FRESH, PSEUDOTACHYLYTE-BEARING MANTLE PERIDOTITES FROM THE LAWSONITE ECLOGITE-FACIES SAN PETRONE UNIT, ALPINE CORSICA

Alberto Vitale Brovarone*,**,✉, **Francesca Piccoli*****, **Gianluca Frasca**° and **Francesco Giuntoli***

* *Dipartimento di Scienze Biologiche, Geologiche e Ambientali (BiGeA), Università di Bologna, Italy.*
** *Sorbonne Université, Muséum National d'Histoire Naturelle, Institut de Minéralogie, de Physique des Matériaux et de Cosmochimie, IMPMC, Paris, France.*
*** *Institute of Geological Sciences, University of Bern, Switzerland.*
° *Istituto di Geoscienze e Georisorse (IGG), CNR, Torino, Italy.*
✉ *Corresponding author, e-mail: alberto.vitaleb@unibo.it*

Keywords: *Mantle peridotite, ocean-continent transition; subduction; serpentinization; pseudotachylyte; redox; Alpine Corsica.*

ABSTRACT

Mantle peridotites exhumed in mountain belts provide important insights on the composition and evolution of the upper mantle, and additionally inform on metamorphic, geochemical, and tectonic processes -including seismic activity- at convergent margins. In this contribution, we present field, microstructural, and mineralogical data of fresh, pseudotachylyte-bearing mantle peridotites from the lawsonite eclogite-facies San Petrone unit, Alpine Corsica, France. The present case study represents the first example of subducted fresh peridotite associated with fresh lawsonite eclogite-facies assemblages. Two bodies of fresh peridotite are embedded in fully serpentinized ultramafic rocks forming the substratum of a subducted ocean-continent transition of the Piemonte-Liguria Basin. Clinopyroxene and spinel mineral chemistry indicates that the investigated peridotite samples were part of a refertilized mantle and, therefore, the San Petrone unit likely belonged to the more distal part of the ocean-continent transition. Because small bodies of fresh peridotite embedded in fully serpentinized rocks can hardly be identified by means of geophysical investigations, this finding suggests that small, yet disseminated bodies of fresh mantle peridotite can potentially be more abundant than previously supposed at ocean-continent transition and, potentially, at mid-ocean ridges and in subduction zones. The preservation of fresh mantle peridotite bodies in subducting slabs is also discussed with respect to its potential implications on intermediate depth seismicity and geochemical cycling -including production of natural energy sources- from rifting to subduction.

INTRODUCTION

Rifted margins are characterized by zones of exhumed crustal and mantle rocks, which separate continental from frankly oceanic domains (e.g., Decandia and Elter, 1972; Manatschal, 2004 and references therein). These zones are called ocean-continent transitions (OCT) and bear important information on how the strength of the lithosphere evolves during continental rifting, and on which factors control the rift architecture (Manatschal 2004; Peron-Pinvidic and Manatschal 2009; Brun et al., 2017). Ocean-continent transition zones are in a favourable position to reach high/ultra high-pressure conditions during subduction (Beltrando et al., 2010; Beltrando et al., 2014). Therefore, their study may provide important insights both on the rifting and oceanization stages as well as on the subsequent subduction zone evolution.

In the case of magma-poor margins, such as the Piemonte-Liguria Basin, rifting results in the exhumation, at the sea floor, of subcontinental mantle along lithospheric detachments. During extension, mantle rocks exposed at OCT zones may record complex melt-rock interactions related to both the onset and development of the oceanic lithosphere (Rampone et al., 2008; 2009; Müntener et al., 2010, Piccardo et al., 2010; Picazo et al., 2016). Petrography, major and trace element data can be used to infer the composition of mantle peridotites from OCT zones that are today exposed in mountain belts, including metamorphic belts. Spinel peridotites with pyroxenite veins, plagioclase-peridotites, and orthopyroxene-rich harzburgites are typical of OCT settings (Picazo et al., 2016 and references therein). The preservation of fresh oceanic/OCT peridotites in exhumed metamorphic units also provides important insights on the evolution of rifted margins in subduction zones.

Fresh peridotites exposed in metamorphic belts may also provide insights on seismic processes occurring at convergent margins. Several studies over the last years have in fact focused on the formation of pseudotachylytes in some Alpine peridotite bodies as markers of subduction zone seismicity (Andersen and Austrheim, 2006; Austrheim and Andersen, 2004; Deseta et al., 2014a; 2014b; Magott et al., 2016; 2017, Scambelluri et al., 2017; Pennacchioni et al., 2020). Despite the attribution of ultramafic pseudotachylytes to high-pressure seismic events may be challenging, the local exceptional preservation of these structures in peridotite bodies has provided crucial information about the possible triggers of intermediate-depth earthquakes (e.g., Andersen et al., 2008; Scambelluri et al., 2017).

Lastly, peridotite bodies may also inform on the chemistry and redox state of subduction zone fluids. Fresh mantle assemblages may in fact be extremely reactive in the presence of aqueous fluids through the process of serpentinization (e.g., Früh-Green et al., 2004; Seyfried et al., 2007; Andreani et al., 2013; Klein et al., 2014; Roumejon et al., 2015). During serpentinization, either at the seafloor or in the subduction zone, iron oxidation and the formation of magnetite and Fe^{3+}-bearing serpentine drive the production of molecular hydrogen and abiotic light hydrocarbons (e.g., Charlou and Donval, 1993; Mottl et al., 2003; Emmanuel and Ague, 2007; Cannat et al., 2010; Evans, 2010; Klein et al., 2013; Malvoisin, 2015; Plümper et al., 2017; Merdith et al., 2020 Vitale Brovarone et al., 2020). Additionally, the conditions at which serpentinization takes place, and to what extent, may ultimately influence geochemical fluxes and large-scale elemental recycling in subduction zones (e.g., Hacker, 2003; Padrón-Navarta et al., 2009; Kodolàny et al., 2012; Alt et al., 2013; Peters et al., 2017; Piccoli et al., 2019).

In this contribution, we present new data on a recently discovered occurrence of fresh, pseudotachylyte-bearing mantle peridotites preserved in the lawsonite eclogite-facies San Petrone unit, Alpine Corsica. With the aim of stimulating future work on these rocks, we present petrographic and major element data of the mantle peridotites and discuss the implications of this finding on; (i) the understanding of the pre-subduction ocean-continent transition setting; (ii) the formation of potential markers of intermediate depth seismicity in subduction zones, such as pseudotachylytes, and; (iii) subduction zone geochemistry, with particular focus on H_2 and abiotic CH_4 generation.

GEOLOGIC SETTING

Alpine Corsica occupies the northeastern part of the island of Corsica, France. It represents a segment of the Alpine belt that was isolated from the European mainland by the opening of the Liguro-Provençal and Tyrrhenian basins (Jolivet et al., 1998; Molli and Malavieille 2010). The belt mainly consists of a stack of oceanic and transitional units of the Jurassic, slow-spreading Piemonte-Liguria Basin. Belt-scale, coherent tectono-metamorphic units underwent variable Alpine metamorphism ranging from sub-greenschist to lawsonite-eclogite facies conditions in the Late Eocene (Brunet et al., 2000; Martin et al., 2011; Vitale Brovarone et al., 2013 and references therein; Vitale Brovarone and Herwartz, 2013;). Four bodies containing fresh peridotite are documented within the Schistes Lustrés complex of Alpine Corsica (i.e., the metamorphosed remnants of the oceanic/transitional Piemonte-Liguria lithosphere; e.g., Lahondère, 1996; Vitale Brovarone et al., 2013 and references therein): (i) the mafic-ultramafic Pineto massif (Sanfilippo and Tribuzio, 2013), which belongs to the weakly metamorphosed Nappes Supérieures (280-310°C 0.3-0.4 GPa) (Vitale Brovarone et al., 2013); (ii) the Monte Maggiore ultramafic massif (e.g., Rampone et al., 2009; Piccardo and Guarnieri, 2010); (iii) Cima di Gratera (Austrheim and Andersen, 2004) mafic-ultramafic bodies, which both belong to lawsonite-blueschist facies unit and experienced metamorphic conditions in the range of 400-430°C 1-1.8 GPa (Vitale Brovarone et al., 2013; 2014b), and; (iv) the lawsonite eclogite-facies San Petrone ultramafic body, for which only a preliminary description is available (Vitale Brovarone et al., 2020). Among these bodies, the Monte Maggiore and Cima di Gratera bodies include ultramafic pseudotachylytes formation of which has been ascribed to high-pressure, subduction zone conditions (Austrheim and Andersen, 2004; Deseta et al., 2014a; 2014b; Magott et al., 2016; 2017; Fabbri et al., 2018). For the San Petrone body, similar interpretations were suggested by analogy with the Monte Maggiore, Gratera, and Lanzo pseudotachylytes (Vitale Brovarone et al., 2020; cf. Scambelluri et al., 2017, for Lanzo).

The lawsonite eclogite-facies San Petrone unit is interpreted to represent a segment of the ocean-continent transition involved in the Alpine subduction (Vitale Brovarone et al., 2011; Beltrando et al., 2014). The unit consists of a basal body of serpentinized peridotites structurally overlain by a laterally variable tectonostratigraphy including metabasalts, metasedimentary rocks and isolated slivers of continental rocks -the so-called continental extensional allochthons- characteristic of magma-poor ocean-continent transition (Manatschal et al., 2006; Beltrando et al., 2014). All lithologies of the San Petrone unit experienced a consistent structural and metamorphic evolution culminating at ~ 480-550°C and 2-2.2 GPa (Vitale Brovarone et al., 2011). The serpentinization of the San Petrone ultramafic rocks has been interpreted to result from two main stages related to the rifting and oceanization of the Piemonte Liguria Basin (Vitale Brovarone et al., 2011; Beltrando et al., 2014) and to the high-pressure conditions in the Alpine subduction zone (Vitale Brovarone et al., 2020), respectively. The fresh peridotite bodies presented in this study represent relicts that fully or at least largely escaped fluid-rocks interactions and serpentinization from rifting stage to subduction and exhumation.

FIELD RELATIONSHIPS

The fresh mantle bodies presented in this study are located in the northern part of the San Petrone unit, close to Col de Prato pass (Fig. 1; 42° 25’ 39’’ N; 9° 19’ 35’’ E) and form two lenticular bodies inside weaker serpentinized peridotites. The surface outcrop of the two peridotite boudins ranges from 50 to 200 m^2. In both localities, several well-exposed outcrops define a core of fresh peridotite (Fig. 2a) surrounded by undeformed, partially to fully serpentinized peridotite extending outward to foliated antigorite serpentinite. The undeformed serpentinized peridotite includes statically serpentinized pseudotachylytes (Vitale Brovarone et al., 2020). Metabasalts, metagabbros, and metasedimentary rocks are closely associated with the fresh peridotite bodies and exposed at a few tens of meters from them. In detail, in the northwestern locality, the peridotites are capped by a thin layer of serpentinite, followed upwards by foliated metabasalts, radiolarian metacherts (Fig. 2d), and calcschists. This lithological association, which extends southwards for at least ~ 10 km, locally includes slices of continental basement rocks directly juxtaposed on top of the serpentinized peridotites and interpreted to reflect the primary tectonostratigraphy of the ocean-continent transition of the Piemonte-Liguria Basin (Vitale Brovarone et al., 2011; Beltrando et al., 2014).

