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Earthquakes in the western alpine mantle wedge

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ABSTRACT

The assessment of seismic activity in the shallow continental mantle has long been hindered by the low resolution of both seismic imaging and earthquake locations in young collision zones. Here, we combine the most recent and high-resolution image of the lithospheric structure of the Western Alps with a high quality dataset of anomalously deep earthquakes recorded in the same area in the past 25 yrs. We show that these earthquakes are aligned on an active lithospheric strike-slip fault, and we provide evidence that this fault is located in the mantle wedge beneath the Adriatic Moho. Our results: (i) provide direct evidence that deep material can be seismogenic or not depending on the lithology; (ii) confirm the role of serpentinization in favoring the aseismic creep of mantle rocks; and (iii) demonstrate that the upper mantle can be stiff and seismogenic not only in cold cratons, but also in young orogenic belts.

1. Introduction

The mechanical properties of the continental upper mantle are very important for the interpretation of lithospheric processes at all time and spatial scales (Richards et al., 2001; Bürgmann and Dresen, 2008), but in spite of the relevant implications, these properties are still highly debated (Chen and Molnar, 1983; Jackson, 2002; Burov and Watts, 2006; Monsalve et al., 2006; Priestley et al., 2008; Chen et al., 2013). A strong and rigid mantle may explain the topographic stability of mountain belts and the slab integrity during subduction (Burov and Watts, 2006; Mouthereau et al., 2013), while the shallow depth of most continental earthquakes may instead suggest that the long-term strength of the continental lithosphere resides in the crust (Maggi et al., 2000a; Jackson, 2002). So far, evidence of seismic activity and brittle faulting in the continental mantle has limited spatial coverage (Chen and Molnar, 1983; Maggi et al., 2000b; Monsalve et al., 2006; Priestley et al., 2008; Frohlich et al., 2015; Inbal et al., 2016) and the loci of deep earthquakes are often poorly constrained relative to nearby plate interfaces (Negredo et al., 2007; Priestley et al., 2008; Kufner et al., 2016). In the field, some xenoliths of mantle rocks show brittle cataclastic textures (Takeuchi and Arai, 2015) and pseudotachylytes do occur in outcrops of mantle peridotite (Andersen and Austrheim, 2006), yet most exhumed mantle slivers bear sole evidence of high-temperature ductile shear (Vauchez et al., 2012).

Here, we shed light on this issue by combining the most recent high-resolution image of the lithospheric structure of the Western Alps with a high quality dataset of anomalously deep earthquakes recorded in the same area during the past 25 yrs. Our results provide new constraints on mantle rheology along convergent plate boundaries, and have major implications for a wide range of studies, from the local scale to large scale geodynamics.

2. The Western Alps study area

The Western Alps are the result of the Cretaceous-to-Paleogene oblique subduction of the European plate beneath the Adriatic microplate (Jolivet et al., 2003; Handy et al., 2010; Malusà et al., 2015). They include a thick subduction complex, now exhumed at the surface (Lardeaux et al., 2006; Malusà et al., 2011), and they are seismically active despite subduction ceased >30 Myrs ago (Eva and Solarino, 1998; Delacou et al., 2004). During the collision stage, deformation propagated towards the European foreland (Dumont et al., 2012; Bellahsen et al., 2014), and GPS measurements attest that Adria-Europe convergence is now chiefly accommodated outside the Western Alps accretionary wedge (e.g., Serpelloni et al., 2005).

Seismicity in the Western Alps typically shows low to moderate energy ($2 < Ml < 4$ magnitude), and is usually confined within the upper

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crust (Eva et al., 1997; Eva and Solarino, 1998; Sue et al., 1999; Perrone et al., 2010), but hundreds of anomalously deep earthquakes have been also recorded on the upper plate side of the orogenic belt, along the boundary with the Po Plain (Eva et al., 2015). However, the low resolution of earthquake locations, and the lack of high-resolution images of the Western Alps lithospheric structure, have long precluded a reliable positioning of these earthquakes relative to the plate interface, hindering any further step in the investigation of the rheological properties of the continental lithosphere in the study area.

In order to shed light on this issue, the whole earthquake dataset was recently reprocessed by Eva et al. (2015) to improve earthquake locations, whereas new constraints on the lithospheric structure were provided by the passive seismic experiment CIFALPS (China-Italy-France Alps Seismic survey) using the P-receiver-function technique (Zhao et al., 2015). These two datasets are combined here for the first time.

