



HAL
open science

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

Stefano Solarino, Marco Malusà, Elena Eva, Stéphane Guillot, Anne Paul,
Stéphane Schwartz, Liang Zhao, Coralie Aubert, Thierry Dumont, Silvia
Pondrelli, et al.

► To cite this version:

Stefano Solarino, Marco Malusà, Elena Eva, Stéphane Guillot, Anne Paul, et al.. Mantle wedge exhumation beneath the Dora-Maira (U)HP dome unravelled by local earthquake tomography (Western Alps). *Lithos*, 2018, 296-299, pp.623-636. 10.1016/j.lithos.2017.11.035 . insu-02124458

HAL Id: insu-02124458

<https://insu.hal.science/insu-02124458>

Submitted on 5 Mar 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 Pre-print

2

3 Solarino S., Malusa M. G., Eva E., Guillot S., Paul A. et al. (2018)

4

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

8

9 Lithos, 296, 623-636.

10

11 <https://doi.org/10.1016/j.lithos.2017.11.035>

12

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

15 Stefano Solarino¹, Marco G. Malusà², Elena Eva¹, Stéphane Guillot³, Anne Paul³, Stéphane
16 Schwartz³, Liang Zhao⁴, Coralie Aubert³, Thierry Dumont³, Silvia Pondrelli⁵, Simone Salimbeni⁵,
17 Qingchen Wang⁴, Xiaobing Xu⁴, Tianyu Zheng⁴, Rixiang Zhu⁴

18 ¹ *Istituto Nazionale di Geofisica e Vulcanologia, CNT, Genova, Italy*

19 ² *Department of Earth and Environmental Sciences, University of Milano-Bicocca, Milano, Italy*

20 ³ *Univ. Grenoble Alpes, Univ. Savoie Mont-Blanc, CNRS, IRD, IFSTTAR, ISTerre, Grenoble, France*

21 ⁴ *Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China*

22 ⁵ *Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy*

23 Authors for correspondence : S. Solarino and M.G. Malusà (stefano.solarino@ingv.it; marco.malusa@unimib.it)

24 **Abstract**

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

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

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

47 **Highlights:**

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

51 **1. Introduction**

52 Exhumed (ultra)high-pressure [(U)HP] rocks bear compelling evidence of the interaction
53 between subducting plates and the overlying mantle wedge (Carswell and Compagnoni, 2003;
54 Hacker et al., 2006; Ferrando et al., 2009; Scambelluri et al., 2010; Deschamps et al., 2013; Gilotti,
55 2013). However, the role played by the mantle wedge during (U)HP rock exhumation is still poorly
56 understood. Some numerical models point to a negligible mantle involvement during exhumation
57 (Yamato et al., 2008; Butler et al., 2013), whereas other models suggest that mantle rocks may be
58 strongly involved, and may follow the exhumation path of buoyant (U)HP rocks towards the Earth's
59 surface (Schwartz et al., 2001; Petersen and Buck, 2015). The behaviour of the mantle wedge
60 during (U)HP rock exhumation may thus provide a key to discriminate among competing
61 exhumation models (e.g., Agard et al. 2009; Guillot et al., 2009a; Liou et al., 2009; Warren, 2013).

62 In the Cenozoic metamorphic belt of the Western Alps, the geologic record of subduction and
63 exhumation is exceptionally well preserved (e.g., Lardeaux et al., 2006; Malusà et al., 2011), but a
64 high-resolution image of the mantle wedge is still lacking. A detailed analysis of the seismic
65 velocity structure beneath the Dora-Maira (U)HP dome, where coesite attesting deep continental
66 subduction was first described three decades ago (Chopin, 1984), may thus provide new insights on
67 the ongoing debate concerning the mechanisms triggering the exhumation of (U)HP rocks (e.g.,
68 Jolivet et al., 2003; Schwartz et al., 2001; Agard et al., 2009; Little et al., 2011; Butler et al., 2013;
69 Malusà et al., 2015; Ducea, 2016). Moreover, this kind of analysis may provide new interpretation
70 keys to understand the field relationships between mantle-wedge rocks and continental (U)HP rocks
71 in deeply unroofed pre-Cenozoic orogenic belts (e.g., van Roermund, 2009; Scambelluri et al.,
72 2010), where the geophysical record of subduction and exhumation is no longer preserved (e.g.,
73 Zhao et al. 2017).

74 In this article, we exploit a comprehensive seismic dataset, also including anomalously deep
75 earthquakes (Eva et al., 2015), to derive a local earthquake tomography model of the mantle wedge
76 beneath the Dora-Maira (U)HP dome, which is then compared with the results provided by receiver
77 function analysis along the CIFALPS transect (China-Italy-France Alps seismic survey; Zhao et al.,
78 2015). Our results indicate that part of the mantle wedge was metasomatized above the Alpine
79 subduction zone, and subsequently exhumed at shallow depth beneath continental (U)HP rocks now
80 exposed at the surface. This suggests that mantle-wedge exhumation may be a prominent feature of
81 the deep structure of many (U)HP belts, which should be integrated in future theoretical models of
82 continental subduction and (U)HP rock exhumation.

83 **2. Tectonic framework**

84 ***2.1 The orogenic wedge of the southern Western Alps***

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

87 European paleomargins during the Cenozoic (Coward and Dietrich, 1989; Dewey et al., 1989;
88 Lardeaux et al., 2006; Handy et al. 2010; Malusà et al., 2016a). The resulting slab structure is still
89 largely preserved (Zhao et al., 2016a), as well as the orogenic wedge formed atop the European slab
90 (Lardeaux et al., 2006; Beltrando et al., 2010; Malusà et al., 2011). In the southern Western Alps,
91 along the CIFALPS transect (X-X' in Fig. 1), the Alpine orogenic wedge mainly consists of rocks
92 derived from the Piedmont ocean-continent transition and from the adjoining European paleomargin
93 (Lemoine et al., 1986; Dumont et al., 2012). The external zone, exposed to the west of the Frontal
94 Pennine Fault (FPF in Fig. 1), includes the Pelvoux and Argentera basements and their deformed
95 Meso-Cenozoic sedimentary cover sequences (Ford et al., 2006), which record a transition from
96 thin-skinned to thick-skinned compressional tectonics during the Neogene (Schwartz et al., 2017).
97 East of the Frontal Pennine Fault, in the Alpine metamorphic wedge, the Briançonnais nappe stack
98 (Br in Fig. 1) mainly consists of Upper Paleozoic to Mesozoic metasediments and underlying pre-
99 Alpine basement rocks that underwent subduction starting from the Paleocene, and were later
100 exhumed in the Eocene - early Oligocene (Malusà et al., 2002, 2005a; Ganne et al., 2007; Lanari et
101 al., 2014). The Briançonnais nappe stack forms the core of the present-day Alpine fan-shaped
102 structure (Michard et al., 2004) that was overprinted by a dense network of extensional faults during
103 the Neogene (Sue et al., 2007; Malusà et al., 2009). The eastern part of the fan is formed by oceanic
104 metasediments of the Schistes lustrés complex (SL in Fig. 1; Lemoine et al., 1986; Lagabrielle and
105 Cannat, 1990), including boudinaged decametre-to-kilometre-sized ophiolitic bodies that were
106 deformed and metamorphosed during Alpine subduction under blueschist to transitional blueschist-
107 eclogite facies conditions (Agard et al., 2002; Tricart and Schwartz, 2006; Schwartz et al., 2009)
108 (Fig. 2A). A ductile normal fault (DF1 in Fig. 2A; Ballèvre et al., 1990) separates the Schistes
109 lustrés complex from the Viso metaophiolites (Vi in Fig. 1; Lombardo et al., 1978; Angiboust et al.,
110 2012), representing major imbricated remnants of the Tethyan oceanic lithosphere that were
111 deformed and metamorphosed under eclogite facies conditions during the Eocene (Duchêne et al.,
112 1997; Schwartz et al., 2000; Rubatto and Hermann, 2003). Another ductile normal fault (DF2 in

113 Fig. 2A; Blake and Jayko, 1990) separates the Viso eclogites from the underlying stack of deeply
114 subducted continental basement slices referred to as the Dora-Maira (U)HP dome (DM in Fig. 1;
115 Henry et al., 1993; Michard et al., 1993), which also includes the coesite-bearing Brossasco-Isasca
116 eclogitic unit (black star in Figs. 1 and 2A; Chopin et al., 1991; Compagnoni and Rolfo, 2003).
117 Along the boundary with the Po Plain, the CIFALPS transect crosses the southern tip of the Lanzo
118 massif (La in Fig. 1; Boudier, 1978; Piccardo et al., 2007), an eclogitized mantle slice separated
119 from the Dora-Maira dome by a near-vertical active fault system rooted in the upper mantle (Rivoli-
120 Marene deep fault - RMF in Fig. 1) at the southward prolongation of the Insubric Fault (Eva et al.
121 2015; Malusà et al., 2017). The Lanzo massif consists of slightly serpentinized spinel plagioclase
122 peridotites surrounded by a 3–5 km thick envelope of foliated serpentinites (Müntener et al., 2004;
123 Debret et al., 2013), and records a high-pressure metamorphic peak of early Eocene age (Rubatto et
124 al., 2008). Beneath the Po Plain, the complex transition zone between the Adriatic upper plate and
125 the Apennines, also involving rotated fragments of the Alpine orogenic wedge (Maffione et al.,
126 2008; Eva et al. 2015), is mainly covered by thick Cenozoic to Quaternary sedimentary successions.

127 ***2.2 The Dora-Maira (U)HP dome***

128 The Dora-Maira (U)HP dome is exposed all along the internal side of the southern Western
129 Alps (Chopin et al., 1991; Lardeaux et al., 2006) (Fig. 1). To the west of Torino, it is juxtaposed
130 against the Lanzo massif along the Lis-Trana deformation zone (Perrone et al., 2010), possibly
131 representing a shallow splay of the Rivoli-Marene deep fault (Eva et al., 2015). To the south, it is
132 partly buried by the sedimentary successions of the Po Plain (Fig. 1), and is exposed as a half-dome
133 including coesite-bearing eclogitic rocks (Brossasco-Isasca unit) sandwiched between quartz-
134 eclogite facies rocks, above, and blueschist facies rocks, below (Compagnoni et al. 1995; Avigad et
135 al., 2003; Compagnoni and Rolfo, 2003) (Fig. 2A). The Brossasco-Isasca unit is a coherent
136 continental crust sliver composed of granitic gneisses (Lenze and Stöckhert, 2007), whiteschists
137 (Chen et al., 2017), mafic eclogites (Groppo et al., 2007) and impure marbles (Ferrando et al.,

138 2017). It was subducted to depths greater than ~100 km by the late Eocene (e.g., Chopin et al.,
139 1991; Rubatto and Hermann, 2001; Hermann, 2003), and was exhumed close to the Earth's surface
140 by the early Oligocene, at rates faster than subduction rates (Rubatto and Hermann, 2001; Malusà et
141 al., 2015), as confirmed by low-temperature thermochronology data (Gebauer et al., 1997; Tricart et
142 al., 2007; Beucher et al., 2012). The overlying quartz-eclogite Venasca *p.p.* and Dronero units,
143 including gneisses and metasediments derived from a Permian-Triassic detrital sequence, and the
144 underlying blueschist-facies Sanfront-Pinerolo unit, consisting of orthogneisses and metasediments
145 intruded by Permian diorites (Avigad et al., 2003), were piled up together with the Brossasco-Isasca
146 and Viso units during late Eocene exhumation (Schwartz et al., 2009; Malusà et al., 2011), to
147 become part of the Eocene Eclogite belt now exposed along the upper-plate side of the Western
148 Alps (Fig. 1), at the rear of a lower-pressure Paleogene wedge (LP in Fig. 2B,C).

