment along the CIFALPS profile, which would also imply a much stronger and continuous negative anomaly beneath the Dora-Maira.

The right panel of Fig. 9 also includes the fast Vs anomaly imaged by Kästle et al. (2018) by analysis of surface wave dispersion data from ambient noise and earthquakes (black hatched area in Fig. 9). The Kästle et al. (2018)'s model is sometimes invoked, together with the Lippitsch et al. (2003)'s and the Beller et al. (2018)'s models, to support the hypothesis of a detached slab beneath the Western Alps (see discussion in Kästle et al. 2020). However, the recent review paper by Kästle et al. (2020) may suggest that the Kästle et al. (2018)'s model does not provide an accurate image of the subducted lithosphere beneath the Western Alps. Indeed, the body-wave tomography models compared by Kästle et al. (2020) in their Fig. 2 (Lippitsch et al. 2003; Koulakov et al. 2009; Zhao et al. 2016b) invariably include an ENE-WSW trending high-Vp anomaly located to the south and well outside the Switzerland borders in the 120 and 200 km depth slices, whereas the Kästle et al. (2018)'s model, by contrast, shows an E-W trending high-Vs anomaly that is located more to the north and within the Switzerland borders.

### 8.5 Seismic anisotropy

The birefringence of core-refracted shear waves (SKS phase) and associated transverse anisotropy of seismic velocities (Savage 1999; Mainprice et al. 2000) can provide information on the lattice-preferred-orientation of olivine crystals in the mantle. Salimbeni et al. (2018) analysed the seismic anisotropy properties beneath seismic stations of the CIFALPS profile using the waveforms of 40 teleseismic events with  $M_w > 5.8$ , considering the azimuth of the fast axis ( $\phi$ ) and the delay time (dt) as proxies for the preferred orientation of olivine  $a$  axes and the thickness

of the anisotropic layer (Silver et al. 1999). The resulting distributions of delay times and fast axis orientations are plotted in Fig. 8c using different colours according to the back-azimuth of the seismic events.

Three different segments of the CIFALPS profile (western, central and eastern segments) are distinguished by Salimbeni et al. (2018) based on seismic anisotropy data. The western segment shows quite homogeneous fast-axis directions in the range of  $-60^\circ \pm 20^\circ$ , with minor differences depending on the back-azimuth. Along the western segment, ray paths coming from the West (dark blue marks in Fig. 8c) show increasing delay times from  $\sim 1$  s (at abscissae  $\sim 40$  km) to  $\sim 2.4$  s (at abscissae  $\sim 140$  km). In the central segment, ray paths coming from the West (dark blue marks) define a trend of linearly decreasing delay times from  $\sim 2.4$  s (at abscissae  $\sim 140$  km) to  $\sim 1.0$  s (at abscissae  $\sim 220$  km). No such trend is observed in the eastern segment of the profile, where the fast-axis directions are much more dispersed and the delay time is strongly scattered in a range from  $<1$  s to 2.8 s. The abrupt change in seismic anisotropy pattern between the central and the eastern segments of the CIFALPS profile occurs in correspondence with the transition (green dashed line in Fig. 8b,c) between the high-velocity anomaly marking the Western Alps slab and the low velocity anomaly detected to the west. West of the green dashed line, delay time variations for ray paths coming from the west show some correlation with the low P-wave velocity perturbations shown in Fig. 8b (red to yellow colors): higher delay times are found where the low-velocity anomaly in the mantle is weaker (i.e., at abscissae  $\sim 140$  km), whereas lower delay times are found where the low-velocity anomaly in the mantle is stronger. A geologic interpretation of this seismic anisotropy pattern requires a 3-D analysis of delay times and fast-axis directions with respect to the slab structure of the entire Alpine region, which is presented in Sect. 9.

## 9 Slab structure of the broader Alpine region

The complex slab structure of the broader Alpine region is still actively debated (e.g., Schmid et al. 2013; Handy et al. 2015; Rosenberg et al. 2018; Ji et al. 2019; Kästle et al. 2020). Within the framework of the CIFALPS experiment, useful pinpoints are provided by teleseismic P-wave tomography (Zhao et al. 2016b) and 3-D Pn tomography (Sun et al. 2019).

### 9.1 Continental subduction from 3-D Pn tomography

Sun et al. (2019) mapped the seismic velocity signature of continental subduction in the broader Alpine region by inversion of Pn phase traveltimes, using data recorded by permanent and temporary stations since the 1960s (Fig. 1a). Pn phases, i.e., the first arrivals at regional distance, propagate through the crust, penetrate the uppermost mantle and are finally refracted at the Moho and return to the free surface (Hearn 1999). The tomography model of Sun et al. (2019) is based on a three-step 3-D approach (Sun and Kennett 2016a, b) applied to a dataset of  $>395,000$  Pn arrivals for  $>9500$  events and 1080 stations, and provides absolute P-wave velocities in the uppermost 80 km of the Alpine lithosphere. In their model, the expected seismic velocity signature of continental subduction is given by P-wave velocities lower than those expected for upper-mantle peridotites (i.e.,  $V_p < 7.7$  km s $^{-1}$ , see Fig. 4). Oceanic subduction should remain undetected using the Sun et al. (2019)'s approach, because the high  $V_p$  values of the oceanic crust after eclogitization ( $V_p > 7.9$  km s $^{-1}$  for mafic eclogites) are undistinguishable from the high  $V_p$  values of upper-mantle peridotites (Fig. 4).

The P-wave velocity structure retrieved by Sun et al. (2019) is illustrated in the 50-km depth slice of Fig. 10a. It shows elongated regions characterized by  $V_p < 7.7$  km s $^{-1}$  (yellow-to-red colors)

all along the northeastern, northwestern and southwestern boundaries of the Adriatic microplate, providing evidence for continental subduction along the Dinaric, Alpine and Apenninic subduction zones, respectively. The low-velocity belt corresponding to Dinaric subduction displays a remarkable continuity from Austria to Albania. The Dinaric low-velocity belt terminates at high-angle (1 in Fig. 10a) against the low-velocity belt of the Eastern Alps, which shows an ENE–WSW trend consistent with major thrust faults formed during Alpine subduction. In the western Alpine region, the low-velocity belts provided by 3-D Pn tomography show an abrupt change in orientation (2 in Fig. 10a) likely marking the boundary between the Alpine and Apenninic subduction zones. Underthrusting of continental material by Apenninic subduction can be detected as far north as near Genoa. Prominent breaks (3 and 4 in Fig. 10a) are also observed in the Northern and Central Apennines. Higher  $V_p$  values in the Southern Apennines suggest that subduction in southern Italy was dominantly oceanic, as also indicated by the geochemistry of subduction-related magmatism (Peccerillo and Frezzotti 2015).

### 9.2 Slab structure from $V_p$ anomalies in teleseismic tomography models

The previously mentioned P-wave tomography model of Zhao et al. (2016b) provides constraints for the upper-mantle velocity structure of the broader Alpine region down to 600 km depth. The main features of the model are illustrated in Fig. 10 by three horizontal slices at 100, 200 and 300 km depth (Fig. 10b-d) and by four cross-sections (Fig. 10e). Salient features of the model include the lateral continuity, from the Central Alps to the Western Alps, of the high-velocity anomaly ascribed to the Alpine slab, and the lateral continuity of the high-velocity anomaly ascribed to the Apenninic slab that is particularly evident in the Northern Apennines. In the 100-km depth slice (Fig. 10b), at the transition between the Northern and the Southern Apennines, the model shows a major gap in the Apenninic high-velocity anomaly that was already detected by previous work and interpreted as a potential slab window (Amato et al. 1998; Faccenna et al. 2014). Another important feature of the model is the step between the ENE-WSW trending high-velocity anomaly ascribed to the Alpine slab beneath the Central Alps, and the NW-SE trending high-velocity anomaly detected beneath the Eastern Alps (Zhao et al. 2016b; Hua et al. 2017). The latter is shifted northward and forms an angle of  $30^\circ$  to  $60^\circ$  (depending on the depth range) relative to the strike of the Alpine frontal thrusts. The model also shows two main low-velocity anomalies (yellow-to-red colors in Fig. 10 b-e), labelled as “low  $V_p$  anomaly A” and “low  $V_p$  anomaly B” in Fig. 10 b-e. The former is located in the upper mantle of the Western Alps at 100–300 km depth, and does not extend east of  $8^\circ\text{E}$ . The latter is located in the Adriatic upper mantle beneath the Po Plain, and lays above the Alpine slab (see Fig. 10e, cross-section D-D’).

In cross-section, the Zhao et al. (2016b)’s tomography model shows a steep SW-dipping high-velocity anomaly beneath the northern Tyrrhenian region corresponding to the Apenninic slab, and an even steeper NE-dipping high-velocity anomaly beneath the Eastern Alps and the northernmost Dinarides (A-A’ in Fig. 10e). The origin of this latter anomaly, also detected by several other tomography models (e.g., Lippitsch et al. 2003; Dando et al. 2011; Mitterbauer et al. 2011; Hua et al. 2017), is still debated. It is either interpreted as due to continental Dinaric subduction during the Neogene (Schmid et al. 2013; Handy et al. 2015), as stemming from an oceanic and detached Alpine slab (Rosenberg et al. 2018), or as resulting from a more complex interaction between the Alpine and Dinaric slabs (Ji et al. 2019; Sun et al. 2019; Kästle et al. 2020) as discussed in more detail in Sect. 9.3. The relationships between the Alpine and Apenninic slabs are clearer. In cross-section B-B’ (Fig. 10e), the Alpine slab dips towards the SW and the steeply dipping Apenninic slab is almost overturned to a northeastward dip. The down-dip continuity of the Alpine

slab in the Central Alps is as debated as in the Western Alps (e.g., Kissling and Schlunegger 2018; Ji et al. 2019; Kästle et al. 2020). The Zhao et al. (2016b)'s model shows a remarkable down-dip continuity of the high-velocity anomaly in the Central Alps (see cross-sections B-B', C-C' and D-D' in Fig. 10e) that conflicts with the hypothesis of slab breakoff (e.g., von Blanckenburg and Davies 1995; Kissling and Schlunegger 2018). The amount of subducted lithosphere shown in cross-section D-D' is consistent with the amount of subduction predicted by paleomagnetic and geologic constraints (Handy et al. 2010; Malusà et al. 2015). About 450 km subduction took place in the Central Alps based on geologic evidence (Malusà et al. 2016a), which is also the amount that can be inferred from the length of the high-velocity anomaly in cross-section D-D'.

### 9.3 Interpretive slab structure beneath the Alpine region

Constraints on the slab structure provided by teleseismic P-wave and 3-D Pn tomography (Zhao et al. 2016b; Sun et al. 2019) are summarized in Fig. 11. Outside of the well-resolved areas of the Zhao et al. (2016b)'s model, slab traces (thick blue lines in Fig. 11a) are based on a previous, lower-resolution tomography model by Piromallo and Morelli (2003). In general terms, there is a good match between the sites of continental subduction documented by 3-D Pn tomography (thick brown lines in Fig. 11a) and the slab structure inferred from teleseismic P-wave tomography, in spite of the different techniques and data sets used (see event locations in Fig. 10f). As shown in the cartoon of Fig. 11b, two opposite-dipping slabs are attached to the southwestern and northeastern boundaries of the Adriatic microplate, forming a reversed U-profile in cross section (Vignaroli et al. 2008; Salimbeni et al. 2013; Zhao et al. 2016b; Sun et al. 2019). To the southwest, the segmented low-Vp belt attesting to subduction of Adriatic crust beneath the Northern Apennines matches with the Apenninic slab trace documented by teleseismic P-wave tomography (Fig. 11a), whereas subduction beneath the Southern Apennines mainly involved Ionian oceanic crust (Fig. 11b). On the northeastern boundary of the Adriatic microplate, the Adriatic crust underthrust beneath the Dinarides is connected with a NE-dipping high-velocity anomaly interpreted as the Dinaric slab (Fig. 11a). The ophiolitic rocks of the Sava and Vardar units exposed farther east (dashed green lines in Fig. 11a) are likely relics of older, Mesozoic subduction zones (Sun et al. 2019).

During the progressive northward motion of the Adriatic microplate in the Cenozoic (Dewey et al. 1989; Jolivet et al. 2003), the Apenninic and Dinaric slabs have likely interacted with the SE-dipping Alpine slab to the North (Malusà et al. 2016b, 2018; Ji et al. 2019). It has been suggested that the interaction between the northward shifting Apenninic slab and the Central Alps slab may have controlled the location of the northern tip of the Ligurian-Provençal basin during Apenninic slab retreat and associated Neogene extension in the Apenninic backarc region (Malusà et al., 2016b). At the transition between the Eastern Alps and the Dinarides, the NE-dipping high-velocity anomaly detected in the 100-200 km depth range beneath the remnants of the former Alpine subduction zone (question mark in Fig. 11a) may also provide evidence of the interaction between different slabs. This enigmatic feature may either represent the northern edge of the Dinaric slab, or the overturned remnants of the Alpine slab, or a combination of the two slabs (Salimbeni et al. 2013; Schmid et al. 2013; Zhao et al. 2016b; Rosenberg et al. 2018; Sun et al. 2019; Kästle et al. 2020). Further constraints to the complicated slab structure in that region are expected in the next future from the AlpArray experiment (e.g., Paffrath et al. 2020; Plomerova et al. 2020).

To the West of the Giudicarie Fault, subducted continental material imaged by Pn tomography is clearly connected with the SE-dipping high-velocity anomaly of the Alpine slab,

which is continuously imaged from the Western to the Central Alps (Fig. 11a). To the east of the Giudicarie Fault, this high-velocity anomaly shows a systematic northward step, interpreted by Ji et al. (2019) as the evidence of a vertical tear in the Alpine slab (Fig. 11), possibly formed after the onset of Dinaric subduction in the Eocene (e.g., Carminati et al. 2012). According to Ji et al. (2019), the interaction between the Alpine and Dinaric slabs, and the consequent progressive steepening of the Alpine slab would explain the timing, distribution and geochemistry of Periadriatic magmatism in the absence of slab breakoff, providing a viable alternative to the classic slab-breakoff model of Periadriatic magmatism proposed by von Blanckenburg and Davies (1995).