Noteworthy, the linear transect defined by the CIFALPS temporary broadband seismic stations is located just in correspondence of the main cluster of anomalously deep earthquakes (Fig. 1). This was particularly important in the light of the complex 3D structure expected in the Western Alps, where Adria-Europe convergence was strongly oblique relative to the orogen trend during most of the Cenozoic (Dewey et al., 1989; Jolivet et al., 2003), and deformation during subduction and collision was strongly partitioned across the orogen (Malusà et al., 2009, 2015).

3. Methods

The methods employed for earthquake analysis and seismic imaging are described in full in Eva et al. (2015) and Zhao et al. (2015), and are summarized here to underline the reliability of the datasets employed in this work. We considered the anomalously deep earthquakes (depth > 20 km) recorded from 1990 to 2014 within the quadrangle 44°00′N – 45°30′N and 6°30′E – 8°30′E. The network used to record the seismicity (red triangles in Fig. 1) includes stations from RSN INGV Roma, SISMALP Grenoble Observatory, OCA GeoAzur Nice and SED-ETH Zürich. Data were selected according to the number of phase readings (at least 8 P + S), which led to a dataset of 590 earthquakes and ~12,500 three-component waveforms, equally distributed between P- and S-wave

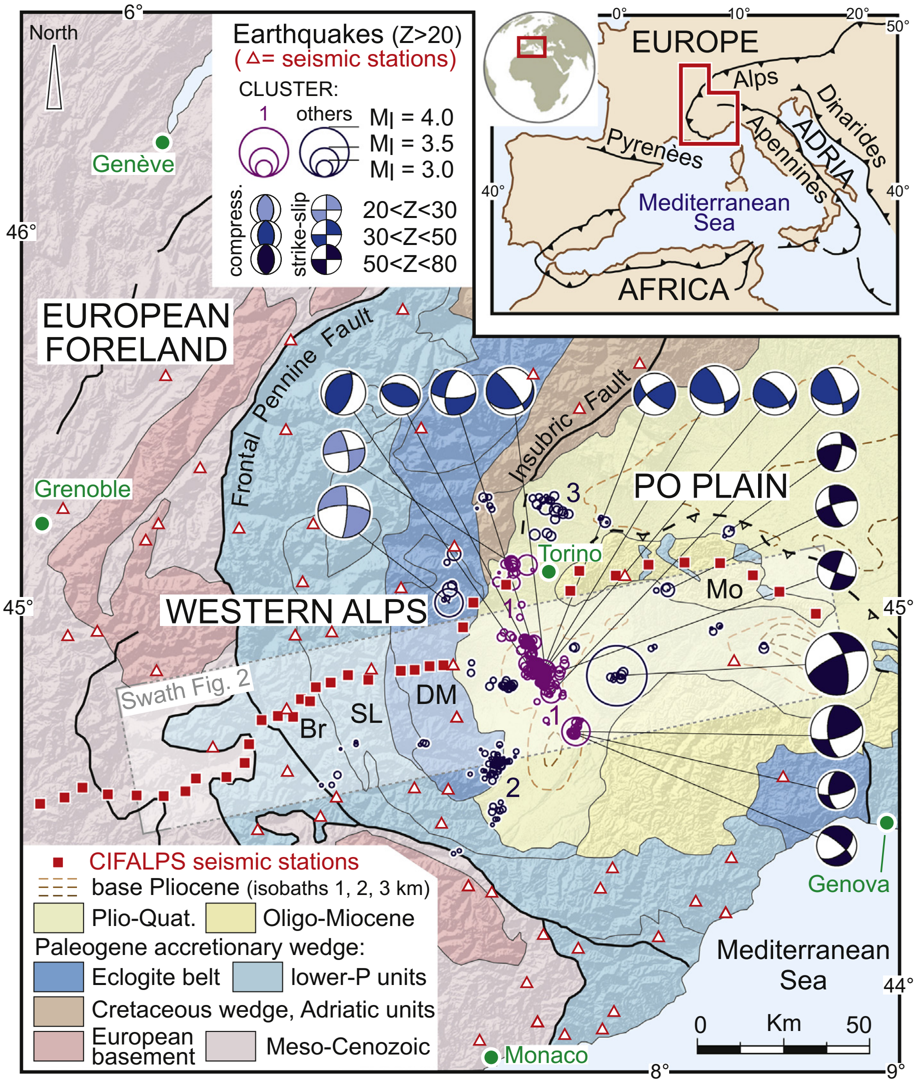

Fig. 1. The anomalously deep earthquakes of the Western Alps. Circles show the magnitude (Ml) and distribution of all the events, recorded between 1990 and 2014, located at depth (Z) >20 km ($n = 317$ after HypoDD relocation); beach balls show focal solutions in different depth ranges; 1 to 3 indicate earthquake clusters as discussed in the text: cluster 1 (purple) marks an active lithospheric fault masked by thick Plio-Quaternary sediments. The red triangles indicate the network used to record the seismicity, the red squares indicate the location of the broadband seismic stations of the CIFALPS experiment (Zhao et al., 2015). Abbreviations: Br, Briançonnais; DM, Dora Maira; Mo, Monferrato; SL, Schistes lustrés. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

pickings. Seismograms were revised by a complete manual phase picking. We applied to the dataset the double difference relocation technique (HypoDD) (Waldhauser and Ellsworth, 2000). Cross-correlations were computed for stations at <100 km distance from the center of the selected area, whereas stations at >100 km distance were additionally considered for catalogue data. We thus obtained ~25,000 cross correlation difference times to use in the computation with HypoDD, complemented by ~780,000 catalogue differential times.

Fault plane solutions were computed by E.E. for relocated events with magnitude >2.6 Ml, according to the first onset technique and using the FPFIT software (Reasenberg and Oppenheimer, 1985). We selected earthquakes having at least 15 readable, evenly distributed polarities (gap <110°), using for computation the output hypocentral parameters obtained with HypoDD.