Metasedimentary rocks are separated from the fresh peridotite bodies by 10 to 500 m of serpentinized peridotites or metagabbros. Although at least some Alpine structural overprint on the original architecture of the unit cannot be excluded, the overall, exceptional structural preservation of the unit (Vitale Brovarone et al., 2011) suggests that the fresh peridotite bodies were originally close (tens of meters) to detachment fault responsible for the mantle unroofing. The presence of a rim of partially to fully serpentinized peridotite formed at high-pressure conditions at the expense of the fresh peridotite bodies (Vitale Brovarone et al., 2020) suggests that the fresh peridotite bodies were bigger prior to subduction, and that the distance between the fresh peridotite and the Mesozoic cover rocks was originally shorter (see discussion).

In the field, the peridotite displays an isotropic to weakly anisotropic structure, defined by the distribution of coarse-grained mantle minerals such as olivine, clinopyroxene, orthopyroxene, and spinel. Based on field and microstructural observations, the rock composition is inferred to span from harzburgite to lherzolite. Locally, 5-10 cm wide dunite layers are also found and characterized by the presence of relatively large (> 0.5 cm) spinel crystals (Fig. 2b). Small (~ 10 cm wide) plagioclase-rich pods are locally found and interpreted as the result of peridotite impregnation, by analogy

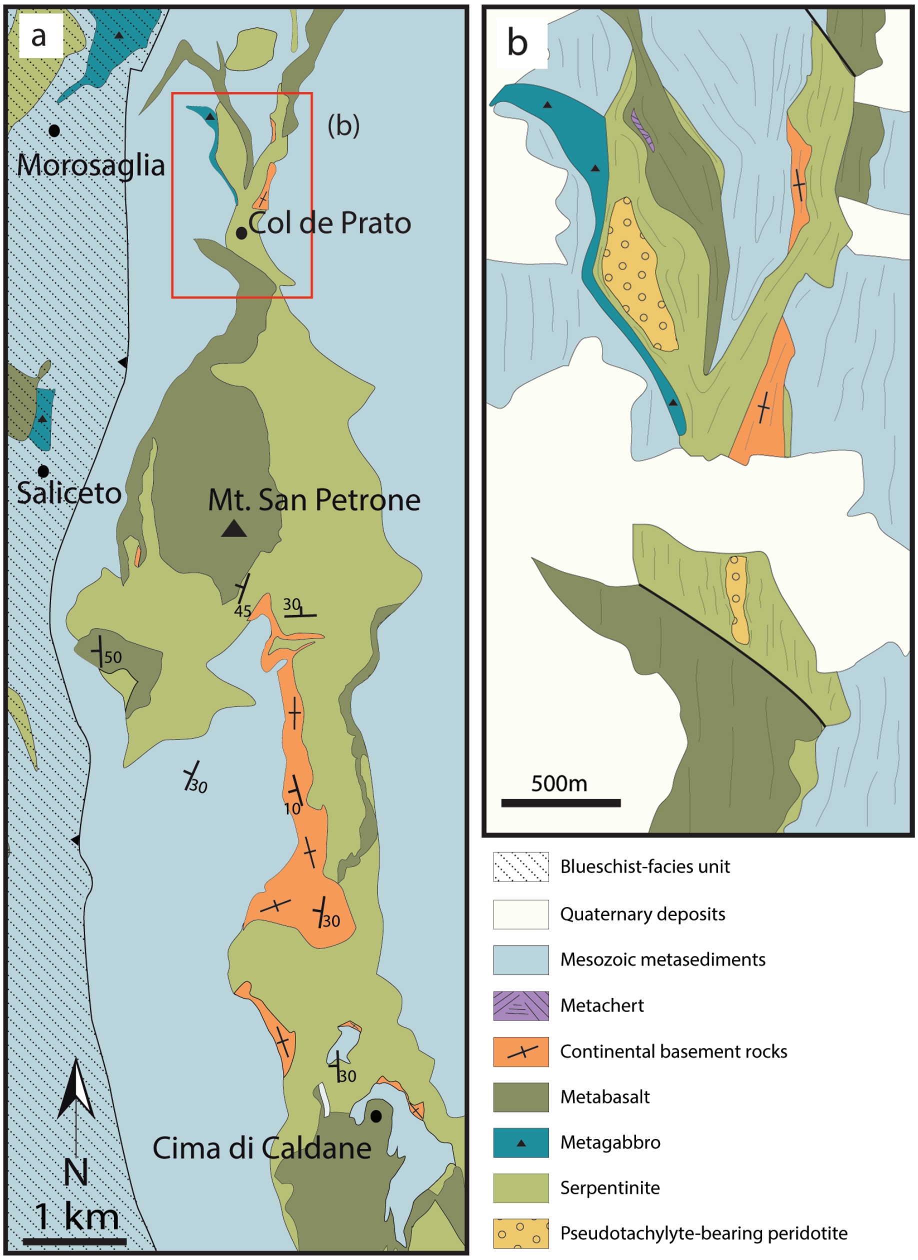


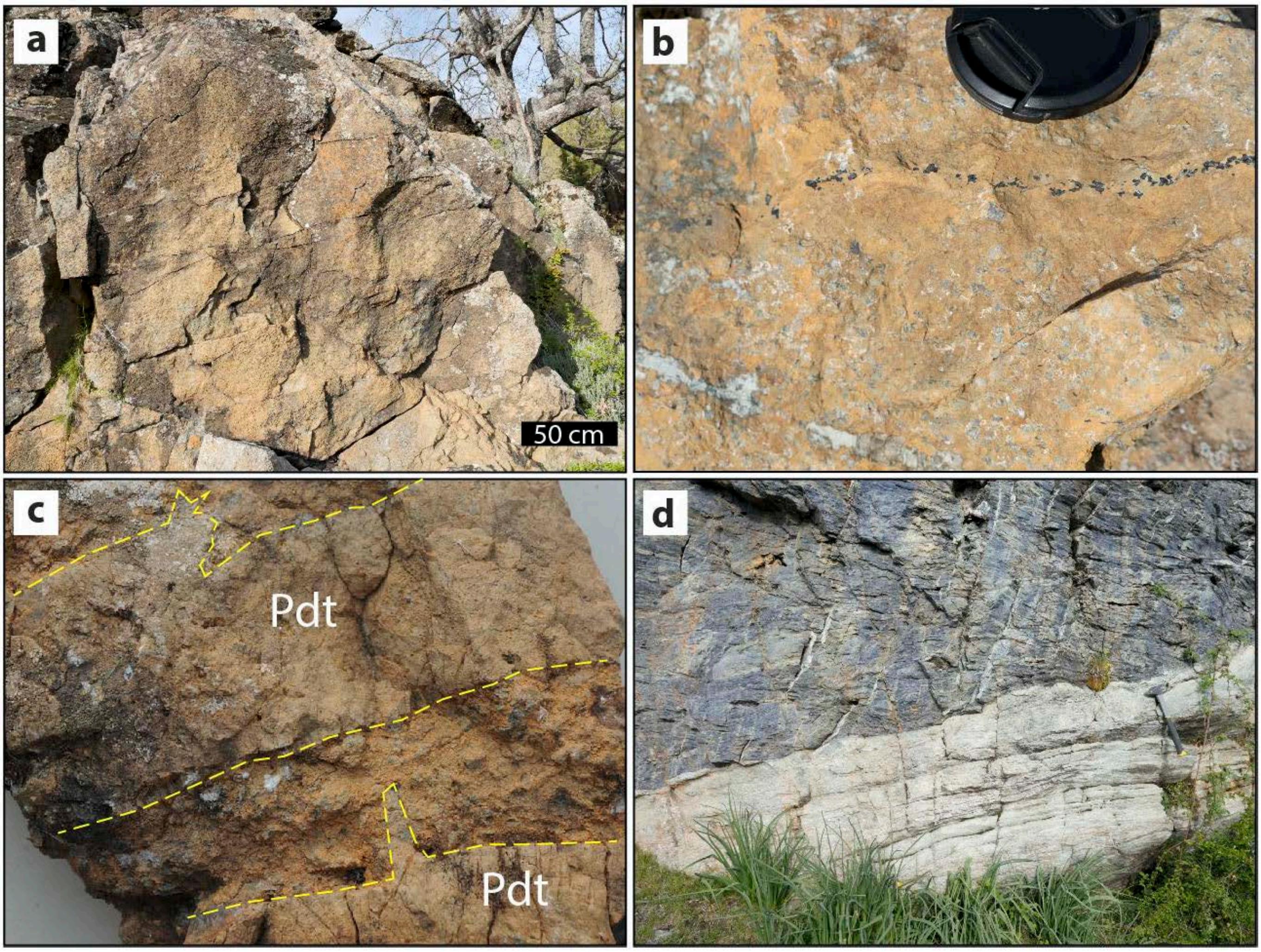
Fig. 1 - Interpreted geological map of the San Petrone unit. Modified after Rossi et al. (1994) and Vitale Brovarone et al. (2014). In (a), symbols for the general orientation of the Alpine foliation are shown. In (b), the main trend of the Alpine foliation is displayed on the map. The reader is referred to the PDF version of the article for a colour version.

with similar structures recognized in several slow-spreading and transitional ultramafic bodies (Müntener and Piccardo 2003; Piccardo and Guarnieri, 2010). Plagioclase is common in many of the collected samples and is found both fresh and fully converted into pseudomorphic products, as documented in thin section (see below). Nevertheless, plagioclase-rich domains and metagabbroic rocks within the San Petrone peridotite body appear to be less abundant compared to the Gratera and Monte Maggiore peridotites in Alpine Corsica. The majority of the metagabbro bodies was found inside or adjacent to the serpentinites surrounding the northern peridotite body (Fig. 1). These bodies appear intensely metamorphosed and variably deformed. Blue amphibole can be easily recognized on the hand specimen in Mg-Al-rich metagabbro, whereas omphacite, garnet and lawsonite can be identified in Fe-Ti-rich bodies.

The peridotites are crosscut by a multitude of pseudotachylyte veins, ranging from a few mm to several cm in thickness and from a few cm to at least 1 m in length (Fig. 2c). Pseudotachylyte veins are more abundant in the south-eastern locality, whereas only two outcrops containing a few pseudotachylyte veins were found in the northern body. Injection veins characteristic of pseudotachylytes are common at all scales.