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

163 *2.3 Exhumation models and implications on the deep orogenic structure*

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

171 Classic tectonic reconstructions of the Alpine belt suggest that synconvergent exhumation
172 could be favoured by deep duplex formation via the accretion of continental material derived from
173 the lower plate (Schmid et al., 2004; Agard et al., 2009), which may be followed by indentation of
174 the upper-plate mantle beneath the accretionary wedge (Schmid and Kissling, 2000; Béthoux et al.,
175 2007). This scenario would imply that seismic velocities in the upper-plate mantle should be similar
176 beneath the orogenic wedge and in the hinterland (Fig. 2B). In case of divergent motion between the
177 upper plate and the descending slab, (U)HP rock exhumation might be instead associated to the
178 emplacement of serpentinized mantle-wedge rocks at shallow depth beneath (U)HP continental
179 rocks, provided that divergence is sufficiently high (Fig. 2C). Because of widespread mantle-wedge
180 serpentinization during subduction (Lafay et al., 2013; Plümpner et al., 2017), seismic velocities are
181 predicted to be lower in mantle-wedge rocks beneath the (U)HP dome, and higher in adjoining dry
182 mantle rocks of the upper plate (Fig. 2C).

183 These alternative scenarios would be in agreement with alternative end-member tectonic
184 reconstructions of the southern Western Alps, based on recent geophysical data from the CIFALPS
185 experiment (Zhao et al., 2016b). One possible end-member reconstruction, consistent with
186 geophysical data, invokes a thick complex of (U)HP continental slivers, in line with predictions of
187 numerical models of syn-convergent exhumation, whereas a second end-member reconstruction
188 invokes a larger volume of mantle rocks possibly exhumed at shallow depth during divergent

189 motion within the subduction zone (Zhao et al., 2015; Malusà et al., 2017). A local earthquake
190 tomography model, complementing previous studies based on receiver function analysis, would be
191 extremely useful to discriminate between these end-member tectonic reconstructions, and may
192 allow a decisive step forward in our understanding of mechanisms leading to exhumation of (U)HP
193 rocks.

194 **3. Methods**

195 ***3.1. Building the database***

196 The local earthquake tomography presented in this work is largely based on the dataset collected
197 during the CIFALPS experiment (Zhao et al., 2016b), which was integrated by data recorded in the
198 same time interval by permanent seismic networks operating in Italy and France, and complemented
199 with selected older events. The temporary network of the CIFALPS experiment (blue marks in
200 Figure 1B) includes 46 broadband seismic stations deployed along a linear WSW-ESE transect
201 from the European foreland to the western Po Plain, and 9 additional stations installed to the north
202 and to the south of the main profile. Stations operated from July 2012 to September 2013, and were
203 specifically deployed for a direct comparison between receiver function and local earthquake
204 tomography. Stations located along the main profile were conceived for receiver function analysis
205 (Zhao et al., 2015). Their spacing ranges from ~5 km in the Western Alps mountain range to ~10
206 km in the European foreland and in the western Po Plain. Off profile stations were installed to
207 improve the crossing of seismic rays for local earthquake tomography.

208 The high number of recording stations along the main CIFALPS profile may increase the
209 computational burden during local earthquake tomography (e.g. in ray tracing) without a direct
210 improvement in the final resolution. However, it ensures a number of advantages. For example, any
211 potential loss of data due to station malfunctioning is easily recovered by adjacent instruments, and
212 doubtful data can be discarded without jeopardizing the quality of the dataset. In order to improve
213 the ray coverage and ensure ray crossing from any azimuth in the study volume, we added to the

214 dataset all published phase pickings recorded by permanent seismic stations operating in France and
215 Italy during the CIFALPS experiment (red marks in Figure 1B). We additionally considered few
216 events that occurred before the experiment to fill specific spatial gaps. This was the case of the
217 intermediate depth earthquakes that were useful to sample anomalies at the bottom of the study
218 volume. Because these earthquakes are relatively rare (Eva et al., 2015), only few events were
219 recorded during the CIFALPS experiment. In summary, 270 events on a total of 1088 events
220 utilized in this work were added as supplementary entries from datasets available at French and
221 Italian seismic networks; about 80% of the remaining events were merged with existing phase
222 pickings. The final P and S ray coverage is shown in Figure 3A.

223 ***3.2. Seismic tomography setup and reconstruction test***

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

231 The resolution capability of the coupling between inversion setup and data was evaluated by
232 checkerboard and reconstruction tests. These tests were useful to choose an adequate geometry of
233 the starting model and evaluate the smearing due to the contrast between high and low velocity
234 anomalies. The reconstruction test was specifically conceived to test the potential impact of the
235 high-velocity Ivrea body, a long recognized tectonic feature associated to a positive gravimetric
236 anomaly (red dotted line in Fig. 1) and interpreted as a slice of Adriatic mantle emplaced at shallow
237 depth (Closs and Labrouste, 1963; Nicolas et al., 1990). We used a “stairwell” geometry to simulate
238 a high-velocity east-dipping layer along the CIFALPS profile (Fig. 3B) and test the resolution

239 capability of the coupling between seismic dataset and inversion setup. The same geometry after
240 interpolation by the algorithm used in SIMULPS is shown in Figure 3C. A comparison with Figure
241 3B shows that the interpolation process introduces a smoothing of the anomalies and a band of fake
242 colors around them. Figure 3D shows the reconstruction of the imposed stairwell structure based on
243 our seismic dataset. The inversion of synthetic data does not consider the resolution, and Figure 3D
244 only displays the reconstructed model as if it was completely resolved except for areas that were not
245 sampled (in white). As shown in the reconstruction test, the shape of the anomaly is well
246 reproduced, but the velocity of the first and second steps is lowered from ~ 8.0 km/s (blueish) to
247 about ~ 7.5 km/s (greenish), and weak vertical and horizontal periodic stripes of yellow color appear
248 at ~ 50 km depth. These artifacts, and the underestimation of the magnitude of the high velocity
249 anomalies in the uppermost 10 km of the crust, have been considered during the subsequent phases
250 of tomography interpretation. The real data tomographic model is about 700×700 km wide, and was
251 obtained after 6 iterations on a 12 layers model of 36×36 nodes each. In the central part of the
252 model, spacing between nodes is equal to 15 km.

253 **4. Results**

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

263 2015) and surface geology (Lardeaux et al., 2006; Malusà et al., 2015) are also indicated for
264 comparison (black lines in Fig. 4).

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

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

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

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

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

307 **5. Comparison with receiver function analysis**

308 Results of local earthquake tomography are compared in Figure 7 with published CIFALPS
309 results of receiver function analysis (Zhao et al., 2015). Unlike local earthquake tomography, the
310 receiver function technique is based on the analysis of teleseismic earthquakes, and enhances P-to-S
311 (Ps)-converted waves on velocity interfaces beneath an array. The polarity of the converted signal
312 depends on the sign of the velocity change, and interfaces with velocity increase can be
313 discriminated from interfaces with velocity decrease. Assumptions and arbitrary choices of the

314 receiver function approach applied to the CIFALPS transect (e.g., magnitude threshold, epicentral
315 distance, seismograms filtering, velocity model, choice of the direction of back azimuths) are
316 described in full in Zhao et al. (2015).

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

329 On the eastern side of the CIFALPS transect, the sharp velocity increase from $V_p < 6.5$ km/s to
330 $V_p > 8$ km/s evidenced by local earthquake tomography faithfully matches the location of the
331 downward velocity increase highlighted by receiver function analysis. Localized anomalies in
332 V_p/V_s ratios, e.g., in region “g”, match with major breaks in the alignment of positive-polarity Ps-
333 conversions. Beneath the Dora-Maira (U)HP dome, the downward increase in V_p values from
334 region “h” ($V_p < 6.5$ km/s) to region “a” ($V_p \sim 7.5$ km/s) is consistent with the observed positive-
335 polarity Ps-conversions, whereas the downward velocity decrease from regions “a” and “b” (V_p
336 ~ 7.5 km/s and > 8 km/s) to region “c” ($V_p \sim 7.0-7.5$ km/s) is consistent with the spot of negative-
337 polarity Ps-conversions located at 20-40 km depth in Figure 7B. The shape of the high-velocity
338 region labelled with “a” is also mirrored by the distribution of seismic events recorded since 1990.
339 Region “a” is virtually aseismic (Malusà et al., 2017), and earthquakes are chiefly located along its

340 external boundaries or in the surrounding regions (Fig. 7B). On the western side of the CIFALPS
341 transect, the alignment of positive-polarity Ps-conversions generated along the European Moho is
342 partly included within the resolved area of the local earthquake tomography model, and fits with a
343 downward velocity increase from ~ 6.7 km/s (region “d”) to ~ 7.6 km/s (region “e”). The velocity
344 structure unravelled by the analysis of local earthquakes is thus independently confirmed by the
345 analysis of teleseismic earthquakes (Zhao et al., 2015) and by the distribution of seismic events
346 (Eva et al., 2015; Malusà et al., 2017).

347 **6. Geologic interpretation**

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

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

363 The increase in V_p values evidenced at ~ 40 km depth by local earthquake tomography, from
364 ~ 6.7 km/s in region “d” to ~ 7.6 km/s in region “e”, may mirror a progressive eclogitization of lower

365 crust rocks with consequent density increase by metamorphic phase changes (e.g., Hacker et al.,
366 2003; De Paoli et al., 2012). Mineral equilibria at the granulite-eclogite transition depend on rock
367 composition. The eclogitization of a felsic granulite strongly increases the garnet content, and
368 consequently the density from 2.90 to 3.30 kg/dm³, and the P velocity up to a maximum of 7.6 km/s
369 (e.g., Christensen, 1989; Hacker et al., 2003, 2015; Hacker and Abers, 2004; Hetényi et al., 2007).
370 These values are consistent with the V_p values observed in region "e". The increase in P velocity
371 from region "d" to region "e" is associated with a progressive increase in S velocity up to 4.2 km/s
372 (Lyu et al., 2017), which may be either interpreted as an increase in mafic component, or as an
373 effect of metamorphic reactions under increasing pressure-temperature conditions. However, V_p
374 values in region "e" are far too low for a pure mafic eclogite (Bezacier et al., 2010; Reynard, 2013),
375 thus suggesting no major compositional changes from west to east in the European lower crust, but
376 only a progressive change in metamorphic assemblage during subduction. This interpretation also
377 explains the progressive weakening of the positive-polarity converted phases observed along the
378 European Moho, from red to yellow background colours in Fig. 7B, as previously described by
379 Zhao et al. (2015).