The location of the temporary broadband seismic stations of the CIFALPS passive seismic experiment, which operated from July 2012 to September 2013, is shown in Fig. 1. Their spacing ranges from 5 km in the mountain belt to 10 km in the Po Plain, where specific problems related to anthropogenic noise and unconsolidated sediments were minimized by selecting sites in outcrops of Oligo-Miocene sedimentary rocks exposed atop the Monferrato thrust fronts (Fig. 1). Events with magnitude ≥5.5 and epicentral distance from 30° to 90° were selected for calculation of the receiver functions. Three-component recordings of distant earthquakes were band-pass filtered and rotated into the local coordinate system. We excluded P-wave records with signal-to-noise ratio < 2 on the radial component, and removed the remaining low-quality records by visual inspection. After computing radial and transverse receiver functions according to the method described in Ligorría and Ammon (1999), we performed a second round of visual inspections to remove low-quality receiver functions. As a result, we obtained a dataset of 1647 radial receiver functions from 84 events.

To produce a depth image beneath the receiver array, we migrated the time data to depth, and stacked the radial receiver functions using the common conversion point (CCP) method (Zhu, 2000). We used the resulting depth section and other geophysical and geologic constraints to define the geometry of possible 2D models and the main layer boundaries and velocity contrasts (Zhao et al., 2015). After constructing the model geometry, we checked its compatibility with the Bouguer anomaly data by gravity modeling, and performed 2D synthetic tests in order to test the interpretation of the CCP section that fits the Bouguer anomaly data.

4. Earthquake distribution

The 317 events out of 590 recorded in the Western Alps at depth > 20 km, and successfully relocated with the HypoDD algorithm, are distributed within a roughly N—S trending belt in map view (Fig. 1). These anomalously deep earthquakes show, in 90% of the cases, both horizontal and vertical location errors <2.5 km, and their epicenters define three clusters. The main linear cluster (1, purple in Fig. 1), recently referred to as the Rivoli-Marene deep fault (Eva et al., 2015), is located beneath the Western Po Plain, and includes the highest magnitude events, with depth constrained between 25 and 75 km. In cross section, these events define an apparent plane steeply dipping towards ENE (Fig. 2a). Minor clusters of lower magnitude events, with depth constrained between 20 and 40 km, are found on the southeastern margin of the Dora-Maira massif (2 in Fig. 1), and north of the Monferrato thrust front (3 in Fig. 1). No anomalously deep earthquake is found farther north, possibly due to a change in tectonic boundary conditions (Malusà et al., 2009, 2015). Fault plane solutions invariably show a strike-slip component (see beach balls in Fig. 1), which contrasts with the dominant extensional solutions associated with earthquakes shallower than 20 km (e.g., Eva and Solarino, 1998; Sue et al., 1999). Along the analyzed cross section, the 30–50 km depth earthquakes show compressive to transpressive solutions, whereas the 50–80 km depth earthquakes show strike-slip solutions with a slight compressive component (Fig. 2b). Fault plane solutions thus depict an heterogeneity of focal mechanisms with a stacking of extensional, compressional and strike-slip events as a function of depth (Fig. 3a), that will be discussed in more detail in Section 6.1.