MICROSTRUCTURAL RELATIONSHIPS

The San Petrone peridotite exhibit various degrees of preservation, from fully preserved with minor serpentinization along veins and grain boundaries, to fully serpentinized through static replacement of the original mineralogy. In the latter case, even though the original structure of the peridotite is still recognized in this section, the only relicts of the precursor mineralogy are small cores of spinel embedded in serpentinization-related magnetite. Despite the intense brittle deformation and shuttering related to the pseudotachylyte-forming events that affecting several peridotite samples, the



Fig, 2 - a) Field occurrence of the San Petrone fresh peridotite. b) Dunite channels within the San Petrone peridotite. Note the presence of coarse spinel crystals within the dunite. c) Sample of pseudotachylyte (Pdt) veins cutting the peridotite. The sample is about 15 cm wide. d) Contact separating metabasalt (bluish colour) from Mn-rich metachert. The outcrop is located at few tens of meters from the fresh peridotite to the N of the northern peridotite body (Fig. 1b).

mantle mineralogy is commonly very fresh (Fig. 3a-c). In this study, we present a preliminary petrographic investigation aimed at highlighting the similarity of the San Petrone peridotite with other well-studied Alpine peridotite bodies. A more detailed petrological-geochemical study will be required in the future.

Olivine is present as large (> 0.5 mm) crystals as well as smaller grain-size lobate crystals (Fig. 3d). The latter are found as partial replacement of large (> 0.5 mm) exsolved orthopyroxene crystals, as indicated by the lobate orthopyroxene grain boundaries (Fig. 3b). In some cases, the orthopyroxene shows extremely irregular outlines, including mouse tail-shaped extremities (white arrow in Fig. 3d) (see also Rampone et al., 2008 for equivalent microstructures). These microstructures suggest that the San Petrone peridotite recorded melt-rock interactions, by analogy with several Alpine peridotites (Rampone et al., 2008). Clinopyroxene is less abundant than orthopyroxene and is present as smaller crystals. Spinel is found both as individual crystals and as symplectites in association with orthopyroxene (Fig. 3e). The latter microstructure may testify to the reequilibration of former garnet in the spinel stability field (Morishita and Arai, 2003; Rampone et al., 2009; Piccardo and Guarnieri, 2010), even though other interpretations are also possible (Secchiari et al., 2019). Despite the strong brittle deformation related to the pseudotachylyte formation in the spinel stability field (see below), fresh plagioclase was found in some peridotite samples, even in the close proximity of pseudotachylyte veins (Fig. 3f), whereas in other samples its former presence was inferred based on the presence of zoisite-rich pseudomorphoses.

Several samples are characterized by a remarkable abundance of pseudotachylyte veins cutting each other and resulting in networks overprinting the original structure of the host peridotite. Crosscutting relationships indicate the presence of multiple generations of pseudotachylyte veins, as already documented in the other known bodies of pseudotachylyte-bearing peridotites in Corsica and Lanzo Massif (e.g., Deseta et al., 2014a; 2014b; Magott et al., 2016; 2017; Scambelluri et al., 2017). In some cases, the injection veins propagate from sharp micro-fault zones free of any pseudotachylyte-type material. Marked strain gradients, including grain size reduction and fracturing, are observed from the host rock towards the pseudotachylytes (Fig. 3b). The pseudotachylyte microstructures generally vary with their thickness. Small veins are characterized by a fully recrystallized, dark-brown matrix including variably deformed clasts of the host peridotite and commonly displaying flow structures (Fig. 4a, b). Large veins commonly exhibit spinifex structures (Fig. 4c-e), with individual rods up to ~ 1 cm long decreasing in size towards the vein selvages. As for most of the veins, the spinifex structures are completely recrystallized into fine-grained granoblastic aggregates of the same mineralogy observed in the host peridotite, including olivine, ortho- and clinopyroxene, and spinel (Fig. 4e). The presence of spinel as a quench product of the pseudotachylyte indicates that the veins formed in the spinel stability field, as

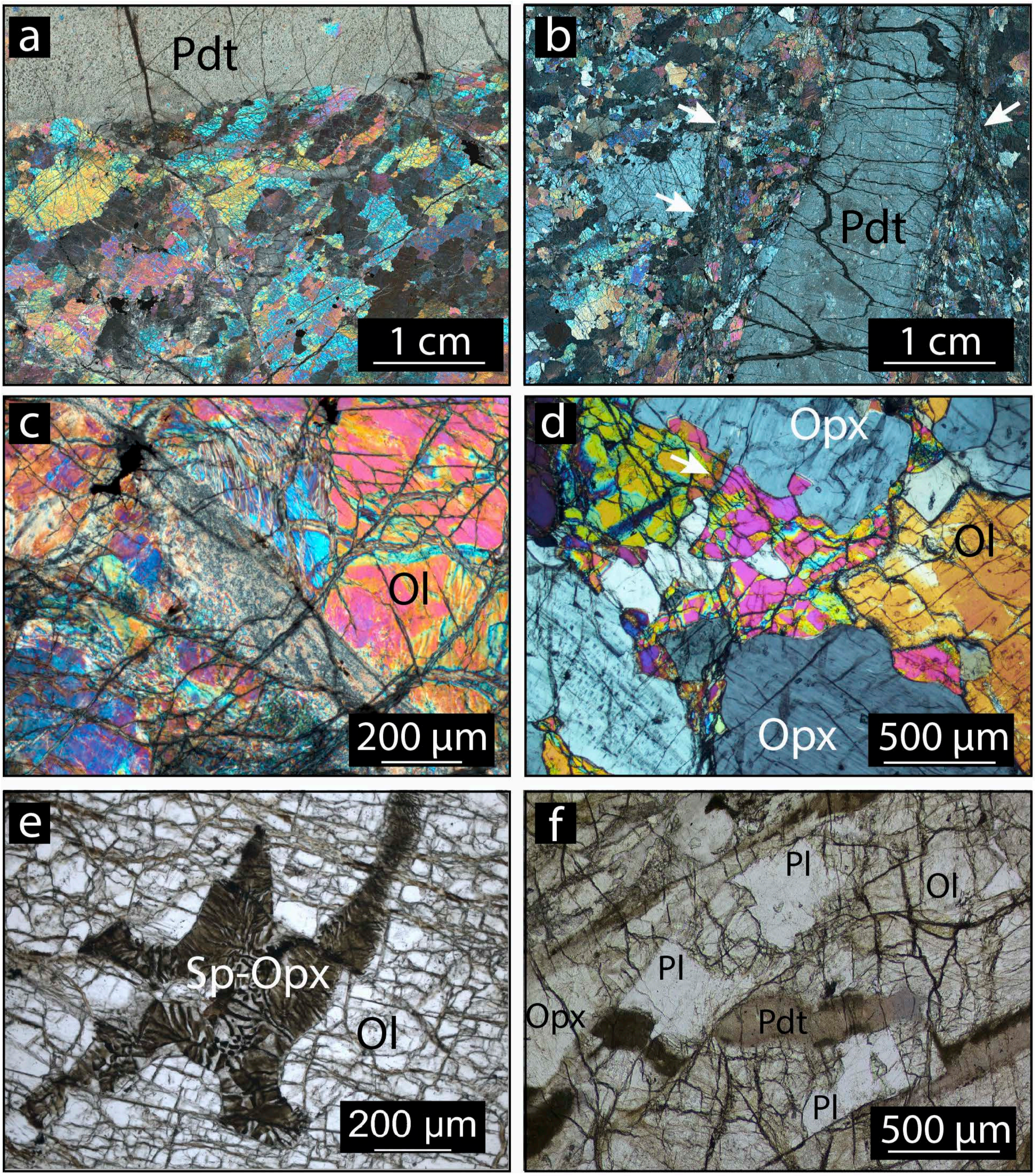


Fig. 3 - a-b) Cross-polarized light scans of thin sections of pseudotachylyte (Pdt)-bearing peridotite from the San Petrone unit. In (b), note the grain-size reduction in the proximity of the pseudotachylyte vein (white arrows). c) Intense brittle deformation and shuttering of olivine related to the pseudotachylyte-forming event. d) Orthopyroxene (Opx) irregular outlines and lobate olivine (Ol) suggesting melt-rock interaction (see Rampone et al., 2008 for details). The white arrow indicates the position of a mouse tail-shaped orthopyroxene edge. e) Spinel (Spl)-orthopyroxene (Opx) symplectite suggesting the former presence of garnet. f) Preserved plagioclase (Pl) in pseudotachylyte-bearing peridotite. Plane-polarized light.