380 On the eastern side of the Western Alps, V_p values >8 km/s confirm the presence of Adriatic
381 mantle at shallow depth beneath the western Po Plain (10-15 km), just in correspondence with the
382 positive gravimetric anomaly classically referred to as the Ivrea body (Closs and Labrouste, 1963;
383 Nicolas et al., 1990) and in line with results of previous tomographic models (e.g., Solarino et al.,
384 1997; Paul et al., 2001; Scafidi et al., 2006; 2009; Diehl et al., 2009; Wagner et al., 2012). East of
385 the Ivrea body gravimetric anomaly, the Adriatic Moho is located at 30-35 km depth, which is a
386 much more reliable estimate of the Moho depth beneath the Po Plain compared to previous
387 estimates based on receiver function alone (Zhao et al., 2015). The locally high V_p/V_s ratios >1.8,
388 associated to V_p of 7.0-7.5 km/s (region "g"), may be supportive of gabbro (Weiss et al., 1999)
389 underplated at the base of the Adriatic lower crust. Noteworthy, Permian gabbros are indeed
390 exposed north of the Po plain, where they are intruded into lower crust rocks belonging to the

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

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

415 But the most relevant results of the tomography model presented in this work is related to the
416 velocity structure beneath the Dora-Maira (U)HP dome. This information is critical to discriminate

417 between contrasting models of (U)HP rock exhumation (Malusà et al., 2011, 2015; Jamieson and
418 Beaumont, 2013), and to discern between end-member tectonic reconstructions recently proposed in
419 the light of available geophysical data (Malusà et al., 2017). The velocity structure of the mantle
420 wedge region “a”, showing Vp velocity of ~7.5 km/s from depths as shallow as ~10 km down to
421 ~30 km, is largely inconsistent with the presence of imbricated continental crust units (e.g., Schmid
422 et al., 2017) or dry mantle peridotite beneath the Dora-Maira (U)HP dome. Instead, it may suggest a
423 complex evolution of mantle-wedge rocks in terms of P-T conditions and fluid-rock interaction.
424 Such Vp values point in fact to widespread serpentinization of mantle rocks (~60% according to
425 Reynard, 2013), that may locally exceed 90% both in the uppermost part of anomaly “a” and in the
426 Lanzo massif, although velocity values in the uppermost crustal levels may be slightly
427 underestimated, as unravelled by the reconstruction tests of Fig. 3D. The degree of serpentinization
428 at 30-40 km depth is instead much lower (<30%), and consistent with the occurrence of
429 intermediate-depth earthquakes (Fig. 7B). Vp/Vs ratios are in the range of 1.70-1.72 in region “a”,
430 but sharply increase to values >1.74 in region “b”, where Vp values (~8.0 km/s) are consistent with
431 dry mantle peridotite. The high Vp/Vs ratios in region “b” point to low shear wave velocities, which
432 are in line with a potential impact of the Rivoli-Marene deep fault on the rock fabric. According to
433 previous work, the deepest part of the mantle wedge beneath the thick blue spot of negative polarity
434 conversions (region “c” in Fig. 7B) may either include serpentinites, or slivers of (U)HP rocks. On a
435 geophysical ground, serpentinites can be easily distinguished from other lithologies possibly found
436 in high-pressure mélange zones (e.g., Marschall and Schumacher, 2012) such as eclogitic
437 metasediments and mafic eclogites (Reynard, 2013). Our results indicate that the velocity values
438 observed in region “c” (Vp ~7.0-7.5 km/s; Vp/Vs <1.70) are neither consistent with eclogitic
439 metasediments (Vp ~7.0 km/s; Vp/Vs ~1.75) nor with mafic eclogite (Vp > 8.0 Vp/Vs ~1.73), but
440 are instead supportive of ultramafic rocks with a degree of serpentinization ranging between 50%
441 and 75% (Weiss et al., 1999; Reynard, 2013). However, minor slivers of eclogitic metasediments

442 could be present at ~40 km depth at the top of the European slab, in regions showing the highest
443 V_p/V_s ratios (Fig. 7A).

444 **7. Implication for (U)HP rock exhumation**

445 In the southern Western Alps, the positive gravimetric anomaly ascribed to the Ivrea body is
446 classically interpreted in terms of upper mantle indentation (e.g., Lardeaux et al., 2006; Béthoux et
447 al., 2007), in line with previous tectonic interpretations proposed for the Central Alps and for the
448 northern Western Alps (e.g., Schmid and Kissling, 2000). According to these interpretations, the
449 uppermost part of the Adriatic mantle would act as an indenter beneath the Alpine accretionary
450 wedge, and would transfer compression towards the European foreland. The main geologic
451 implications of this model include major crustal shortening in the upper plate, and fast erosion
452 focused above the indenter (Fig. 2B). These latter features are indeed observed in the Central Alps,
453 where upper mantle indentation, accommodated by back-folding of (U)HP domes (Keller et al.,
454 2005) and by backthrusting of Adriatic units (Zanchetta et al., 2015), triggered the fast erosional
455 exhumation of the amphibolite-facies rocks of the Lepontine dome (Anfinson et al., 2016; Malusà et
456 al., 2016b). However, these features are not common to the southern Western Alps, where
457 shortening in the accretionary wedge was minor during and after (U)HP rock exhumation (Malusà
458 et al., 2009; Dumont et al., 2012), and erosion was much slower compared to the Lepontine dome,
459 as attested by low-temperature thermochronometers (Malusà et al., 2005b; Vernon et al., 2008; Fox
460 et al., 2015) and by preserved Oligocene corals unconformably lying on top of Eocene eclogites
461 (Molare Fm; Quaranta et al. 2009). A tectonic scenario exclusively invoking upper-plate mantle
462 indentation beneath the accretionary wedge would also imply that seismic velocities in the upper-
463 plate mantle should be quite similar beneath the orogenic wedge and in the hinterland (Fig. 2B).
464 Major seismic velocity changes, e.g., by metamorphic phase changes triggered by fluids released by
465 the downgoing slab, would remain undetected in local earthquake tomography models, because they
466 would take place at much greater depths (Deschamps et al., 2013; Abers et al., 2017).

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

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

485 No exhumed mantle-wedge serpentinites are recognized so far at outcrop in the southern
486 Western Alps (Scambelluri et al., 1995; Piccardo et al., 2004; Hattori and Guillot, 2007; Deschamps
487 et al., 2013). However strong fluid-rock interactions are recognized in subducted serpentinites and
488 associated ophiolitic rocks (Scambelluri and Tonarini, 2012; Lafay et al., 2013; Plümper et al.,
489 2017), suggesting that fluid release may have occurred during oceanic and even during continental
490 subduction (e.g., Castelli et al., 2007; Ferrando et al., 2009), possibly triggering the partial
491 serpentinitization of the Adriatic mantle wedge. Part of the Adriatic mantle wedge was then exhumed
492 at shallow crustal levels during late Eocene transtension along the Western Alps subduction zone

493 (Malusà et al., 2015) and coeval rapid exhumation of the Dora-Maira (U)HP rocks (Rubatto and
494 Hermann, 2001) (step 1 in Fig. 8). The exhumed mantle wedge was finally indented beneath the
495 Alpine belt during early Oligocene tectonic shortening (Dumont et al., 2012; Jourdan et al., 2012,
496 2013) (step 2 in Fig. 8). Along the Adria-Europe plate boundary, the divergent component of
497 Eocene transtension progressively decreased towards the north to become negligible in the Central
498 Alps (Fig. 8A), where Adria was indented more deeply beneath the accretionary wedge compared to
499 the Western Alps, and rocks now exposed in the Lepontine dome were exhumed at lower rates
500 through the upper crust (Fig. 8B). We speculate that, north of the Dora-Maira dome, upper plate
501 divergence was probably insufficient to allow an effective exhumation of the mantle wedge (Fig.
502 8C). However, testing this hypothesis would require a high resolution tomographic image of the
503 northern Western Alps, which may be precluded by the lack of deep earthquakes.

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

514 The occurrence of mantle-wedge serpentinites exhumed at shallow depth within a continental
515 subduction zone is not specific of the southern Western Alps. Mantle wedge serpentinites associated
516 with (U)HP rock are described, for example, in the Indus Suture Zone in the Himalaya, in the
517 Carribean (Guillot et al., 2001; Deschamps et al., 2012), in the Western Gneiss Region in Norway
518 (Scambelluri et al., 2010), and are inferred by geophysical evidence under the Dabie-Sulu (Liu et

519 al., 2015). Our findings suggest that orogen-scale exhumation of the mantle wedge may represent a
520 prominent, but still underestimated feature of the deep structure of many orogenic belts. As such, it
521 should be integrated in more advanced theoretical models of subduction and exhumation. Moreover,
522 widespread mantle-wedge exhumation may explain the common occurrence of boudinaged mantle-
523 wedge rocks within continental UHP rocks in the roots of old orogenic belts now unroofed by
524 erosion. In pre-Cenozoic orogenic belts such as the Dabie-Sulu or the Western Gneiss Region,
525 where the evidence of minor erosion during UHP exhumation, if any, is no longer preserved, the
526 occurrence of mantle wedge rocks at shallow depth may represent the only evidence supporting
527 (U)HP rock exhumation triggered by divergent motion between upper plate and accretionary
528 wedge.

529 **8. Conclusions**

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

544 **Acknowledgments.** This work is funded by the State Key Laboratory of Lithospheric Evolution, China, the National
545 Natural Science Foundation of China (Grant 41350001), and a grant from LabEx OSUG@2020 (Investissements
546 d'avenir; ANR10 LABX56, France). The earthquake waveforms used in this study are available at the European
547 Integrated Data Archive (eida.rm.ingv.it) (see also doi:10.13127/SD/X0FXnH7QfY; doi:10.12686/sed/networks/2a).
548 The CIFALPS seismic data are archived at the data center of the Seismic Array Laboratory, Institute of Geology and
549 Geophysics, Chinese Academy of Sciences, and at the data center of the French Seismologic and Geodetic Network
550 RESIF (doi:10.15778/RESIF.YP2012). The manuscript benefited from constructive reviews by F. Rossetti and an
551 anonymous reviewer, comments by M. Scambelluri, and insightful discussions with S. Baldwin, S. Ferrando and N.
552 Malaspina.

553 **References**

- 554 Abers, G. A., van Keken, P. E., Hacker, B. R., 2017. The cold and relatively dry nature of mantle forearcs in
555 subduction zones. *Nature Geoscience* 10(5), 333-337.
- 556 Agard, P., Monie, P., Jolivet, L., Goffé, B., 2002. Exhumation of the Schistes Lustrés complex: In situ laser
557 probe Ar-40/Ar-39 constraints and implications for the western Alps. *Journal of Metamorphic*
558 *Geology* 20, 599–618.
- 559 Agard, P., Yamato, P., Jolivet, L., Burov, E., 2009. Exhumation of oceanic blueschists and eclogites in
560 subduction zones: timing and mechanisms. *Earth-Science Reviews* 92(1), 53-79.
- 561 Angiboust, S., Langdon, R., Agard, P., Waters, D. J., Chopin, C. 2012. Eclogitization of the Monviso ophiolite
562 (W Alps) and implications on subduction dynamics. *Journal of Metamorphic Geology* 30, 37–61.
- 563 Avigad, D., Chopin, C., Le Bayon, R., 2003. Thrusting and extension in the southern Dora-Maira ultra-high-
564 pressure massif (Western Alps): view from below the coesite-bearing unit. *The Journal of geology*
565 111(1), 57-70.
- 566 Ballèvre, M., Lagabrielle, Y., Merle, O., 1990. Tertiary ductile normal faulting as a consequence of
567 lithospheric stacking in the western Alps. *Société Géologique de France, Mémoires* 156, 227–236.
- 568 Beaumont, C., Jamieson, R.A., Nguyen, M.H., Lee, B., 2001. Himalayan tectonics explained by extrusion of
569 a low-viscosity crustal channel coupled to focused surface denudation. *Nature* 414, 738-742.
- 570 Becker, H., 1993. Garnet peridotite and eclogite Sm-Nd mineral ages from the Lepontine dome (Swiss Alps):
571 New evidence for Eocene high-pressure metamorphism in the central Alps. *Geology* 21, 599-602.
- 572 Beltrando, M., Compagnoni, R., Lombardo, B., 2010. (Ultra-) High-pressure metamorphism and orogenesis:
573 An Alpine perspective. *Gondwana Research* 18(1), 147-166.
- 574 Bergomi, M.A., Dal Piaz, G.V., Malusà M.G., Monopoli, B., Tunesi, A. The Grand St Bernard -
575 Briançonnais nappe system and the Paleozoic inheritance of the Western Alps unravelled by zircon U-
576 Pb dating. *Tectonics* (in review).
- 577 Béthoux, N., Sue, C., Paul, A., Virieux, J., Fréchet, J., Thouvenot, F., Cattaneo, M., 2007. Local tomography
578 and focal mechanisms in the south-western Alps: comparison of methods and tectonic implications.
579 *Tectonophysics* 432, 1–19.
- 580 Beucher, R., van der Beek, P., Braun, J., Batt, G. E., 2012. Exhumation and relief development in the
581 Pelvoux and Dora-Maira massifs (western Alps) assessed by spectral analysis and inversion of
582 thermochronological age transects. *Journal of Geophysical Research: Earth Surface*, 117(F3).