5. Lithospheric structure

The lithospheric structure imaged by the P-receiver-function technique is shown in Fig. 2a, whereas the corresponding 2D velocity and gravity model is shown in Fig. 2b. The P-receiver-function technique enhances P-to-S (Ps)-converted waves on velocity interfaces beneath an array in the records of teleseismic earthquakes. The polarity of the converted signal depends on the sign of the velocity change, which allows for an easy discrimination between interfaces with velocity increase (red-to-yellow in Fig. 2a) and interfaces with velocity decrease (blue in Fig. 2a). Our seismic experiment imaged two major interfaces with velocity increase, corresponding to the European and Adriatic Mohos already imaged by previous work (e.g., Thouvenot et al., 2007; Molinari et al., 2015), and a major interface with velocity decrease. The European Moho is continuously marked by Ps-conversions with positive polarity, dipping towards the east from ~40 km depth beneath the Frontal Pennine Fault to ~75 km depth beneath the westernmost Po Plain. The weakening of this converted phase beneath the accretionary wedge may be due to eclogitization, and consequent density increases with metamorphic phase changes, of the European lower crust at depth > 40 km. The European Moho is not imaged by the P-receiver-function technique at depth > 75 km. However, it is expected to become steeper below 75 km depth, in the light of the attitude of the European slab inferred from P-wave tomography constraints (e.g., Piromallo and Faccenna, 2004; Zhao et al., 2016).

The Adriatic Moho imaged by our receiver function analysis is marked, in Fig. 2a, by shallower positive-polarity Ps-conversions, recognized at 20–30 km depth to the east and 10–15 km depth to the west. In the westernmost Po Plain, this interface coincides with the top of the so-called 'Ivrea body' (Closs and Labrouste, 1963), classically interpreted as a southward-plunging slice of Adriatic mantle at shallow crustal depth (Nicolas et al., 1990; Scafidi et al., 2009). Synthetic tests show that the underlying red spots located at 40–55 km depth (see Fig. 2a) are instead multiples (Zhao et al., 2015). A shallow positive-polarity converted phase is also observed beneath the Dora-Maira massif, and it is interpreted to mark a downward velocity increase from (ultra)high-pressure [(U)HP] crustal rocks to mantle rocks underneath (Fig. 2b). The main negative polarity conversions (thick blue spot in Fig. 2a) recognized at 20–40 km depth beneath the Dora-Maira massif, may mark instead a downward velocity decrease from mantle rocks to (U)HP slivers of European crust and associated serpentinites of the suture zone (Fig. 2b). Two end-member tectonic reconstructions, both consistent with geophysical data (Zhao et al., 2015) are shown in Fig. 3, and will be used to discuss the relationships between seismicity and lithospheric structure in Section 6. In Fig. 3a, the downward velocity decrease revealed by the CIFALPS experiment is entirely ascribed to a thick complex of (U)HP continental slivers, in line with the predictions of recent numerical models of synconvergent exhumation (e.g., Jamieson and Beaumont, 2013). In Fig. 3b, instead, the downward velocity decrease is entirely ascribed to the serpentinization of the mantle wedge on top of the slab, with a larger volume of mantle involved that may be expected, for instance, in the case of exhumation triggered by divergence between upper plate and accretionary prism (e.g., Malusà et al., 2015). Discriminating between these end-member models is beyond the aim of this work. Both (U)HP continental slivers and serpentinites may be found in correspondence of the thick blue spot of negative polarity conversions shown in Fig. 2a, but the relative proportion of these rocks cannot be assessed on the basis of available geophysical constraints, and would require further investigations.