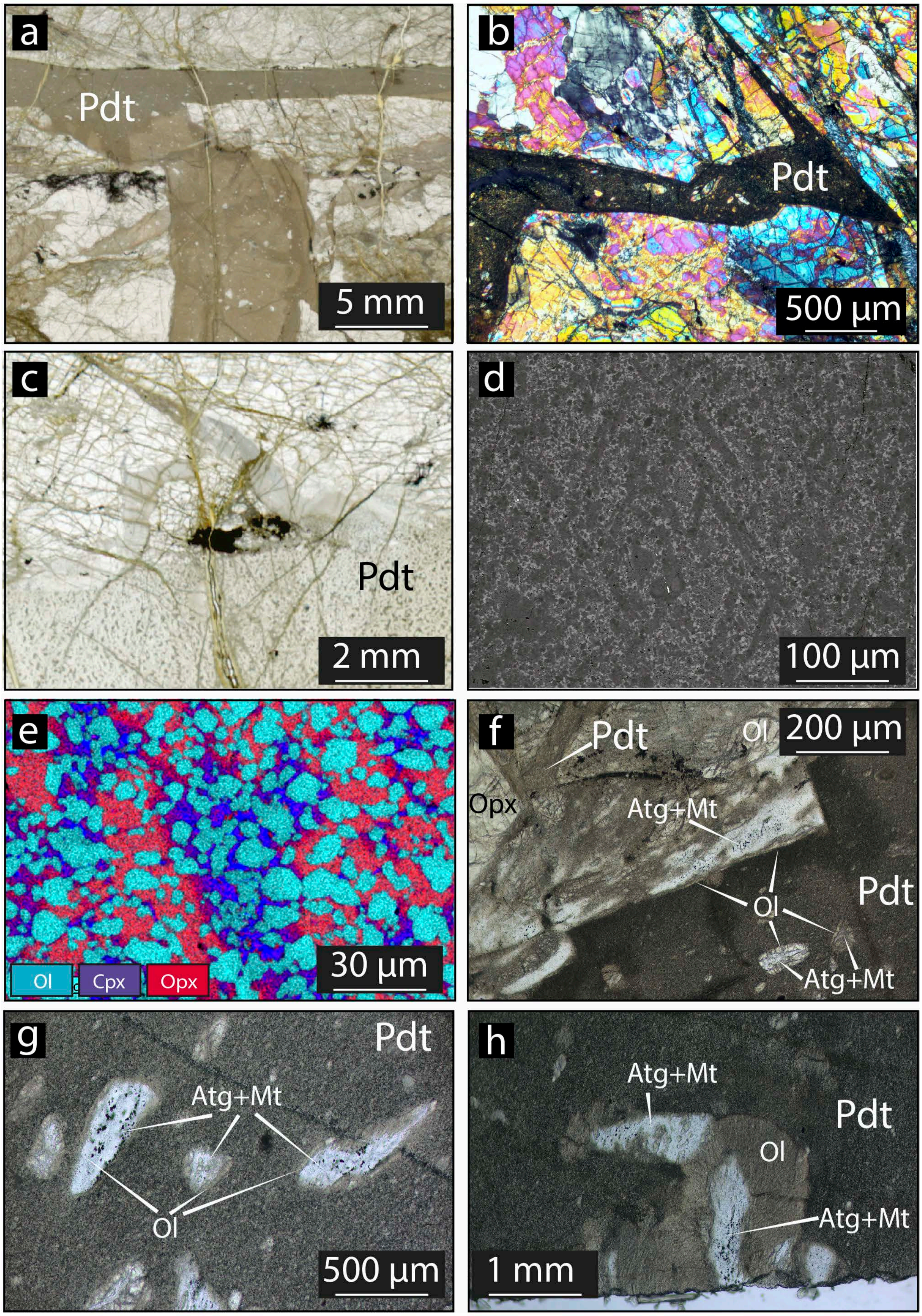


Fig. 4 - a-c) Examples of pseudotachylyte (Pdt) veins cutting across fresh mantle peridotite. (a, c: plane-polarized light, b. Cross-polarized light). d-e) Backscattered-electron image (d) and EDS-based X-ray composite (Al-Si-Mg) compositional map (e, close-up of d) of a recrystallized, spinifex-like pseudotachylyte. Note that the spinifex-like rods consist of fine-grained granoblastic aggregates of olivine (Ol), orthopyroxene (Opx) and clinopyroxene (Cpx) (+ spinel, not visible in this area). f-h) Example of pseudotachylyte (Pdt) hosted in a partially serpentinized peridotite; Atg = antigorite, Mt = magnetite. Although the timing of serpentinization relative to the pseudotachylyte formation is not clear, the formation of secondary olivine rims along the selvages of pseudotachylytes in contact with serpentine (f) and around serpentinite clasts within the pseudotachylyte (see also g-h) suggests that the seismic event formed after the partial serpentinization of the rock. Despite that, future work will be needed to confirm this hypothesis (see text for further discussion).

already documented in the Gratera and Lanzo pseudotachylytes (e.g., Andersen and Austrheim, 2006; Scambelluri et al., 2017). Talc and garnet were found in close association with the pseudotachylyte veins and typically formed as a replacement product of former orthopyroxene and plagioclase, as already documented in the Gratera (talc; e.g., Austrheim and Andersen, 2004) and Lanzo (talc and garnet; Scambelluri et al., 2017) pseudotachylytes. The presence of secondary garnet in the San Petrone plagioclase pseudomorphs is consistent with the eclogite-facies peak metamorphic conditions, as also documented in Lanzo (Scambelluri et al., 2017). In some cases, rather fresh pseudotachylyte veins are embedded in partially serpentinized peridotites and show secondary olivine formation along the vein selvages (Fig. 4f). Similar microstructures, interpreted as the result of thermal decomposition of matrix serpentine during the pseudotachylyte formation event, are documented in the Monte Maggiore peridotite and used to constrain the formation of the Monte Maggiore pseudotachylytes to high-pressure conditions in the Alpine subduction (Magott et al., 2020). Moreover, some pseudotachylyte veins include clasts of serpentinite (antigorite + magnetite) rimmed by secondary olivine. (Fig. 4f-h; cf. Fig. 3f in Austrheim and Andersen, 2004). Similar microstructures were described by Austrheim and Andersen (2004) and suggested to have formed by partial dehydration of antigorite during the pseudotachylyte formation.

METHODS

Scanning Electron Microscopy (SEM) and Electron Dispersive X-ray Spectrometry (EDS) were performed with a Zeiss Ultra 55 field emission gun (FEG) SEM at IMPMC, Paris, France. The analyses were done with a working distance of 7.5 mm and operated at 15 kV with a 120 μm aperture. Backscattered-electron (BSE) mode was used to investigate chemical heterogeneities using an Angle Selective Backscattered Detector (AsB) or an Energy Selective Backscattered Detector (EsB). Energy dispersive X-ray spectrometry (EDS) maps were acquired using an EDXS QUANTAX system equipped with a silicon drift detector XFlash 4010 (Bruker). Data were processed with the software Esprit (Bruker).

Mineral chemistry was determined by wavelength-dispersive spectrometry using a JEOL JXA 8200 superprobe at the Institute of Geological Sciences (University of Bern). Analytical conditions included 15KeV accelerating voltage, 20 nA specimen current, 40 s dwell times (including 2 x 10 s of background measurements), and a beam diameter of 2 μm. Higher current and larger beam size were used for spinel measurements (50 nA and 5 μm). For silicate minerals, nine oxide compositions were measured, using synthetic and natural standards: wollastonite (SiO_2), anorthite (Al_2O_3), wollastonite (CaO), almandine (FeO), olivine (MgO), tephroite (MnO), bunsenite (NiO), rutile (TiO_2), spinel (Cr_2O_3). For oxide minerals, eight oxide compositions were measured, using synthetic and natural standards: almandine (FeO), spinel (Al_2O_3), olivine (MgO), tephroite (MnO), bunsenite (NiO), rutile (TiO_2), spinel (Cr_2O_3), sphalerite (ZnO).

Mineral chemistry

In this section, we provide major element analyses of the main mineral phases of the San Petrone peridotite. Mineral analyses are provided as supplementary material (Tables 1S-4S).

Olivine

Coarse-grained primary mantle olivine in the host peridotite has average Mg number [Mg# = Mg/(Mg + Fe)] of 0.90 (n. 166, SD = 0.01), and a relatively high NiO_2 (0.39 wt.%; n. 166; SD = 0.03) and low MnO (0.14 wt.%; SD = 0.01) content (OL1 in Fig. 5a, b). Transects across individual olivine crystals do not show any significant variation from core to rim. Olivine recrystallized along deformation bands related to the pseudotachylyte events has Mg# = 0.90 (n. 3) and NiO_2 content (0.36 wt.%, n. 5, SD = 0.02; OL2 in Fig. 5a,b) comparable to the coarse-grained olivine. Olivine in the pseudotachylytes (OL3 in Fig. 5a,b) includes clasts of mantle olivine, as well as a newly formed granoblastic metamorphic olivine formed during the quenching of the pseudotachylyte. MnO is 0.12 wt.% (SD = 0.02), consistently with crystallization together with pyroxenes.

Metamorphic olivine associated with HP serpentinization has Mg#1 = 0.91 (n. 29, SD = 0.01), slightly higher than the coarse olivine, a NiO_2 content comparable with it (0.39 wt. %, n. 29, SD = 0.03), and high MnO (0.35 wt.%; SD = 0.06).

Orthopyroxene

Coarse-grained mantle orthopyroxene in the host rock has Mg#) = 0.91 (n. 80, SD = 0.01), Cr# (Cr# = Cr/(Cr + Al)*100 = 13 (n. 80, SD = 0.01), an average CaO content of 1 wt.% (n. 80, SD = 0.62), and an average Al_2O_3 content of 3 wt.% (n. 80, SD = 0.64) (Fig. 5c,d). In the pseudotachylyte, the orthopyroxene formed during quenching has comparable Mg# (0.90; n. 15, SD = 0.01) and Al_2O_3 (2.8 wt.%, n. 80, SD = 0.48) to the host rock orthopyroxene, but higher Cr# up to 27 (n. 15, SD = 0.03) and higher CaO (2.56 wt.%; n. 15, SD = 0.66),

Clinopyroxene

Primary mantle clinopyroxene in the host rock has Mg# = 0.91 (n. 49; SD = 0.01), Al_2O_3 = 4.2 wt.% (n.49, SD = 0.63), TiO_2 = 0.38 wt.% (n. 49, SD= 0.17), and Cr_2O_3 = 1.19 wt.% (n. 49, SD = 0.22) (Fig. 6a,b). Clinopyroxene formed after quenching of the pseudotachylyte has lower Mg# (0.85; n. 13, SD = 0.02), much higher Al_2O_3 (9.81 wt.%; n. 12, SD = 2.37), and lower TiO_2 (0.3 wt.%; n. 12, SD = 0.12) and Cr_2O_3 (0.52 wt.%; n. 12, SD = 0.46) compared to the primary clinopyroxene.

Spinel

Spinel in the host peridotite has low TiO_2 (median value of 0.06 wt.%; n. 8, SD = 0.18) and Cr number (Cr# = Cr/(Cr + Al) = 0.38 (n. 8, SD = 0.04) (Fig. 6c,d). In the pseudotachylyte, spinel displays variable TiO_2 (0.57 and 0.12 wt.%) and Cr# of 0.39 and 0.28, thus falling in the range of composition of primary mantle spinel.