- 583 Bezacier, L., Reynard, B., Bass, J.D., Wang, J., Mainprice, D., 2010. Elasticity of glaucophane, seismic
584 velocities and anisotropy of the subducted oceanic crust. *Tectonophysics* 494, 201–210.
- 585 Blake, M.C., Jayko, A.S., 1990. Uplift of very high pressure rocks in the western Alps: Evidence for
586 structural attenuation along low angle faults. In: Roure, F., Heitzmann, P., Polino, R. (Eds.), *Deep*
587 *structure of the Alps. Mémoire de la Société Géologique de France* 156, pp. 228–237.
- 588 Boudier, F., 1978. Structure and petrology of the Lanzo peridotite massif (Piedmont Alps). *Geological*
589 *Society of America Bulletin* 89(10), 1574-1591.
- 590 Brouwer, F.M., van de Zedde, D.M.A., Wortel, M.J.R., Vissers, R.L.M., 2004. Late-orogenic heating during
591 exhumation: Alpine PTt trajectories and thermomechanical models. *Earth and Planetary Science*
592 *Letters* 220, 185-199.
- 593 Brun, J. P., Faccenna, C., 2008. Exhumation of high-pressure rocks driven by slab rollback. *Earth and*
594 *Planetary Science Letters* 272(1), 1-7.
- 595 Butler, J.P., Beaumont, C., Jamieson, R.A., 2013. The Alps 1: A working geodynamic model for burial and
596 exhumation of (ultra) high-pressure rocks in Alpine-type orogens. *Earth and Planetary Science Letters*
597 377, 114–131.
- 598 Carosi, R., Montomoli, C., Tiepolo, M., Frassi, C., 2012. Geochronological constraints on post-collisional
599 shear zones in the Variscides of Sardinia (Italy). *Terra Nova* 24(1), 42-51.
- 600 Carswell, D. A., R. Compagnoni (Eds.), 2003. *Ultrahigh Pressure Metamorphism*, 508 pp., Eotvos Univ.
601 Press, Budapest.
- 602 Castelli, D., Rolfo, F., Groppo, C., Compagnoni, R., 2007. Impure marbles from the UHP Brossasco-Isasca
603 Unit (Dora-Maira Massif, western Alps): evidence for Alpine equilibration in the diamond stability
604 field and evaluation of the X(CO₂) fluid evolution *Journal of Metamorphic Geology*, 25, 587-603
- 605 Chen, Y. X., Zhou, K., Zheng, Y. F., Schertl, H. P., 2017. Zircon geochemical constraints on the protolith
606 nature and metasomatic process of the Mg-rich whiteschist from the Western Alps. *Chemical Geology*
607 467, 177-195.
- 608 Chopin, C., 1984. Coesite and pure pyrope in high-grade blueschists of the Western Alps: A first record and
609 some consequences. *Contributions to Mineralogy and Petrology* 86, 107–118.
- 610 Chopin, C., Henry, C., Michard, A., 1991. Geology and petrology of the coesite bearing terrain, Dora-Maira
611 massif, western Alps. *European Journal of Mineralogy* 3, 263–291.
- 612 Christensen, N.I., 1989. Seismic velocities. In: Carmichael, R.S. (Ed.), *Practical Handbook of Physical*
613 *Properties of Rocks and Minerals*. CRC Press, Boca Raton, p. 741.
- 614 Closs, H. and Labrouste Y. (Eds.), 1963. *Recherches séismologiques dans les Alpes occidentales au moyen*
615 *de grandes explosions en 1956, 1958 et 1960. Mem. Coll. Année Geophys. Int.* 12-2. CNRS Paris, 241
616 pp.
- 617 Compagnoni, R., Hirajima, T., Chopin, C., 1995. Ultra-high-pressure metamorphic rocks in the Western
618 Alps. In: Coleman, R.G., Wang, X. (Eds.), *Ultrahigh Pressure Metamorphism*. Cambridge University
619 Press, Cambridge, UK, pp. 206–243.
- 620 Compagnoni, R., Rolfo, F., 2003. UHPM units in the western Alps: *European Mineralogy Union Notes in*
621 *Mineralogy* 5, 13–49.
- 622 Coward, M., Dietrich, D., 1989. Alpine tectonics: an overview. In: Coward, M., Dietrich, D., Park, R.G.
623 (Eds), *Alpine Tectonics*. Geological Society, London, Special Publications 45, pp. 1–29.
- 624 De Paoli, M. C., Clarke, G. L., Daczko, N. R., 2012. Mineral equilibria modeling of the granulite–eclogite
625 transition: effects of whole-rock composition on metamorphic facies type-assemblages. *Journal of*
626 *Petrology* 53(5), 949-970.
- 627 Debret, B., Nicollet, C., Andreani, M., Schwartz, S., Godard, M., 2013. Three steps of serpentinitization in an
628 eclogitised oceanic serpentinitisation front (Lanzo massif - Western Alps). *Journal of Metamorphic*
629 *Geology* 31, 165–186.

- 630 Deschamps, F., Godard, M., Guillot, S., Chauvel, C., Andreani, M., Hattori K., Wunder B., France L., 2012.
631 Behavior of fluid-mobile elements in serpentines from abyssal to subduction environments: Examples
632 from Cuba and Dominican Republic. *Chemical Geology* 313, 93–117.
- 633 Deschamps, F., Godard, M., Guillot, S., Hattori, K.H., 2013. Geochemistry of subduction zone serpentinites:
634 A review. *Lithos* 178, 96-127.
- 635 Dewey, J.F., 1980. Episodicity, sequence and style at convergent plate boundaries. *Geological Association
636 of Canada Special Paper* 2, 553-576.
- 637 Dewey, J. F., Helman, M. L., Knott, S. D., Turco, E., Hutton, D. H. W. (1989). Kinematics of the western
638 Mediterranean. *Geological Society, London, Special Publications* 45(1), 265-283.
- 639 Diehl, T., Husen, S., Kissling, E., Deichmann, N., 2009. High-resolution 3-D P-wave model of the Alpine
640 crust. *Geophysical Journal International* 179(2), 1133–1147.
- 641 Ducea, M. N., 2016. Research Focus: Understanding continental subduction: A work in progress. *Geology*
642 44, 239-240.
- 643 Duchêne, S., Blichert-Toft, J., Luais, B., Télouk, P., Lardeaux, J.M., and Albarède, F., 1997. The Lu-Hf
644 dating of garnets and the ages of the Alpine high-pressure metamorphism. *Nature* 387, 586–589.
- 645 Dumont, T., Schwartz, S., Guillot, S., Simon-Labric, T., Tricart, P., Jourdan, S., 2012. Structural and sedimentary
646 records of the Oligocene revolution in the Western Alps. *Journal of Geodynamics* 56, 18–38.
- 647 Eberhart-Phillips, D., 1986. Three-dimensional velocity structure in northern California Coast Ranges from
648 inversion of local earthquake arrival times. *Bulletin of the Seismological Society of America* 76(4),
649 1025–1052.
- 650 Eva, E., Malusà, M.G., Solarino, S., 2015. A seismotectonic picture of the inner southern Western Alps
651 based on the analysis of anomalously deep earthquakes. *Tectonophysics* 661, 190–199.
- 652 Ewing, T. A., Rubatto, D., Hermann, J., 2014. Hafnium isotopes and Zr/Hf of rutile and zircon from lower
653 crustal metapelites (Ivrea–Verbanò Zone, Italy): implications for chemical differentiation of the crust.
654 *Earth and Planetary Science Letters* 389, 106-118.
- 655 Ferrando, S., Frezzotti, M. L., Petrelli, M., Compagnoni, R., 2009. Metasomatism of continental crust during
656 subduction: the UHP whiteschists from the Southern Dora-Maira Massif (Italian Western Alps).
657 *Journal of Metamorphic Geology* 27(9), 739-756.
- 658 Ferrando, S., Groppo, C., Frezzotti, M. L., Castelli, D., Proyer, A., 2017. Dissolving dolomite in a stable
659 UHP mineral assemblage: Evidence from Cal-Dol marbles of the Dora-Maira Massif (Italian Western
660 Alps). *American Mineralogist* 102(1), 42-60.
- 661 Ford, M., Duchêne, S., Gasquet, D., Vanderhaeghe, O., 2006. Two-phase orogenic convergence in the
662 external and internal SW Alps. *Journal of the Geological Society* 163, 815–826.
- 663 Fox, M., Herman, F., Kissling, E., Willett, S.D., 2015, Rapid exhumation in the Western Alps driven by slab
664 detachment and glacial erosion. *Geology*, 43, 379–382.
- 665 Ganne, J., Bertrand, J.M., Fudral, S., Marquer, D., Vidal, O., 2007. Structural and metamorphic evolution of
666 the Ambin massif (western Alps): toward a new alternative exhumation model for the Briançonnais
667 domain. *Bulletin de la Société Géologique de France* 178, 437–458.
- 668 Gebauer, D., 1996. A P-T-t path for an (ultra?-) high-pressure ultramafic/mafic rock-association and its felsic
669 country-rocks based on SHRIMP-dating of magmatic and metamorphic zircon domains. Example:
670 Alpe Arami (Central Swiss Alps), in: Basu, A., Hart, S. (Eds.), *Earth Processes: Reading the Isotopic
671 Code*. *Geophys. Monograph* 95, Am. Geophys. Union, Washington, DC, pp. 307-330.
- 672 Gebauer, D. H. P. S., Schertl, H. P., Brix, M., Schreyer, W., 1997. 35 Ma old ultrahigh-pressure
673 metamorphism and evidence for very rapid exhumation in the Dora Maira Massif, Western Alps.
674 *Lithos* 41, 5-24.
- 675 Gilotti, J. A., 2013. The realm of ultrahigh-pressure metamorphism. *Elements* 9, 255–260.