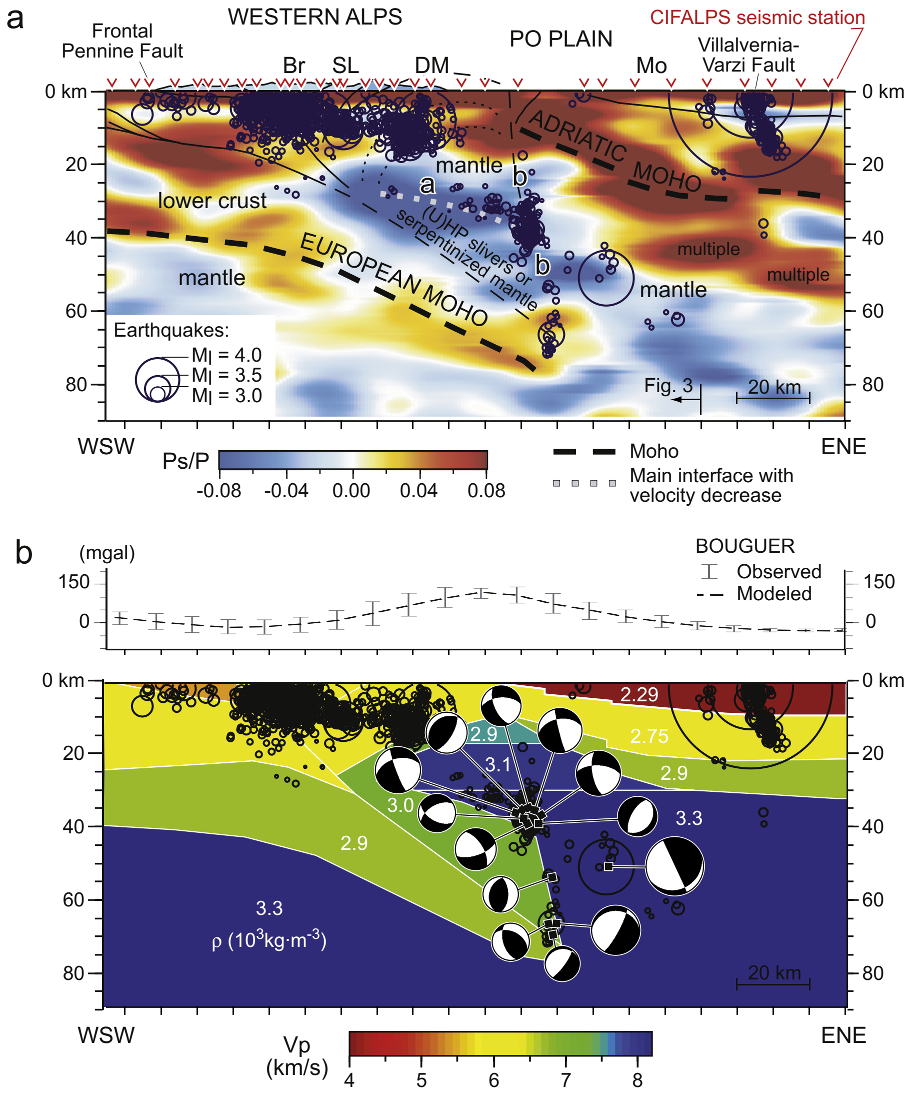

Fig. 2. Relocated earthquakes and seismic imaging combined. a) Earthquakes within the 40-km-thick stripe in Fig. 1 are plotted on the receiver-function cross-section of the CIFALPS experiment (Zhao et al., 2015, abbreviations as in Fig. 1). Positive- and negative-polarity Ps-converted phases are shown in red and blue, respectively, according to the color scale. The dashed black lines indicate the European and Adriatic Mohos, the dashed grey line indicates a main interface with velocity decrease; "a" and "b" indicate earthquake alignments with different dip angles, as discussed in the text; events located at depth < 20 km are also included. b) Focal solutions for events deeper than 20 km are projected, onto the vertical plane, on the 2D velocity and gravity model of the CIFALPS experiment (density values in white). Modeled and observed Bouguer gravity anomaly data are also shown (Zhao et al., 2015). The largest strike-slip earthquake (Z > 50 km) occurring ~20 km to the east of the main alignment "b", which marks a lithospheric fault, might be also located along a similar structure located farther east. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

