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Mantle wedge exhumation beneath the Dora-Maira (U)HP dome unravelled by local earthquake tomography (Western Alps)

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Abstract

In continental subduction zones, the behaviour of the mantle wedge during exhumation of (ultra)high-pressure [(U)HP] rocks provides a key to distinguish among competing exhumation mechanisms. However, in spite of the relevant implications for understanding orogenic evolution, a high-resolution image of the mantle wedge beneath the Western Alps is still lacking. In order to fill this gap, we perform a detailed analysis of the velocity structure of the Alpine belt beneath the Dora-Maira (U)HP dome, based on local earthquake tomography independently validated by receiver function analysis. Our results point to a composite structure of the mantle wedge above the subducted European lithosphere. We found that the Dora-Maira (U)HP dome lays directly above partly serpentinized peridotites (Vp ~7.5 km/s; Vp/Vs = 1.70-1.72), documented from ~10 km depth down to the top of the eclogitized lower crust of the European plate. These serpentinized peridotites, possibly formed by fluid release from the subducting European slab to the Alpine mantle wedge, are juxtaposed against dry mantle peridotites of the Adriatic upper plate along an active fault rooted in the lithospheric mantle. We propose that serpentinized mantle-wedge peridotites were exhumed at shallow crustal levels during late Eocene transtensional tectonics, also

triggering the rapid exhumation of (U)HP rocks, and were subsequently indented under the Alpine metamorphic wedge in the early Oligocene. Our findings suggest that mantle-wedge exhumation may represent a major feature of the deep structure of exhumed continental subduction zones. The deep orogenic levels here imaged by seismic tomography may be exposed today in older (U)HP belts, where mantle-wedge serpentinites are commonly associated with coesite-bearing continental metamorphic rocks.

Keywords: continental subduction; ultra-high-pressure metamorphism; mantle wedge exhumation; peridotite serpentinization; local earthquake tomography; Western Alps

Highlights:

- High-resolution image of the seismic velocity structure of the Alpine mantle wedge
- First geophysical evidence of mantle-wedge exhumation during continental subduction
- Mantle wedge exhumation is favoured by upper plate divergent motion

1. Introduction

Exhumed (ultra)high-pressure [(U)HP] rocks bear compelling evidence of the interaction between subducting plates and the overlying mantle wedge (Carswell and Compagnoni, 2003; Hacker et al., 2006; Ferrando et al., 2009; Scambelluri et al., 2010; Deschamps et al., 2013; Gilotti, 2013). However, the role played by the mantle wedge during (U)HP rock exhumation is still poorly understood. Some numerical models point to a negligible mantle involvement during exhumation (Yamato et al., 2008; Butler et al., 2013), whereas other models suggest that mantle rocks may be strongly involved, and may follow the exhumation path of buoyant (U)HP rocks towards the Earth's surface (Schwartz et al., 2001; Petersen and Buck, 2015). The behaviour of the mantle wedge during (U)HP rock exhumation may thus provide a key to discriminate among competing exhumation models (e.g., Agard et al. 2009; Guillot et al., 2009a; Liou et al., 2009; Warren, 2013).

In the Cenozoic metamorphic belt of the Western Alps, the geologic record of subduction and exhumation is exceptionally well preserved (e.g., Lardeaux et al., 2006; Malusà et al., 2011), but a high-resolution image of the mantle wedge is still lacking. A detailed analysis of the seismic velocity structure beneath the Dora-Maira (U)HP dome, where coesite attesting deep continental subduction was first described three decades ago (Chopin, 1984), may thus provide new insights on the ongoing debate concerning the mechanisms triggering the exhumation of (U)HP rocks (e.g., Jolivet et al., 2003; Schwartz et al., 2001; Agard et al., 2009; Little et al., 2011; Butler et al., 2013; Malusà et al., 2015; Ducea, 2016). Moreover, this kind of analysis may provide new interpretation keys to understand the field relationships between mantle-wedge rocks and continental (U)HP rocks in deeply unroofed pre-Cenozoic orogenic belts (e.g., van Roermund, 2009; Scambelluri et al., 2010), where the geophysical record of subduction and exhumation is no longer preserved (e.g., Zhao et al. 2017).

In this article, we exploit a comprehensive seismic dataset, also including anomalously deep earthquakes (Eva et al., 2015), to derive a local earthquake tomography model of the mantle wedge beneath the Dora-Maira (U)HP dome, which is then compared with the results provided by receiver function analysis along the CIFALPS transect (China-Italy-France Alps seismic survey; Zhao et al., 2015). Our results indicate that part of the mantle wedge was metasomatized above the Alpine subduction zone, and subsequently exhumed at shallow depth beneath continental (U)HP rocks now exposed at the surface. This suggests that mantle-wedge exhumation may be a prominent feature of the deep structure of many (U)HP belts, which should be integrated in future theoretical models of continental subduction and (U)HP rock exhumation.

2. Tectonic framework

2.1 The orogenic wedge of the southern Western Alps

The Western Alps are the result of oblique subduction of the Alpine Tethys under the Adriatic microplate since the Late Cretaceous, followed by continental collision between the Adriatic and

European paleomargins during the Cenozoic (Coward and Dietrich, 1989; Dewey et al., 1989; Lardeaux et al., 2006; Handy et al. 2010; Malusà et al., 2016a). The resulting slab structure is still largely preserved (Zhao et al., 2016a), as well as the orogenic wedge formed atop the European slab (Lardeaux et al., 2006; Beltrando et al., 2010; Malusà et al., 2011). In the southern Western Alps, along the CIFALPS transect (X-X' in Fig. 1), the Alpine orogenic wedge mainly consists of rocks derived from the Piedmont ocean-continent transition and from the adjoining European paleomargin (Lemoine et al., 1986; Dumont et al., 2012). The external zone, exposed to the west of the Frontal Pennine Fault (FPF in Fig. 1), includes the Pelvoux and Argentera basements and their deformed Meso-Cenozoic sedimentary cover sequences (Ford et al., 2006), which record a transition from thin-skinned to thick-skinned compressional tectonics during the Neogene (Schwartz et al., 2017). East of the Frontal Pennine Fault, in the Alpine metamorphic wedge, the Briançonnais nappe stack (Br in Fig. 1) mainly consists of Upper Paleozoic to Mesozoic metasediments and underlying pre-Alpine basement rocks that underwent subduction starting from the Paleocene, and were later exhumed in the Eocene - early Oligocene (Malusà et al., 2002, 2005a; Ganne et al., 2007; Lanari et al., 2014). The Briançonnais nappe stack forms the core of the present-day Alpine fan-shaped structure (Michard et al., 2004) that was overprinted by a dense network of extensional faults during the Neogene (Sue et al., 2007; Malusà et al., 2009). The eastern part of the fan is formed by oceanic metasediments of the Schistes lustrés complex (SL in Fig. 1; Lemoine et al., 1986; Lagabrielle and Cannat, 1990), including boudinaged decametre-to-kilometre-sized ophiolitic bodies that were deformed and metamorphosed during Alpine subduction under blueschist to transitional blueschist–eclogite facies conditions (Agard et al., 2002; Tricart and Schwartz, 2006; Schwartz et al., 2009) (Fig. 2A). A ductile normal fault (DF1 in Fig. 2A; Ballèvre et al., 1990) separates the Schistes lustrés complex from the Viso metaophiolites (Vi in Fig. 1; Lombardo et al., 1978; Angiboust et al., 2012), representing major imbricated remnants of the Tethyan oceanic lithosphere that were deformed and metamorphosed under eclogite facies conditions during the Eocene (Duchêne et al., 1997; Schwartz et al., 2000; Rubatto and Hermann, 2003). Another ductile normal fault (DF2 in

Fig. 2A; Blake and Jayko, 1990) separates the Viso eclogites from the underlying stack of deeply subducted continental basement slices referred to as the Dora-Maira (U)HP dome (DM in Fig. 1; Henry et al., 1993; Michard et al., 1993), which also includes the coesite-bearing Brossasco-Isasca eclogitic unit (black star in Figs. 1 and 2A; Chopin et al., 1991; Compagnoni and Rolfo, 2003). Along the boundary with the Po Plain, the CIFALPS transect crosses the southern tip of the Lanzo massif (La in Fig. 1; Boudier, 1978; Piccardo et al., 2007), an eclogitized mantle slice separated from the Dora-Maira dome by a near-vertical active fault system rooted in the upper mantle (Rivoli-Marene deep fault - RMF in Fig. 1) at the southward prolongation of the Insubric Fault (Eva et al. 2015; Malusà et al., 2017). The Lanzo massif consists of slightly serpentinized spinel plagioclase peridotites surrounded by a 3–5 km thick envelope of foliated serpentinites (Müntener et al., 2004; Debret et al., 2013), and records a high-pressure metamorphic peak of early Eocene age (Rubatto et al., 2008). Beneath the Po Plain, the complex transition zone between the Adriatic upper plate and the Apennines, also involving rotated fragments of the Alpine orogenic wedge (Maffione et al., 2008; Eva et al. 2015), is mainly covered by thick Cenozoic to Quaternary sedimentary successions.