Farther South, at the transition between the Alpine and Apenninic slabs, previous tomography models (e.g., Piromallo and Morelli 2003) have suggested the occurrence of a major slab gap. This gap would have allowed the development of an asthenospheric toroidal flow compensating the long-recognized retreat of the Apenninic slab (Vignaroli et al. 2008; Faccenna and Becker 2010; Salimbeni et al. 2013), which is attested to by a progressive migration of Cenozoic orogenic magmatism across the Mediterranean (Fig. 11a) (e.g., Lustrino et al. 2011; Carminati and Doglioni 2012). However, the slab structure revealed by the CIFALPS experiment shows no evidence of a major gap between the Alps and the Apennines at upper mantle depths (Fig. 11b). This finding has major implications for the interpretation of the seismic anisotropy pattern at the scale of the broader Alpine region, as described below.

#### **9.4 Polyphase development of anisotropic mantle fabrics**

In Fig. 12a, shear wave splitting measurements on CIFALPS data (Salimbeni et al. 2018) and from previous work (Barruol et al. 2004, 2011; Salimbeni et al. 2008, 2013) are plotted on the 150-km depth slice of the Zhao et al. (2016b)'s tomography model as segments parallel to the fast axis and scaled with the delay time. Because the Alpine and Adriatic slabs are both very steep, any depth slice of the Zhao et al. (2016b)'s model would provide similar relationships between velocity anomalies and anisotropy. These relationships reveal a polyphase development of anisotropic mantle fabrics in the Alpine region, which may either reflect fossil or active mantle flows (Salimbeni et al. 2018). Note that the shear wave splitting measurements indicated by the purple segments in Fig. 12a integrate the seismic anisotropy over the uppermost 300 km and are mainly due to the lattice-preferred-orientation of olivine crystals in the mantle (Savage and Sheehan 2000; Piromallo et al. 2006). In order to discriminate upper mantle and crustal contributions to the observed seismic anisotropy, S wave anisotropy measurements from local earthquakes (Baccheschi et al. 2019) are also shown in Fig. 12a and are indicated by different shades of green for different depth ranges. However, the contribution of crustal anisotropy to the total seismic anisotropy is minor, as highlighted by the different scales adopted for the different splitting measurements (Fig. 12a). This negligible contribution of crustal anisotropy to total shear-wave splitting measured on SKS phases is confirmed at the scale of the greater Alps by preliminary results from the AlpArray seismic experiment (Link et al. 2020).

According to Salimbeni et al. (2018), shear wave splitting measurements plotting on the high-velocity anomalies of the Zhao et al. (2016b)'s model may reflect fossil fabrics in the lithospheric mantle of the Alpine and Apenninic slabs (1 in Fig. 12a). Fossil fabrics within slabs are generally considered a negligible source of anisotropy (Long and Silver 2008, 2009; Audet 2013). However, a fossil fabric defined by olivine crystallographic preferred orientation (CPO) can be preserved in the oceanic lithosphere since the time of plate formation (Mercier et al. 2008) and is generally aligned with the direction of plate spreading (Shinohara et al. 2008). In the Alpine region, fossil fabrics acquired during Tethyan rifting are described in several mantle slivers

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accreted in the Alpine and Apenninic orogenic belts (e.g., Nicolas et al. 1972; Vissers et al. 1995). They include coarse-grained spinel lherzolite tectonites with olivine CPO consistent with deformation by dislocation creep (Tommasi et al. 1999; Vauchez et al. 2012). This tectonite fabric, developed at 900°–1000 °C and ~1.4 GPa during low-angle simple shearing and asymmetric rifting in the Jurassic (Hoogerduijn Strating et al. 1993), may characterize a thick slab section (Fig. 12b). It is generally overprinted by spinel-, plagioclase-, hornblende- and chlorite-bearing mylonites, and by serpentine mylonites developed as a result of strain localization during progressive mantle exhumation towards the Tethys seafloor (Piccardo and Vissers 2007). Because these fabrics can survive subsequent deformation at eclogitic depths within the Alpine subduction channel (Scambelluri et al. 1995; Hermann et al. 2000), they are also likely preserved in low-strain domains within the slab. Their present-day attitude depends on: (i) the direction of plate spreading, (ii) the trench orientation relative to the paleomargin, and (iii) the present-day slab dip (Fig. 12b). The spreading direction in the Jurassic was likely perpendicular to the trend of the European and Adriatic paleomargins, which is constrained by stratigraphic, tectonic and thermochronologic data (e.g., Winterer and Bosellini 1981; Lemoine et al. 1986; Guillot et al. 2009b; Fantoni and Franciosi 2010; Malusà et al. 2016b), whereas the orientations of the Alpine and Apenninic trenches and the dip angle of the Alpine and Apenninic slabs are well constrained by paleotectonic reconstructions (Jolivet et al. 2003; Vignaroli et al. 2008; Malusà et al. 2015) and available tomography models. Based on the above constraints, the fossil fabrics acquired during Tethyan rifting should be marked, in the Alpine region, by slab-parallel to oblique fast axis directions (Fig. 12b), which are indeed observed in the map of Fig. 12a (Salimbeni et al. 2018). In the Northern Apennines, slab-parallel fast-axis directions are detected at depths as shallow as 20 km (green segments in Fig. 12a) (Baccheschi et al. 2019).

The low Vp anomaly region to the North of the Apenninic slab shows instead NNW–SSE to NE–SW fast-axis directions (2 in Fig. 12a) that are consistent with the direction of relative Adria-Europe plate motion inferred from magnetic anomalies since the Late Cretaceous (Fig. 12c) (Dewey et al. 1989; Jolivet and Faccenna 2000). This suggests that the anisotropic fabric in that region may have formed during post-Jurassic Adria-Europe convergence, and possibly before the onset of Apenninic slab rollback (Salimbeni et al. 2018). If this interpretation is correct, fast-axis directions consistent with Adria-Europe plate motion should be also recorded by seismic stations in the Adriatic Sea (Molinari et al. 2018). WNW–ESE fast-axis directions parallel to the Jurassic spreading directions are poorly represented beneath the Adriatic microplate, which provides support for the hypothesis of asymmetric Tethyan rifting as already proposed on a geologic basis (e.g., Lemoine et al. 1986; Manatschal and Müntener 2009; Malusà et al. 2015). In fact, asymmetric rifting implies that, during lithospheric extension, tectonite fabrics should be best developed within the Tethys oceanic lithosphere and the European subcontinental mantle but should not be expected in the Adriatic subcontinental mantle (Fig. 12b), in line with the results reported in Fig. 12a.

Finally, the low Vp anomaly region to the west of the Alpine and Apenninic slabs shows a continuous trend of fast-axis directions (3 in Fig. 12a) that follows the arc of the Western Alps down to the Ligurian coast, where this trend merges with a WNW–ESE trend of fast-axis directions already described in SE France by Barruol et al. (2004). This seismic anisotropy pattern has a clear asthenospheric origin. It shows different directions compared to Pn anisotropy that samples the shallow lithospheric mantle (Díaz et al. 2013) and azimuthal anisotropy from noise and surface waves that samples a maximum depth of 120–125 km (Fry et al. 2010; Zhu and Tromp 2013). Since its first detection, the anisotropy “trend 3” was interpreted as an effect of asthenospheric

flow due to the eastward retreat of the Apenninic slab (Barruol et al. 2004; Lucente et al. 2006; Jolivet et al. 2009), an interpretation confirmed by the CIFALPS experiment (Salimbeni et al. 2018). This continuous trend of fast-axis directions provides additional evidence against the hypothesis of Alpine slab breakoff. In fact, slab breakoff would imply a mantle flow through the slab that should be revealed by slab-perpendicular fast-axis directions (Fig. 12d). These slab-perpendicular fast axes are not observed in Fig. 12a.

### **9.5 Contrasting origin of the low-velocity anomalies in the Alpine upper mantle**

The observed correspondence between the continuous trend of fast-axis directions and the low Vp anomaly in the European upper mantle provides pinpoints for further interpretation of the upper mantle structure beneath the Alpine region. This low Vp anomaly may either attest to the presence of fluids or have a thermal origin. The former hypothesis can be excluded in light of the location and the depth of the low Vp anomaly with respect to the nearby slabs (Figs. 10e, 11). On the other hand, a potential thermal origin may be related to asthenospheric upwelling, possibly due to the counterflow induced by Apenninic slab retreat in the absence of an adequate mass compensation by a toroidal mantle flow around the northern tip of the retreating slab (Salimbeni et al. 2018). An efficient toroidal mantle flow would compensate the effects of slab retreat on the adjoining mantle by transferring asthenospheric material from the rear of the Apenninic slab towards a supraslab position (Vignaroli et al. 2008; Faccenna and Becker 2010; Salimbeni et al. 2013). However, seismic anisotropy data are not supportive of an efficient toroidal flow beneath the Po Plain (Fig. 12a). Recent tomography models show no major gap in the slab structure between the Alps and the Apennines (Fig. 11), and the absence of enough space between the two slabs may preclude flow around the northern tip of the Apenninic slab during its rollback, with major implications for the asthenospheric mantle flow farther west. In fact, the absence of an efficient toroidal flow implies that Apenninic slab rollback may have induced not only a suction effect and an asthenospheric counterflow at the rear of the unbroken Western Alps slab (Barruol et al. 2004; Jolivet et al. 2009), but also a component of asthenospheric upwelling to compensate the lack of mantle material transferred from the rear to the front of the Apenninic slab (Salimbeni et al. 2018). Although the magnitude of mantle upwelling is probably much smaller than the magnitude of the horizontal component of the mantle flow (Fig. 12d), the vertical component associated with mantle flow may have led to a temperature increase in the upper mantle, which may explain the low Vp anomaly imaged by P-wave tomography (Zhao et al. 2016b).

The low Vp anomaly B located atop the Alpine slab beneath the Po Plain may instead attest to the impact of slab released fluids, as first suggested by Giacomuzzi et al. (2011). This topic has been recently addressed by Malusà et al. (2018), who combined geodynamic reconstructions with geophysical imaging and petrological modeling to reveal large-scale carbon processes associated with the complex slab configuration of the Alpine region. According to Malusà et al. (2018), the low-velocity anomaly in the upper mantle beneath the Po Plain would be generated by extraction of carbon-rich melts from the asthenosphere, favoured by the breakdown of slab carbonates and hydrous minerals after cold Alpine subduction. Carbonates and hydrous minerals (e.g., phengite) can escape breakdown if the geothermal gradient during subduction is sufficiently low (Fig. 13c) and can be dragged into the upper mantle by the downgoing slab (1 in Fig. 13c). After subduction, the slab is progressively thermally reequilibrated towards ambient mantle conditions, with a temperature increase (2 in Fig. 13c) that may promote dehydration reactions and carbonate breakdown. Consequent generation of carbon-rich supercritical fluids at the slab interface triggers melting in the overlying mantle wedge, with low density and low viscosity carbon-rich melts rising



in the Adriatic asthenosphere (Fig. 13b) to be finally frozen at ~180 km depth (3 in Fig. 13b), where the mantle geotherm crosses the carbonated hydrous peridotite solidus (3 in Fig. 13c). This implies sequestration of carbon in the upper mantle without immediate release (Malusà et al. 2018).

The low-velocity anomalies A and B located on either side of the Alpine slab may thus have different origins, that is asthenospheric upwelling to the west (Zhao et al. 2016b; Salimbeni et al. 2018) and fluids released from the Alpine slab to the east (Malusà et al. 2018). This makes numerical modeling exercises applied to the analysis of sub-lithospheric mantle convection (e.g., Sternai et al. 2019) more challenging than expected, because the commonly assumed relationships between seismic velocity, temperature and rock density (e.g., Simmons et al. 2010) are not necessarily met. This may explain why both the tomography models of Lippitsch et al. (2003) and Zhao et al. (2016b), when analyzed in terms of mantle convection modeling (Sternai et al. 2019), point to positive dynamic uplift in the Po Plain that is at odds with observations. If not properly accounted for, the different origins of the different low-velocity anomalies in the Alpine region may preclude a reliable quantification of the contribution from mantle convection to the measured uplift rates (e.g., Serpelloni et al. 2013; Walpersdorf et al. 2015; Nocquet et al. 2016).

## 10 Interpretive cross sections at lithospheric and upper-mantle scales

Based on the geophysical constraints provided by the CIFALPS experiment, interpretive cross sections at the scale of the lithosphere and the upper mantle are shown in Fig. 13. In the southern Western Alps, the uppermost 20-25 km of the European lower plate consists of a mainly granitic upper crust and associated sedimentary cover (Fig. 13a). These upper crustal rocks rest on top of a relatively homogeneous lower crust, likely consisting of granulitic rocks of felsic to intermediate composition (Solarino et al. 2018). At depths >40 km beneath the Alpine subduction wedge, the European lower crust is progressively eclogitized, but seismically distinguishable from the underlying mantle lithosphere down to depths of ~75 km (Zhao et al. 2015; Solarino et al. 2018). The eastward-dipping European Moho is located at 30-40 km depth beneath the Southeast basin and the External zone, reaching ~75 km depth beneath the Dora-Maira and the western Po Plain (Zhao et al. 2015, 2020). The main NE-SW trending Moho step detected to the NW of the Belledonne and Mont Blanc massifs (Lu et al. 2018; Zhao et al. 2020) is not observed in the southern Western Alps, where the European Moho shows a more continuous profile (Fig. 13a). No deep seismicity is observed along the European Moho or along its continuation at depth, as expected since subduction is no longer active (Malusà et al. 2017) (Fig. 13b).

On the upper-plate side of the orogen, the mainly gneissic and anisotropic Adriatic upper crust is 10-15 km thick beneath the Po Plain and the Monferrato thrust sheets (Fig. 13a). At the western tip of the Adriatic upper plate, the westward pinching Adriatic lower crust has a more heterogeneous composition compared to the lower crust of the European plate, and locally includes granulitic metapelites and underplated gabbro (Solarino et al. 2018). The eastward-dipping Adriatic Moho is located at ~30 km depth under the Monferrato and at much shallower depth of 10-15 km in correspondence with the former necking zone of the southern Tethyan margin (Zhao et al. 2015). In the Adriatic lithospheric mantle, the dry to partly serpentinized peridotites of the former necking zone are underthrust by the peridotites of the European lithospheric mantle (Zhao et al. 2020) (Fig. 13a).