DISCUSSION

Pre-subduction magmatic history of the San Petrone peridotite

The study of mantle peridotites provides important insights on the geodynamic evolution of the lithosphere in connection with slow to ultra-slow oceanization (Müntener and Piccardo, 2003; Rampone and Borghini, 2008; Müntener et al., 2010). The Alpine-Apennine ophiolites are fossil analogous of such geodynamic settings, though the Alpine overprint may hamper the investigation of the early magmatic evolution, and

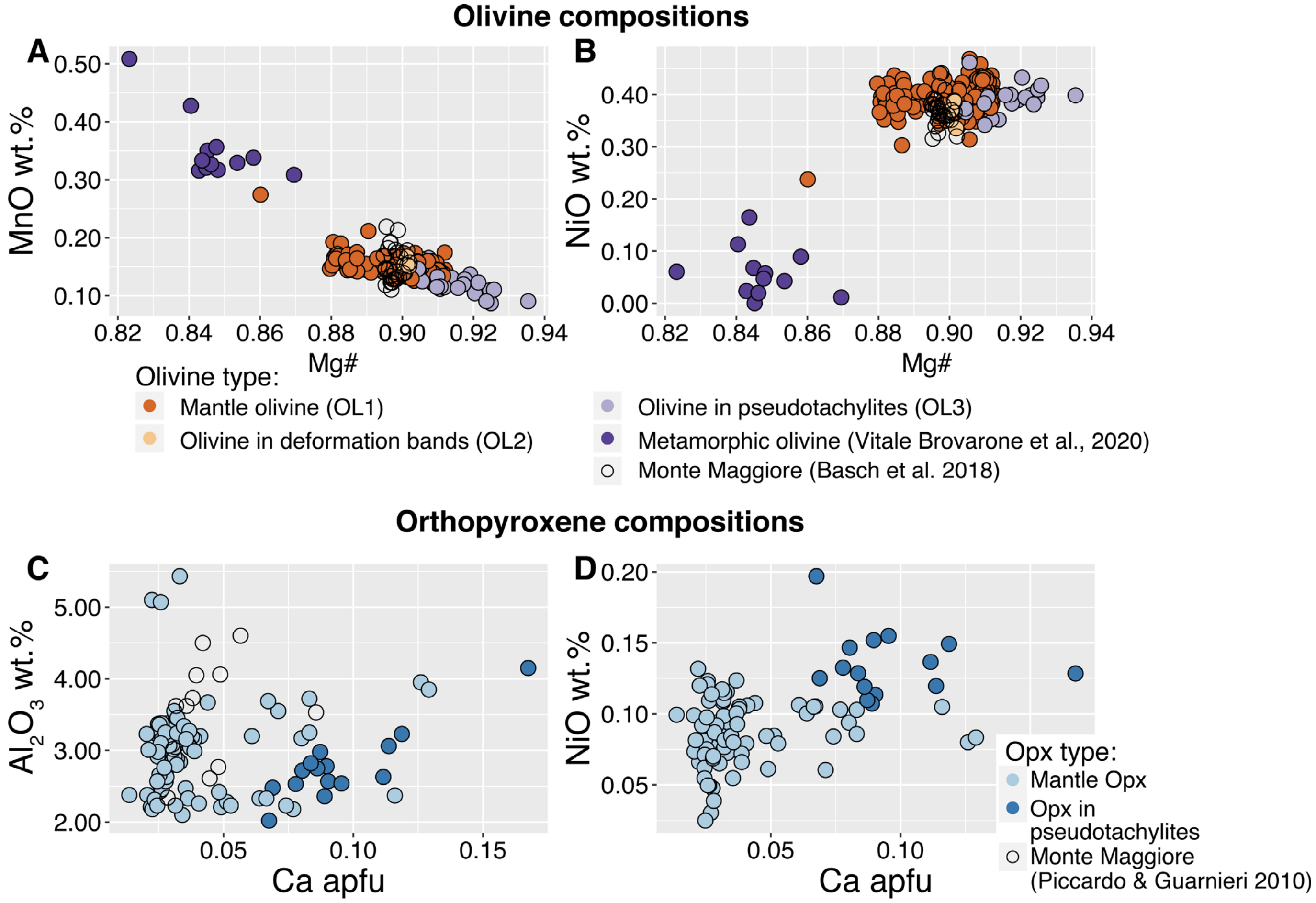


Fig. 5 - Major element compositional features of olivine and orthopyroxene from the San Petrone peridotite. Olivine compositions from Monte Maggiore spinel peridotite, plagioclase peridotite, spinel dunite, olivine-rich troctolite and troctolite are also reported (Basch et al., 2018). Orthopyroxene composition from spinel peridotite and plagioclase peridotite from Monte Maggiore are reported for comparison (Piccardo and Guarnieri 2010).

unaltered peridotites are only scattered and preserved in type localities through the Alpine-Apennine chain (Bezzi and Piccardo, 1971; Müntener and Piccardo, 2003; Müntener et al., 2004; 2010; Rampone et al., 2005; McCarthy and Müntener, 2015). Therefore, the finding of preserved fresh or even exceptionally fresh (fresh plagioclase) mantle rocks within the San Petrone unit provides new insights on the origin and evolution of the mantle lithosphere of a magma poor ocean-continent transition. Structural and petrologic studies of ophiolitic units of the Alpine-Apennine chain allowed classifying them between peri-continental and intra-oceanic settings (Marroni and Pandolfi, 2007; Manatschal and Müntener, 2009; Mohn et al., 2010; Picazo et al., 2016; Rampone et al., 2020). Recent works have proposed a simplified scheme to recognize different mantle domains and associated melt-related history on the basis of pyroxene and spinel mineral chemistry (Mohn et al., 2010; Picazo et al., 2016). Three main mantle-type were identified: (i) inherited subcontinental mantle, with a further subdivision in inherited (type 1a) vs. post-orogenic depleted mantle (type 1b) (see Fig. 9 in Picazo et al., 2016), (ii) refertilized mantle (type 2), and (iii) oceanic depleted mantle. Pitfalls of this approach include the fact that transition from inherited (1a) to infiltrated (1b) mantle domains are visible at the outcrop scale, and heterogeneities might be due to multiple processes, such as inheritance, pyroxenite-mantle interaction or subsolidus re-equilibration (Rampone et al., 1993; 2020). In such a case, a detailed geochemical and isotopic study is required. For the purpose of this study, the simplified scheme based on clinopyroxene and spinel composition of Picazo et al. (2016) was adopted. Fig. 6 displays the measured mantle clinopyroxene and spinel compositions from the San Petrone unit (this study), together with mineral chemistry data of the Monte Maggiore peridotite in Corsica (empty circles in Fig. 6 Basch et al., 2018) and of other Alpine and Apennines localities from Picazo et al. (2016). Clinopyroxene compositions display a very good match with expected compositions for refertilized mantle domains, with very depleted Na_2O and moderate Al_2O_3 content (Fig. 6) and overlap with reported clinopyroxene compositions from Monte Maggiore (Basch et al., 2018). Comparable compositions of mantle olivine (OL1 and OL2 in Fig. 5) and orthopyroxene from San Petrone and Monte Maggiore are also observed (Piccardo and Guarnieri, 2010; Basch et al., 2018). Silicates in pseudotachylite are compositionally different from mantle relicts. Olivine has higher Mg#, orthopyroxene is more Ca-rich, and clinopyroxene has lower Cr and higher Al content. Spinel Mg#-Cr# composition is intermediate between refertilized mantle with important inheritance (type 1b) and refertilized mantle (type 2), and Ti content is lower compared to what reported by Picazo et al. (2016) for refertilized mantle samples. Nevertheless, low Ti content in spinel could be explained if melt impregnation occurred mainly by reactive porous flow

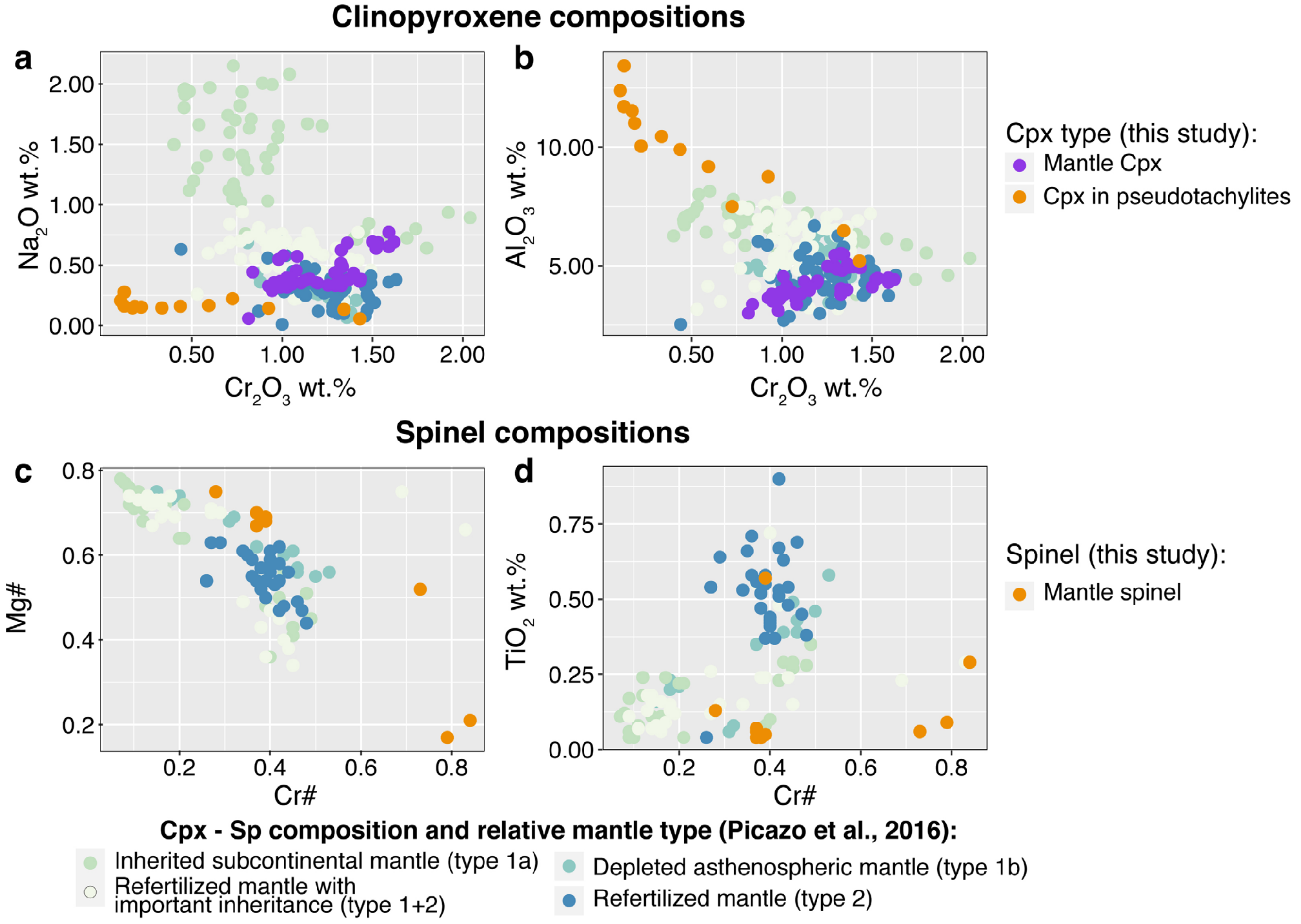


Fig. 6 - Major element compositional features of clinopyroxene and spinel from the San Petrone peridotite compared to literature data (Picazo et al., 2016).

at spinel facies conditions, which would be consistent with the observation of replacive dunite layers, scarcity of plagioclase, and Si depletion (inferred by the formation of brucite during HP serpentinization, Vitale Brovarone et al., 2020).

The intermediate composition might be explained by the original structural position of the peridotite body, considering that refertilization has been shown to increase towards the footwall of large mantle shear zone (Kaczmarek and Müntener, 2010), and that the amount of inheritance decreases towards the more distal parts of the ocean-continent transition (Picazo et al., 2016). In the case of the San Petrone unit, such an original transitional position (Fig. 7) is also consistent with previous paleogeographic reconstructions of the unit position in the Piemonte-Liguria Basin (Vitale Brovarone et al., 2011; Beltrando et al., 2014).