- 676 Goffé, B., Bousquet, R., Henry, P., Le Pichon, X., 2003. Effect of the chemical composition of the crust on
677 the metamorphic evolution of orogenic wedges. *Journal of metamorphic geology* 21(2), 123-141.
- 678 Groppo, C., Lombardo, B., Castelli, D., Compagnoni, R., 2007. Exhumation history of the UHPM
679 Brossasco-Isasca Unit, Dora-Maira Massif, as inferred from a phengite-amphibole eclogite.
680 *International Geology Review* 49(2), 142-168.
- 681 Guillot, S., Hattori, K.H., de Sigoyer, J., Nägler, T., Auzende, A.L., 2001. Evidence of hydration of the mantle
682 wedge and its role in the exhumation of eclogites. *Earth and Planetary Science Letters* 193, 115–127.
- 683 Guillot, S., Hattori, K., Agard, P., Schwartz, S., Vidal, O., 2009a. Exhumation Processes in Oceanic and
684 Continental Subduction Contexts: A Review, Springer, Berlin.
- 685 Guillot, S., di Paola, S., Ménot, R. P., Ledru, P., Spalla, M. I., Gosso, G., Schwartz, S., 2009b. Suture zones
686 and importance of strike-slip faulting for Variscan geodynamic reconstructions of the External
687 Crystalline Massifs of the western Alps. *Bulletin de la Société Géologique de France* 180(6), 483-500.
- 688 Hacker, B. R., Abers, G. A., 2004. Subduction Factory 3: An Excel worksheet and macro for calculating the
689 densities, seismic wave speeds, and H₂O contents of minerals and rocks at pressure and temperature.
690 *Geochemistry, Geophysics, Geosystems* 5(1).
- 691 Hacker, B.R., Abers, G.A., Peacock, S.M., 2003. Subduction factory 1. Theoretical mineralogy, densities,
692 seismic wave speeds, and H₂O contents. *Journal of Geophysical Research: Solid Earth* 108 (B1).
- 693 Hacker, B.R., McClelland, W.C., Liou J.G. (Eds.), 2006. Ultrahigh-pressure metamorphism: Deep
694 continental subduction, Special Paper Geological Society of America 403, 206 pp.
- 695 Hacker, B. R., Kelemen, P. B., Behn, M. D., 2015. Continental lower crust. *Annual Review of Earth and*
696 *Planetary Sciences* 43, 167-205.
- 697 Handy, M.R., Schmid, S.M., Bousquet, R., Kissling, E., Bernoulli, D., 2010. Reconciling plate-tectonic
698 reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction
699 in the Alps. *Earth-Science Reviews* 102(3), 121-158.
- 700 Hattori, K.H., Guillot, S., 2007. Geochemical character of serpentinites associated with high- to ultrahigh-
701 pressure metamorphic rocks in the Alps, Cuba, and the Himalayas: Recycling of elements in
702 subduction zones, *Geochemistry, Geophysics, Geosystems* 8, Q09010, doi:10.1029/2007GC001594.
- 703 Henry, C., Michard, A., Chopin, C., 1993. Geometry and structural evolution of ultra-high pressure and high-
704 pressure rocks from the Dora-Maira massif, western Alps, Italy. *Journal of Structural Geology* 15,
705 965–981.
- 706 Hermann, J., 2003. Experimental evidence for diamond-facies metamorphism in the Dora-Maira massif.
707 *Lithos* 70(3), 163-182.
- 708 Hermann, J., Müntener, O., Scambelluri, M., 2000. The importance of serpentinite mylonites for subduction
709 and exhumation of oceanic crust. *Tectonophysics* 327(3), 225-238.
- 710 Hetényi, G., Cattin, R., Brunet, F., Bollinger, L., Vergne, J., Nábělek, J. L., Diament, M., 2007). Density
711 distribution of the India plate beneath the Tibetan plateau: Geophysical and petrological constraints on
712 the kinetics of lower-crustal eclogitization. *Earth and Planetary Science Letters* 264(1), 226-244.
- 713 Jamieson, R.A., Beaumont, C., 2013. On the origin of orogens. *Geological Society of America Bulletin*
714 125(11-12), 1671–1702.
- 715 Jolivet, L., Faccenna, C., Goffé, B., Burov, E., Agard, P., 2003. Subduction tectonics and exhumation of
716 high-pressure metamorphic rocks in the Mediterranean orogens. *American Journal of Science* 303(5),
717 353-409.
- 718 Jourdan, S., Bernet, M., Schwartz, S., Guillot, S., Tricart, P., Chauvel, C., Dumont, T., Montagnac, G.,
719 Bureau, S., 2012. Tracing the Oligocene-Miocene evolution of the Western Alps drainage divide with
720 pebble petrology, geochemistry, and Raman spectroscopy of foreland basin deposits. *Journal of*
721 *Geology* 120(6), 603–624.

- 722 Jourdan, S., Bernet, M., Tricart, P., Hardwick, E., Paquette, J. L., Guillot, S., Dumont, T., Schwartz, S.,
723 2013. Short-lived, fast erosional exhumation of the internal western Alps during the late early
724 Oligocene: Constraints from geothermochronology of pro-and retro-side foreland basin sediments,
725 *Lithosphere* 5(2), 211–225.
- 726 Keller, L.M., Hess, M., Fügenschuh, B., Schmid, S.M., 2005. Structural and metamorphic evolution of the
727 Camughera–Moncucco, Antrona and Monte Rosa units southwest of the Simplon line, Western Alps.
728 *Eclogae Geologicae Helvetiae* 98(1), 19–49.
- 729 Kienast, J.R., Pognante, U., 1988. Chloritoid-bearing assemblages in eclogitised metagabbros of the Lanzo
730 peridotite body (western Italian Alps). *Lithos* 21(1), 1–11.
- 731 Lafay, R., Deschamps, F., Schwartz, S., Guillot, S., Godard, M., Nicollet, C. 2013. High pressure
732 serpentinites, a trap and release system controlled by metamorphic conditions: Example from the
733 Piedmont zone of the western Alps. *Chemical Geology* 343, 38–54.
- 734 Lagabrielle, Y., Cannat, M., 1990. Alpine jurassic ophiolites resemble the modern central atlantic basement.
735 *Geology* 18, 319–322.
- 736 Lanari, P., Rolland, Y., Schwartz, S., Vidal, O. Guillot, S., Tricart, P., Dumont, T., 2014. P-T-t estimation of
737 deformation in low-grade quartz-feldspar bearing rocks using thermodynamic modeling and ⁴⁰Ar/³⁹Ar
738 dating techniques: example of the Plan-de-Phasy shear zone unit (Briançonnais Zone, Western Alps).
739 *Terra Nova* 26, 130–138.
- 740 Lardeaux, J.M., Schwartz, S., Tricart, P., Paul, A., Guillot, S., Béthoux, N., Masson, F., 2006. A crustal-scale
741 cross-section of the south-western Alps combining geophysical and geological imagery. *Terra Nova*
742 18, 6, 412–422.
- 743 Lemoine, M., Bas, T., Arnaud-Vanneau, A., Arnaud, H., Dumont, T., Gidon, M., Bourbon, M., De
744 Graciansky, P.C., Rudkiewicz, J.L., Megard-Galli, J., Tricart, P., 1986. The continental margin of the
745 Mesozoic Tethys in the Western Alps. *Marine Petroleum Geology* 3, 179–199.
- 746 Lenze, A., Stöckhert, B., 2007. Microfabrics of UHP metamorphic granites in the Dora Maira Massif, western
747 Alps – no evidence of deformation at great depth. *Journal of Metamorphic Geology* 25(4), 461–475.
- 748 Liou, J. G., Ernst, W. G., Zhang, R. Y., Tsujimori, T., Jahn, B. M., 2009. Ultrahigh-pressure minerals and
749 metamorphic terranes—the view from China. *Journal of Asian Earth Sciences* 35(3), 199–231.
- 750 Little, T. A., Hacker, B. R., Gordon, S. M., Baldwin, S. L., Fitzgerald, P. G., Ellis, S., Korchinski, M., 2011.
751 Diapiric exhumation of Earth's youngest (UHP) eclogites in the gneiss domes of the D'Entrecasteaux
752 Islands, Papua New Guinea. *Tectonophysics* 510(1), 39–68.
- 753 Liu, Y.H., Yang, H.J., Takazawa, E., Satish-Kumar, M., You, C.F., 2015. Decoupling of the Lu-Hf, Sm-Nd,
754 and Rb-Sr isotope systems in eclogites and a garnetite from the Sulu ultra-high pressure metamorphic
755 terrane: Causes and implications. *Lithos* 234, 1–14.
- 756 Lombardo, B., Nervo, R., Compagnoni, R., Messiga, B., Kienast, J.R., Mével, C., Fiora, L., Piccardo, G.B.,
757 Lanza, R., 1978, Osservazioni preliminari sulle ofiolite metamorfiche del Monviso (Alpi Occidentali).
758 *Rendiconti della Società Italiana di Mineralogia e Petrologia* 34, 253–305.
- 759 Lyu, C., Pedersen, H., Paul, A., Zhao, L., Solarino, S. and the CIFALPS Working Group, 2017. Shear wave
760 velocities in the upper mantle of the Western Alps: new constraints using array analysis of seismic
761 surface waves. *Geophysical Journal International*, doi : 10.1093/gji/ggx166.
- 762 Malusà, M. G., Balestrieri, M. L., 2012. Burial and exhumation across the Alps–Apennines junction zone
763 constrained by fission-track analysis on modern river sands. *Terra Nova* 24(3), 221–226.
- 764 Malusà, M., Mosca, P., Borghi, A., Dela Pierre, F., Polino, R., 2002. Approccio multidisciplinare per la
765 ricostruzione dell'assetto tettono-stratigrafico e dell'evoluzione metamorfico-strutturale di un settore di
766 catena orogenica: l'esempio dell'Alta Valle di Susa (Alpi occidentali). *Memorie della Società*
767 *Geologica Italiana* 57(2), 249–257.

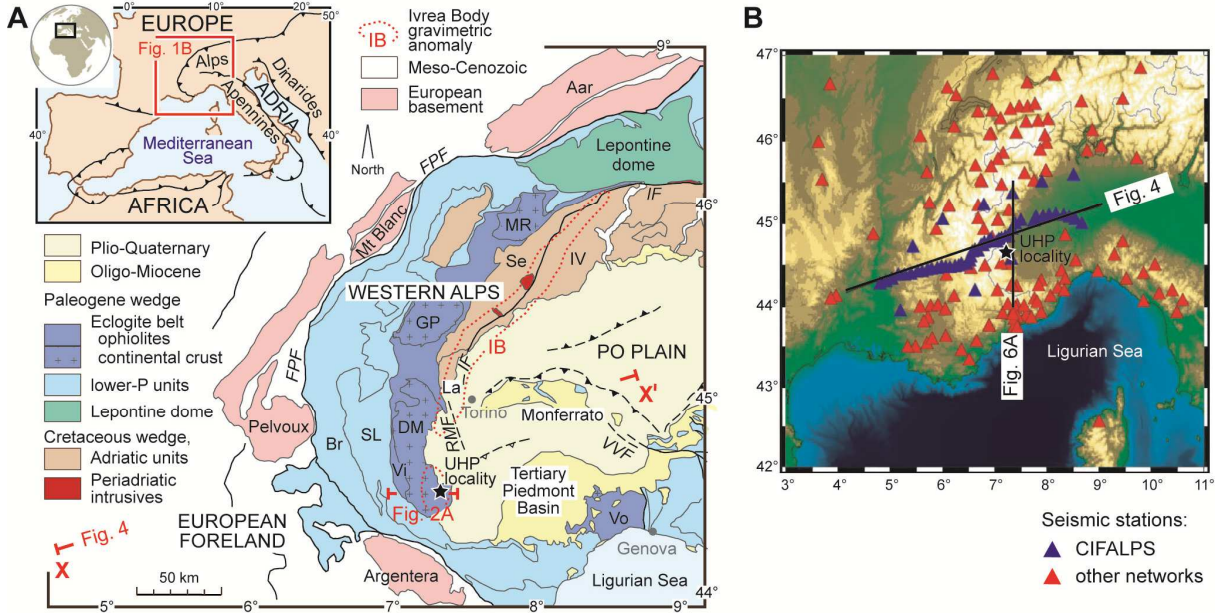
- 768 Malusà, M.G., Polino, R., Martin, S., 2005a. The Gran San Bernardo nappe in the Aosta valley (western
769 Alps): a composite stack of distinct continental crust units. *Bulletin de la Société géologique de France*
770 176(5), 417-431.
- 771 Malusà, M.G., Polino, R., Zattin, M., Bigazzi, G., Martin, S., Piana, F., 2005b. Miocene to Present differential
772 exhumation in the Western Alps: Insights from fission track thermochronology. *Tectonics* 24(3).
- 773 Malusà, M.G., Polino, R., Zattin, M., 2009. Strain partitioning in the axial NW Alps since the Oligocene.
774 *Tectonics* 28, TC3005, 1-26, doi:10.1029/2008TC002370.
- 775 Malusà, M.G., Faccenna, C., Garzanti, E., Polino, R., 2011. Divergence in subduction zones and exhumation
776 of high-pressure rocks (Eocene Western Alps). *Earth and Planetary Science Letters* 310, 21–32.
- 777 Malusà, M.G., Faccenna, C., Baldwin, S.L., Fitzgerald, P.G., Rossetti, F., Balestrieri, M.L., Danišák, M.,
778 Ellero, A., Ottria, G., Piromallo, C., 2015. Contrasting styles of (U)HP rock exhumation along the
779 Cenozoic Adria-Europe plate boundary (Western Alps, Calabria, Corsica). *Geochemistry, Geophysics,*
780 *Geosystems* 16(6), 1786–1824.
- 781 Malusà, M.G., Danišák, M., Kuhlemann, J., 2016a. Tracking the Adriatic-slab travel beneath the Tethyan
782 margin of Corsica-Sardinia by low-temperature thermochronometry. *Gondwana Research* 31, 135-149.
- 783 Malusà, M.G., Anfinson, O.A., Dafov, L.N., Stockli, D.F., 2016b. Tracking Adria indentation beneath the
784 Alps by detrital zircon U-Pb geochronology: Implications for the Oligocene–Miocene dynamics of the
785 Adriatic microplate. *Geology* 44(2), 155-158.
- 786 Malusà, M.G., Zhao, L., Eva, E., Solarino, S., Paul, A., Guillot, S., Schwartz, S., Dumont, T., Aubert, C.,
787 Salimbeni, S., Pondrelli, S., Wang Q., Zhu, R., 2017. Earthquakes in the western alpine mantle wedge.
788 *Gondwana Research* 44, 89–95.
- 789 Marschall, H. R., Schumacher, J. C., 2012. Arc magmas sourced from mélange diapirs in subduction zones.
790 *Nature Geoscience* 5(12), 862-867.
- 791 Mechie, J., Yuan, X., Schurr, B., Schneider, F., Sippl, C., Ratschbacher, L., Minaev, V., Gadoev, M.,
792 Oimahmadov, I., Abdybachev, U., Moldobekov, B., Orunbaev, S., Negmatullaev, S., 2012. Crustal and
793 uppermost mantle velocity structure along a profile across the Pamir and southern Tien Shan as derived
794 from project TIPAGE wide-angle seismic data. *Geophysical Journal International* 188(2), 385-407.
- 795 Michard, A., Chopin, C., Henry, C., 1993. Compression versus extension in the exhumation of the Dora
796 Maira coesite-bearing unit, Western Alps, Italy. *Tectonophysics* 221, 173–193.
- 797 Michard, A., Avigad, D., Goffé, B., Chopin, C., 2004. The high-pressure metamorphic front of the south
798 Western Alps (Ubaye-Maira transect, France, Italy). *Schweiz. Mineral. Petrogr. Mitt.* 84, 215-235.
- 799 Müntener, O., Pettke, T., Desmurs, L., Meier, M., Schaltegger, U., 2004. Refertilisation of mantle peridotite
800 in embryonic ocean basins: trace element and Nd isotopic evidence and implications for crust mantle
801 relationships. *Earth and Planetary Science Letters* 221, 293–308.
- 802 Nagel, T.J., 2008. Tertiary subduction, collision and exhumation recorded in the Adula nappe, central Alps.
803 *Geological Society, London, Special Publications* 298, 365-392.
- 804 Nicolas, A., Hirn, A., Nicolich, R., Polino, R., 1990. Lithospheric wedging in the western Alps inferred from
805 the ECORS-CROP traverse. *Geology* 18, 587–590.
- 806 Paquette, J. L., Montel, J. M., Chopin, C., 1999. U-Th-Pb dating of the Brossasco ultrahigh-pressure
807 metagranite, Dora-Maira massif, western Alps. *European journal of mineralogy* 11(1), 69–77.
- 808 Paul, A., Cattaneo, M., Thouvenot, F., Spallarossa, D., Béthoux, N., Fréchet, J., 2001. A three-dimensional
809 crustal velocity model of the southwestern Alps from local earthquake tomography. *Journal of*
810 *Geophysical Research* 106(B9), 19367-19389.
- 811 Perrone, G., Eva, E., Solarino, S., Cadoppi, P., Balestro, G., Fioraso, G., Tallone, S., 2010. Seismotectonic
812 investigations in the inner Cottian Alps (Italian Western Alps): an integrated approach.
813 *Tectonophysics* 496(1), 1–16.