The Alpine subduction wedge is apparently thicker in the northern Western Alps compared to the southern Western Alps (Zhao et al. 2020). In the southern Western Alps, the subduction wedge

includes pervasively fractured Schistes lustrés and Briançonnais rocks of the doubly-vergent Frontal wedge, exposed beside (U)HP metaophiolites and poorly fractured granitic gneisses of the Dora-Maira dome. A body of mantle-wedge rocks with variable degrees of serpentinization, ranging from >90% in the uppermost part of the body to <30% at depth >30 km, is inferred under the Dora-Maira at depths as shallow as ~10 km. Similar bodies are not imaged beneath the eclogitic domes exposed farther north (i.e., the Gran Paradiso and Monte Rosa domes) (Solarino et al. 2018; Zhao et al. 2020). The body of mantle-wedge rocks under the Dora-Maira is virtually aseismic (Eva et al. 2020), consistent with the fact that serpentinization promotes aseismic deformation. To the east, these mantle-wedge rocks are delimited by an active left-lateral fault in the lithospheric mantle (Rivoli-Marene deep fault, RMF in Fig. 13a) that is marked by the alignment of anomalously deep earthquake hypocentres (Malusà et al. 2017). Therefore, based on the cross section of Fig. 13a, three different types of mantle rocks may contribute to the Ivrea gravity anomaly in the southern Western Alps: (i) to the west, mantle-wedge rocks emplaced at shallow crustal depth syn or post exhumation of the Dora-Maira (U)HP rocks; (ii) to the east, dry to partly serpentinized peridotites exhumed along the former necking zone of the southern Tethyan margin; (iii) in between, mantle rocks of the Lanzo massif that underwent Alpine subduction and were later exhumed and accreted against the Adriatic upper plate when the Dora-Maira (U)HP rocks were still buried at mantle depths (e.g., Rubatto and Hermann 2001; Rubatto et al. 2008; Angiboust and Glodny 2020).

In the underlying subduction channel, slivers of eclogitic metasediments and other (U)HP rocks are documented starting from depths ~40 km (Solarino et al. 2018). Serpentinites likely mark the subduction channel in the depth range between ~45 and ~70 km (Zhao et al. 2020) and are replaced at greater depth by metasomatized mantle peridotites likely affected by infiltration of slab fluids. At either side of the Alpine subduction wedge, different tectonic styles characterize the lower and upper plate lithosphere. The former is cut by hinterland-dipping thrusts rooted in the Alpine subduction wedge, whereas the latter is cut by near-vertical faults (Fig. 13a).

At the upper-mantle scale (Fig. 13b), the CIFALPS results indicate that the lithosphere-asthenosphere boundary is located at ~110 km depth beneath the European foreland and is approximately parallel to the eastward dipping European Moho, which suggests a ~110 km thick and eastward-dipping European lithosphere (Lyu et al. 2017). Beneath the Po Plain, the Adriatic lithosphere-asthenosphere boundary is located at ~100 km depth (Malusà et al. 2018). The Western Alps slab is apparently continuous beneath the western Po Plain, possibly reaching ~300 km in length (Zhao et al. 2016b). It includes not only European lithosphere, but also Tethys lithosphere and the lithosphere of the adjoining ocean-continent transition zone (OCT in Fig. 13b) (Malusà et al. 2018), all showing a tectonite fabric that is not documented in the Adriatic subcontinental mantle (Salimbeni et al. 2018). The asthenosphere at the rear of the Western Alps slab is affected by slab-parallel mantle flow likely triggered by Apenninic slab rollback (Barruol et al. 2004; Salimbeni et al. 2018). This flow may have induced weakening of the overlying Alpine slab (Fig. 13b). In a supraslab position, independent circulations may have controlled slab-to-mantle exchanges at different depth ranges, with cold subduction possibly favouring long-term sequestration of carbon in the asthenospheric mantle (Malusà et al. 2018).

## 11 Geodynamic evolution and progressive development of the deep Alpine structure

The deep Alpine structure revealed by the CIFALPS experiments was acquired during different steps of the complex evolution of the Adria-Europe plate boundary zone. It results from a combination of pre-Alpine tectonic inheritance, impact of Tethyan rifting, accommodation of

Adria-Europe convergence by Alpine subduction, and activity of nearby subduction zones after Alpine subduction cessation and continent-continent collision.

### ***11.1 Pre-Alpine inheritance and Tethyan rifting***

Tethyan rifting marking the onset of the Alpine tectonic cycle likely reactivated former Paleozoic suture zones (Guillot et al. 2009b; Bergomi et al. 2017). We infer that the different composition of the upper and lower crust in the Adriatic and European plates may be partly inherited from different pre-Alpine evolutions (Solarino et al. 2018). Many Variscan lineaments were re-activated during the opening of the Alpine Tethys (Malusà et al. 2016a), and a Variscan inheritance may be also suggested for the Moho step detected by Lu et al. (2018) and Zhao et al. (2020) to the NW of the Belledonne and Mont Blanc massifs. During the opening of the Alpine Tethys, the Ivrea mantle rocks were exhumed to shallow crustal depths in the necking zone of the southern Tethyan margin (Manatschal and Müntener 2009). This process may have also led to the westward thinning of the Adriatic lower crust along the CIFALPS transect (Fig. 13a). Subcontinental mantle rocks were exhumed to the Tethys seafloor at this stage and underwent serpentinization by seafloor hydrothermal activity and seawater alteration (Deschamps et al. 2013). Due to the low spreading rates characterizing the Alpine Tethys, serpentinization may have occurred over a thickness of 2-4 km reaching extents of 70-80% (e.g., Rouméjon and Cannat 2014). During lithospheric extension, mantle peridotites now belonging to the Alpine slab likely acquired a tectonite fabric controlled by the direction of Jurassic spreading. All of these features were already present during the early stages of oblique Alpine subduction (Fig. 14a) and may have controlled the propagation of deformation during subduction and subsequent continent-continent collision.

### ***11.2 Alpine subduction and exhumation***

During Alpine subduction, abyssal serpentinites formed at the Tethys seafloor were either stacked in the subduction wedge or dragged into the Alpine subduction channel. Subducted European lower crust underwent progressive eclogitization, whereas upper-crust slivers were stacked in the subduction wedge (Zhao et al. 2015; Solarino et al. 2018). Aqueous fluids released from the slab at sub-arc depths promoted serpentinization in the subduction wedge and along the plate interface above the subduction channel. The resulting serpentinized plate interface may have favoured the subduction of European continental lithosphere and the formation of continental (U)HP rocks (Zhao et al. 2020). Northward Adria motion in the late Eocene and associated localized divergence in the western segment of the Alpine subduction zone may have triggered, according to Malusà et al. (2011, 2015), the fast exhumation of buoyant (U)HP rocks now exposed in the Dora-Maira massif (Fig. 14b). Along the CIFALPS transect, serpentinized mantle-wedge rocks may have followed the exhumation path of buoyant (U)HP rocks towards the Earth's surface to be finally emplaced beneath the Dora-Maira dome (Liao et al. 2018b; Solarino et al. 2018), also favouring the final exhumation of continental (U)HP rocks across the upper crust where eclogitized continental-crust rocks may become neutrally buoyant (Schwartz et al. 2001). During transtension, subducted abyssal and deeper mantle-wedge serpentinites likely moved upwards along the subduction channel, which became much thicker compared to the previous stages of plate convergence (Liao et al. 2018b; Zhao et al. 2020). Subducted abyssal serpentinites may also form the uppermost part of the serpentinized mantle wedge beneath the Dora-Maira, where the degree of serpentinization of the precursor peridotite may reach as high as 90%. The exhumed mantle-wedge rocks and the Ivrea mantle rocks were thus juxtaposed at shallow crustal levels in the late Eocene (Solarino et al. 2018). In the northern Western Alps, mantle-wedge exhumation was likely

precluded by the lower amount of divergence due to the coeval indentation of Adria beneath the Central Alps (Liao et al. 2018b), also associated with back-folding of (U)HP domes (Keller et al. 2005) and backthrusting of Southalpine units (Zanchetta et al. 2015). At a broader scale, the interaction between the Dinaric slab and the Alpine slab may have led to the formation, beneath the Giudicarie Fault, of a vertical tear in the Alpine slab (Zhao et al. 2016b) with major implications for the development of Periadriatic magmatism (Ji et al. 2019).

### 11.3 Post-subduction evolution

After cessation of Alpine subduction, Neogene retreat of the Apenninic slab likely induced a counterflow in the asthenospheric mantle at the rear of the Alpine slab (Barruol et al. 2004; Salimbeni et al. 2018). Interaction between the northward shifting Apenninic slab and the SW-dipping Alpine slab may have controlled the location of the northern tip of the scissor-type Ligurian-Provençal basin opening in the Apenninic backarc (Malusà et al. 2016b). In the southern Western Alps, the northward motion of the Adriatic microplate was accommodated by strike-slip activity along the Rivoli-Marene deep fault (Eva et al. 2015), located at the eastern boundary of the exhumed mantle wedge. In the Adriatic mantle lithosphere, earthquakes occurrence down to depths of ~75 km indicates that geothermal gradients in the upper plate have remained low (<8 °C/km) and substantially similar to the gradients experienced by the Dora-Maira (U)HP rocks during their prograde path (Fig. 13c) (Malusà et al. 2017). Thermal reequilibration of the Alpine slab towards ambient mantle conditions promoted the generation of carbon-rich supercritical fluids and carbon storage in the Alpine upper mantle. The Moho step in the European foreland was possibly reactivated as a result of flexural loading by the leading edge of the Adriatic microplate (Fig. 14c). During the final collision stages (Fig. 14d), the Ivrea mantle acted as a rigid buttress constraining crustal shortening to the lower plate, which may have favoured the formation of the Jura fold-and-thrust belt to the NW of the Alps (Liao et al. 2018a), whereas the eastward propagation of the asthenospheric counterflow towards the Ligurian Alps led to the northward tilting of the Tertiary Piedmont basin succession.

## 12. Conclusions and open questions

The CIFALPS experiment has allowed a major step forward in our understanding of the deep structure of the southern Western Alps and of the broader Alpine region more generally. Major tectonic features at the scale of the lithosphere and the upper mantle are now constrained in a compelling way by the integration of independent tomographic methods that exploit different information from high-resolution seismic data sets. The application of a wide range of tomographic methods to the analysis of a single fossil subduction zone and the joint interpretation with geological and petrophysical data make the CIFALPS experiment a reference case that could be exported to other study areas. Major results include:

- (i) the first seismic evidence of European crust subducted into the Adriatic upper mantle, right beneath the place where coesite was first recognized in continental (U)HP rocks in the Alps;
- (ii) evidence of the major involvement of the mantle wedge during crucial steps of (U)HP rock exhumation;
- (iii) the first high-resolution image of a fossil subduction channel providing evidence of a serpentinized plate interface that favours continental subduction;
- (iv) evidence of a continuous slab beneath the Western and Central Alps, ruling out the classic hypothesis of slab breakoff magmatism right in the place where the slab-

- breakoff model was first proposed; however, this does not exclude that slab breakoff magmatism may have affected other regions on Earth;
- (v) evidence of a polyphase development of anisotropic mantle fabrics, either representing active mantle flows inducing localized weakening of the overlying lithosphere, or fossil fabrics inherited from previous rifting stages.

Open questions remain to be addressed, concerning for example the upper mantle structure at the transition between the different slabs imaged beneath the broader Alpine region, the impact of slab-parallel mantle flow on the overlying lithosphere, or the lateral continuity of the finest geologic structures recognized in the fossil subduction channel along the CIFALPS transect. New constraints to the complicated slab structure at the transition between the Eastern Alps and the Dinarides are expected from the Swath-D AlpArray complementary experiment (Heit et al. 2018). Additional insights on the deep tectonic structure of the western Alpine region will be provided by the CIFALPS-2 experiment, a passive seismic survey that crosscuts the northern Western Alps across the Gran Paradiso massifs and the Ivrea body, reaching as far south as the Ligurian Sea.

#### **Acknowledgments, Samples, and Data**

The authors have no conflict of interest to declare. Data is available through Zhao et al. 2015, Zhao et al. 2016b, Lyu et al. 2017, Salimbeni et al. 2018, Solarino et al. 2018, Sun et al. 2019 and Zhao et al. 2020. We thank Rixiang Zhu, Yi Chen, Qin Wang and Helle Pedersen for support and fruitful discussions. This research was supported by CAS program (GJHZ1776), NSFC (grants no. 41625016, 41888101, 91755000), National Key R&D Program of China (grant no. 2017YFC0601206), Agence Nationale de la Recherche (contract ANR-15-CE31-0015) and Labex OSUG@2020 (Investissement d'Avenir, ANR-10-LABX-56).