2.2 The Dora-Maira (U)HP dome

The Dora-Maira (U)HP dome is exposed all along the internal side of the southern Western Alps (Chopin et al., 1991; Lardeaux et al., 2006) (Fig. 1). To the west of Torino, it is juxtaposed against the Lanzo massif along the Lis-Trana deformation zone (Perrone et al., 2010), possibly representing a shallow splay of the Rivoli-Marene deep fault (Eva et al., 2015). To the south, it is partly buried by the sedimentary successions of the Po Plain (Fig. 1), and is exposed as a half-dome including coesite-bearing eclogitic rocks (Brossasco-Isasca unit) sandwiched between quartz-eclogite facies rocks, above, and blueschist facies rocks, below (Compagnoni et al. 1995; Avigad et al., 2003; Compagnoni and Rolfo, 2003) (Fig. 2A). The Brossasco-Isasca unit is a coherent continental crust sliver composed of granitic gneisses (Lenze and Stöckhert, 2007), whiteschists (Chen et al., 2017), mafic eclogites (Groppo et al., 2007) and impure marbles (Ferrando et al., 2017). It was subducted to depths greater than ~100 km by the late Eocene (e.g., Chopin et al., 1991; Rubatto and Hermann, 2001; Hermann, 2003), and was exhumed close to the Earth's surface by the early Oligocene, at rates faster than subduction rates (Rubatto and Hermann, 2001; Malusà et al., 2015), as confirmed by low-temperature thermochronology data (Gebauer et al., 1997; Tricart et al., 2007; Beucher et al., 2012). The overlying quartz-eclogite Venasca *p.p.* and Dronero units, including gneisses and metasediments derived from a Permian-Triassic detrital sequence, and the underlying blueschist-facies Sanfront-Pinerolo unit, consisting of orthogneisses and metasediments intruded by Permian diorites (Avigad et al., 2003), were piled up together with the Brossasco-Isasca and Viso units during late Eocene exhumation (Schwartz et al., 2009; Malusà et al., 2011), to became part of the Eocene Eclogite belt now exposed along the upper-plate side of the Western Alps (Fig. 1), at the rear of a lower-pressure Paleogene wedge (LP in Fig. 2B,C).

The structure and lithologic composition of the orogenic wedge beneath the Dora-Maira (U)HP dome is still largely unknown. The velocity structure provided by available seismic tomography models is well resolved only for the uppermost 15-20 km (Paul et al., 2001; Béthoux et al., 2007). Recent tectonic reconstructions postulated the occurrence of Briançonnais crust slivers down to depths greater than 30 km, and suggested that these slivers would be involved in an east-vergent backfold at the scale of the whole Eclogite belt (Schmid et al., 2017). However, the Dora-Maira dome shows no cartographic evidence of such large-scale backfolding, which is instead observed in the Monte Rosa dome (MR in Fig. 1) of the northern Western Alps, where late backfolding is possibly ascribed to progressive westward shifting of Adria indentation from the Central Alps to the northern Western Alps during the Neogene (Malusà et al., 2016b). As a matter of fact, alternative interpretations of the deep tectonic structure of the southern Western Alps are not adequately supported by geophysical data. This information gap has so far precluded a full understanding of the exhumation mechanisms that were active within the Alpine subduction zone during the late Eocene.

2.3 Exhumation models and implications on the deep orogenic structure

In general terms, exhumation models applied to (U)HP belts can be framed within two different groups, also implying alternative scenarios of mantle involvement: (i) synconvergent exhumation models, either requiring fast erosion or forced circulation in a low-viscosity wedge (e.g., Beaumont et al., 2001; Zeitler et al., 2001; Jamieson and Beaumont, 2013), and (ii) exhumation models that consider boundary divergence within the subduction zone, with a minor role played by erosion (e.g., Dewey, 1980; Brun and Faccenna, 2008). Both categories of models have been applied to the Western Alps (e.g., Malusà et al., 2011; Butler et al., 2013).

Classic tectonic reconstructions of the Alpine belt suggest that synconvergent exhumation could be favoured by deep duplex formation via the accretion of continental material derived from the lower plate (Schmid et al., 2004; Agard et al., 2009), which may be followed by indentation of the upper-plate mantle beneath the accretionary wedge (Schmid and Kissling, 2000; Béthoux et al., 2007). This scenario would imply that seismic velocities in the upper-plate mantle should be similar beneath the orogenic wedge and in the hinterland (Fig. 2B). In case of divergent motion between the upper plate and the descending slab, (U)HP rock exhumation might be instead associated to the emplacement of serpentinized mantle-wedge rocks at shallow depth beneath (U)HP continental rocks, provided that divergence is sufficiently high (Fig. 2C). Because of widespread mantle-wedge serpentinization during subduction (Lafay et al., 2013; Plümper et al., 2017), seismic velocities are predicted to be lower in mantle-wedge rocks beneath the (U)HP dome, and higher in adjoining dry mantle rocks of the upper plate (Fig. 2C).

These alternative scenarios would be in agreement with alternative end-member tectonic reconstructions of the southern Western Alps, based on recent geophysical data from the CIFALPS experiment (Zhao et al., 2016b). One possible end-member reconstruction, consistent with geophysical data, invokes a thick complex of (U)HP continental slivers, in line with predictions of numerical models of syn-convergent exhumation, whereas a second end-member reconstruction invokes a larger volume of mantle rocks possibly exhumed at shallow depth during divergent motion within the subduction zone (Zhao et al., 2015; Malusà et al., 2017). A local earthquake tomography model, complementing previous studies based on receiver function analysis, would be extremely useful to discriminate between these end-member tectonic reconstructions, and may allow a decisive step forward in our understanding of mechanisms leading to exhumation of (U)HP rocks.

3. Methods

3.1. Building the database

The local earthquake tomography presented in this work is largely based on the dataset collected during the CIFALPS experiment (Zhao et al., 2016b), which was integrated by data recorded in the same time interval by permanent seismic networks operating in Italy and France, and complemented with selected older events. The temporary network of the CIFALPS experiment (blue marks in Figure 1B) includes 46 broadband seismic stations 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. Stations operated from July 2012 to September 2013, and were specifically deployed for a direct comparison between receiver function and local earthquake tomography. Stations located along the main profile were conceived for receiver function analysis (Zhao et al., 2015). Their spacing ranges from ~5 km in the Western Alps mountain range to ~10 km in the European foreland and in the western Po Plain. Off profile stations were installed to improve the crossing of seismic rays for local earthquake tomography.

The high number of recording stations along the main CIFALPS profile may increase the computational burden during local earthquake tomography (e.g. in ray tracing) without a direct improvement in the final resolution. However, it ensures a number of advantages. For example, any potential loss of data due to station malfunctioning is easily recovered by adjacent instruments, and doubtful data can be discarded without jeopardizing the quality of the dataset. In order to improve the ray coverage and ensure ray crossing from any azimuth in the study volume, we added to the dataset all published phase pickings recorded by permanent seismic stations operating in France and Italy during the CIFALPS experiment (red marks in Figure 1B). We additionally considered few events that occurred before the experiment to fill specific spatial gaps. This was the case of the intermediate depth earthquakes that were useful to sample anomalies at the bottom of the study volume. Because these earthquakes are relatively rare (Eva et al., 2015), only few events were recorded during the CIFALPS experiment. In summary, 270 events on a total of 1088 events utilized in this work were added as supplementary entries from datasets available at French and Italian seismic networks; about 80% of the remaining events were merged with existing phase pickings. The final P and S ray coverage is shown in Figure 3A.

3.2. Seismic tomography setup and reconstruction test

We adopted the local earthquake tomography code SIMULPS (Thurber, 1983) for tomographic analysis, in its version 14 that implements the ray tracer by Virieux (1991) to cope with models of regional size. We subdivided the study volume into layers containing nodes, and used an initial velocity model derived from previous seismic experiments over a larger area (Scafidi et al., 2009). Several tests were performed for a correct choice of the inversion parameters, and classical damping trade-off curves (Eberhart-Phillips, 1986) were computed to pick up the best values for P and S velocities.