- 814 Petersen, K.D., Buck, W.R., 2015. Eduction, extension, and exhumation of ultrahigh-pressure rocks in
815 metamorphic core complexes due to subduction initiation. *Geochemistry, Geophysics, Geosystems*
816 16(8), 2564-2581.
- 817 Piccardo, G.B., Müntener, O., Zanetti, A., Pettke, T., 2004. Ophiolitic peridotites of the Alpine-Apenine
818 system: mantle processes and geodynamic relevance. *International Geology Review* 46 (12), 1119-1159.
- 819 Piccardo, G.B., Zanetti, A., Müntener, O., 2007. Melt/peridotite interaction in the Southern Lanzo peridotite:
820 field, textural and geochemical evidence. *Lithos* 94(1), 181–209.
- 821 Plümpner, O., John, T., Podladchikov, Y.Y., Vrijmoed, J.C., Scambelluri, M., 2017. Fluid escape from
822 subduction zones controlled by channel-forming reactive porosity. *Nature Geoscience* 10, 150-156.
- 823 Quaranta, F., Piazza, M., Vannucci, G., 2009. Climatic and tectonic control on the distribution of the Oligocene
824 reefs of the Tertiary Piedmont Basin (NW Italy). *Italian Journal of Geosciences* 128(2), 587–591.
- 825 Quick, J. E., Sinigoi, S., Mayer, A., 1994. Emplacement dynamics of a large mafic intrusion in the lower
826 crust, Ivrea-Verbanò Zone, northern Italy. *Journal of Geophysical Research: Solid Earth* 99(B11),
827 21559-21573.
- 828 Reynard, B., 2013. Serpentine in active subduction zones. *Lithos* 178, 171–185.
- 829 Rubatto, D., Hermann, J., 2001. Exhumation as fast as subduction ? *Geology* 29(1), 3–6.
- 830 Rubatto, D., Hermann, J., 2003. Zircon formation during fluid circulation in eclogites (Monviso, Western
831 Alps): implications for Zr and Hf budget in subduction zones. *Geochimica et Cosmochimica Acta*
832 67(12), 2173–2187.
- 833 Rubatto, D., Müntener, O., Barnhoorn, A., Gregory, C., 2008. Dissolution-reprecipitation of zircon at low-
834 temperature high-pressure conditions (Lanzo Massif, Italy). *American Mineralogist* 93, 1519–1529.
- 835 Rudnick, R. L., Fountain, D. M., 1995. Nature and composition of the continental crust: a lower crustal
836 perspective. *Reviews of Geophysics* 33, 267-309.
- 837 Scafidi, D., Solarino, S., Eva, C., 2006. Structure and properties of the Ivrea body and of the Alps-Apennines
838 systems as revealed by local earthquake tomography. *Bollettino Geofisica Teorica Applicata* 47, 497–514.
- 839 Scafidi, D., Solarino, S., Eva C., 2009. P wave seismic velocity and Vp/Vs ratio beneath the Italian Peninsula
840 from local earthquake tomography. *Tectonophysics* 465, 1–23.
- 841 Scambelluri, M., Tonarini, S., 2012. Boron isotope evidence for shallow fluid transfer across subduction
842 zones by serpentinized mantle. *Geology* 40, 907–910.
- 843 Scambelluri, M., Müntener, O., Hermann, J., Piccardo, G.B., Trommsdorff, V., 1995. Subduction of water
844 into the mantle: history of an Alpine peridotite. *Geology* 23, 459–462
- 845 Scambelluri, M., van Roermund, H. L., Pettke, T., 2010. Mantle wedge peridotites: fossil reservoirs of deep
846 subduction zone processes: inferences from high and ultrahigh-pressure rocks from Bardane (Western
847 Norway) and Ulten (Italian Alps). *Lithos* 120(1), 186-201.
- 848 Schaltegger, U., Brack, P., 2007. Crustal-scale magmatic systems during intracontinental strike-slip
849 tectonics: U, Pb and Hf isotopic constraints from Permian magmatic rocks of the Southern Alps.
850 *International Journal of Earth Sciences* 96(6), 1131–1151.
- 851 Schmid, S.M., Kissling, E., 2000. The arc of the western Alps in the light of geophysical data on deep crustal
852 structure. *Tectonics* 19, 62–85.
- 853 Schmid, S. M., Fügenschuh, B., Kissling, E., Schuster, R., 2004. Tectonic map and overall architecture of the
854 Alpine orogen. *Eclogae Geologicae Helveticae* 97, 93-117.
- 855 Schmid, S.M., Kissling, E., Diehl, T., van Hinsbergen, D., Molli, G., 2017. Ivrea mantle wedge, arc of the
856 Western Alps, and kinematic evolution of the Alps–Apennines orogenic system. *Swiss Journal of*
857 *Geosciences* 110, 581-612.
- 858 Schwartz, S., Lardeaux, J.M., Guillot, S., Tricart, P., 2000. Diversité du métamorphisme éclogitique dans le
859 massif ophiolitique du Monviso (Alpes occidentales, Italie). *Geodinamica Acta* 13, 169-188.

- 860 Schwartz, S., Allemand, P., Guillot, S. 2001. Numerical model of the effect of serpentinites on the
861 exhumation of eclogitic rocks: insights from the Monviso ophiolitic massif (Western Alps).
862 *Tectonophysics* 342, 193–206.
- 863 Schwartz, S., Tricart, P., Lardeaux, J.M., Guillot, S., Vidal, O. 2009. Late tectonic and metamorphic
864 evolution of the Piedmont accretionary wedge (Queyras Schistes lustrés, western Alps): Evidences for
865 tilting during Alpine collision. *Geological Society of America Bulletin* 121, 502–518.
- 866 Schwartz, S., Gautheron, C., Audin, L., Dumont, T., Nomade, J., Barbarand, J., 2017. Foreland exhumation
867 controlled by crustal thickening in the Western Alps. *Geology* 45(2), 139–142.
- 868 Solarino, S., Kissling, E., Sellami, S., Smriglio, G., Thouvenot, F., Granet, M., Bonjer, K.P., Slejko, D.,
869 1997. Compilation of a recent seismicity data base of the greater Alpine region from several
870 seismological networks and preliminary 3D tomographic results. *Annals of Geophysics* 40(1).
- 871 Sue, C., Delacou, B., Champagnac, J.D., Allanic, C., Tricart, P., Burkhard, M., 2007. Extensional
872 neotectonics around the bend of the Western/Central Alps: an overview. *International Journal of Earth
873 Sciences* 96(6), 1101–1129.
- 874 Thurber, C.H., 1983. Earthquake locations and three-dimensional crustal structure in the Coyote Lake area,
875 central California. *Journal of Geophysical Research: Solid Earth* 88(B10), 8226–8236.
- 876 Tricart, P., Schwartz, S., 2006. A north - south section across the Queyras Schistes lustrés (Piedmont zone,
877 Western Alps) : syncollision refolding of a subduction wedge. *Eclogae Geologicae Helveticae* 9, 429–442.
- 878 Tricart, P., Schwartz, S., Sue, C., Lardeaux, J.M., 2004. Differential exhumation in the inner western Alpine
879 arc evidenced by late normal faulting (eastern Queyras Schistes lustrés). *Journal of Structural Geology*
880 26, 1633–1645.
- 881 Tricart, P., van der Beek, P., Schwartz, S., Labrin, E., 2007. Diachronous late-stage exhumation across the
882 western Alpine arc: constraints from apatite fission-track thermochronology between the Pelvoux and
883 Dora-Maira Massifs. *Journal of the Geological Society* 164(1), 163–174.
- 884 Vernon, A.J., van der Beek, P.A., Sinclair, H.D., Rahn, M.K., 2008. Increase in late Neogene denudation of
885 the European Alps confirmed by analysis of a fission-track thermochronology database. *Earth and
886 Planetary Science Letters* 270, 316–329.
- 887 Vignaroli, G., Faccenna, C., Jolivet, L., Piromallo, C., Rossetti, F. (2008). Subduction polarity reversal at the
888 junction between the Western Alps and the Northern Apennines, Italy. *Tectonophysics* 450(1), 34–50.
- 889 Virieux, J., 1991. Fast and accurate ray tracing by Hamiltonian perturbation. *Journal of Geophysical
890 Research: Solid Earth* 96(B1), 579–594.
- 891 van Roermund, H. (2009). Mantle-wedge garnet peridotites from the northernmost ultra-high pressure domain
892 of the Western Gneiss Region, SW Norway. *European Journal of Mineralogy* 21(6), 1085–1096.
- 893 Wagner, M., Kissling, E., Husen, S., 2012. Combining controlled-source seismology and local earthquake
894 tomography to derive a 3-D crustal model of the western Alpine region. *Geophysical Journal
895 International* 191(2), 789–802.
- 896 Wang, Q., Ji, S., Salisbury, M. H., Xia, B., Pan, M., Xu, Z., 2005. Pressure dependence and anisotropy of P-
897 wave velocities in ultrahigh-pressure metamorphic rocks from the Dabie–Sulu orogenic belt (China):
898 implications for seismic properties of subducted slabs and origin of mantle reflections. *Tectonophysics*
899 398(1), 67–99.
- 900 Warren, C.J., 2013. Exhumation of (ultra-) high-pressure terranes: Concepts and mechanisms. *Solid Earth*
901 4(1), 75–92.
- 902 Weiss, T., Siegesmund, S., Rabbel, W., Bohlen, T., Pohl, M., 1999. Seismic velocities and anisotropy of the
903 lower continental crust. A Review. *Pure Applied Geophysics* 156, 97–122.
- 904 Yamato, P., Burov, E., Agard, P., Le Pourhiet, L., Jolivet, L., 2008. HP-UHP exhumation during slow
905 continental subduction: Self-consistent thermodynamically and thermomechanically coupled model
906 with application to the Western Alps. *Earth and Planetary Science Letters* 271(1), 63–74.