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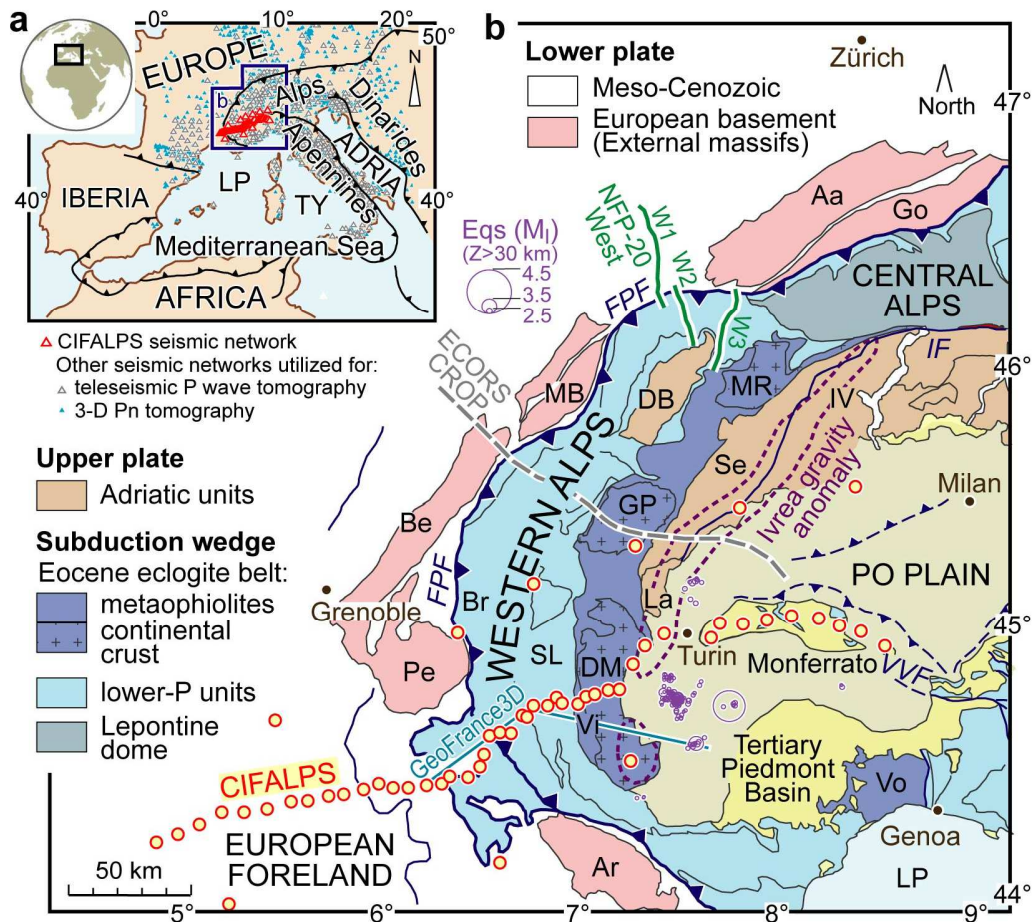
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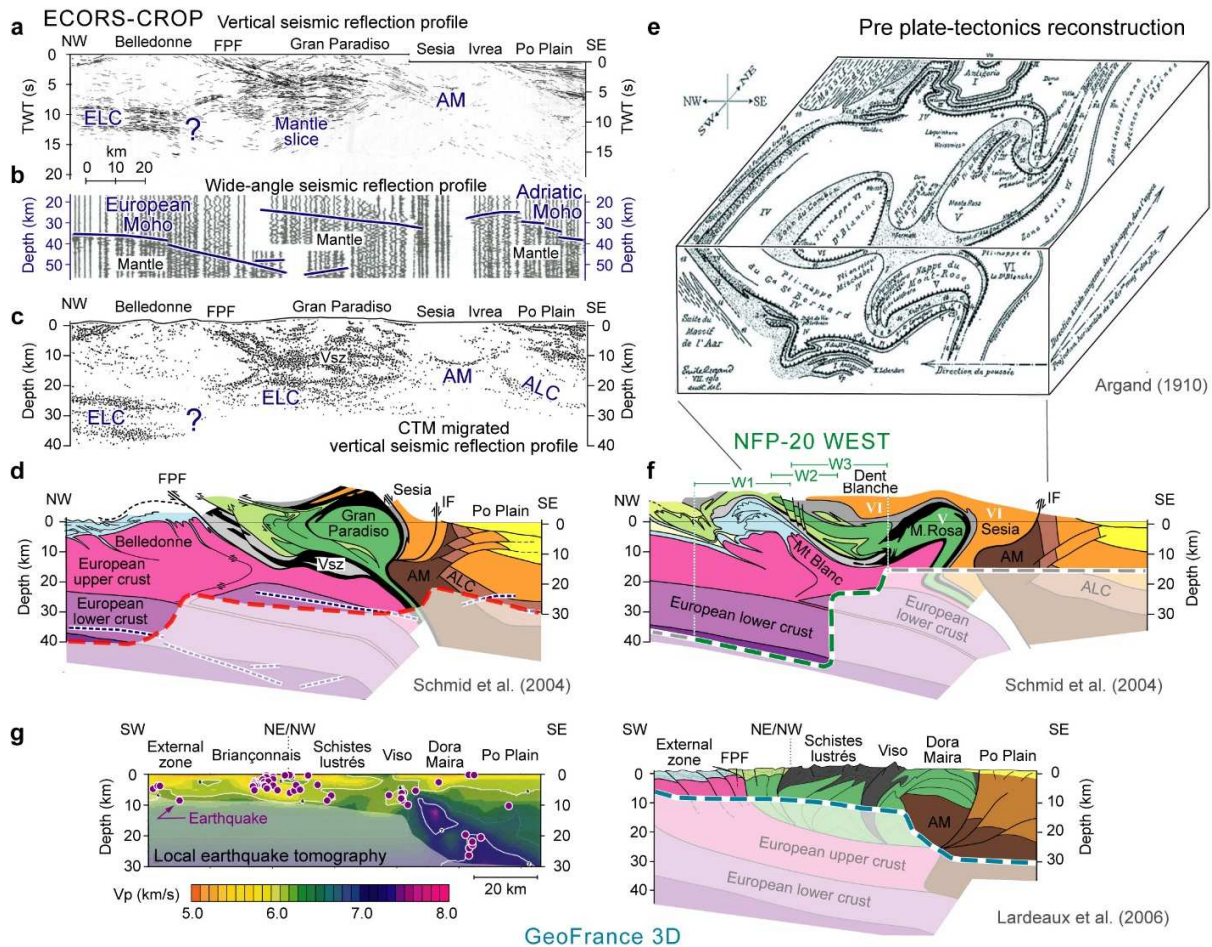
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FIGURE 1



**Figure 1.** Tectonic setting of the study area. **a:** Tectonic sketch map of the Adria-Europe plate boundary zone, and distribution of seismic stations of the CIFALPS experiment and other networks used for the teleseismic P-wave and 3D Pn tomographies of [Zhao et al. \(2016b\)](#) and [Sun et al. \(2019\)](#); **b:** Geologic map of the Western Alps (modified after [Bigi et al. 1990](#); [Malusà et al. 2015](#)), with location of previous geophysical transects indicated (ECORS CROP, NFP-20 West, GeoFrance 3D) and CIFALPS temporary stations. The Ivrea gravity anomaly (0 mGal isoline, in purple, after [Bigi et al. 1990](#)) and the locations of anomalously deep earthquakes beneath the Po Plain ([Eva et al. 2015](#); [Malusà et al. 2017](#)) are also indicated. Acronyms: Aa, Aar; Ar, Argentera; Be, Belledonne; Br, Briançonnais; DB, Dent Blanche; DM, Dora-Maira; FPF, Frontal Pennine Fault; Go, Gotthard; GP, Gran Paradiso; IF, Insubric Fault; IV, Ivrea-Verbano; La, Lanzo; LP, Ligurian-Provençal; MB, Mont Blanc; MR, Monte Rosa; Pe, Pelvoux; Se, Sesia-Lanzo; SL, Schistes lustrés; TY, Tyrrhenian; Vi, Viso; Vo, Voltri; VVF, Villalvernia-Varzi Fault.

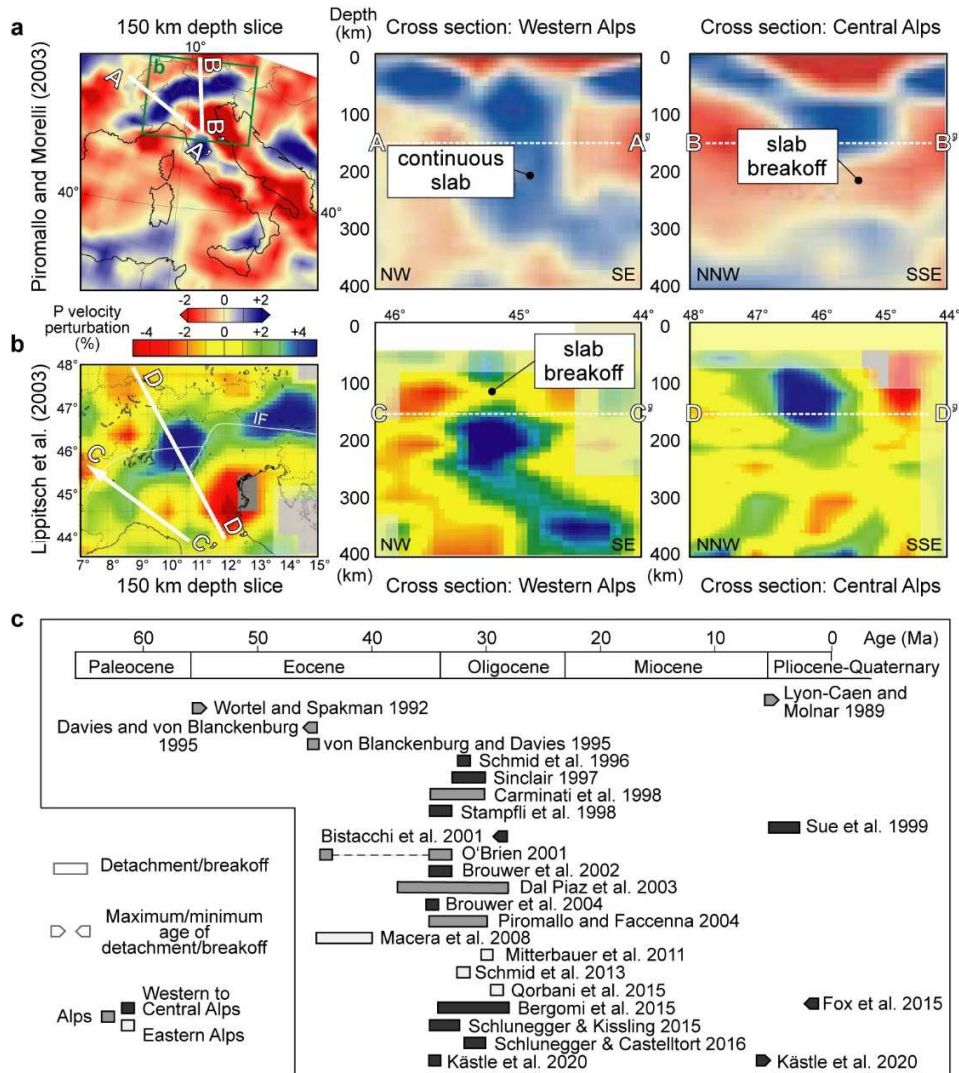
FIGURE 2



**Figure 2.** Crustal structure of the northern Western Alps as imaged prior to the CIFALPS passive seismic experiment. **a:** Line drawing of the ECORS-CROP vertical seismic reflection profile (after [Nicolas et al. 1990](#); see location in [Fig. 1b](#)) (TWT = two-way travel time). The European lower crust (ELC) beneath the European foreland, and the top of the Adriatic mantle (AM) beneath the Ivrea zone are clearly imaged, as well as the SE-dipping Frontal Pennine Fault (FPF) and the Po Plain basin fill. To the east of the FPF, no European Moho is imaged beneath the Alpine subduction wedge. **b:** ECORS-CROP wide-angle reflection seismic profile (same location as profile in “a”) and inferred Moho-like reflectors (thick blue lines, after [Thouvenot et al. 1990](#)). Note the reflector with Moho characteristics imaged beneath the Gran Paradiso at ~25-35 km depth, and the European Moho imaged farther west beneath the frontal part of the Alpine metamorphic wedge. **c:** Migrated ECORS-CROP seismic reflection profile based on the common tangent method (CTM, after [Thouvenot et al. 1996](#)) as reinterpreted by [Schmid and Kissling \(2000\)](#): the reflectors at ~25-35 km depth beneath the Gran Paradiso dome would not mark the top of a mantle slice, as proposed by [Nicolas et al. \(1990\)](#), but the interface between upper and lower European crust; the reflectors located at 10-15 km depth beneath the Gran Paradiso would mark the Valais suture zone (VsZ). ALC = top of the Adriatic lower crust beneath the Po Plain. **d:** Geologic cross-section along the ECORS-CROP traverse as proposed by [Schmid et al. \(2004\)](#), compared with the main

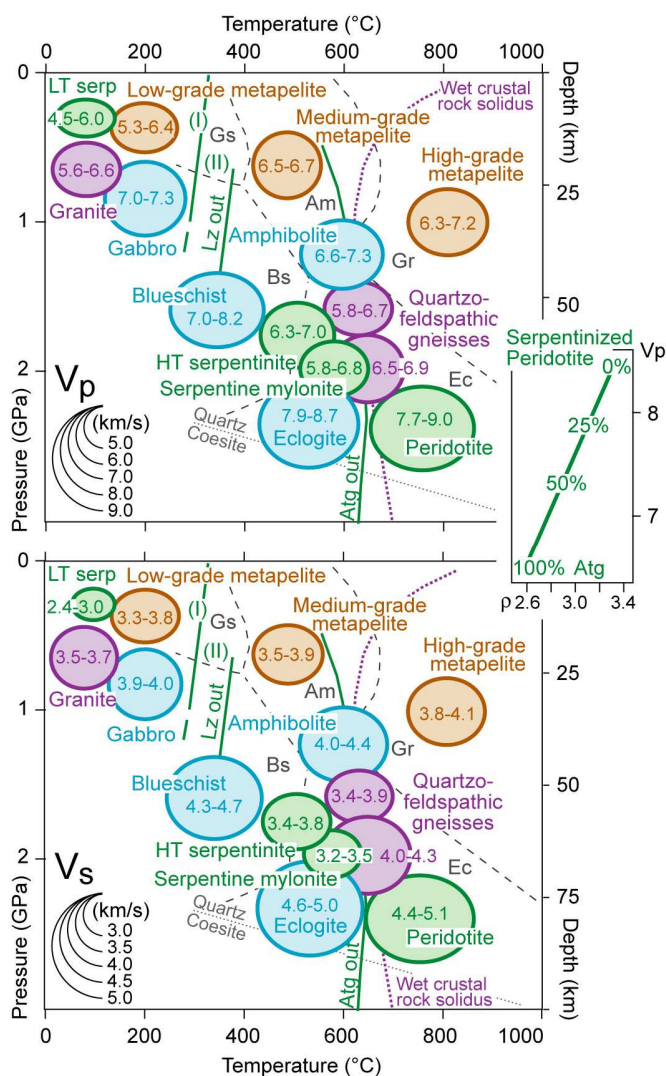
interfaces detected by the wide-angle seismic experiment (dashed blue lines). Below the dashed red line, where the cross-section proposed by Schmid et al. (2004) is masked, no constraint is provided by vertical reflection seismics. **e**: Nappe structure in the northern Western Alps according to the pre-plate-tectonics reconstruction of Argand (1911), showing six major and laterally continuous recumbent folds-nappes (Roman numbers) with crystalline rocks enveloped by Mesozoic metasediments. **f**: Geologic cross-section including the area investigated by the composite NFP-20 West traverse (Frei et al. 1990, see location in Fig. 1b) as proposed by Schmid et al. (2004). Roman numbers (in white) indicate the fold-nappes of Argand (1911). Note the similarities between pre-plate-tectonics (e) and recent (f) tectonic interpretations proposed before the CIFALPS experiment. **g**: P-wave velocity structure (Paul et al. 2001) and geologic cross-section (Lardeaux et al. 2006) along the GeoFrance 3D profile. No constraint was provided by local earthquake tomography below the dashed blue line. See locations in Fig. 1.