The resolution capability of the coupling between inversion setup and data was evaluated by checkerboard and reconstruction tests. These tests were useful to choose an adequate geometry of the starting model and evaluate the smearing due to the contrast between high and low velocity anomalies. The reconstruction test was specifically conceived to test the potential impact of the high-velocity Ivrea body, a long recognized tectonic feature associated to a positive gravimetric anomaly (red dotted line in Fig. 1) and interpreted as a slice of Adriatic mantle emplaced at shallow depth (Closs and Labrouste, 1963; Nicolas et al., 1990). We used a “stairwell” geometry to simulate a high-velocity east-dipping layer along the CIFALPS profile (Fig. 3B) and test the resolution capability of the coupling between seismic dataset and inversion setup. The same geometry after interpolation by the algorithm used in SIMULPS is shown in Figure 3C. A comparison with Figure 3B shows that the interpolation process introduces a smoothing of the anomalies and a band of fake colors around them. Figure 3D shows the reconstruction of the imposed stairwell structure based on our seismic dataset. The inversion of synthetic data does not consider the resolution, and Figure 3D only displays the reconstructed model as if it was completely resolved except for areas that were not sampled (in white). As shown in the reconstruction test, the shape of the anomaly is well reproduced, but the velocity of the first and second steps is lowered from ~8.0 km/s (blueish) to about ~7.5 km/s (greenish), and weak vertical and horizontal periodic stripes of yellow color appear at ~50 km depth. These artifacts, and the undestimation of the magnitude of the high velocity anomalies in the uppermost 10 km of the crust, have been considered during the subsequent phases of tomography interpretation. The real data tomographic model is about 700×700 km wide, and was obtained after 6 iterations on a 12 layers model of 36×36 nodes each. In the central part of the model, spacing between nodes is equal to 15 km.

4. Results

Figure 4 shows the Vp and Vp/Vs cross-sections along the CIFALPS profile. The lighter areas are those where the diagonal elements of the resolution matrix are <0.1. This threshold was chosen as the divider between resolved and non-resolved areas based on a comprehensive comparisons between different resolution indicators (Paul et al., 2001). As expected, the maximum depth of the resolved area is limited by the depth of occurrence of most of the deepest events (Eva et al., 2015; Malusà et al., 2017). Beneath the Dora-Maira (U)HP dome, the tomography model is well resolved down to 50-60 km depth, whereas the two extremes of the CIFALPS cross section are poorly resolved. Letters “a” to “k” indicate the relevant velocity features highlighted by the tomography model. The main tectonic structures previously inferred from receiver function analysis (Zhao et al.

2015) and surface geology (Lardeaux et al., 2006; Malusà et al., 2015) are also indicated for comparison (black lines in Fig. 4).

The most prominent feature of the tomography model is represented by the high velocity body (Vp ~7.5 km/s; Vp/Vs = 1.70-1.72), labelled with “a”, which is located right below the Dora-Maira (U)HP dome, at depths as shallow as ~10 km. Such a high-velocity body was already imaged with similar velocities by previous works (Vp ~7.4-7.7 km/s; Paul et al., 2001; Béthoux et al., 2007), but was only resolved down to depths of 15-20 km. It is still observed to the south of the CIFALPS profile (Fig. 5D,E), but progressively vanishing towards the north (Fig. 5A,B). A series of N-S cross sections, ranging from the Western Alps to the Po Plain (Fig. 6), shows that this high-velocity anomaly is exclusively found beneath the Dora-Maira (U)HP dome (Fig. 6A), and disappears farther east.

The mantle-wedge region labelled with “b” is located at depth of 20-45 km, in correspondence with a cluster of intermediate depth earthquakes that mark the Rivoli-Marene deep fault (RMF in Fig. 4A; Eva et al., 2015). This region shows higher Vp values (~8.0 km/s) compared to region “a”, and anomalously high Vp/Vs ratios (>1.74) that are supportive of low shear wave velocities. This cluster of intermediate depth earthquakes in region “b” is not only observed along the CIFALPS profile, but also in cross sections located more to the north or to the south (Fig. 5). The deepest mantle wedge region resolved by the tomographic model is labelled with “c”. This region, located at depth of ~40-50 km atop the European slab, shows lower Vp and Vp/Vs values compared to region “b” (Vp ~7.0-7.5 km/s; Vp/Vs < 1.70), but the Vp/Vs ratio is locally higher (Vp/Vs ~1.74).

The well-resolved regions of the model also include some subducted European lower crust. This shows a progressive increase in Vp from the region labelled with “d” (Vp ~6.7 km/s) to the region labelled with “e” (Vp ~7.6 km/s), under a rather constant Vp/Vs ratio of 1.70-1.72. Such variations are detected in all of the analyzed WSW-ENE transects of Figure 5. No seismic event was recorded in regions “d” and “e” since 1990 (installation of permanent seismic networks) and during the CIFALPS experiment (Malusà et al., 2017).

On the eastern side of the transect, the region labelled with “f” is located below the Adriatic Moho as determined by receiver function analysis combined with gravity modelling. It shows Vp values ~8.0 km/s and Vp/Vs = 1.70-1.72. This region is affected by intermediate depth earthquakes that are also observed to the north and to the south of the CIFALPS transect (Fig. 5). The vertical and horizontal periodic stripes of yellow color observed at 50 km depth in this region are artifacts, as confirmed by the reconstruction test of Fig. 3D. Above the Adriatic Moho, measured Vp values are much lower, generally <6.7 km/s, but in places they reach values as high as ~7.2 km/s. Very high Vp/Vs values (>1.8) are locally observed at ~30 km depth at the base of the Adriatic crust. This region, labelled with “g”, is also characterized by a cluster of seismic events that are only observed in the vicinity of the main CIFALPS transect.

In the uppermost part of the Alpine orogenic wedge (regions “h” to “k”), Vp values are invariably <6.5 km/s, but major variations in Vp/Vs ratios are locally observed. For example, the region to the east of the Dora-Maira (U)HP dome (labelled with “h”) shows Vp/Vs values >1.72, whereas the region corresponding to the western flank of the Dora-Maira dome (labelled with “j”) shows much lower Vp/Vs ratios, even <1.66. Vp/Vs ratios <1.68 are also observed in the region labelled with “k”, located beneath the Frontal Pennine Fault. The double-vergence accretionary wedge located to the east of the Frontal Pennine Fault, and labelled with “i”, shows instead Vp/Vs values > 1.75, and includes most of the shallow earthquakes recorded in the Western Alps area.

5. Comparison with receiver function analysis

Results of local earthquake tomography are compared in Figure 7 with published CIFALPS results of receiver function analysis (Zhao et al., 2015). Unlike local earthquake tomography, the receiver function technique is based on the analysis of teleseismic earthquakes, and enhances P-to-S (Ps)-converted waves on velocity interfaces beneath an array. The polarity of the converted signal depends on the sign of the velocity change, and interfaces with velocity increase can be discriminated from interfaces with velocity decrease. Assumptions and arbitrary choices of the receiver function approach applied to the CIFALPS transect (e.g., magnitude threshold, epicentral distance, seismograms filtering, velocity model, choice of the direction of back azimuths) are described in full in Zhao et al. (2015).

The image of Figure 7B is based on radial receiver functions from teleseismic events with magnitude ≥5.5, epicentral distance of 30-90°, and ENE back-azimuths (see Zhao et al., 2015). This image shows two major interfaces marked by positive-polarity Ps-conversions (red-to-yellow regions), which attest the downward velocity increase corresponding to the European and Adriatic Mohos (thick dashed lines). The eastward-dipping European Moho is recognized from ~40 km depth beneath the Frontal Pennine Fault to ~75 km depth beneath the Po Plain. The Adriatic Moho is recognized from 20-30 km depth, to the east, to 10-15 km depth, to the west. The red spots located at 40-55 km depth beneath the Adriatic Moho are multiples, as confirmed by synthetic tests (Zhao et al., 2015). A shallow positive-polarity converted phase is also observed beneath the Dora-Maira massif, between regions “a” and “h”, whereas a spot of negative-polarity Ps-conversions marking a downward velocity decrease is located above region “c”, at 20-40 km depth (blue region).

On the eastern side of the CIFALPS transect, the sharp velocity increase from Vp <6.5 km/s to Vp >8 km/s evidenced by local earthquake tomography faithfully matches the location of the downward velocity increase highlighted by receiver function analysis. Localized anomalies in Vp/Vs ratios, e.g., in region “g”, match with major breaks in the alignment of positive-polarity Ps-conversions. Beneath the Dora-Maira (U)HP dome, the downward increase in Vp values from region “h” (Vp <6.5 km/s) to region “a” (Vp ~7.5 km/s) is consistent with the observed positive-polarity Ps-conversions, whereas the downward velocity decrease from regions “a” and “b” (Vp ~7.5 km/s and >8 km/s) to region “c” (Vp ~7.0-7.5 km/s) is consistent with the spot of negative-polarity Ps-conversions located at 20-40 km depth in Figure 7B. The shape of the high-velocity region labelled with “a” is also mirrored by the distribution of seismic events recorded since 1990. Region “a” is virtually aseismic (Malusà et al., 2017), and earthquakes are chiefly located along its external boundaries or in the surrounding regions (Fig. 7B). On the western side of the CIFALPS transect, the alignment of positive-polarity Ps-conversions generated along the European Moho is partly included within the resolved area of the local earthquake tomography model, and fits with a downward velocity increase from ~6.7 km/s (region "d") to ~7.6 km/s (region "e"). The velocity structure unravelled by the analysis of local earthquakes is thus independently confirmed by the analysis of teleseismic earthquakes (Zhao et al., 2015) and by the distribution of seismic events (Eva et al., 2015; Malusà et al., 2017).