6. Discussion

6.1. Earthquakes in the continental mantle

When the earthquakes relocated with HypoDD are plotted on the new lithospheric image provided by the CIFALPS experiment (Fig. 2), it is clear that the shallow earthquakes (<20 km depth) (e.g., Eva and Solarino, 1998; Sue et al., 1999) are concentrated within the uplifting accretionary wedge (Serpelloni et al., 2013), i.e., between the Frontal Pennine Fault and the Dora Maira massif (DM in Fig. 2a). By contrast, no diffuse shallow seismicity is observed farther east in the subsiding Po Plain, where shallow events are clustered along few main tectonic structures such as the Villalvernia-Varzi Fault (e.g., Malusà and Balestrieri, 2012). This confirms that extensional faulting during rock uplift plays a major role in controlling the shallow seismicity of the Western Alps (Eva and Solarino, 1998; Sue et al., 1999).

But the most intriguing information provided by Fig. 2 is that the anomalously deep earthquakes of the Western Alps are located well below the Adriatic Moho. Events deeper than 20 km, and located within the 40-km-thick stripe of Fig. 1, probably originated either within the Adriatic mantle beneath the Po Plain, or within the mantle sandwiched between the Dora Maira (U)HP rocks and the (U)HP metamorphic slivers and/or the serpentinized mantle of the suture zone underneath (Fig. 2b). No deep seismicity is instead observed along the imaged European Moho or its continuation at depth, as expected since subduction is no more active. The earthquakes located below the Adriatic Moho define two main alignments with different dip angles ("a" and "b" in Fig. 2a). The alignment "a" dips at low angle towards the east, and is parallel to the main interface with downward velocity decrease imaged beneath the Dora Maira massif (Fig. 2b). Noteworthy, most of the events ascribed to the alignment "a" lay within the mantle above this interface, and only few events are located within the (U)HP continental slivers (Fig. 3a) or the serpentinized mantle (Fig. 3b) underneath. The alignment "b" dips instead at high angle towards the east, and marks an active sinistral lithospheric fault that crosscuts the whole mantle suture zone between the Adriatic Moho and the European Moho. This fault accommodated the

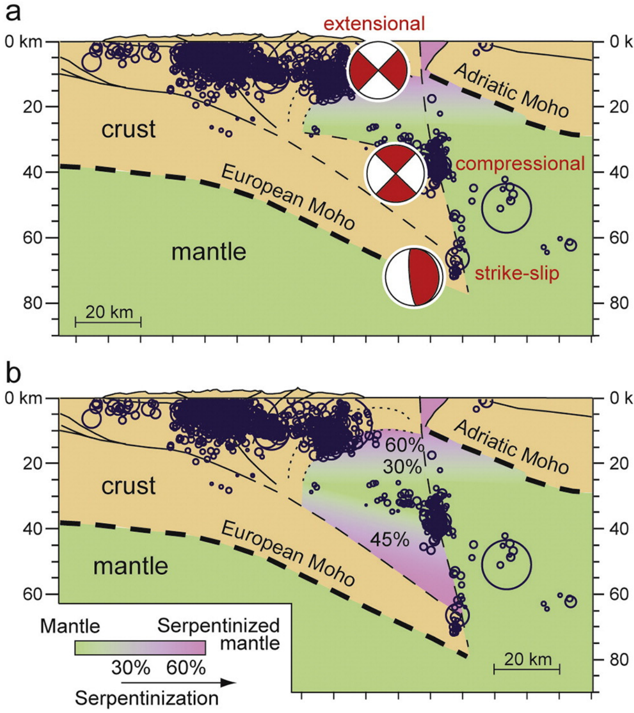

Fig. 3. Earthquakes in the Western Alps mantle and focal mechanism heterogeneity with depth. Frames a and b show two end-member tectonic interpretations, either encompassing a thick complex of (U)HP continental slivers (a) or serpentinized mantle (b) on top of the slab (the amount of serpentinization is inferred from P-wave velocity - e.g., Reynard, 2013). Shallow earthquakes (<20 km depth) are concentrated in the uplifting accretionary wedge, whereas the anomalously deep events (>20 km depth) are concentrated, in both models, in the mantle wedge beneath the Adriatic Moho (Ml scale as in Fig. 2), and in mantle rocks not affected by serpentinization. According to the more conservative end-member hypothesis of Fig. 3a, >200 earthquakes have been recorded in the mantle along the analyzed cross section since 1990. Fault plane solutions (summarized by red beachballs in frame a) define a vertical stacking of extensional (e.g., Eva and Solarino, 1998), compressional and strike-slip events. No seismicity is observed along the European Moho.