FIGURE 3



**Figure 3.** Slab breakoffs beneath the Alps as proposed by previous work. **a:** Teleseismic P-wave tomography model by Piromallo and Morelli (2003), suggesting a continuous slab beneath the Western Alps (A-A') and potential slab breakoff beneath the Central Alps (B-B') (modified after Piromallo and Faccenna 2004; Malusà et al. 2015). **b:** Teleseismic P-wave tomography model by Lippitsch et al. (2003), suggesting shallow slab breakoff beneath the Western Alps (C-C') and a more continuous slab beneath the Central Alps possibly affected by a deeper slab breakoff (D-D') (modified after Schmid et al. 2004); IF, Insubric Fault. **c:** Different ages and sites of slab breakoff/detachment events envisaged in publications on the Alpine region since the late 1980s (modified after Garzanti et al. 2018. Based on: Lyon-Caen and Molnar (1989); Wortel and Spakman (1992); Davies and von Blanckenburg (1995); von Blanckenburg and Davies (1995); Schmid et al. (1996); Sinclair (1997); Carminati et al. (1998); Stampfli et al. (1998); Sue et al. (1999); Bistacchi et al. (2001); O'Brien (2001); Brouwer et al. (2002); Dal Piaz et al. (2003); Brouwer et al. (2004); Piromallo and Faccenna (2004); Macera et al. (2008); Mitterbauer et al. (2011); Schmid et al. (2013); Bergomi et al. (2015); Fox et al. (2015); Qorbani et al. (2015); Schlunegger and Kissling (2015); Schlunegger and Castelltort (2016); Kästle et al. (2020).

FIGURE 4

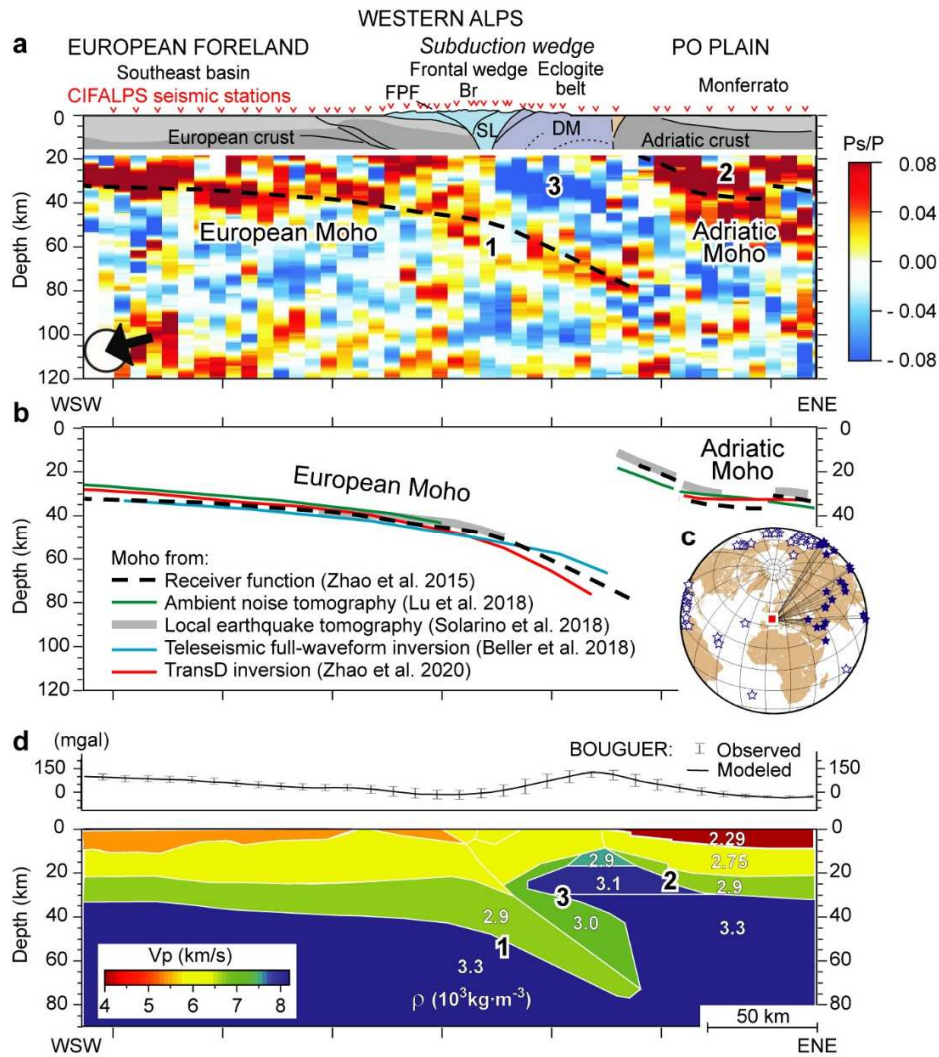


**Figure 4:** Measured  $V_p$  and  $V_s$  ( $\text{km s}^{-1}$ ) for different rock types possibly involved in the Alpine subduction zone (green = ultramafic; blue = mafic; purple = granitic; brown = pelitic) at ambient conditions. The size of the ellipses is proportional to the maximum and minimum seismic velocities; ellipse location depends on the pressure-temperature range at equilibrium for each rock type. The dashed grey lines indicate the metamorphic facies boundaries (Am = Amphibolite; Bs = Blueschist; Ec = Eclogite; Gr = Granulite; Gs = Greenschist). Antigorite (Atg) stability fields after [Hilairt et al. \(2006\)](#); lizardite (Lz) stability fields after [Evans et al. \(2004\)](#) (I - Onset of Lz destabilization into Atg) and [Schwartz et al. \(2013\)](#) (II - Maximal stability limit of Lz observed in natural serpentinites); wet crustal-rock solidus after [Schmidt et al. \(2004\)](#). Note the progressive increase in  $V_p$  and  $V_s$  with depth and metamorphic grade in pelitic, granitic and mafic rocks, and the sharp change in  $V_p$  and  $V_s$  across the Atg-out curve in ultramafic rocks.  $V_p$  variations for partially serpentinitized peridotite at depths greater than 15–20 km, where Atg is stable, are shown on the right (after [Reynard, 2013](#)). Data sources: LT and HT serpentinite after [Ji et al. \(2013\)](#) (the  $V_s$  lower bound for antigorite serpentinitite is calculated from single-crystal elastic data, and is

referred to Reuss approximation and 2 GPa, [Bezacier et al., 2013](#)); HT serpentine mylonite after [Watanabe et al. \(2011\)](#); peridotite after [Khazanehdari et al. \(2000\)](#) and [Pera et al. \(2003\)](#), as compiled by [Bezacier et al. \(2010\)](#); gabbro, blueschist and eclogite after [Bezacier et al. \(2010\)](#); amphibolite after [Brownlee et al. \(2011\)](#); granite after [Rudnick and Fountain \(1995\)](#) and [Khazanehdari et al. \(2000\)](#); quartzo-feldspathic gneiss after [Kern et al. \(2002\)](#) and [Brownlee et al. \(2011\)](#) (the  $V_p$  and  $V_s$  ranges of 6.5-6.9 and 4.0-4.3 km s<sup>-1</sup> are based on calculations for modeled rocks at 700°C and 2 GPa); low-grade metapelite after [Ji et al. \(2015\)](#); medium-grade metapelite (kinzigite) after [Khazanehdari et al. \(2000\)](#); high-grade metapelite after [Weiss et al. \(1999\)](#) and (stronalite) [Khazanehdari et al. \(2000\)](#).



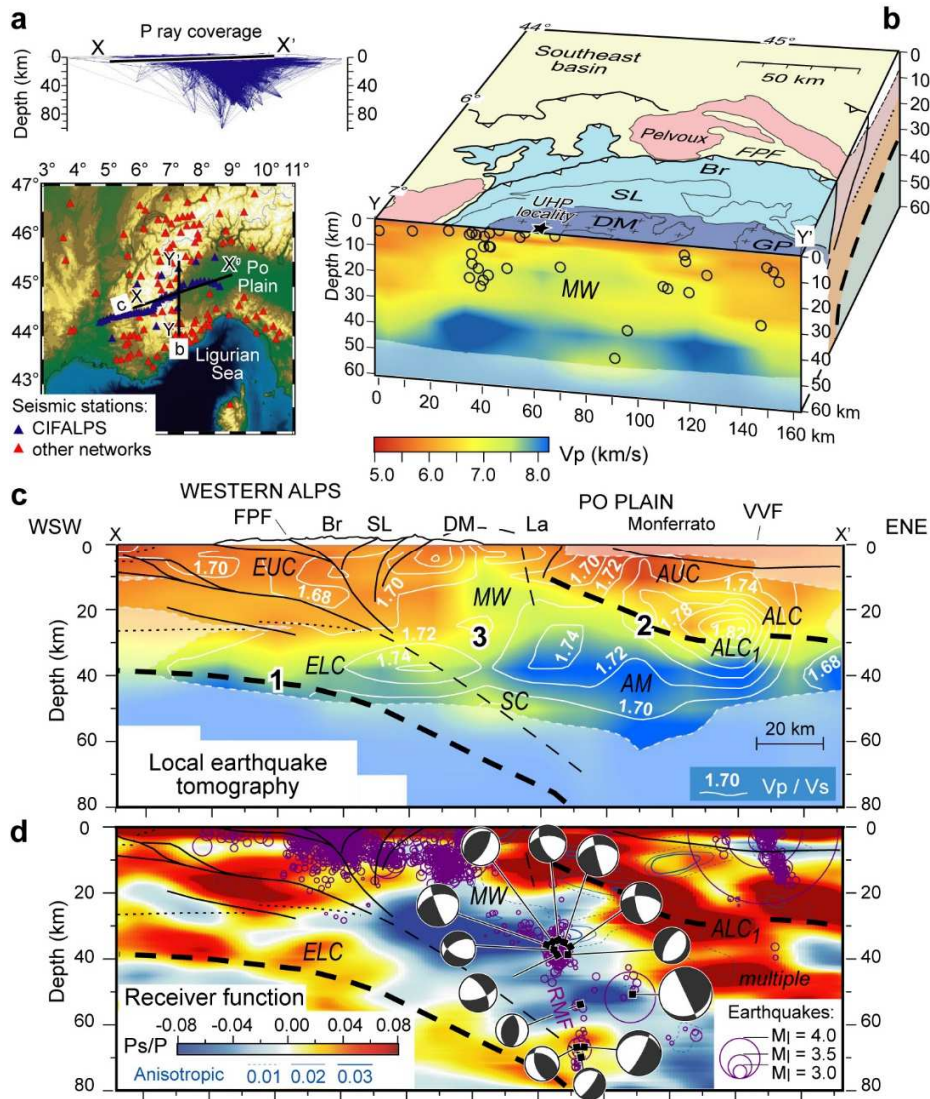
FIGURE 5



**Figure 5.** Moho imaging by receiver function (RF) analysis. **a:** Raw migrated CCP (common conversion point) depth section without horizontal smoothing, using receiver functions corresponding to ENE back-azimuths ( $28^{\circ}$ - $118^{\circ}$ , black arrow on the bottom-left) (after [Zhao et al. 2015](#)), and inferred Moho depth (dashed black lines). The European Moho (1) is continuously marked by Ps-conversions with positive polarity (red to yellow colors), dipping towards the east from  $\sim 40$  km depth beneath the Frontal Pennine Fault (FPF) to  $\sim 75$  km depth beneath the westernmost Po Plain (note the progressive weakening, from red to yellow colors, of this converted phase beneath the Alpine subduction wedge). The Adriatic Moho (2) is marked by shallower positive-polarity Ps-conversions from 10-15 km depth to the west to 20-30 km depth to the east. The negative polarity conversions beneath the Dora-Maira (3, in blue) mark a downward velocity decrease at 20-40 km depth. Acronyms as in [Fig. 1](#). **b:** Comparison with Moho depths as later constrained by other geophysical methods: ambient noise tomography - [Lu et al. 2018](#); local earthquake tomography - [Solarino et al. 2018](#) (see [Fig. 6](#)); teleseismic full-waveform inversion - [Beller et al. 2018](#); transdimensional inversion of Rayleigh wave dispersion data - [Zhao et al. 2020](#)

(see Fig. 7). Note the good consistency of the results despite the different techniques and datasets used. **c**: Locations of teleseismic events used in RF analysis (the blue stars mark events with ENE back-azimuths considered for image (a)). **d**: Velocity and gravity model of the CIFALPS cross section (density values in white) utilized by [Zhao et al. \(2015\)](#) to test the interpretation of the CCP section that fits the Bouguer anomaly data.