6. Geologic interpretation

The geologic cross section of Figure 7C shows the main features of the orogenic wedge of the Western Alps, and of the mantle wedge between the European and the Adriatic plates, as inferred from the velocity structure derived from local earthquake tomography along the CIFALPS profile. Correlation between seismic velocity and lithology in former subduction zones is a challenging task. Subducted rocks are heterogenous, and display anisotropic fabrics and velocity variations as a function of direction (e.g., Rudnick and Fountain, 1995; Weiss et al., 1999). A full 3D coverage of seismic rays is thus required to get a reliable characterization of the velocity structure (see Fig. 3A).

In the European plate, the Vp values ~6.7 km in region "d" are supportive of a relatively felsic composition of the European lower crust (e.g. Rudnick and Fountain 1995; Weiss et al., 1999; Goffé et al. 2003; Wang et al., 2005; Mechie et al. 2012). The homogeneous Vs values < 4 km/s reported by Lyu et al. (2017) suggest that the European lower crust may be rather homogeneous at the scale of seismic observations, and may consist of granulite having felsic to intermediate composition. Major occurrence of granulitic metapelites can be safely excluded, because it would result in much higher Vp (>6.7 km/s up to 7.2 km/s) and Vs values (~4 km/s; Rudnick and Fountain, 1995).

The increase in Vp values evidenced at ~40 km depth by local earthquake tomography, from ~6.7 km/s in region "d" to ~7.6 km/s in region "e", may mirror a progressive eclogitization of lower crust rocks with consequent density increase by metamorphic phase changes (e.g., Hacker et al., 2003; De Paoli et al., 2012). Mineral equilibria at the granulite-eclogite transition depend on rock composition. The eclogitization of a felsic granulite strongly increases the garnet content, and consequently the density from 2.90 to 3.30 kg/dm^3, and the P velocity up to a maximum of 7.6 km/s (e.g., Christensen, 1989; Hacker et al., 2003, 2015; Hacker and Abers, 2004; Hetényi et al., 2007). These values are consistent with the Vp values observed in region "e”. The increase in P velocity from region “d” to region “e” is associated with a progressive increase in S velocity up to 4.2 km/s (Lyu et al., 2017), which may be either interpreted as an increase in mafic component, or as an effect of metamorphic reactions under increasing pressure-temperature conditions. However, Vp values in region “e” are far too low for a pure mafic eclogite (Bezacier et al., 2010; Reynard, 2013), thus suggesting no major compositional changes from west to east in the European lower crust, but only a progressive change in metamorphic assemblage during subduction. This interpretation also explains the progressive weakening of the positive-polarity converted phases observed along the European Moho, from red to yellow background colours in Fig. 7B, as previously described by Zhao et al. (2015).

On the eastern side of the Western Alps, Vp values >8 km/s confirm the presence of Adriatic mantle at shallow depth beneath the western Po Plain (10-15 km), just in correspondence with the positive gravimetric anomaly classically referred to as the Ivrea body (Closs and Labrouste, 1963; Nicolas et al., 1990) and in line with results of previous tomographic models (e.g., Solarino et al., 1997; Paul et al., 2001; Scafidi et al., 2006; 2009; Diehl et al., 2009; Wagner et al., 2012). East of the Ivrea body gravimetric anomaly, the Adriatic Moho is located at 30-35 km depth, which is a much more reliable estimate of the Moho depth beneath the Po Plain compared to previous estimates based on receiver function alone (Zhao et al., 2015). The locally high Vp/Vs ratios >1.8, associated to Vp of 7.0-7.5 km/s (region “g”), may be supportive of gabbro (Weiss et al., 1999) underplated at the base of the Adriatic lower crust. Noteworthy, Permian gabbros are indeed exposed north of the Po plain, where they are intruded into lower crust rocks belonging to the

Adriatic (Southalpine) basement (Quick et al., 1994; Schaltegger and Brack, 2007). Above the Adriatic Moho, local spots with Vp ~7.2 km/s but low Vp/Vs ratios (Fig. 5) are supportive of a more heterogeneous composition of the Adriatic lower crust compared to the European lower crust, and may suggest a local occurrence of granulite facies metapelites (Vp 6.7-7.2 km/s, Vs ~4 km/s; Rudnick and Fountains, 1995) not only at the surface (e.g., Ewing et al., 2014), but also at depth. Differences in velocity structure among crustal sections now exposed on the opposite sides of the Alps probably reflect a different pre-Alpine evolution, rather than processes related to the Cenozoic evolution of the Adria-Europe plate boundary zone (Guillot et al., 2009b; Carosi et al., 2012; Bergomi et al., in review).

In the uppermost part of the Alpine wedge, the structural variability of stacked rocks is largely mirrored by their variability in Vp/Vs ratios. The Vp/Vs values >1.75 observed in the double-vergence accretionary wedge chiefly including Briançonnais and Schistes lustrés units (Lardeaux et al., 2006), may reflect low Vs values, possibly associated to the widespread network of mesoscale faults developed in these rocks since the Neogene (Tricart et al., 2004; Sue et al., 2007; Malusà et al., 2009). To the east, low Vp/Vs values even <1.66 observed on the western flank of the Dora-Maira dome (region “j”) may instead reflect high Vs velocities, suggesting that the poorly fractured granitic gneisses exposed at the surface (Brossasco granite; Paquette et al., 1999; Lenze and Stöckhert, 2007) may be also present at depth. Fracturing may be also invoked to explain the low Vs values observed along the eastern boundary of the Dora-Maira dome, where (U)HP continental rocks are juxtaposed against the eclogitized mantle rocks of the Lanzo massif (Kienast and Pognante, 1988; Piccardo et al., 2007) along the Lis-Trana deformation zone (Perrone et al., 2010). To the west of the Frontal Pennine Fault, Vp/Vs values <1.68 suggest instead that the European upper crust in the External zones is poorly deformed, consistent with minor seismicity recorded in that area (Fig. 7B).

But the most relevant results of the tomography model presented in this work is related to the velocity structure beneath the Dora-Maira (U)HP dome. This information is critical to discriminate between contrasting models of (U)HP rock exhumation (Malusà et al., 2011, 2015; Jamieson and Beaumont, 2013), and to discern between end-member tectonic reconstructions recently proposed in the light of available geophysical data (Malusà et al., 2017). The velocity structure of the mantle wedge region "a", showing Vp velocity of ~7.5 km/s from depths as shallow as ~10 km down to ~30 km, is largely inconsistent with the presence of imbricated continental crust units (e.g., Schmid et al., 2017) or dry mantle peridotite beneath the Dora-Maira (U)HP dome. Instead, it may suggest a complex evolution of mantle-wedge rocks in terms of P-T conditions and fluid-rock interaction. Such Vp values point in fact to widespread serpentinization of mantle rocks (~60% according to Reynard, 2013), that may locally exceed 90% both in the uppermost part of anomaly "a" and in the Lanzo massif, although velocity values in the uppermost crustal levels may be slightly underestimated, as unravelled by the reconstruction tests of Fig. 3D. The degree of serpentinization at 30-40 km depth is instead much lower (<30%), and consistent with the occurrence of intermediate-depth earthquakes (Fig. 7B). Vp/Vs ratios are in the range of 1.70-1.72 in region "a", but sharply increase to values >1.74 in region "b", where Vp values (~8.0 km/s) are consistent with dry mantle peridotite. The high Vp/Vs ratios in region "b" point to low shear wave velocities, which are in line with a potential impact of the Rivoli-Marene deep fault on the rock fabric. According to previous work, the deepest part of the mantle wedge beneath the thick blue spot of negative polarity conversions (region "c" in Fig. 7B) may either include serpentinites, or slivers of (U)HP rocks. On a geophysical ground, serpentinites can be easily distinguished from other lithologies possibly found in high-pressure mélange zones (e.g., Marschall and Schumacher, 2012) such as eclogitic metasediments and mafic eclogites (Reynard, 2013). Our results indicate that the velocity values observed in region "c" (Vp ~7.0-7.5 km/s; Vp/Vs <1.70) are neither consistent with eclogitic metasediments (Vp ~7.0 km/s; Vp/Vs ~1.75) nor with mafic eclogite (Vp > 8.0 Vp/Vs ~1,73), but are instead supportive of ultramafic rocks with a degree of serpentinization ranging between 50% and 75% (Weiss et al., 1999; Reynard, 2013). However, minor slivers of eclogitic metasediments could be present at ~40 km depth at the top of the European slab, in regions showing the highest Vp/Vs ratios (Fig. 7A).