- 907 Zanchetta, S., Malusà, M.G., Zanchi, A., 2015. Precollisional development and Cenozoic evolution of the
908 Southalpine retrobelt (European Alps). *Lithosphere* 7, 662-681.
- 909 Zeitler, P.K., Koons, P.O., Bishop, M.P., Chamberlain, C.P., Craw, D., et al., 2001. Crustal reworking at
910 Nanga Parbat, Pakistan: metamorphic consequences of thermal–mechanical coupling facilitated by
911 erosion, *Tectonics*, 20, 712–728.
- 912 Zhao, L., Paul, A., Guillot, S., Solarino, S., Malusà, M.G., Zheng, T., Aubert, C., Salimbeni, S., Dumont, T.,
913 Schwartz, S., Zhu, R., Wang, Q., 2015. First seismic evidence for continental subduction beneath the
914 Western Alps. *Geology* 43, 815-818.
- 915 Zhao, L., Paul, A., Malusà, M.G., Xu, X., Zheng, T., Solarino, S., Guillot, S., Schwartz, S., Dumont, T.,
916 Salimbeni, S., Aubert, C., Pondrelli, S., Wang, Q., Zhu, R., 2016a. Continuity of the Alpine slab
917 unraveled by high-resolution P wave tomography. *Journal of Geophysical Research: Solid Earth* 121,
918 8720–8737.
- 919 Zhao, L., Paul, A., Solarino S., 2016b. Seismic network YP: CIFALPS temporary experiment (China-Italy-
920 France Alps seismic transect). RESIF - Réseau Sismologique et géodésique Français. Seismic
921 Network. doi:10.15778/RESIF.YP2012.
- 922 Zhao, L., Xu, X., Malusà, M.G., 2017. Seismic probing of continental subduction zones. *Journal of Asian*
923 *Earth Sciences* 145, 37-45.
924

Figure 1



926

927

928

929

930

931

932

933

934

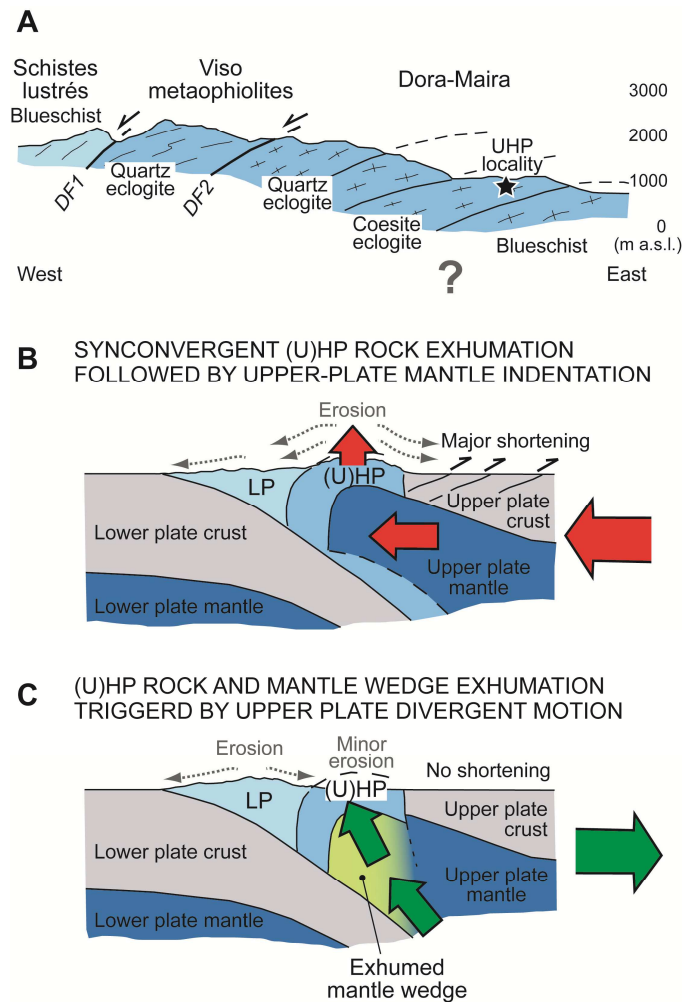
935

936

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-Verbanò; 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).

937
938

Figure 2

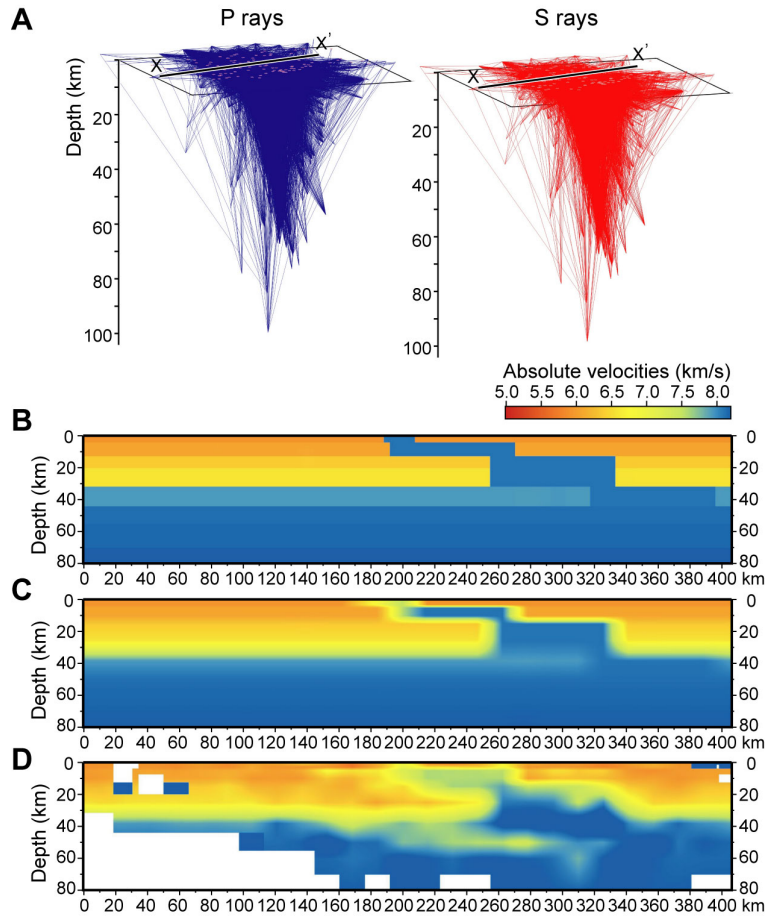


939
940
941
942
943
944
945
946
947
948
949
950
951
952
953
954
955
956
957

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 serpentinitized 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 serpentinitization 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).

958
959

Figure 3

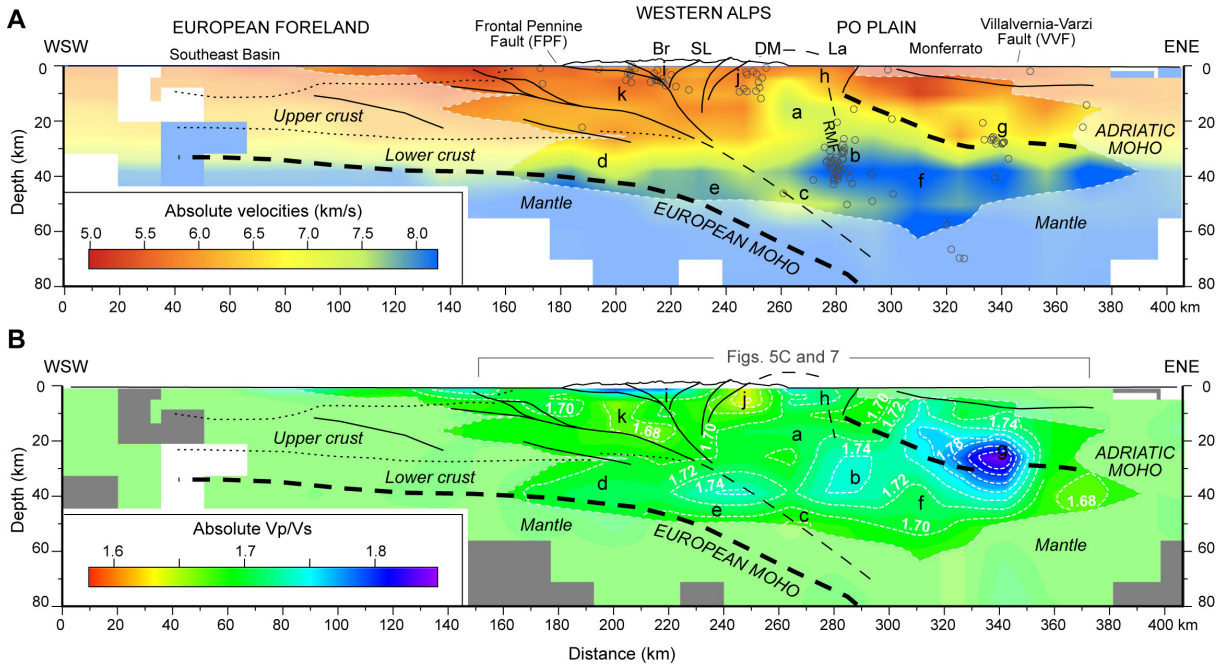


960
961
962
963
964
965
966
967
968
969
970
971
972

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.