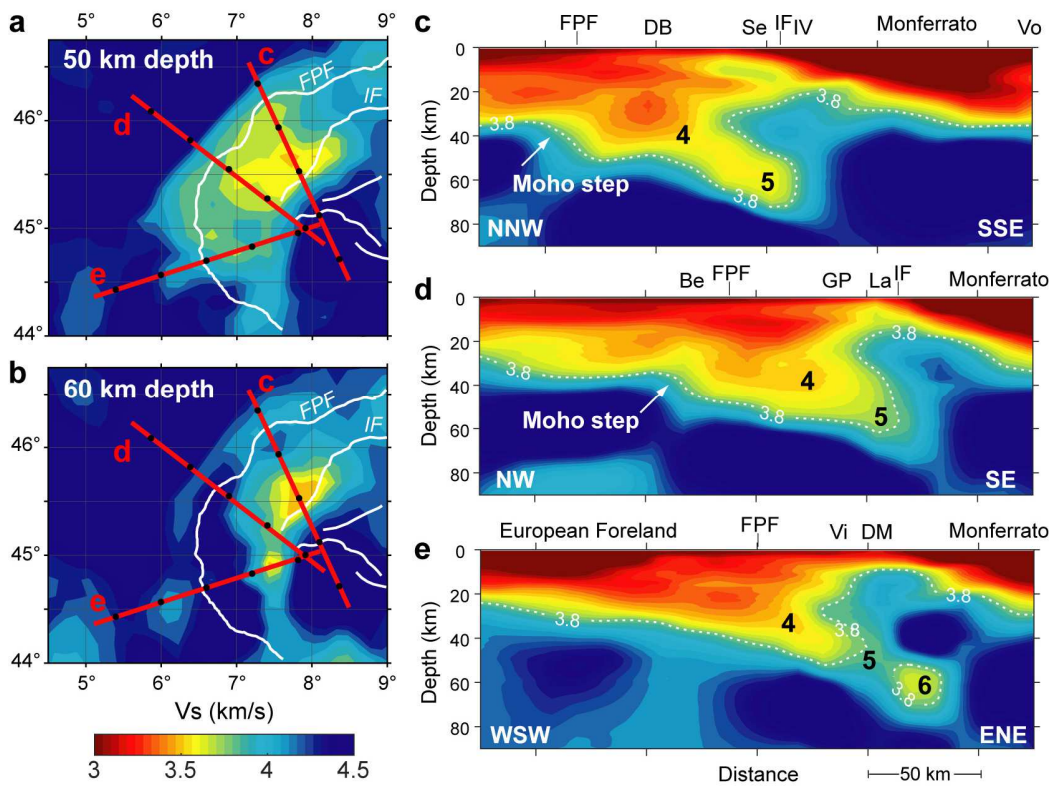
FIGURE 6



**Figure 6.** Crustal and mantle-wedge P velocity structure by local earthquake tomography (LET) (after Solarino et al. 2018). **a:** P ray coverage and location of stations used for LET. **b:** Absolute Vp along a N-S tomographic cross section across the Dora-Maira UHP locality (black star). Note the high-velocity body interpreted as serpentinized mantle wedge (MW); the black circles are projected hypocentres located within  $\pm 3$  km distance off the profile (masked areas have resolution diagonal elements  $< 0.1$ ). **c:** WSW-ENE tomographic cross section along the CIFALPS transect (white lines are isolines of equal Vp/Vs). The black lines indicate tectonic features previously inferred from receiver function (RF) analysis and already indicated in Fig. 5a. Acronyms in italics indicate regions of the model discussed in the main text: ALC and ALC<sub>1</sub>, Adriatic lower crust; AM, Adriatic mantle; AUC, Adriatic upper crust; ELC, European lower crust; EUC, European upper crust; MW, serpentinized mantle wedge. **d:** Smoothed RF cross section for the same transect shown in (c), also including the amplitude of RF anisotropic component from azimuthal harmonic decomposition (blue contours, Piana Agostinetti et al. 2017), earthquakes (in purple) plotted from

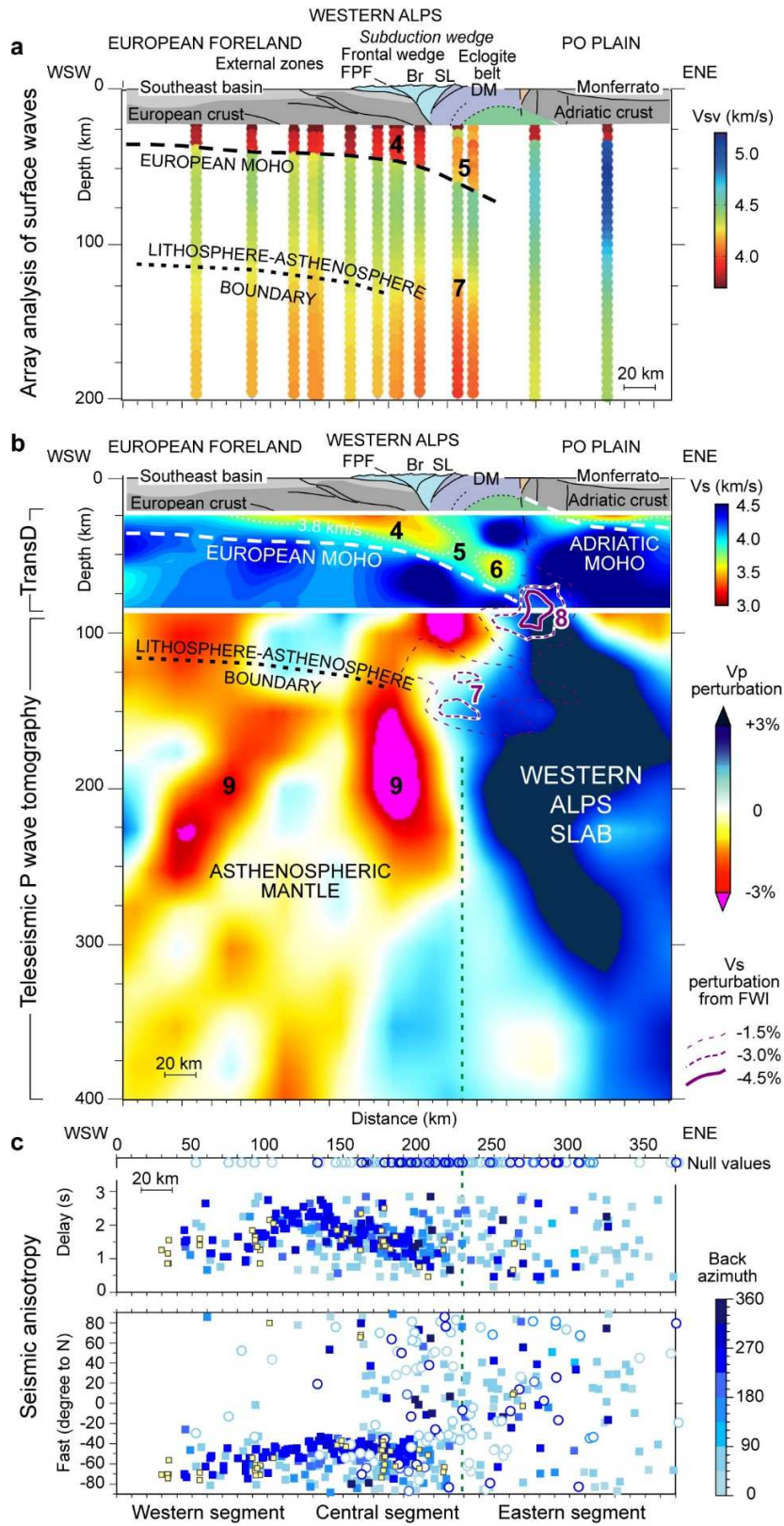
$\pm 20$  km distance off the profile, and focal solutions for events deeper than 30 km (beach balls in grey, after [Malusà et al. 2017](#)). Note the consistency between structures imaged by the analysis of local (c) and teleseismic (d) events. RMF, Rivoli-Marene Deep Fault. Other acronyms as in [Fig. 1](#).

FIGURE 7



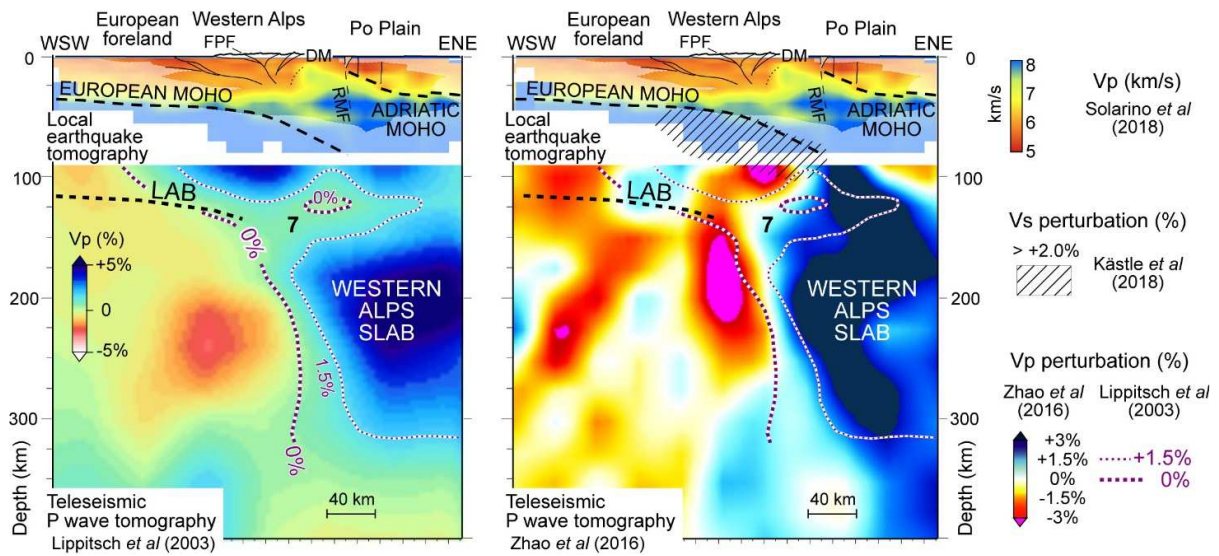
**Figure 7:** S velocity structure of the crust and the mantle wedge as revealed by Bayesian transdimensional (TransD) inversion of Rayleigh wave dispersion data (after Zhao et al. 2020). **a-b:** Depth slices of the Vs tomography model at 50 and 60 km depth. **c-e:** Inversion results showing absolute Vs in the 0-90 km depth range along the NFP-20 West (c), ECORS-CROP (d) and CIFALPS (e) cross-sections. The white dashed isovelocity lines indicate  $V_s = 3.8 \text{ km s}^{-1}$ . Numbers 4-to-6 indicate regions of the model discussed in the text (acronyms as in Fig. 1). The white arrow in (d) indicates a major ( $\sim 8 \text{ km}$ ) Moho step beneath the western front of the Belledonne massif (Be), first highlighted by Lu et al. (2018). A similar Moho step is observed in (c) in correspondence with the Frontal Pennine Fault (FPF). Note the sharp Vs decrease at  $\sim 60 \text{ km}$  depth along cross-section (e), which is not observed along cross-sections (c) and (d).

FIGURE 8



**Figure 8.** Upper mantle velocity structure along the CIFALPS transect. **a:** Absolute  $V_s$  based on array analysis of seismic surface waves (after [Lyu et al. 2017](#)); numbers in bold indicate regions of the model discussed in the main text. Acronyms as in [Fig. 1](#). **b:** Composite cross section showing, in the upper panel (20-90 km depth), the absolute  $V_s$  values (in  $\text{km s}^{-1}$ ) based on Bayesian TransD inversion of surface-wave dispersion data ([Zhao et al. 2020](#)) and, in the lower panel (90-400 km depth), the  $V_p$  perturbations (in %) based on teleseismic P-wave tomography ([Zhao et al. 2016b](#)); lithosphere-asthenosphere boundary as in (a). Purple lines are isolines of equal  $V_s$  anomaly (relative to the preliminary reference Earth model of [Dziewonski and Anderson, 1981](#)) as derived from teleseismic full-waveform inversion (FWI, [Beller et al. 2018](#)). Numbers 4-to-9 indicate regions of the model discussed in the main text. All of the anomalies discussed in the original publications are indicated. The European lithosphere in the upper panel is directly connected with the steeply dipping Western Alps slab (in blue) in the lower panel. A prominent low-velocity anomaly (yellow to red colors in the lower panel) is located to the west of the Western Alps slab, beneath the core of the Western Alps and the European foreland. **c:** Distribution of delay times and fast axis orientations of SKS splitting measured in a 60-km wide swath profile along the CIFALPS transect. In blue are splitting measurements from [Salimbeni et al. \(2018\)](#) (color coded according to the back-azimuth), in yellow are splitting measurements pre-dating the CIFALPS experiment (from [Barruol et al. 2004, 2011](#); [Salimbeni et al. 2008, 2013](#)). Null measurements (empty circles) are plotted as fast axes parallel to the back-azimuth and  $dt > 3$  s. Note the sharp change in fast axis orientation and delay time across the dashed green line, which reflects a major change in upper mantle structure as shown in (b). In the western and central segments of the CIFALPS profile, delay times are lower in correspondence of stronger low- $V_p$  perturbations.