Preservation of peridotite bodies at exhumed mantle domains of a Tethyan fossil rifted margins

Despite the Alpine high-pressure metamorphic evolution, the San Petrone unit preserves the rift-related architecture of the Piemonte-Liguria ocean-continent transition (Vitale Brovarone et al., 2011). During the Mesozoic, subcontinental mantle rocks were unroofed along the Piemonte-Liguria Basin margins and covered by post-rift sediments (e.g., Manatscal, 2004; Beltrando et al., 2012; Ribes et al., 2019; Epin et al., 2019). Mantle exhumation at rifted margins is typically accommodated by low-angle detachment faults or shear zones that also promote fluid infiltration and intense serpentinization of mantle rocks, as inferred from geophysical and drill core data, and from fossil analogous (Manatschal and Müntener, 2009; Pinto et al., 2015; Mateeva et al., 2017; Vieira Duarte et al., 2020). Along the Iberia margin, for example, the extent of serpentinization varies from 1 to 3 km of depth (Sutra et al., 2013; Stanton et al., 2016; Pinto et al., 2017). Serpentinization appears more intense when brittle lithosphere cools down and deformation localizes along high-angle normal faults (Bayrakci et al., 2016), as also preserved in fossil rifted margins such as the large peridotite body of Ronda, Spain (Frasca et al., 2016).

In the San Petrone unit, Mesozoic metasedimentary rocks, as well as slivers of continental basement rocks and Jurassic metabasalts, are directly juxtaposed onto serpentinized, refertilized subcontinental mantle rocks. The serpentinization of these rocks was initially interpreted to have happened during the formation of the Piemonte-Liguria Basin prior to subduction (Vitale Brovarone et al., 2011; Beltrando et al., 2014). Nevertheless, the identification of high-pressure serpentinization replacing at least a part of the San Petrone peridotite in the Alpine subduction zone (Vitale Brovarone et al., 2020) indicates that the size of the fresh mantle bodies was originally larger.

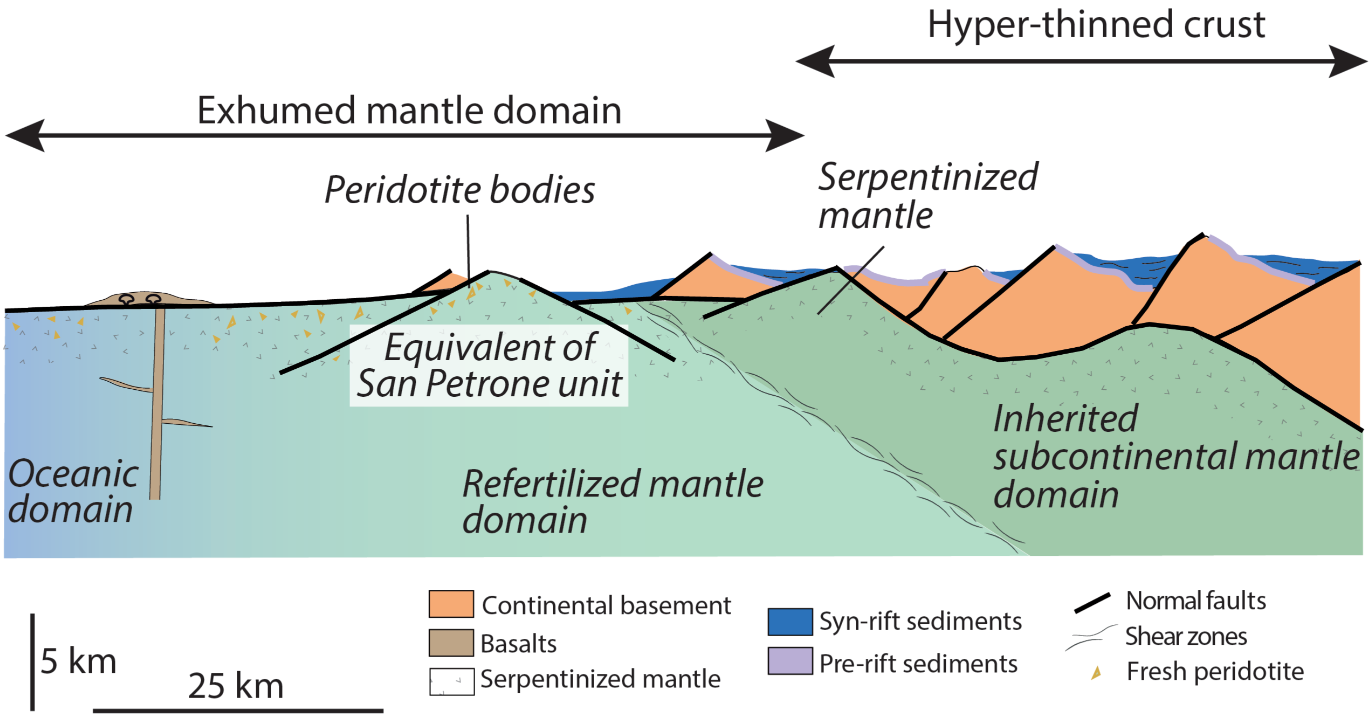


Fig. 7 - Conceptual sketch showing the architecture of an idealized magma-poor ocean-continent transition at the end of continental rifting. Modified after Sutra et al. (2013), Picazo et al. (2016) and Piccoli (2017).

Fresh mantle rocks are rarely preserved along oceanic/OCT detachment faults or in their direct proximity (e.g., Gakkel ridge; Michael et al., 2003; Lutz et al., 2018). Nevertheless, fresh peridotite bodies with sizes similar to San Petrone ones would be difficult to be detected by means of geophysical investigation in ultra-distal areas of rifted margins or along mid-ocean ridges. Moreover, the size of these bodies does not allow for direct comparison with large ultramafic massifs interpreted as subducted ultra-distal portions of rifted margins, like the Lanzo Massif in the Western Alps (Boudier, 1978; Pelletier and Müntener, 2006), or with obducted fossil continental rifted margin peridotites like the one exposed in the Ronda massif (Frasca et al., 2016). In particular, seismic velocities do not directly correlate with lithologies and derive from average of different lithologies, if no strong impedance contrast exists between them. For example, partially serpentinized peridotites may be indistinguishable from gabbros (Miller and Christensen, 1997; Carlson, 2001). Gabbros occur commonly as relatively small bodies within unroofed mantle sections in Alpine analogous, but these are usually complex to identify with seismic velocities in present-day slow-spreading ridges (Lagabrielle and Cannat, 1990; Manatschal et al., 2011 and references therein; Lagabrielle et al., 2015). The small size of peridotite bodies like those preserved in the San Petrone unit would make the recognition equally challenging with seismic velocities.

Pseudotachylyte formation conditions and analogies with other of peridotite-hosted examples

The newly discovered ultramafic pseudotachylytes exhibit remarkable structural and microstructural analogies with the four previously described peridotite-hosted pseudotachylytes within the Alpine realm: (i) the Balmuccia ultramafic body, which represents a lens of subcontinental mantle lithosphere not involved in the Alpine subduction (Obata and Karato, 1995; Ueda et al., 2008; Souquière and Fabbri, 2010); (ii) the eclogite-facies Lanzo ultramafic massif, Italian Western Alps (Scambelluri et al., 2017; Piccardo et al., 2010); (iii) the blueschist-facies mafic-ultramafic body of Cima di Gratera (Austrheim and Andersen, 2004; Andersen and Austrheim, 2006; Deseta et al., 2014a; 2014b; Magott et al., 2016; 2017) and; (iv) the blueschist-facies Monte Maggiore ultramafic body (Fabbri et al., 2018; Magott et al., 2020), both in Alpine Corsica. Size, spatial distribution, and mineralogy are rather equivalent in all the above occurrences of ultramafic. Constraining the regional P-T conditions of pseudotachylyte formation in ultramafic rocks is challenging, owing to the little mineralogical variations expected in the rock. In all the above four cases, the pseudotachylyte assemblages include spinel, which constrain P to minimum values of 0.8 GPa.

However, inferences on the conditions and tectonic settings of formation of these rocks have required a combination of multiple lines of evidence. The formation conditions of the Balmuccia pseudotachylytes have been proposed to range from late Variscan (collision)/Early Permian (transtension) ("A-type" pseudotachylyte) to late Alpine (collision; "B-type") (Souquière and Fabbri, 2010). In Lanzo, Monte Maggiore, and Cima di Gratera, previous works have constrained the formation of ultramafic pseudotachylytes to high-P conditions during the Alpine subduction (Andersen and Austrheim, 2006; Scambelluri et al., 2017; Magott et al., 2020;). The lines of evidence supporting the latter hypothesis include: (i) the presence of dendritic high-P minerals forming during the quenching of the pseudotachylyte in mafic rocks associated with the peridotite; (ii) the presence of antigorite (i.e. the serpentine polysome stable in subduction zone high-P conditions) veins crosscut by the pseudotachylytes; (iii) the presence of high-P pseudomorphic assemblages after mantle plagioclase corroded by the pseudotachylyte melt, and; (iv) the presence of rims of metamorphic olivine formed at the expense of antigorite inside the pseudotachylytes or along their selvages.

The studied samples of ultramafic pseudotachylytes from the San Petrone unit exhibit some of the above features, such as the presence of olivine rims around serpentinite clasts inside the pseudotachylytes, and discontinuous rims of olivine separating rather fresh pseudotachylytes from intensely serpentinized host rocks (Fig. 4f-h). Equivalent microstructures have been documented in the Gratera and Monte Maggiore pseudotachylytes and suggested to have formed through thermal breakdown of preexisting antigorite associated to the seismic event. This feature would constrain the formation of the San Petrone ultramafic pseudotachylytes to T ≥ 400°C (antigorite-in) during the Alpine subduction. However, future work will be needed to confirm this hypothesis.

In addition, a comparison between the distribution of ultramafic pseudotachylytes and mantle peridotites in Central and Western Europe suggests a tight link between the formation of these structures and the subduction of oceanic/transitional lithosphere to high-pressure conditions. Fig. 8 shows the distribution of peridotite bodies all over Central and Western Europe, and including present-day mid-ocean ridges (Mid Atlantic Ridge), present-day and fossil passive margins (Iberia; Central Alps), weakly metamorphosed Tethyan ophiolite suites (Liguria; Tuscany; Dinarides; Hellenides; Pineto), various orogenic peridotite massifs (Balmuccia, Finero, Betic-Rif), subducted passive margin or oceanic peridotites (Lanzo; Monte Maggiore; Cima di Gratera; San Petrone, Cima di Gagnone); mantle xenoliths are also included. From Fig. 8, it clearly emerges that all the documented cases of ultramafic pseudotachylyte are found in terranes related to compressional settings, and four out of five of them, including the San Petrone pseudotachylytes, are found in segments of rifted margin or oceanic lithosphere subducted to high-pressure conditions > 1 GPa. The only ultramafic pseudotachylytes that do not follow this trend are from Balmuccia, which did not experience subduction zone metamorphism, but their formation is still referred to collisional stages (Souquière and Fabbri, 2010).