7. Implication for (U)HP rock exhumation

In the southern Western Alps, the positive gravimetric anomaly ascribed to the Ivrea body is classically interpreted in terms of upper mantle indentation (e.g., Lardeaux et al., 2006; Béthoux et al., 2007), in line with previous tectonic interpretations proposed for the Central Alps and for the northern Western Alps (e.g., Schmid and Kissling, 2000). According to these interpretations, the uppermost part of the Adriatic mantle would act as an indenter beneath the Alpine accretionary wedge, and would transfer compression towards the European foreland. The main geologic implications of this model include major crustal shortening in the upper plate, and fast erosion focused above the indenter (Fig. 2B). These latter features are indeed observed in the Central Alps, where upper mantle indentation, accommodated by back-folding of (U)HP domes (Keller et al., 2005) and by backthrusting of Adriatic units (Zanchetta et al., 2015), triggered the fast erosional exhumation of the amphibolite-facies rocks of the Lepontine dome (Anfinson et al., 2016; Malusà et al., 2016b). However, these features are not common to the southern Western Alps, where shortening in the accretionary wedge was minor during and after (U)HP rock exhumation (Malusà et al., 2009; Dumont et al., 2012), and erosion was much slower compared to the Lepontine dome, as attested by low-temperature thermochronometers (Malusà et al., 2005b; Vernon et al., 2008; Fox et al., 2015) and by preserved Oligocene corals unconformably lying on top of Eocene eclogites (Molare Fm; Quaranta et al. 2009). A tectonic scenario exclusively invoking upper-plate mantle indentation beneath the accretionary wedge would also imply that seismic velocities in the upper-plate mantle should be quite similar beneath the orogenic wedge and in the hinterland (Fig. 2B). Major seismic velocity changes, e.g., by metamorphic phase changes triggered by fluids released by the downgoing slab, would remain undetected in local earthquake tomography models, because they would take place at much greater depths (Deschamps et al., 2013; Abers et al., 2017).

Our study points to a complex velocity structure in the upper-plate mantle of the southern Western Alps. The region beneath the Dora-Maira (U)HP dome is dominated by serpentinized peridotites, documented from ~10 km depth down to the top of the European slab. To the east, these rocks are juxtaposed against dry mantle peridotites of the Adriatic upper plate along a steeply dipping fault rooted in the lithospheric mantle (RMF in Fig. 7C). In between, mantle rocks of the Lanzo massif underwent subduction during the Alpine orogeny, and were later exhumed and accreted against the Adriatic upper plate when the Dora-Maira (U)HP rocks were still buried at mantle depths (Rubatto and Hermann, 2001). This scenario is supportive of (U)HP rock and mantle-wedge exhumation triggered by upper plate divergent motion (Fig. 2C).

Serpentinized peridotites with Vp ~7.5 km/s that are found beneath the Dora-Maira dome may have favoured the exhumation of (U)HP rocks across the upper crust, in the depth range where eclogitized continental crust rocks may have become neutrally buoyant (Schwartz et al., 2001). According to Agard et al. (2009), exhumation of eclogitized ophiolites woud be favoured by accretion of continental material. Our results point instead to a decisive role played by buoyant serpentinites (e.g., Hermann et al., 2000; Schwartz et al., 2001) during continental (U)HP rock exhumation, within a broadly extensional tectonic framework that is common to many recent tectonic reconstructions of the Central Mediterranean area (e.g., Vignaroli et al., 2008; Malusà et al., 2015) (Fig. 8).

No exhumed mantle-wedge serpentinites are recognized so far at outcrop in the southern Western Alps (Scambelluri et al., 1995; Piccardo et al., 2004; Hattori and Guillot, 2007; Deschamps et al., 2013). However strong fluid-rock interactions are recognized in subducted serpentinites and associated ophiolitic rocks (Scambelluri and Tonarini, 2012; Lafay et al., 2013; Plümper et al., 2017), suggesting that fluid release may have occurred during oceanic and even during continental subduction (e.g., Castelli et al., 2007; Ferrando et al., 2009), possibly triggering the partial serpentinization of the Adriatic mantle wedge. Part of the Adriatic mantle wedge was then exhumed at shallow crustal levels during late Eocene transtension along the Western Alps subduction zone

(Malusà et al., 2015) and coeval rapid exhumation of the Dora-Maira (U)HP rocks (Rubatto and Hermann, 2001) (step 1 in Fig. 8). The exhumed mantle wedge was finally indented beneath the Alpine belt during early Oligocene tectonic shortening (Dumont et al., 2012; Jourdan et al., 2012, 2013) (step 2 in Fig. 8). Along the Adria-Europe plate boundary, the divergent component of Eocene transtension progressively decreased towards the north to become negligible in the Central Alps (Fig. 8A), where Adria was indented more deeply beneath the accretionary wedge compared to the Western Alps, and rocks now exposed in the Lepontine dome were exhumed at lower rates through the upper crust (Fig. 8B). We speculate that, north of the Dora-Maira dome, upper plate divergence was probably insufficient to allow an effective exhumation of the mantle wedge (Fig. 8C). However, testing this hypothesis would require a high resolution tomographic image of the northern Western Alps, which may be precluded by the lack of deep earthquakes.

Our results demonstrate that recent geologic cross-sections postulating a thick wedge of Briançonnais eclogites beneath the Dora-Maira dome (e.g., Schmid et al., 2017) are likely incorrect. The palinspastic reconstructions derived from such geologic cross-sections, and exclusively considering a Cenozoic evolution within a broadly compressional framework, should be reconsidered at the advantage of palinspastic reconstructions also including major episodes of divergence within the plate boundary zone (e.g., Vignaroli et al., 2008; Malusà et al., 2015). Mantle wedge exhumation is in fact more consistent with a late Eocene transtensional tectonic framework (Fig. 8C) followed by early Oligocene convergence (Fig. 8D), accommodated by orogen-perpendicular shortening in the external Alps (Dumont et al., 2012) and by transpressional tectonics in the Alps-Apennines transition zone (Malusà and Balestrieri, 2012).

The occurrence of mantle-wedge serpentinites exhumed at shallow depth within a continental subduction zone is not specific of the southern Western Alps. Mantle wedge serpentinites associated with (U)HP rock are described, for example, in the Indus Suture Zone in the Himalaya, in the Carribbean (Guillot et al., 2001; Deschamps et al., 2012), in the Western Gneiss Region in Norway (Scambelluri et al., 2010), and are inferred by geophysical evidence under the Dabie-Sulu (Liu et al., 2015). Our findings suggest that orogen-scale exhumation of the mantle wedge may represent a prominent, but still underestimated feature of the deep structure of many orogenic belts. As such, it should be integrated in more advanced theoretical models of subduction and exhumation. Moreover, widespread mantle-wedge exhumation may explain the common occurrence of boudinaged mantle-wedge rocks within continental UHP rocks in the roots of old orogenic belts now unroofed by erosion. In pre-Cenozoic orogenic belts such as the Dabie-Sulu or the Western Gneiss Region, where the evidence of minor erosion during UHP exhumation, if any, is no longer preserved, the occurrence of mantle wedge rocks at shallow depth may represent the only evidence supporting (U)HP rock exhumation triggered by divergent motion between upper plate and accretionary wedge.

8. Conclusions

The new local earthquake tomography model of the southern Western Alps, independently validated by receiver function analysis, unravels a complex seismic velocity pattern consistent with a composite structure of the mantle wedge above the subducted European lithosphere. Seismic velocities indicate that the Dora-Maira (U)HP dome lays directly above serpentinized peridotites, documented from ~10 km depth down to the top of the eclogitized lower crust of the European plate. We propose that peridotite serpentinization was the result of fluids released to the Adriatic mantle wedge during Alpine subduction. During late Eocene transtension, when the subduction wedge was largely exhumed at the Earth’s surface, part of the mantle wedge was also exhumed at shallow crustal levels, to be finally indented under the Alpine metamorphic units in the early Oligocene. Our results suggest that mantle wedge exhumation may represent an important feature of the deep structure of exhumed continental subduction zones. Deep orogenic levels, as those imaged by local earthquake tomography in the southern Western Alps, may be exposed today in older continental subduction zones, where mantle wedge serpentinites are commonly associated to continental (U)HP metamorphic rocks.