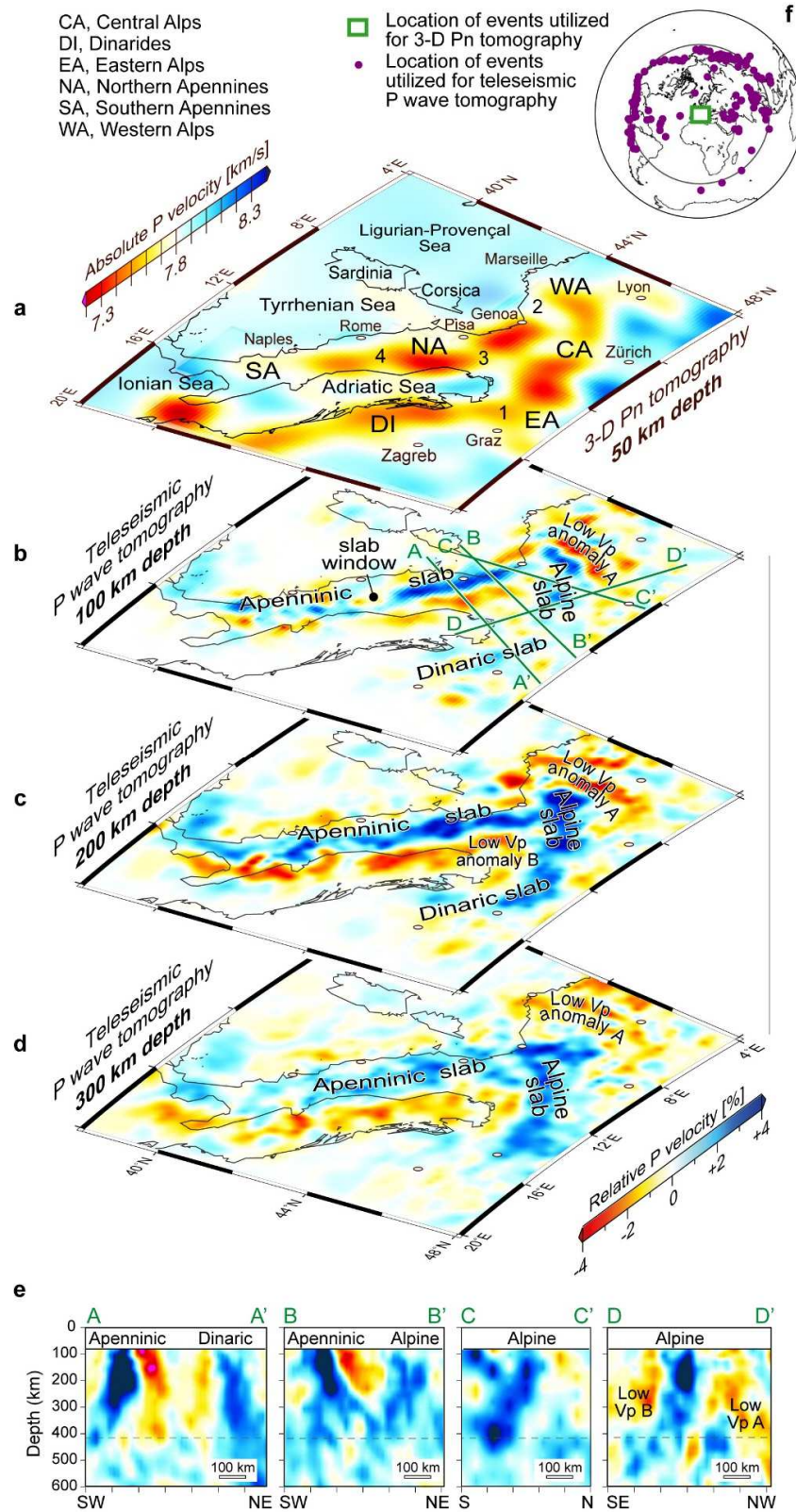
FIGURE 9



**Figure 9:** Comparison of upper mantle  $V_p$  perturbations beneath the CIFALPS transect according to the teleseismic P-wave tomography models of [Lippitsch et al. \(2003\)](#) (left) and [Zhao et al. \(2016b\)](#) (right). Absolute  $V_p$  values in the 0-60 km depth range are from [Solarino et al. \(2018\)](#) (see [Fig. 6](#)). Note the good correspondence between the high velocity anomaly detected by [Zhao et al. \(2016b\)](#) (in blue on the panel to the right) and the first-order features of the [Lippitsch et al. \(2003\)](#) model as highlighted by isolines of equal  $V_p$  anomaly (in purple, also reported in the panel to the right for the sake of clarity). Despite the broadly similar velocity structures, either a continuous or broken-off slab was proposed (see text for discussion). The region of positive  $V_s$  perturbation ( $> +2\%$  relative to the preliminary reference Earth model of [Dziewonski and Anderson, 1981](#)) proposed by [Kästle et al. \(2018\)](#) is also reported (black hatched area to the right). Acronyms: DM, Dora-Maira; FPF, Frontal Pennine Fault; LAB, lithosphere-asthenosphere boundary; RMF, Rivoi-Marene Deep Fault.

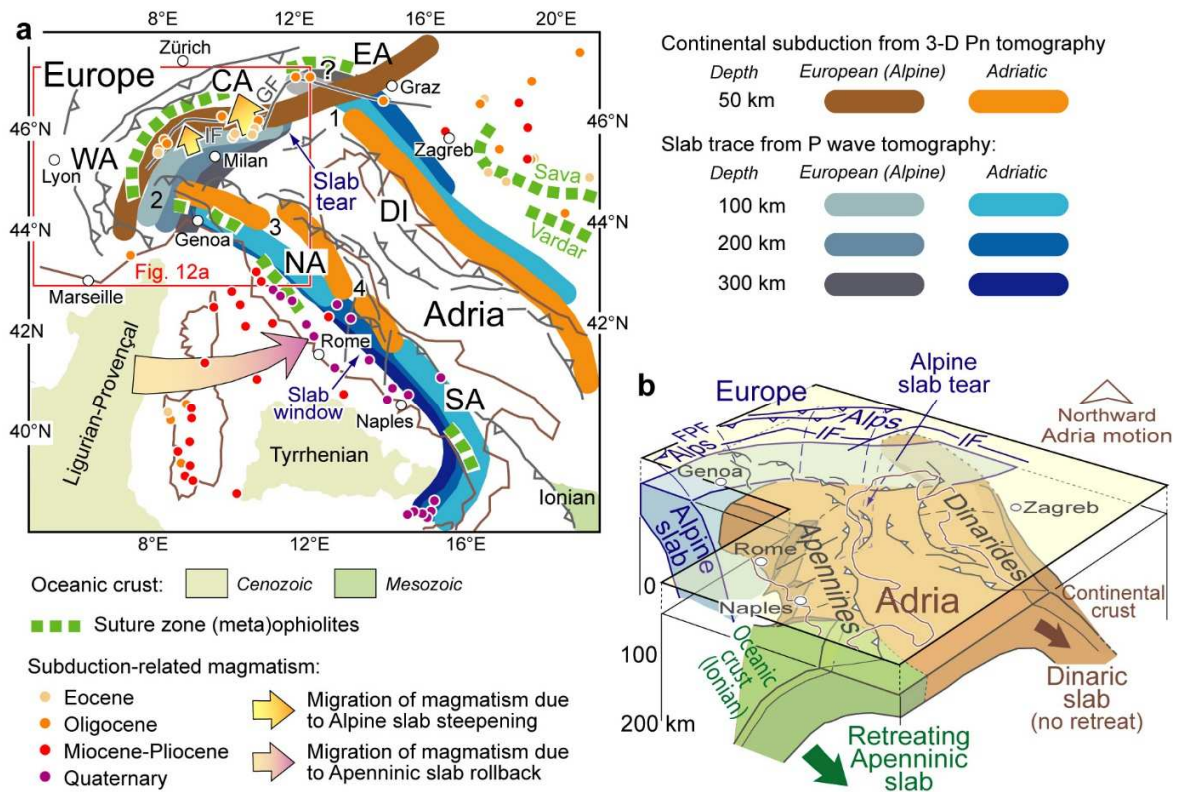


FIGURE 10



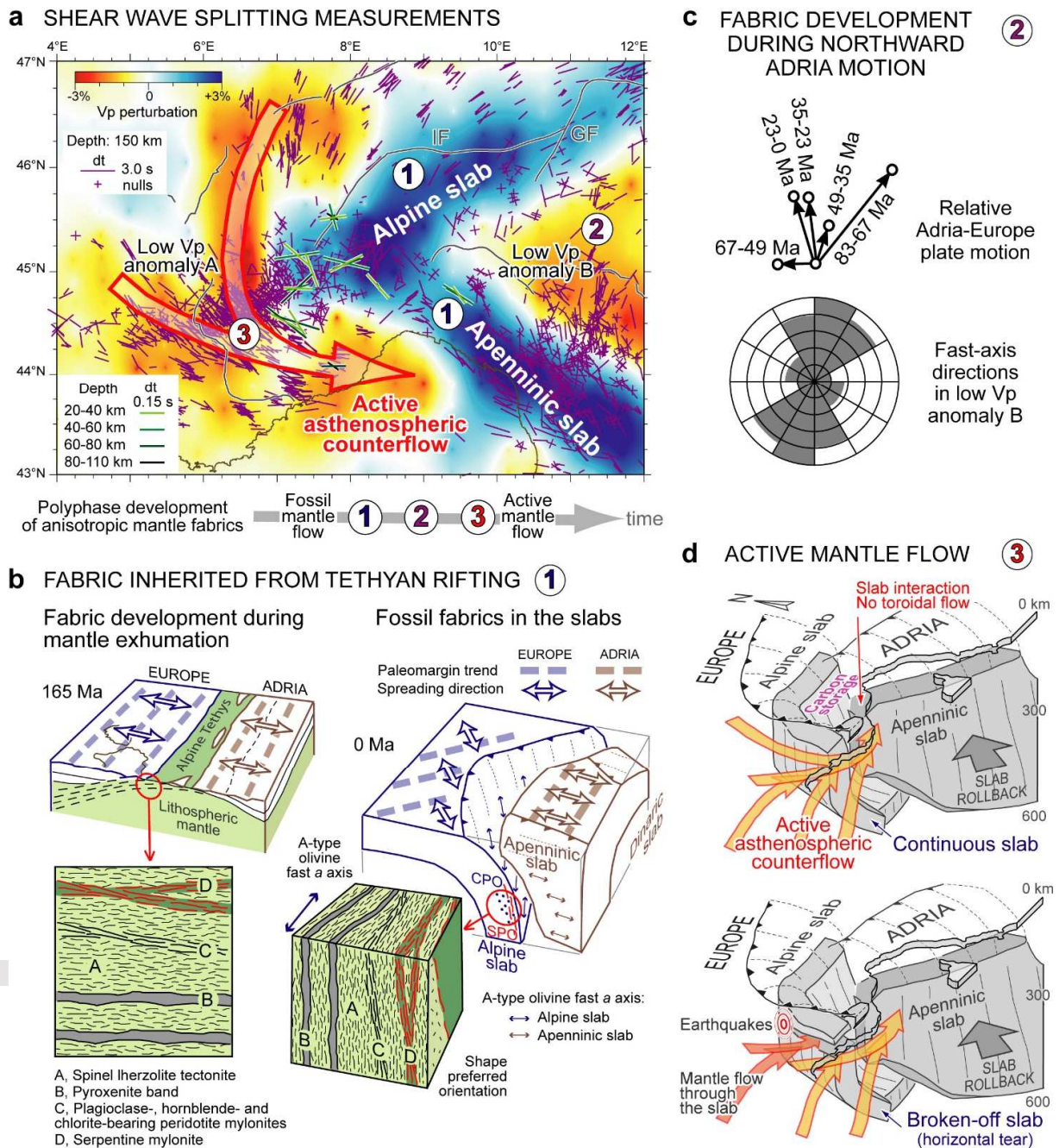
**Figure 10.** Upper mantle velocity structure in the broader Alpine region. **a:** Absolute P velocities at 50 km depth according to the 3-D Pn tomography model of [Sun et al. \(2019\)](#). Belts of yellow-to-orange colors indicate the lateral extent of continental subduction (numbers 1 to 4 indicate features discussed in the main text). **b-d:** Vp anomalies in the teleseismic tomography model of [Zhao et al. \(2016b\)](#) at 100, 200 and 300-km depth. Low-velocity anomalies (A and B, yellow-to-red colors) are detected on both sides of the Alpine slab, which is underlined by a laterally continuous high-velocity anomaly (blue colors). **e:** Representative cross sections (see locations in (b) - green solid lines) of the teleseismic tomography model of [Zhao et al. \(2016b\)](#), showing the attitude of the Alpine, Apenninic and Dinaric slabs. **f:** Seismic events used for the tomography models of [Sun et al. \(2019\)](#) (green box) and [Zhao et al. \(2016b\)](#) (purple dots).

FIGURE 11



**Figure 11.** Interpretive slab structure beneath the Alpine region as constrained by recent tomography studies. **a:** Tectonic sketch map showing the relations among slab structure (Sun et al. 2019), distribution of orogenic magmatism (Carminati and Doglioni 2012; Ji et al. 2019; Kovacs et al. 2007) and accreted (meta)ophiolites (Bigi et al. 1990; Ustaszewski et al. 2008). The present-day slab traces at 100, 200 and 300-km depth are based on the P-wave tomography models of Zhao et al. (2016b) and Piromallo and Morelli (2003) (which was only considered outside of the well-resolved areas of the Zhao et al. (2016b)'s model). Numbers 1 to 4 (same as in Fig. 10a) indicate features discussed in the main text. The question mark indicates the controversial high-velocity anomaly beneath the remnants of the former Alpine subduction zone. IF, Insubric Fault; GF, Giudicarie Fault; other acronyms as in Fig. 10a. **b:** Cartoon summarizing the relationships between the Alpine slab and the Apenninic and Dinaric slabs (modified after Sun et al. 2019).