post-Oligocene differential motion between the Adriatic lithosphere and the Alpine wedge on top of the European slab, locally juxtaposing crustal rocks against mantle rocks. Outside of the main alignment "b", earthquakes predominantly lay within the Adriatic mantle east of the fault, whereas only few events lay within the continental crust and/or the serpentinized mantle to the west of the fault.

The heterogeneity of focal mechanisms with depth observed below the Adriatic Moho may be explained with strain partitioning along pre-existing tectonic structures. In the depth range from 30 to 50 km, seismic events have oblique focal mechanisms and a less important strike–slip component compared to the events deeper than 50 km. At 30–50 km depth, the receiver-function cross-section also highlights a vertical change in lithospheric structure, which is dominated by the shallow dipping contact between mantle rocks not affected by serpentinization on top, and the (U)HP continental slivers and/or serpentinized mantle rocks below (Fig. 2b). This suggests that the anomalously deep earthquakes with oblique and strike-slip focal mechanisms could be a response to the same global stress field controlled by the ongoing convergence between Africa and Europe, but accommodated along shallow dipping and steeply dipping pre-existing faults, respectively, at different depths within the lithosphere (Jolivet et al., 2003; Serpelloni et al., 2005). The Western Alps are oriented near-parallel to present-day Adria motion relative to stable Europe (Serpelloni et al., 2005), which explains the importance of strike-slip deformation along this segment of the Adria-Europe plate boundary.

Previous work suggested the occurrence of earthquakes at shallow mantle depth (Chen and Molnar, 1983; Chen and Yang, 2004; Monsalve et al., 2006), but the mantle origin of those earthquakes was not proven (Maggi et al., 2000b; Priestley et al., 2008). The locations of the anomalously deep earthquakes of the Western Alps have been progressively confirmed by improved techniques over 25 years of continuous recording (Eva et al., 2015). By combining this high-quality dataset and the highest-resolution image of the Alpine subduction complex, we demonstrate here that these anomalously deep earthquakes originate in the shallow mantle. Even under the most conservative tectonic reconstruction of Fig. 3a, the number of mantle earthquakes recorded along the analyzed cross section since 1990 is >200.

6.2. Temperature and lithology control on seismicity

The vertical stacking of continental crust and mantle rocks described beneath the Western Alps provides an excellent framework for testing the role of temperature and lithology on seismicity. Rocks with contrasting rheological properties are in fact juxtaposed at similar depths (Fig. 3), and deformation is strongly localized along an active lithospheric strike-slip fault (Eva et al., 2015). Within this complex lithospheric puzzle, earthquakes are indeed concentrated in the upper crust, but they are also continuously recorded down to 75 km depth in the lithospheric mantle beneath the Adriatic Moho, without any major gap with depth. As shown in Fig. 3, most of the earthquakes originate in the continental crust within the uppermost 15–20 km of the Alpine accretionary wedge, but earthquakes are also observed in the 20–30 km depth range, either in European lower crust or in mantle rocks not affected by serpentinization. At depth > 30 km, earthquakes are no more observed within the subducted lower crust, but they are clustered in mantle rocks both in Fig. 3a and in Fig. 3b. Therefore, our results provide observational evidence that deep material located at the same depth, and thus at very similar temperature along the same fault, under the same stress conditions can be seismogenic or not depending on the lithology. In previous work, this kind of analysis was precluded by insufficient information concerning both the lithospheric structure of the collision zone, and the localization of deep earthquakes relative to the plate interface.

The distribution of earthquake depths observed in the Western Alps confirms the global view of seismicity (e.g., Priestley et al., 2008; Chen et al., 2013), which states that (i) earthquakes dominantly occur in upper crust colder than ~300 °C, and predicts that (ii) earthquakes might potentially occur in the mantle, if colder than ~600 °C. Our results provide direct evidence confirming this prediction. This general behaviour is ascribed to the onset of crystal plasticity of quartz in the crust and olivine in the upper mantle, which precludes frictional instability at higher temperatures (Scholz, 1998; Raterron et al., 2004). Serpentinization is an additional player possibly favoring aseismic deformation in mantle rocks (Peacock and Hyndman, 1999; Hilairet et al., 2007), as confirmed by both Fig. 3a and b, which show that the anomalously deep earthquakes of the Western Alps chiefly originate in mantle rocks not affected by serpentinization.