The Alpine belt seems to host the majority of ultramafic pseudotachylytes so far identified in Europe and worldwide, which calls for future investigations in other ultramafic massifs. For example, in the Erro-Tobbio ultramafic massif, Ligurian Alps, Italy, metric-size fresh peridotite lenses are embedded in mylonitic serpentinites (Scambelluri et al., 1991; Hermann et al., 2000), but pseudotachylytes have not been documented yet. In this case, however, the absence of pseudotachylytes may be explained by the preexisting partial serpentinization of the massif, which has been shown to inhibit pseudotachylyte formations during subduction due to the formation of interconnected weaker antigorite network and more diffuse deformation (Ferrand et al., 2017).

Implications of natural H_2 production through the Wilson cycle

The volume of fresh peridotite preserved along mid ocean ridges has recently been estimated for the last 200 Ma (Merdith et al., 2020). Fig. 9 shows the estimated amount of fresh peridotite unaffected by serpentinization (referred to as residual fresh peridotite) along the Piemonte-Liguria Basin in the Jurassic (166 Ma), as well as a global plate reconstruction for reference (data from Merdith et al., 2020 courtesy of A. Merdith). The colour codes in Fig. 9 (see online version) refer to the estimated thickness, in km, of fresh peridotite unaffected by serpentinization within the uppermost 4 km of oceanic lithosphere, which was calculated on the basis of geophysical data and their extrapolation to global scales (Merdith et al., 2020). Because the process of serpentinization may be accompanied by iron oxidation and release of natural H_2, which in turn favours the conversion of dissolved [C] into abiotic light hydrocarbons such as CH_4, Merdith et al. (2020) estimated global H_2 fluxes related to serpentinization along mid-ocean ridges for the last 200 Ma at 0.2-14.1 • 10^5 Mt/Ma. The fact that small peridotite bodies, such as the San Petrone bodies, can hardly be detected by geophysical investigations at present-day mid-ocean ridges and passive margins, may suggest that assessments of the amount of residual peridotite

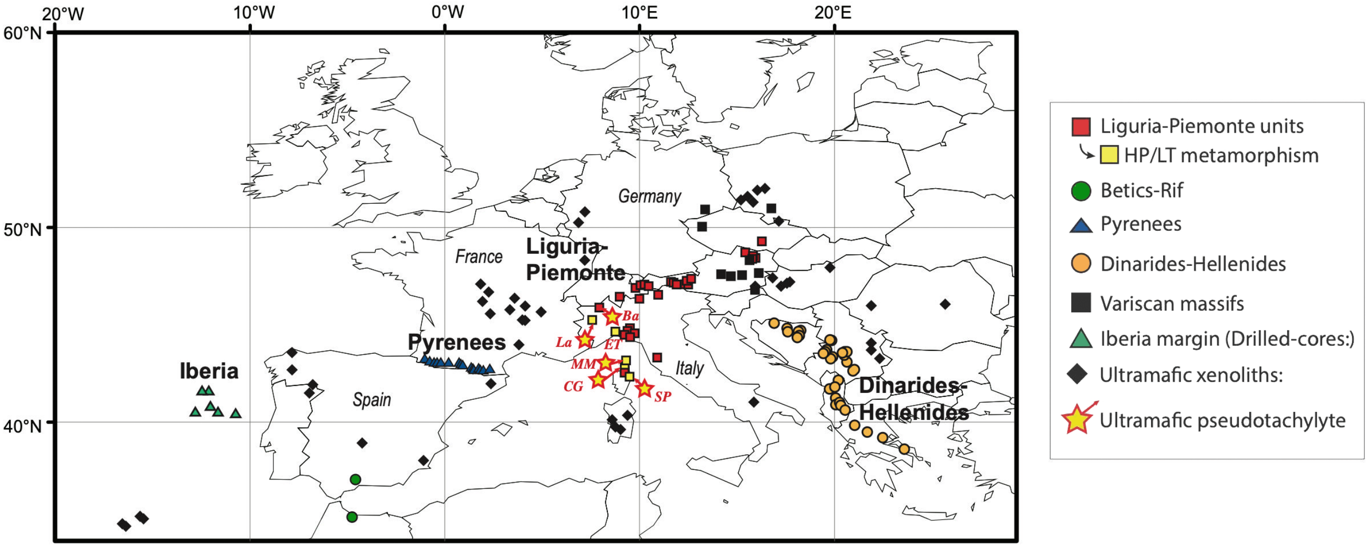


Fig. 8 - Present-day map location of outcrops, drill-cores and xenoliths of peridotitic composition (modified after Picazo et al., 2016). The distribution of lithospheric mantle peridotites having experienced high-pressure metamorphism is also shown, together with the documented occurrences of ultramafic pseudotachylytes.

in these settings may be conservative or, in other words, the extent of serpentinization may be lower than predicted by geophysical investigations. Thereby, the estimates of H_2 production through serpentinization in these settings may potentially be overestimated.

In Fig. 9, the Jurassic Piemonte-Liguria Basin shows larger proportions of residual peridotite with respect to the coeval Neotethys and the Pacific Oceans mid-ocean ridges. However, only a relatively small number of fresh peridotite bodies are identified today in the Alpine orogenic system. This feature may result from the serpentinization events affecting the ultramafic rocks of the Piemonte-Liguria Basin later than the rifting-spreading stages (e.g., Ranero et al., 2003; Vitale Brovarone et al., 2020).

The possibility for serpentinization to happen during plate convergence bears important implications on the genesis of deep H_2 and CH_4 in subduction zones (Vitale Brovarone et al., 2017; 2020; Boutier et al., 2021). Data from the San Petrone, Gratera, and Lanzo peridotites constrain the serpentinization of large volumes of the subducted Piemonte-Liguria lithosphere to post-pseudotachylyte, antigorite grade high-pressure conditions ($P > 1$ GPa; $T \geq 400°C$) (Vitale Brovarone et al., 2020). A quantitative assessment of the actual volumes of serpentinite formed at high-pressure conditions relative to the enclosing subducted oceanic serpentinite in the San Petrone unit was not possible for this study and would require future geochemical investigations. Nevertheless, the possibility for serpentinization to occur at high-pressure conditions increases the potential to generate H_2 during subduction and calls for a possible reassessment of the context of formation of several serpentinite bodies exposed in metamorphic belts. Fig. 10 shows an idealized cartoon of a subducted oceanic to OCT lithosphere. The schematic representation of the distribution of fresh peridotite bodies that escaped seafloor and trench serpentinization is also displayed. The effect of progressive hydration by aqueous metamorphic fluids and serpentinization is idealized by the decrease in size of the residual peridotite bodies with depth. This hypothetic cartoon aims at suggesting a potential pathway for deep H_2 and CH_4 formation through slab serpentinization, and the progressive disappearance of subducted peridotites in metamorphic terranes.

Potentially, many exhumed high-pressure serpentinite bodies are suitable to have formed during subduction from residual fresh peridotites. Future studies could identify the characteristic geochemical patterns of high-pressure serpentinization relative to its seafloor equivalents. Boron isotopes have been used to distinguish between subducted serpentinites and mantle wedge serpentinites (Scambelluri and Tonarini, 2012; Martin et al., 2016; 2020). The discovery of widespread slab mantle serpentinization may add additional complexity to the range of $\delta^{11}B$ signatures of subduction zone serpentinites.

Implications for deep seismicity in subduction zones

Previous work has suggested that subducted fresh peridotite bodies are suitable lithologies to favour the formation of seismic events through stress propagation from partially hydrated rocks and/or accumulation of large differential stress, leading to the formation of pseudotachylytes in ultramafic rocks and related lithologies (Scambelluri et al., 2017; Pennacchioni et al., 2020). The San Petrone peridotite bodies host ultramafic pseudotachylytes that, by analogy with several other equivalents in the Alpine belt (Austrheim and Andersen, 2004; Magott et al., 2016; Scambelluri et al., 2017), can be inferred to represent seismic events occurring during subduction. The preservation of small and potentially

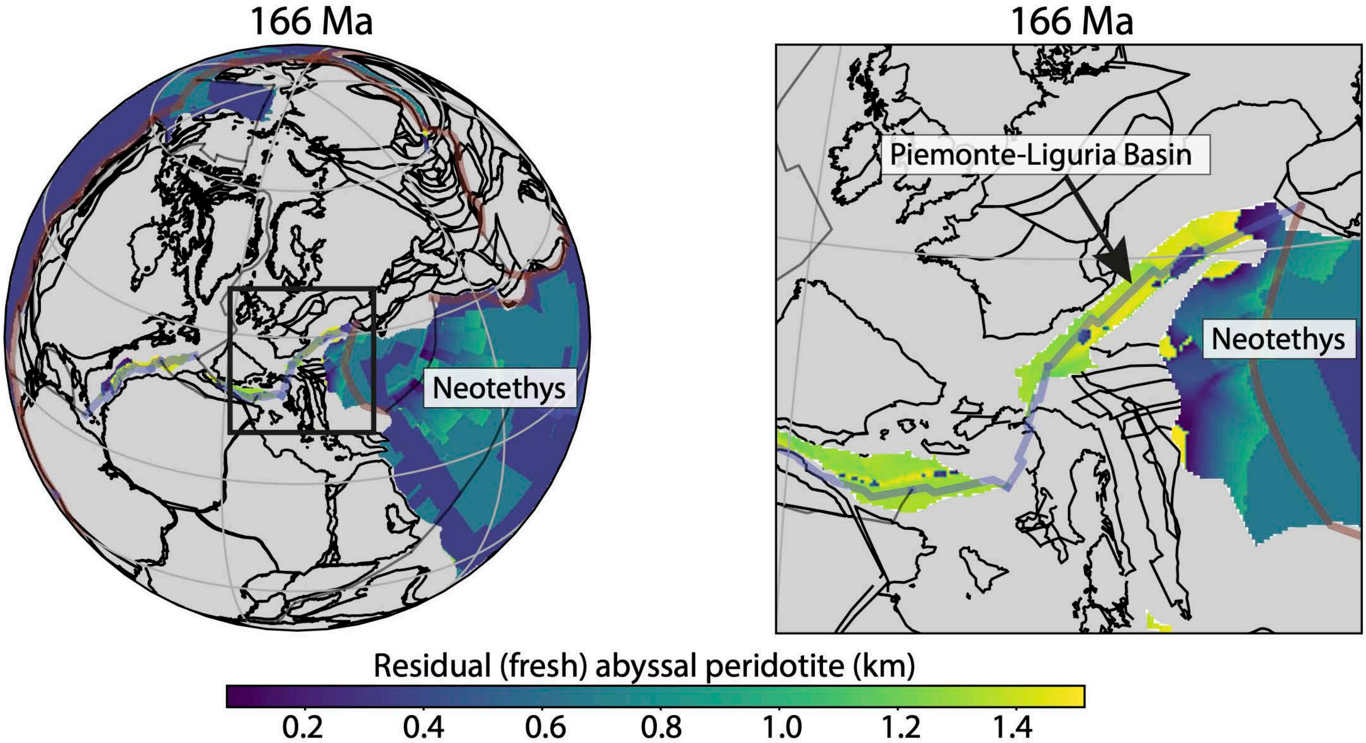


Fig. 9 - a, b) GPlates plate tectonics reconstruction and close up of the Piemonte-Liguria Basin at 166 Ma. The colour codes refer to the possible thickness in km of fresh peridotites unaffected by serpentinization within the uppermost 4 km of oceanic lithosphere. Based on Merdith et al. (2019). Courtesy of A. Merdith.