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Figure 1

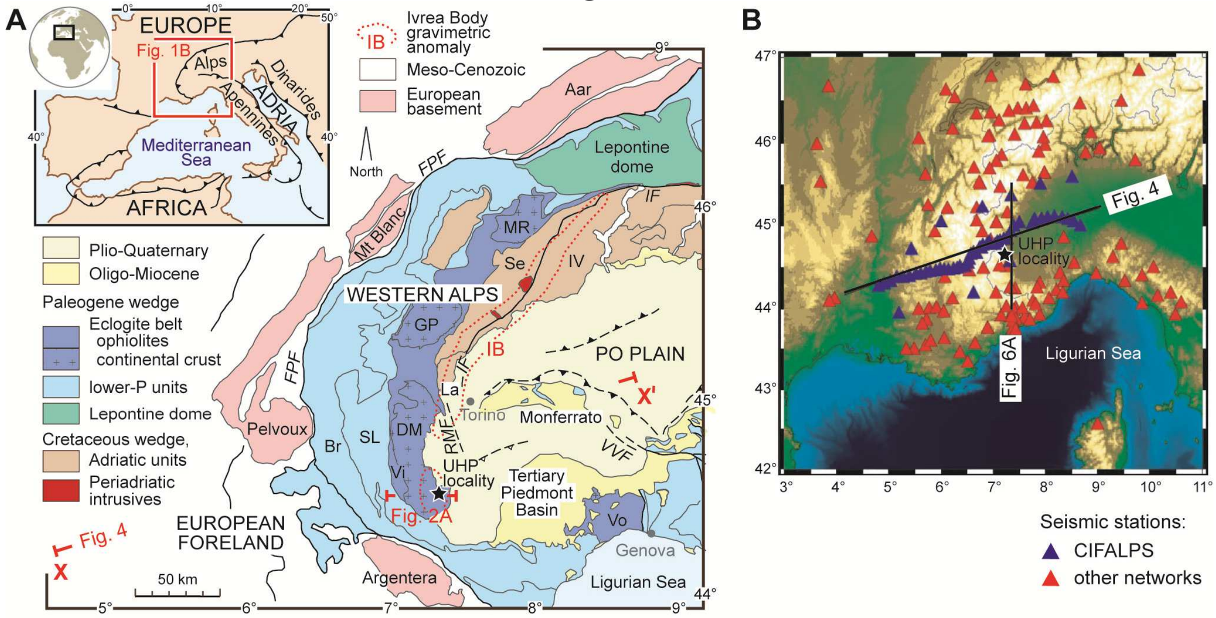

Figure 1: A) Tectonic sketch map showing the (U)HP domes of the Western Alps (dark blue), the gravimetric anomaly of the Ivrea body (0 mGal isoline in red), and the location of the CIFALPS transect (X-X'). Acronyms: Br, Briançonnais; DM, Dora-Maira; FPF, Frontal Pennine Fault; GP, Gran Paradiso; IF, Insubric Fault; IV, Ivrea-Verbano; La, Lanzo; MR, Monte Rosa; RMF, Rivoli-Marene deep fault; Se, Sesia-Lanzo; SL, Schistes lustrés; Vi, Viso; Vo, Voltri; VVF, Villalvernia-Varzi Fault. The black star marks the Brossasco-Isasca UHP locality. B) Seismic stations utilized in this work (blue = CIFALPS; red = other networks) and location of tomographic cross sections (black lines).

Figure 2

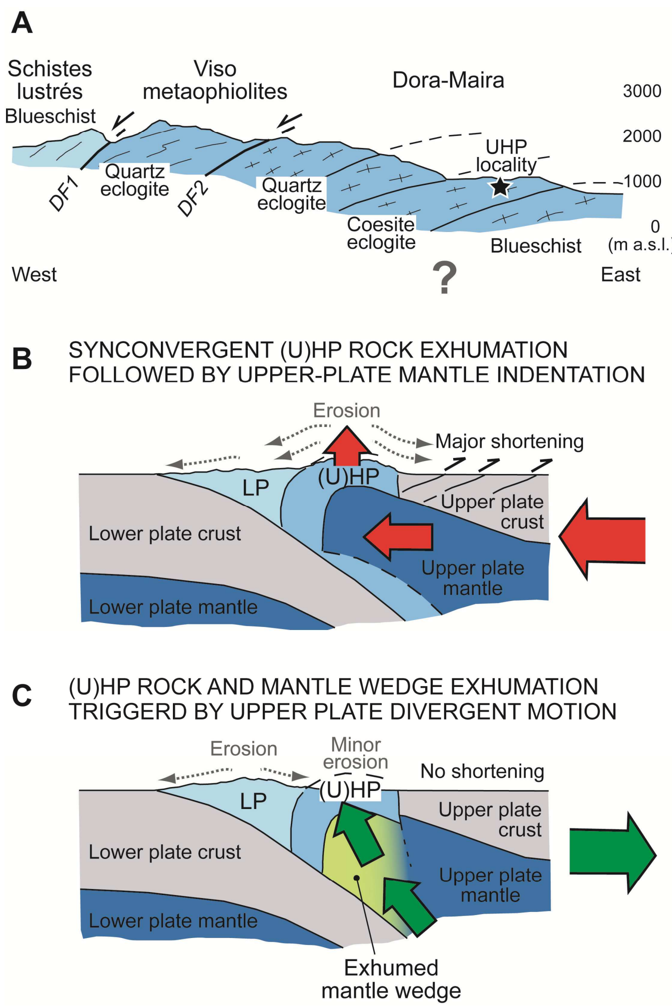

Figure 2: **A)** Geologic cross-section of the Dora-Maira (U)HP dome (see location in Fig. 1A; based on Avigad et al., 2003; Lardeaux et al., 2006). **B, C)** Alternative scenarios of mantle involvement in (U)HP orogenic belts. In (B), synconvergent exhumation of (U)HP rocks (e.g., Butler et al., 2013), possibly associated with deep duplex formation (Schmid et al., 2017), is followed by indentation of the upper-plate mantle beneath the accretionary wedge, with consequent fast erosion of the (U)HP dome and major tectonic shortening in the upper plate (e.g., Béthoux et al., 2007). Seismic velocities in the upper-plate mantle are similar beneath the orogenic belt and in the hinterland, as indicated by the uniform dark blue colour. In (C), divergence between upper plate and accretionary wedge triggers the exhumation of (U)HP rocks (Malusà et al., 2011) and the emplacement of serpentinized mantle-wedge rocks at shallow depth. Erosion on top of the (U)HP dome is minor at this stage, and shortening is negligible. Because of widespread serpentinization of the mantle wedge during subduction, seismic velocities will be lower in the mantle-wedge rocks beneath the (U)HP dome (as indicated by the pale green colour), and higher in the adjoining dry mantle rocks of the upper plate (dark blue).

Figure 3

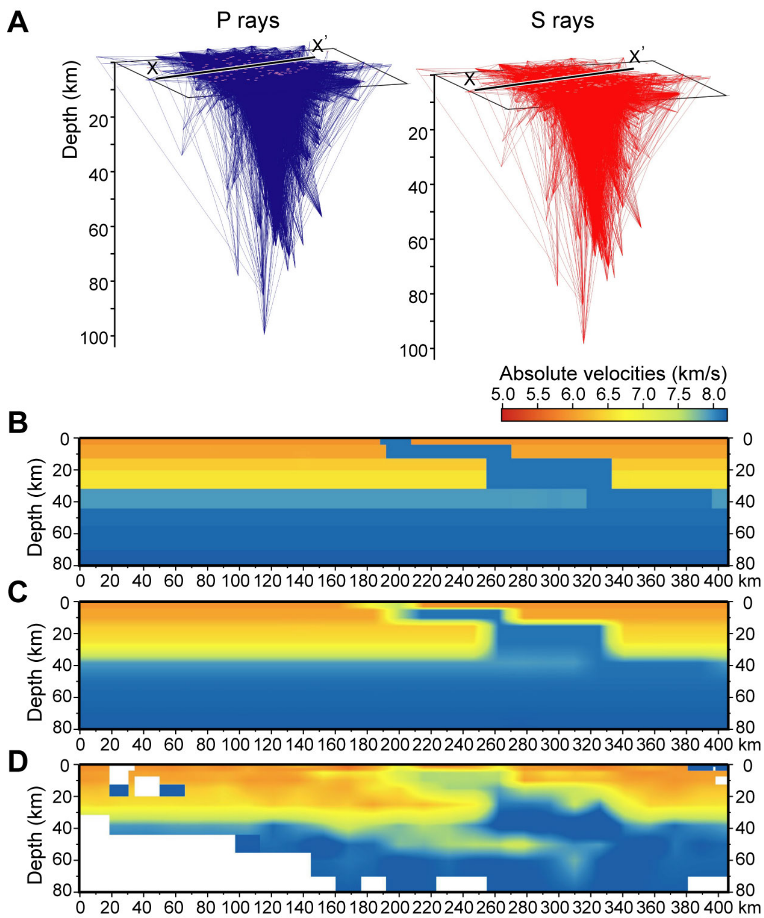

Figure 3. A) Three-dimensional P and S ray coverage based on the seismic events considered in this study (X-X' indicates the CIFALPS transect, see Fig. 1). B) Imposed stairwell geometry along the CIFALPS transect for testing the resolution capability of the coupling between seismic dataset and inversion setup. C) Same geometry after interpolation by the algorithm used in SIMULPS, which introduces a smoothing and a thin band of fake colors around the anomalies. D) Reconstruction test showing that the shape of the imposed stairwell structure is well reproduced using our dataset, but the high velocities in the uppermost 10 km are converted to lower values (as less as 0.5 km/s); the weak vertical and horizontal periodic stripes of yellow color at 50 km depth within the blue area are artifacts; white areas are not sampled.