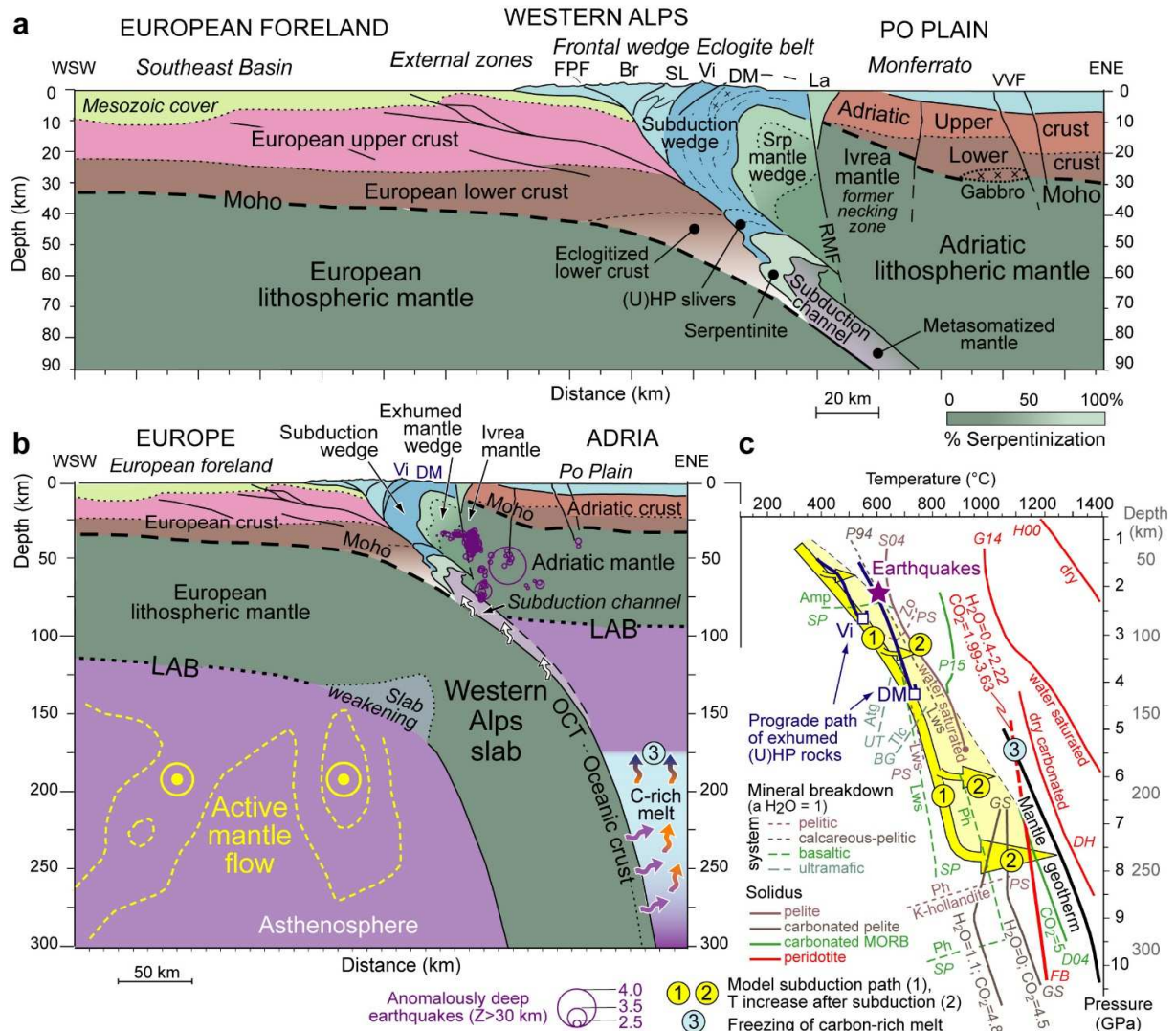
FIGURE 12



**Figure 12.** Polyphase development of anisotropic mantle fabrics in the Alpine region. **a:** Map of single SKS splitting measurements (in purple) (Barruol et al. 2004, 2011; Salimbeni et al. 2008, 2013, 2018) and S-wave anisotropy measurements from local earthquakes (in green) (Baccheschi et al. 2019). Measurements are plotted on the 150-km depth slice of the tomography model of Zhao et al. (2016b) (GF, Giudicarie Fault; IF, Insubric Fault). Segments are parallel to the fast-velocity axis and scaled with delay time (note the different scales for SKS and S waves). Numbers 1 to 3 indicate different anisotropic fabrics as described in (b) to (d): fabric 1 is found in correspondence

with the high Vp anomalies marking the Alpine and Apenninic slabs; fabrics 2 and 3 are from low Vp anomalies B and A, respectively. No toroidal mantle flow is observed around the northern tip of the Apenninic slab. **b**: Anisotropic mantle fabric 1 inherited from Tethyan rifting. To the left, as observed in outcrops of exhumed mantle rocks within the Alpine orogenic wedge (e.g., Erro-Tobbio unit). To the right, expected attitude of fabric 1 in the Alpine and Apenninic slabs, based on the direction of plate spreading, trench orientation (Malusà et al. 2015, 2016b) and slab dip. CPO = crystallographic preferred orientation; SPO = shape preferred orientation. **c**: Fast-axis directions of anisotropic mantle fabric 2 as compared to the direction of relative Adria-Europe plate motion (Dewey et al. 1989; arrows are scaled with distance; numbers indicate the age in Ma). **d**: Alternative slab structures beneath the Alpine region (i.e., continuous vs. broken-off Alpine slab) and expected patterns of active asthenospheric mantle flows resulting from Apenninic slab rollback (fabric 3). Slab breakoff beneath the Western Alps (e.g. Kästle et al., 2020) would imply mantle flow through the slab and anomalously deep earthquakes beneath the northern Po Plain, unlike observed. Note the different origin of the low Vp anomaly A (explained by a vertical component of active asthenospheric counterflow by Salimbeni et al. 2018) and the low Vp anomaly B (explained by the presence of carbon-rich melts released from the Alpine slab by Malusà et al. 2018).

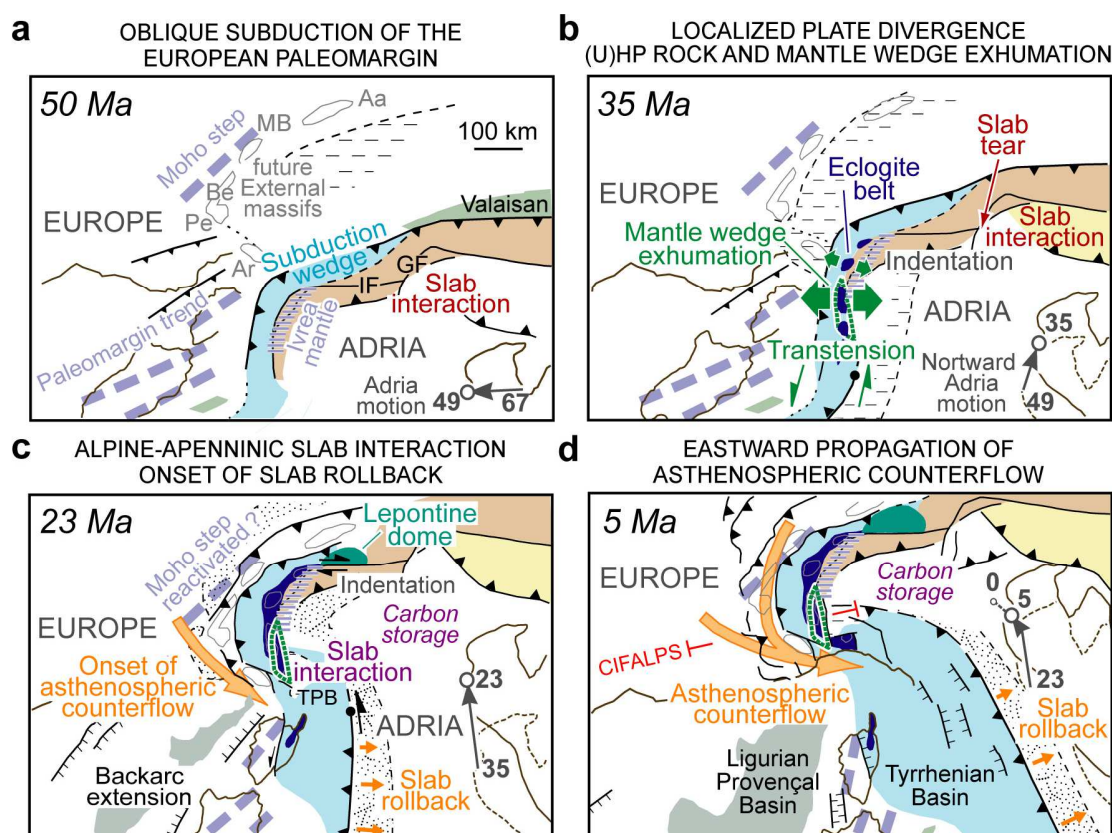
FIGURE 13



**Figure 13.** Geologic cross sections based on geophysical constraints along the CIFALPS transect (Beller et al. 2018; Lyu et al., 2017; Malusà et al. 2017; Salimbeni et al. 2018; Solarino et al. 2018; Zhao et al. 2015, 2016b, 2020). **a:** Lithospheric-scale cross section showing the serpentinized mantle wedge beneath the Dora-Maira (U)HP dome (DM) (Solarino et al. 2018) and the slivers of serpentinite and (U)HP rocks exhumed along the subduction channel (Zhao et al. 2020) (the amount of serpentinization is inferred from seismic velocities, see Fig. 4). The Ivrea mantle, representing the former necking zone of the southern Tethyan margin, is juxtaposed against serpentinized mantle-wedge rocks along the Rivoli-Marene deep Fault (RMF). Other acronyms: Br, Briançonnais; FPF, Frontal Pennine Fault; LA, Lanzo; SL, Schistes lustrés; Vi, Viso; VVF, Villalvernia-Varzi Fault. **b:** Cross section at upper-mantle scale. Active mantle flow beneath the European foreland, likely triggered by Apenninic slab rollback (Salimbeni et al. 2018), promote thermal weakening of the overlying Alpine slab, which is unbroken (Zhao et al. 2016b). Carbon-rich melt released from the Alpine slab may determine supersolidus conditions in the overlying mantle-wedge peridotite, and the resulting network of carbonate-silicate melt is solidified at  $\sim 180$

km depth (Malusà et al. 2018). White arrows indicate potential fluid flow in the subduction channel. Anomalous deep earthquakes with hypocentral depth > 30 km (in purple) mainly originate in the Adriatic lithospheric mantle. Acronyms: OCT, ocean-continent transition; LAB, lithosphere-asthenosphere boundary (after Lyu et al. 2017; Malusà et al. 2018). **c:** Subduction paths in the southern Western Alps and associated mineral reactions (modified after Malusà et al. 2018); depth (y-axis) as in (b); DM, Dora-Maira; Vi, Viso. Cold subduction (yellow path 1, after Syracuse et al. 2010) favours the preservation of carbonates and hydrous minerals to asthenospheric depths. The temperature increase after subduction cessation (2) is consistent with the occurrence of anomalously deep earthquakes in peridotites of the Adriatic upper plate (purple star). Increasing temperatures induce: (i) dehydration reactions with fluids possibly rising along the subduction channel; and (ii) melting of metasediments and carbonated metabasics, with carbon-rich melts that determine supersolidus conditions in the mantle-wedge peridotite, at depth greater than 180 km (freezing point 3). Keys to solidus curves (continuous lines): in brown, wet solidus and second critical end-point of pelite (S04, Schmidt et al. 2004); in grey, carbonated pelite solidi with bulk H<sub>2</sub>O and CO<sub>2</sub> contents in wt% (GS, Grassi and Schmidt 2011); in green, part of the solidus of carbonated basaltic eclogite (D04, Dasgupta et al. 2004) and hydrated and carbonated gabbro (P15, Poli, 2015); in red, solidi of dry peridotite (H00, Hirschmann 2000), water saturated peridotite (G14, Green et al. 2014), dry carbonated peridotite (DH, Dasgupta and Hirschmann 2006) and potassium-rich hydrated carbonated peridotite (FB, as compiled by Grassi and Schmidt 2011). Keys to mineral breakdown curves (dashed lines): parts of amphibole-, zoisite-, lawsonite- and phengite-out curves in basalts (SP, Schmidt and Poli 1998) and pelites/greywakes (PS, Poli and Schmidt, 2002), part of the lawsonite-out curve in a CASH system (P94, Pawley 1994); part of antigorite- and talc-out curves in ultramafic system (UT, Ulmer and Trommsdorff 1999; BG, Bose and Ganguly 1995).

FIGURE 14



**Figure 14.** Cenozoic evolution of the Adria-Europe plate boundary zone in four steps (modified after Malusà et al. 2015) showing the progressive development of crustal and upper mantle structures revealed by geophysical experiments. **a:** 50 Ma – Oblique subduction of the European paleomargin beneath Adria. The European plate includes a Moho step near the future External massifs (likely an inheritance of pre-Alpine tectonics); the Adriatic plate includes the Ivrea mantle (former necking zone of the southern margin of the Tethys). Subduction of Tethys ocean lithosphere is almost completed; the SE-dipping Alpine slab starts interacting with the NE-dipping Dinaric slab. **b:** 35 Ma – Northward Adria motion induces tearing of the Alpine slab beneath the Eastern Alps, indentation of Adriatic lithosphere beneath the Alpine subduction wedge in the Central Alps, and transtension in the Western Alps, leading to mantle-wedge and (U)HP rock exhumation (the exhumed mantle wedge of the southern Western Alps is juxtaposed against the previously exhumed Ivrea mantle). **c:** 23 Ma – Onset of Alpine-Appenninic slab interaction and Appenninic slab rollback inducing extension in the Appenninic backarc. The lack of a toroidal mantle flow around the northern tip of the Appenninic slab starts to be compensated by SE-ward directed counter flow in the asthenospheric mantle beneath the European foreland. The Moho step near the future External massifs is possibly reactivated by flexural loading. Carbon-rich melts are released from the Alpine slab due to progressive thermal re-equilibration of the slab after subduction cessation, carbon starts to be stored in the overlying asthenospheric mantle. **d:** 5 Ma – Further Appenninic slab retreat determines the E-ward propagation of the asthenospheric counterflow towards the Ligurian Alps, with consequent tilting of the Tertiary Piedmont basin (TPB) succession. Other keys as in Fig 1.



**Table 1.** Summary table of the CIFALPS geophysical approaches and main information retrieved

<i>Method</i>	<i>Main information retrieved</i>	<i>Reference</i>
Receiver function analysis	Moho imaging beneath the subduction wedge	Zhao et al. 2015
Teleseismic P-wave tomography	Upper mantle velocity structure and slab configuration	Zhao et al. 2016b
Array analysis of surface waves	Lithosphere-asthenosphere boundary beneath the European plate	Lyu et al. 2017
HypoDD earthquake relocation	Detection of lithospheric faults	Malusà et al. 2017
Receiver function azimuthal harmonic decomposition	Detection of anisotropic rocks in the lithosphere	Piana Agostinetti et al. 2017
Teleseismic full-waveform inversion	Moho imaging and detection of velocity anomalies in the Alpine subduction channel	Beller et al. 2018
Local earthquake tomography	Moho imaging and absolute P-wave velocity structure of the European and Adriatic crust, the uppermost Adriatic mantle and the subduction wedge	Solarino et al. 2018
SKS splitting measurement	Seismic anisotropy due to lattice preferred orientation of olivine crystals in the upper mantle	Salimbeni et al. 2018
S wave splitting of intermediate-depth earthquakes	Seismic anisotropy in the crust and lithospheric mantle	Baccheschi et al. 2019
3-D Pn tomography	Seismic signature of continental subduction	Sun et al. 2019
TransD inversion of Rayleigh wave dispersion data	Moho imaging and absolute S wave velocity structure of the European and Adriatic lithosphere, the subduction wedge and the subduction channel	Zhao et al. 2020