Our results thus confirm the major role played by temperature and lithology in controlling the earthquake distribution with depth. In the light of the low stress inferred from earthquake magnitudes, this implies that the Adriatic mantle at ~75 km depth is colder than ~600 °C (e.g., Raterron et al., 2004), which requires geothermal gradients (<8 °C/km) on the order of those experienced by the European crust during Alpine subduction (Malusà et al., 2015). Geothermal gradients, on the upper plate side of the Western Alps subduction system, thus remained very low even after the choking of Alpine subduction, in agreement with the lack of orogenic magmatism and with the predictions of numerical models (e.g., Jamieson and Beaumont, 2013). Within the accretionary wedge, by contrast, the relatively low thickness of the seismogenic layer, and the absence of earthquakes at depth > 30 km, is supportive of an increase in geothermal gradients after the end of subduction, possibly due to the advection of heat transported by exhuming (U)HP rocks, as confirmed by independent petrologic and geochronologic evidence (Malusà et al., 2015). A similar situation is observed north of eastern Papua New Guinea, where anomalously deep earthquakes are recorded at ~100 km depth (Eilon et al., 2015) on the upper plate side of a chocked subduction zone that brought a ribbon of Australian continental crust down to (U)HP depth (Baldwin et al., 2012). Like in the Western Alps, these anomalously deep earthquakes have no clear linkage with a subducting slab.

6.3. Implications for lithosphere rheology

The rheological properties of the continental lithosphere are an open issue with relevant implications for a wide range of studies (Burov and Watts, 2006; Bürgmann and Dresen, 2008), and contrasting 1D rheological models have been proposed so far. On the one hand, the conventional “jelly sandwich” rheological model (Chen and Molnar, 1983; Chen and Yang, 2004) envisages a weak aseismic lower crust separating two rigid seismogenic layers, represented by the upper crust and the uppermost mantle. On the other hand, the alternative “crème brûlée” model (Jackson, 2002; Priestley et al., 2008) envisages a single strong seismogenic layer that may either involve the upper crust or the whole crust, but does not include the mantle. These simple end-member models have been applied to orogenic belts with a relatively constant structure along strike, such as the Himalayas (Chen and Yang, 2004; Priestley et al., 2008), but they might be more difficult to apply in the case of a complex 3D structure as expected in the Western Alps.

The Western Alps case study shows that major gaps in earthquake distribution with depth, as predicted by the jelly sandwich model (Chen and Molnar, 1983; Burov and Watts, 2006), are not necessarily required. Moreover, it demonstrates that the upper mantle can be stiff and seismogenic not only in cold cratons, as predicted by the crème brûlée model (Priestley et al., 2008), but also in young orogenic belts.

7. Conclusions

The combined analysis of lithospheric structure and distribution of anomalously deep earthquakes in the Western Alps shed new light on the rheological properties of the continental lithosphere, and led to the following main conclusions:

1) The anomalously deep earthquakes of the Western Alps are aligned on an active lithospheric fault located in the mantle wedge between the European Moho and the Adriatic Moho. This provides compelling evidence that seismic activity and brittle faulting can occur in the shallow continental mantle of a young collision zone.

2) Earthquakes in the Western Alps are concentrated in the upper crust, but they are also continuously recorded in the lithospheric mantle down to 75 km depth. No earthquake is instead observed in the subducted European crust at depth >30 km. This provides direct evidence that temperature and lithology exert a major role in controlling earthquake distribution with depth.
3) The anomalously deep earthquakes of the Western Alps chiefly originate in mantle rocks not affected by serpentinization. This confirms the role of serpentinization in favoring aseismic creep.
4) The earthquake distribution with depth observed in the Western Alps shows that the major seismic gap predicted by the jelly sandwich rheologic model is not necessarily required, and demonstrates that the mantle of a young continental plate can be stiff and seismogenic unlike predicted by the crème brûlée model. These findings should be integrated in future, more realistic rheologic models of the continental lithosphere.

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