973
974

Figure 4

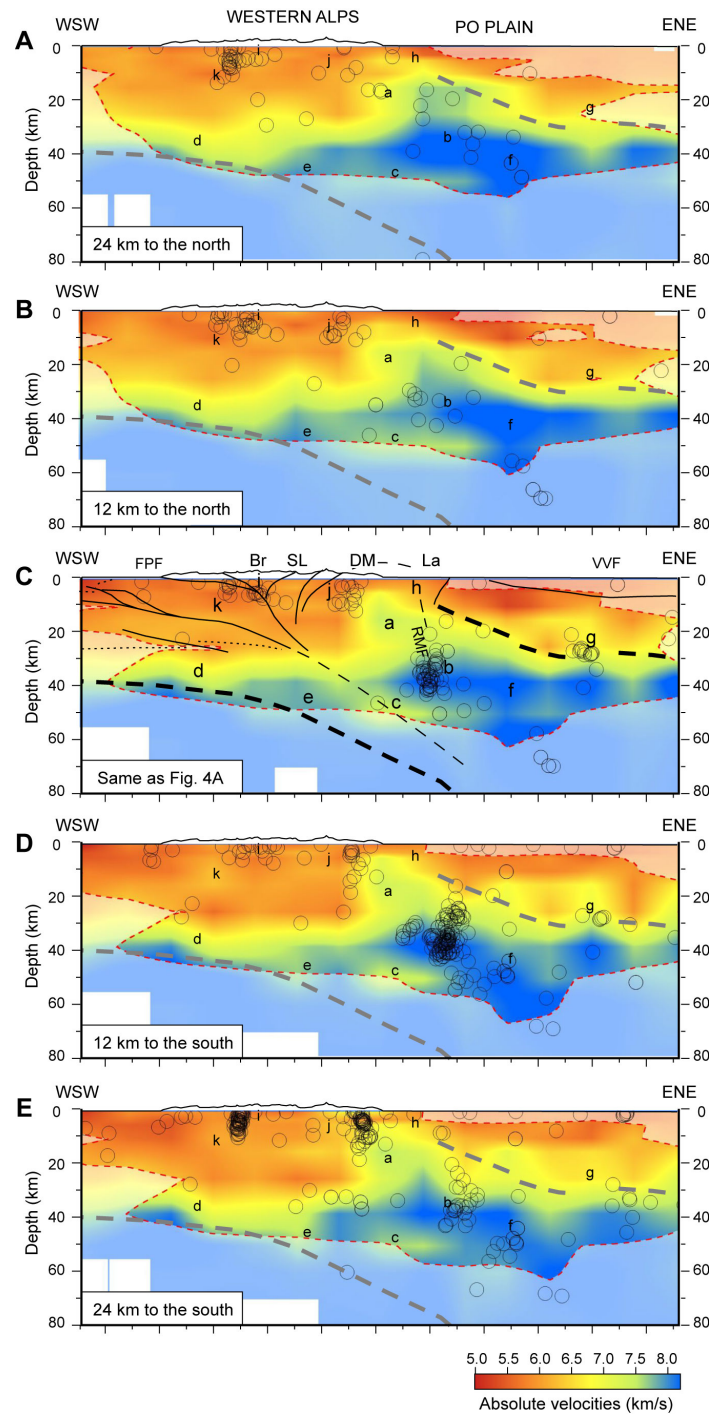


975
976
977
978
979
980
981
982
983
984
985
986
987

Figure 4: Tomographic cross sections along the CIFALPS transect. A) Absolute V_p 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) V_p/V_s ratios. White dashed lines are isolines of equal V_p/V_s , grey areas are not sampled (other keys as in frame A).

988
989

Figure 5

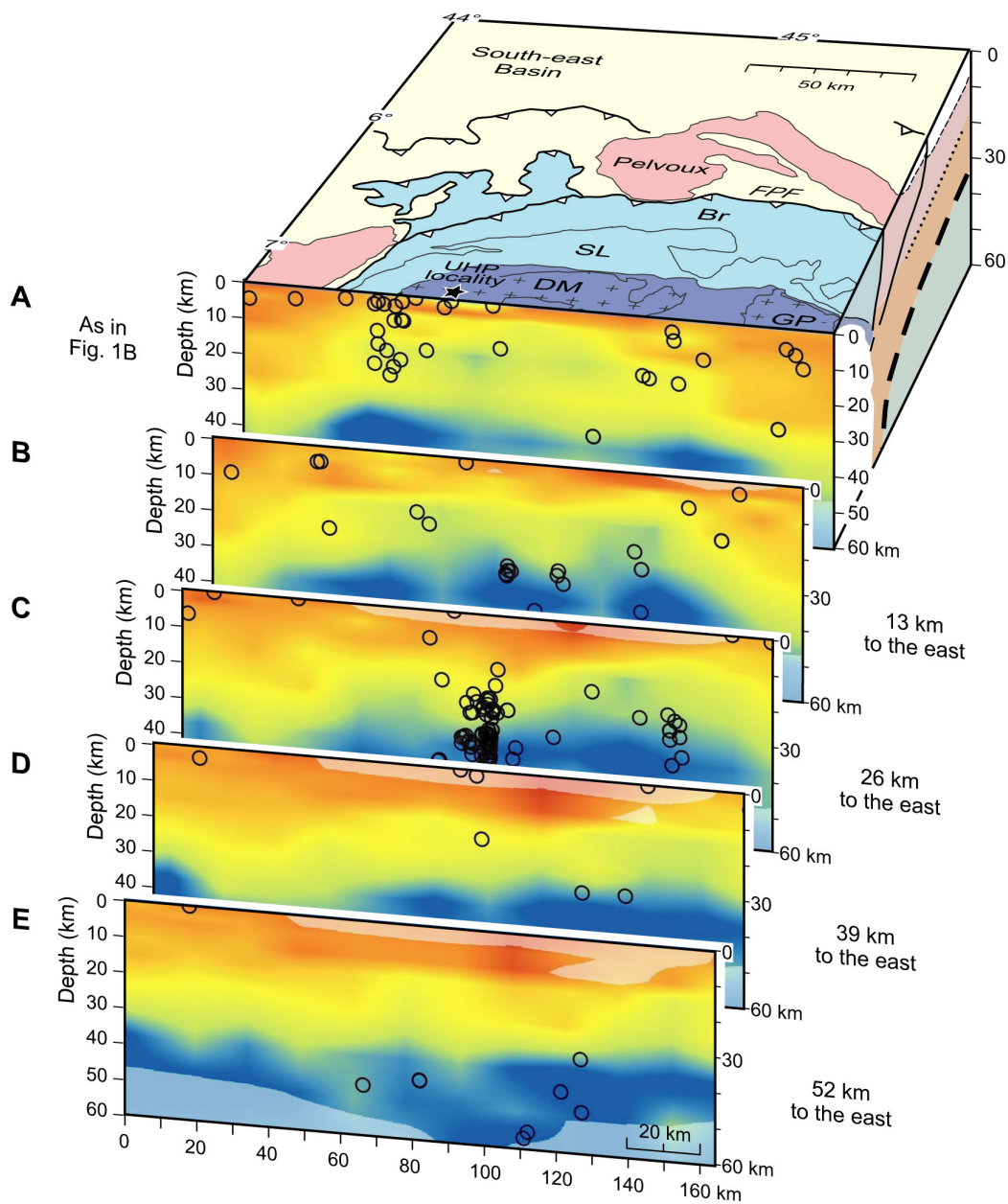


990
991
992
993
994
995
996
997
998

Figure 5: Lateral variations in V_p 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.

999
1000
1001

Figure 6

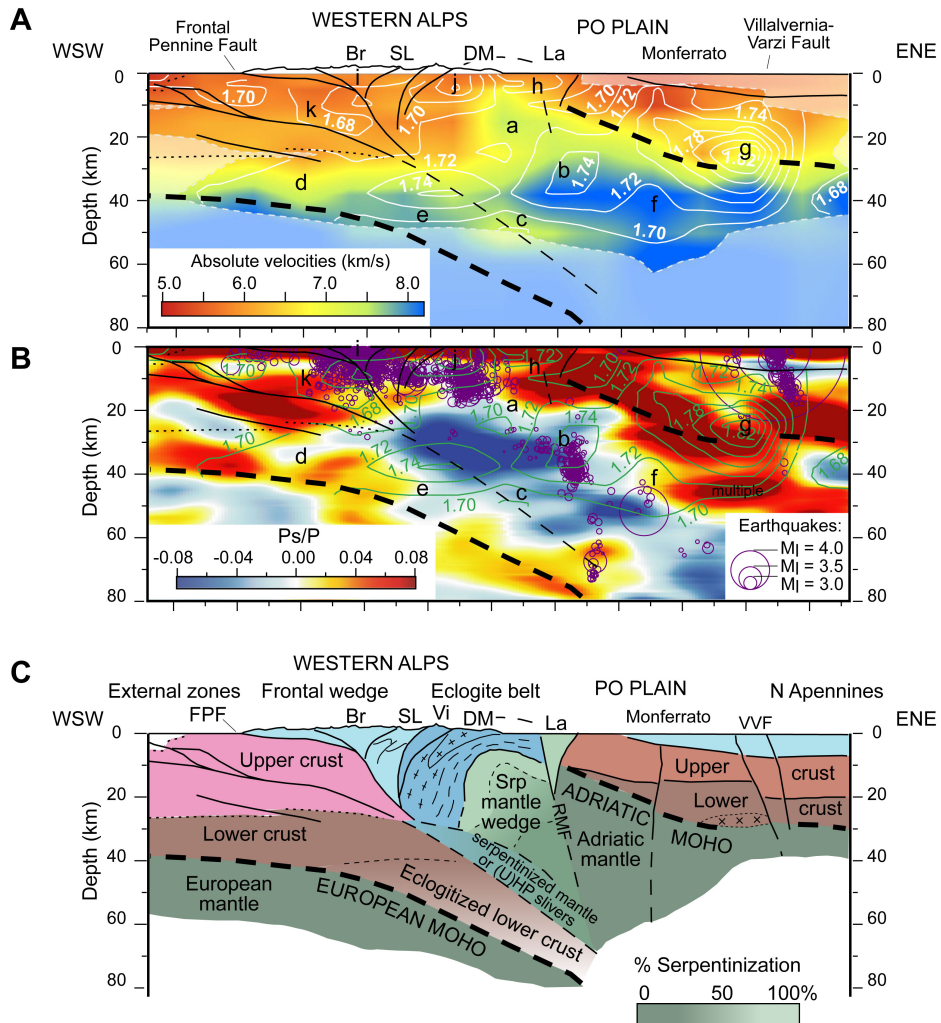


1002
1003
1004
1005
1006
1007
1008
1009

Figure 6: Lateral variations in V_p 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.

1010
1011

Figure 7

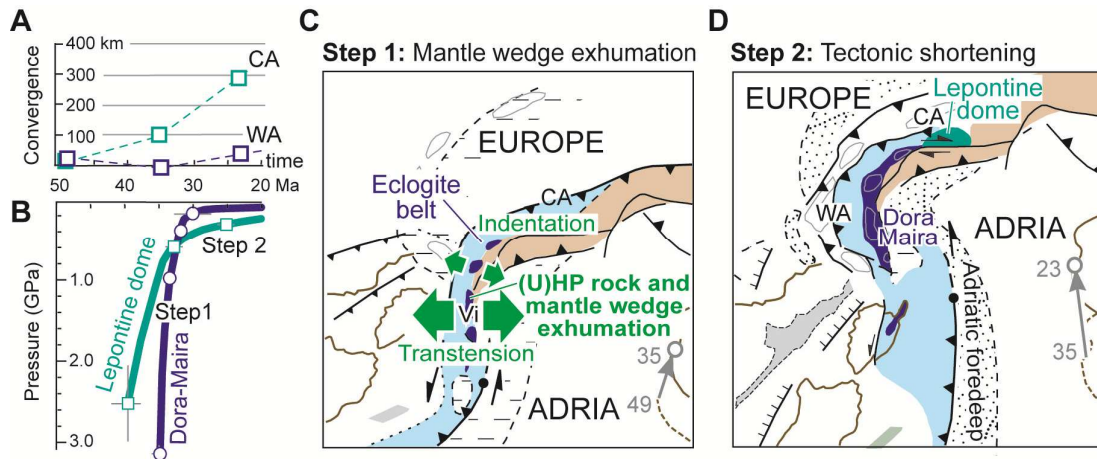


1012
1013
1014
1015
1016
1017
1018
1019
1020
1021
1022
1023

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 V_p/V_s ; purple circles in B are earthquakes recorded since 1990 (Malusà et al., 2017). The amount of serpentinitization 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.

1024
1025
1026

Figure 8



1027
1028
1029
1030
1031
1032
1033
1034
1035

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).