Figure 4

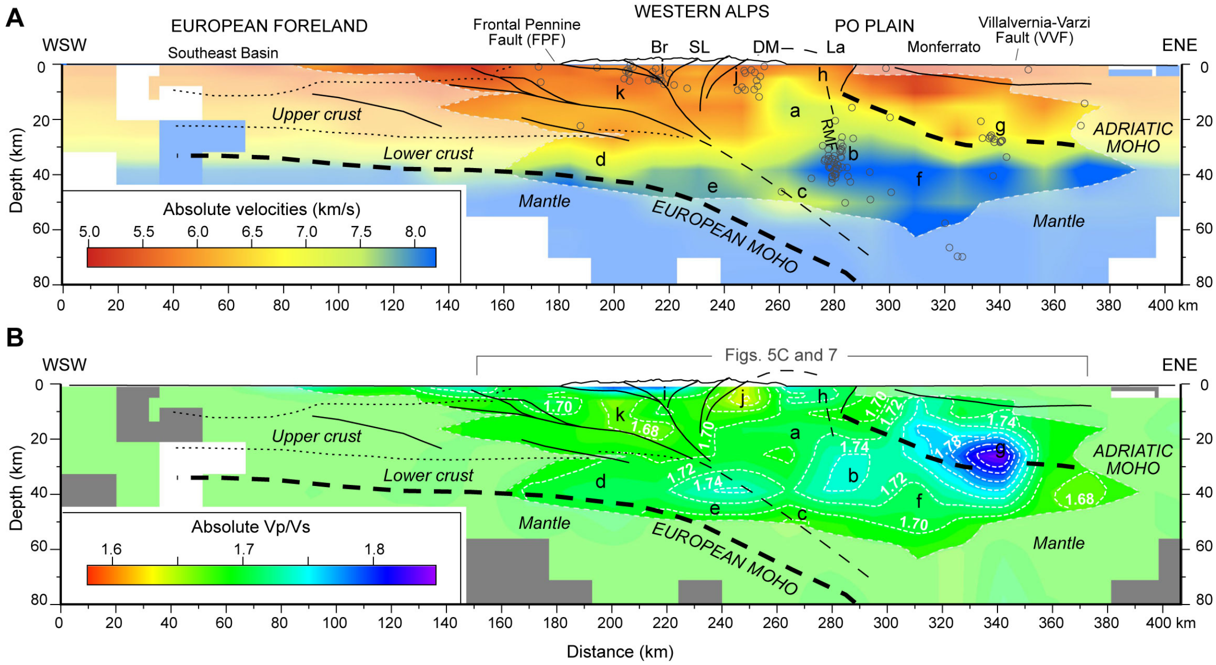

Figure 4: Tomographic cross sections along the CIFALPS transect. A) Absolute Vp velocity. The velocity structure beneath the Dora-Maira (U)HP dome is well resolved down to 50-60 km depth (acronyms as in Fig. 1A); areas with resolution diagonal elements <0.1 are masked, white areas are not sampled; letters a to k indicate regions of the model discussed in the main text; black circles indicate earthquakes as located with the 3D model; black lines and text in italics indicate the main tectonic features previously inferred from receiver function analysis (Zhao et al., 2015; Malusà et al., 2017, see Fig. 7B). Note the prominent high velocity body (labelled with "a") located right below the Dora-Maira (U)HP dome. The vertical and horizontal periodic stripes of yellow color at 50 km depth are artifacts, as attested by the reconstruction test of Fig. 3D. B) Vp/Vs ratios. White dashed lines are isolines of equal Vp/Vs, grey areas are not sampled (other keys as in frame A).

Figure 5

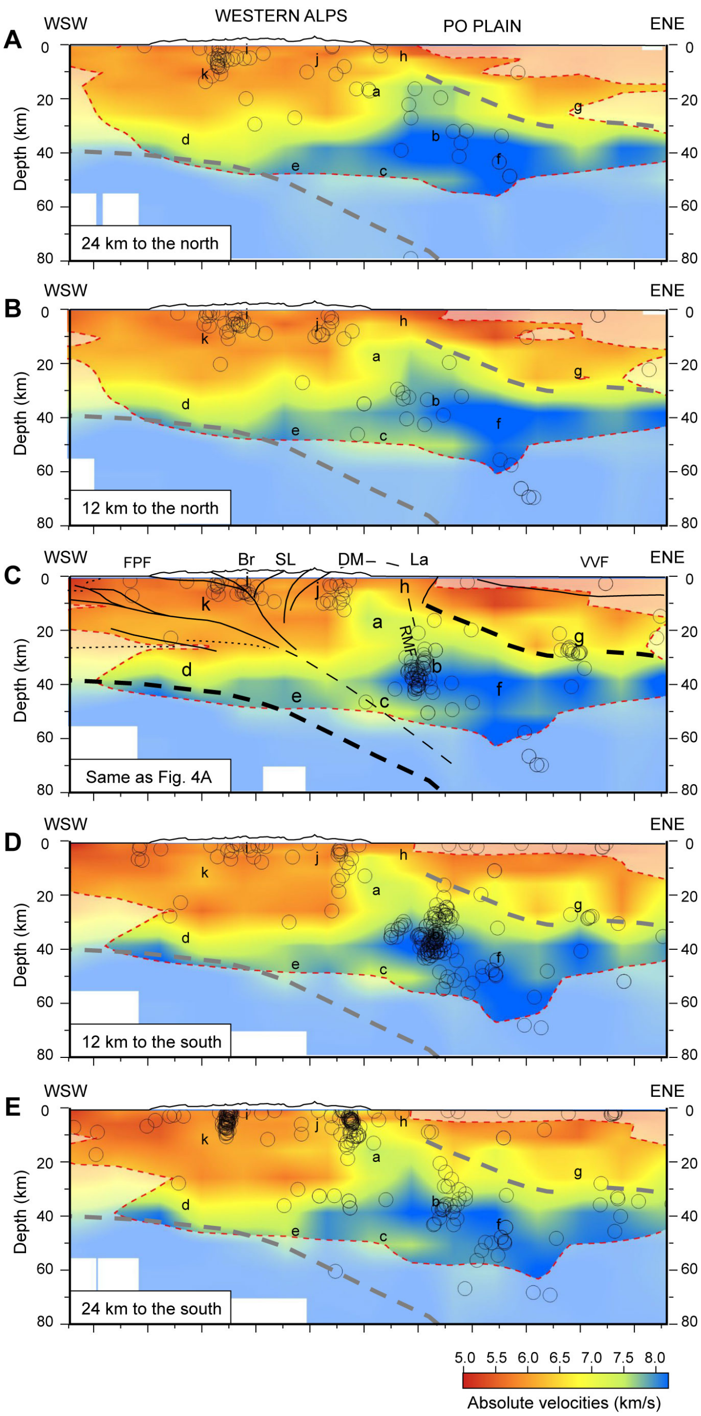

Figure 5: Lateral variations in Vp velocity in the mantle wedge as shown in a series of WSW-ENE cross-sections lying to the north (A, B) and to the south (D, E) of the main CIFALPS transect (C). The high velocity body labelled with "a" progressively disappears moving to the north. Black circles are projected hypocentres located within ±5 km distance off the profiles. The thick dashed lines, reported in all sections for comparison, indicate the European and Adriatic Mohos inferred from receiver function analysis (cf. Fig. 7B). Other keys as in Fig. 4.

Figure 6

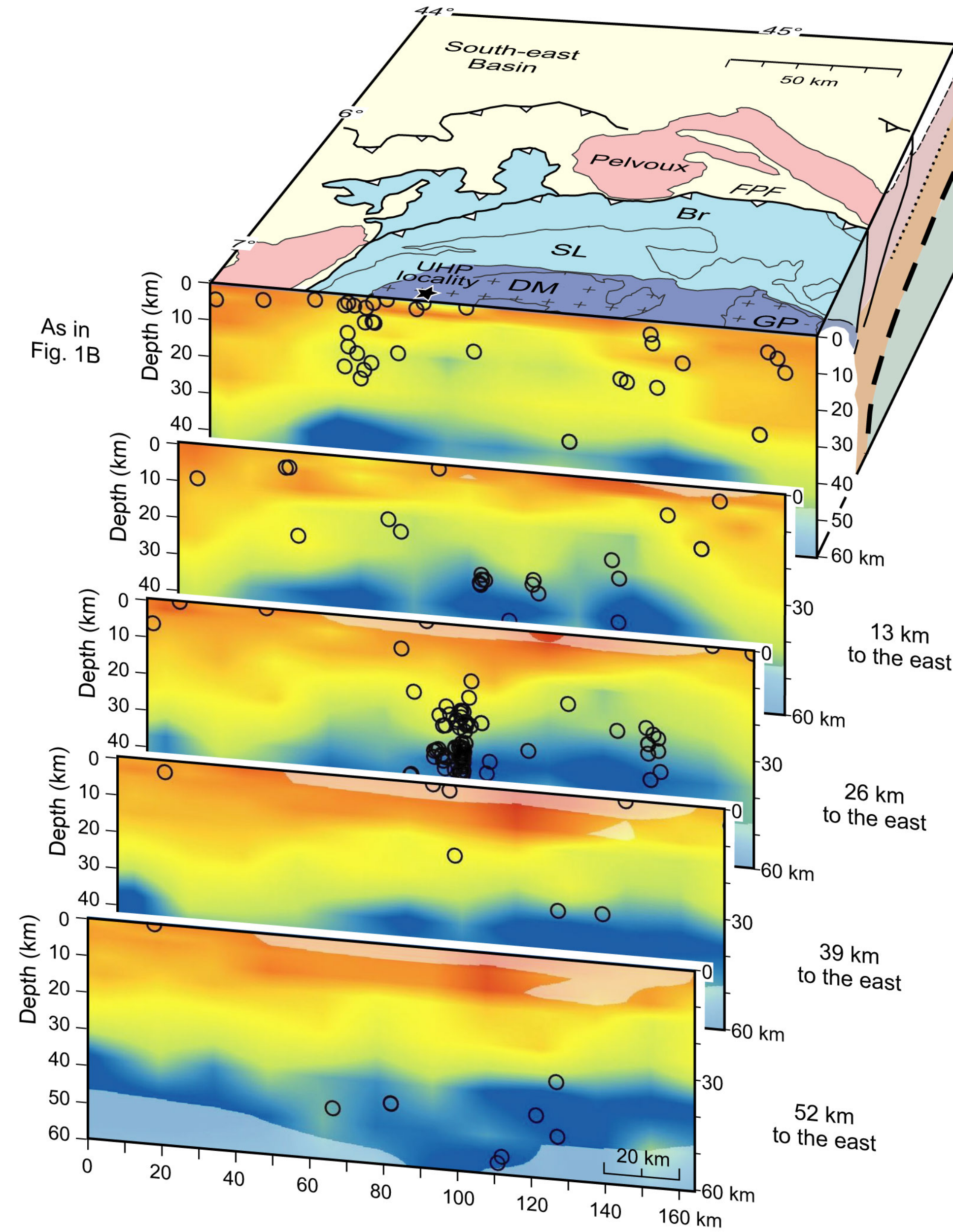

Figure 6: Lateral variations in Vp velocity beneath the Dora-Maira (U)HP dome, as shown in a series of N-S cross-sections from the mountain range to the Po Plain. Black circles are projected hypocentres located within ±3 km distance off the profiles. The high-velocity body labelled with "a" in Figs. 4 and 5 is exclusively found beneath the Dora-Maira dome (see cross section A) and progressively disappears towards the east. Acronyms as in Fig. 1.

Figure 7

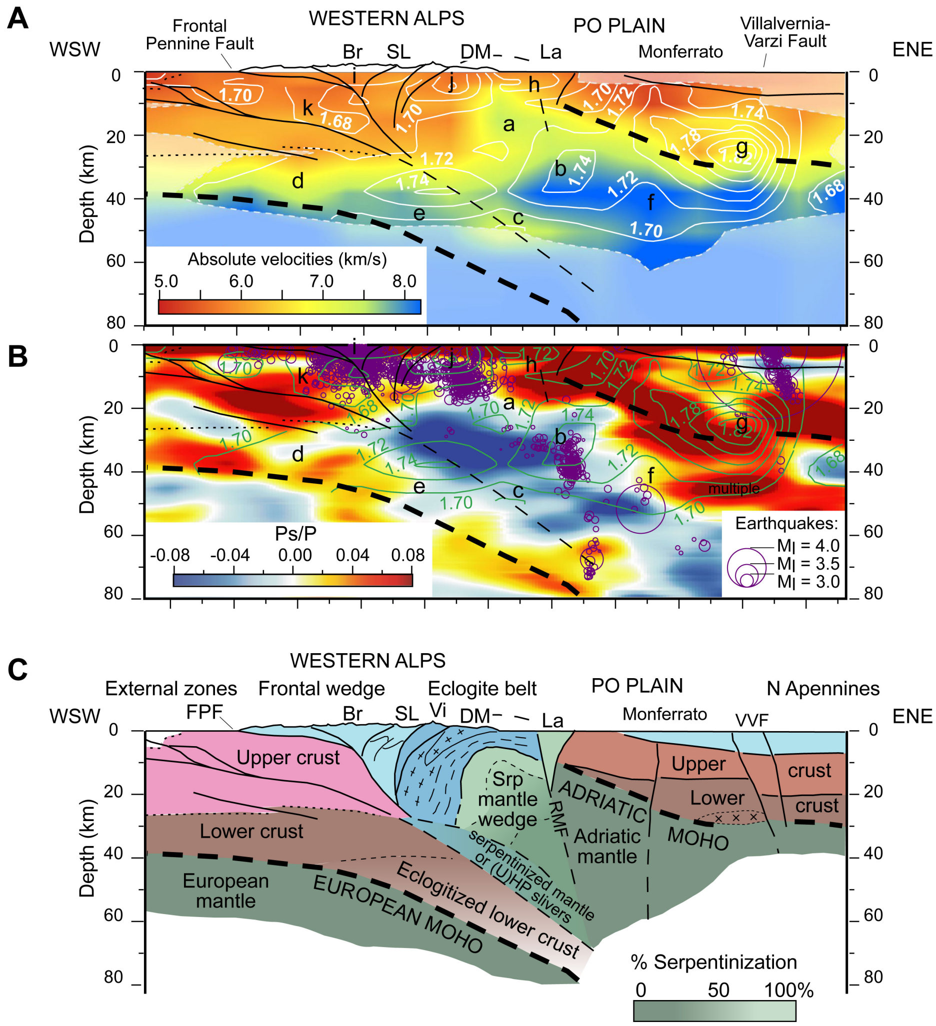

Figure 7: Synthesis of geophysical data (A, B) and inferred mantle wedge structure (C). Black lines in A and B are tectonic features based on receiver function analysis (colors in B indicate positive- and negative-polarity Ps-converted phases, Zhao et al., 2015); contours are isolines of equal Vp/Vs; purple circles in B are earthquakes recorded since 1990 (Malusà et al., 2017). The amount of serpentinization in C, in the mantle wedge underlying the Dora-Maira (U)HP dome, is inferred from seismic velocities (Reynard, 2013). Note the consistency between structures unravelled by local (A) and teleseismic (B) events. Acronyms as in Fig. 1, letters a to k as in Fig. 4.

Figure 8

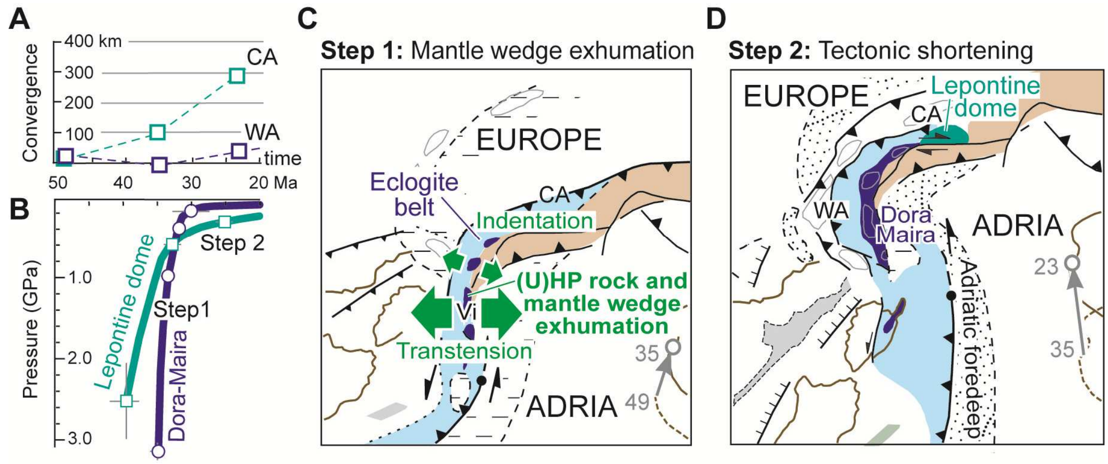

Figure 8: Geodynamic framework of mantle wedge exhumation. **A)** Trench-normal component of Adria-Europe relative motion in the Central (CA) and Western Alps (WA) segments of the Alpine subduction zone (Malusà et al., 2015). **B)** Pressure-time exhumation paths (Dora-Maira: Chopin et al., 1991; Rubatto and Hermann, 2001; Lepontine dome: Becker, 1993; Gebauer, 1996; Brouwer et al., 2004; Nagel, 2008). **C,D)** Late Eocene transtension leading to (U)HP rock and mantle wedge exhumation, and subsequent tectonic shortening in the early Oligocene; grey arrows indicate Adria motion relative to Europe (modified after Malusà et al., 2015).