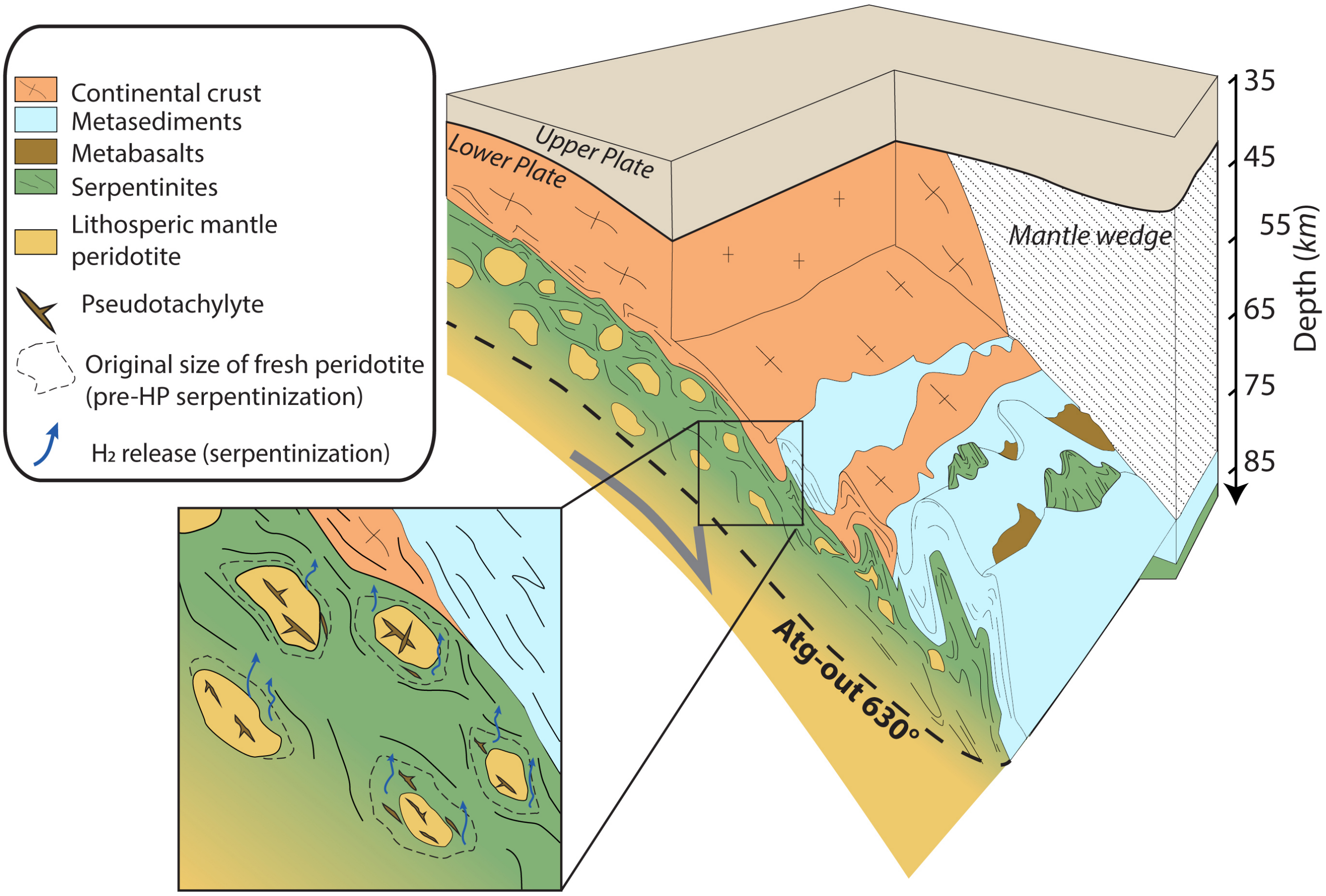


Fig. 10 - Conceptual reconstruction of the subduction of the oceanic to transitional Piemonte-Liguria lithosphere. The idealized distribution of fresh peridotite bodies is shown, according to the present study. As proposed by earlier work (Scambelluri et al., 2017; Pennacchioni et al., 2020) and supported by the present study, rigid blocks of fresh peridotite may localize the development of seismic events through stress propagation. The interaction of these bodies with circulating metamorphic aqueous fluids is suggested at the origin of high pressure serpentinization and the release of deep H_2-rich fluids. The antigorite-out curve (Atg-out) is shown for reference. Figure modified after Angiboust et al. (2012) and Piccoli et al. (2021).

widespread bodies of fresh peridotite as those presented in this study, may therefore have potential implications on the distribution of seismic events associated with stress propagation, including segments of subducting slabs expected to consist primarily of serpentinite. This survey summarized in Fig. 8 strongly supports the hypothesis that the preservation of small and potentially widespread bodies of fresh mantle peridotite embedded in the uppermost sections of subducting oceanic/transitional mantle lithosphere expected to consist primarily of serpentinite, may favour the developments of seismic events associated with stress propagation (Scambelluri et al., 2017; Pennacchioni et al., 2020). Moreover, during subduction competent peridotite bodies could experience seismic failure due to jamming, while the surrounding less competent serpentinized shell could experience ductile deformation (Tarling et al., 2018; Beall et al., 2019).

The implications of the present study on subduction zone seismic events are not limited to processes taking place inside fresh peridotite bodies. Recent work has in fact shown that the release of H_2-rich fluid produces through high-pressure serpentinization reactions may affect the rheology of carbonate rocks, which may be abundant right above the subducting lithospheric mantle, and favour seismic activity (Giuntoli et al., 2020).

CONCLUSIONS

This study provides field and preliminary petrographic, microstructural and geochemical data on two small bodies of fresh peridotite preserved in a subducted ocean-continent transition of the Piemonte-Liguria Basin. The San Petrone peridotite bodies give important insights on the preservation of dry mantle assemblages during a polyphase evolution started with subcontinental mantle unroofing and hydration along the Piemonte-Liguria margin, and followed by intense high-pressure metamorphism to about 2 GPa and 500°C in the Eocene, including hydration. Tracking the evolution of these bodies through the Wilson cycle also informs on the patterns of hydration and related geochemical cycling, notably the generation of H_2 and abiotic CH_4, during the entire cycle. Based on the collected data, it is proposed that the presence of small bodies of fresh peridotite may affect the current estimates of mantle hydration within the first kilometers of transitional and slow to ultraslow oceanic lithosphere. Thereby, the related fluxes of H_2 from serpentinization may be slightly overestimated. In turn, the preservation of peridotite bodies might increase the potential for H_2 generation during subduction. Lastly, the good correlation between the occurrence of peridotite bodies and formation of high-pressure pseudotachylytes within the

Alpine belt, suggests that the preservation of fresh peridotite bodies potentially informs on the mechanisms and distribution of intermediate-depth seismicity in subduction zones.

ACKNOWLEDGEMENTS

This work is authored by three former students of Marco, and a former student of one of them. The manuscript was conceived to express Marco's legacy in different forms. The authors are grateful to the promoters and Editors of this issue for giving them the opportunity to work together on this contribution. This work would have never existed without Marco's boosts on our training.

AVB: I am and will always be indebted to Marco. I would not have had so many opportunities so far in my career without benefiting from Marco's influence, ambitions, and research approach. I will do my very best to keep transferring this precious legacy to the new generations. To Marco, to all the things left unsaid. "For Science!".

FP: Marco's enthusiasm and courage in pushing forward scientific knowledge is and will always be a source of inspiration. From him, I learned that it is not only a matter of talent, but a lot about hard work, persistence and keeping an open mind to new ideas and concepts. I will be always grateful for the scientific exchanges we had. His legacy is and will be of inspiration for many new exciting projects and advances in Earth Sciences.

FG: Marco profoundly shaped my education with his talent and enthusiasm. He taught me to look beyond the general accepted interpretation, being always open to new ideas and using a multidisciplinary approach. I will do my best to transfer his approach and his enthusiasm.

GF: Marco had a strong influence in my early education and in the career path I undertook. Marco's energy in pushing forward his ideas was definitely an example for me. It was great to learn from him that Science is a fantastic mix of enthusiasm, rigorous work and fun.

The authors wish to thank Suzanne Picazo for providing the original file of Fig. 7, and Andrew Merdith for providing Fig. 9, Paolo Nimis for helpful discussion, and the Editors of this issue. Riccardo Tribuzio is thanked for editorial handling and for his constructive comments. Marco Scambelluri and Michel Ballèvre are thanked for their thorough and constructive review of this work. AVB acknowledges an ERC CoG Grant 864045 (DeepSeep), a MIUR Levi Montalcini, and a Richard Lounsbery Foundation.

REFERENCES

Alt J.C., Schwarzenbach E.M., Früh-Green G.L., Shanks W.C.III, Bernasconi S.M., Garrido C.J., et al., 2013. The role of serpentinites in cycling of carbon and sulfur: Seafloor serpentinization and subduction metamorphism. Lithos, 178 (C): 40-54. http://doi.org/10.1016/j.lithos.2012.12.006.

Andersen T.B. and Austrheim H., 2006. Fossil earthquakes recorded by pseudotachylytes in mantle peridotite from the Alpine subduction complex of Corsica. Earth Planet. Sci. Lett., 242: 58-72, doi:10.1016/j.epsl.2005.11.058.

Andersen T.B., Mair K., Austrheim H., Podladchikov Y.Y. and Vrijmoed J.C., 2008. Stress release in exhumed intermediate and deep earthquakes determined from ultramafic pseudotachylites. Geology, 36: 995-998.

Andréani M., Munoz M., Marcaillou C. and Delacour A., 2013. µXANES study of iron redox state in serpentine during oceanic serpentinization. Lithos, 178: 70-83, doi:10.1016/j.lithos.2013.04.008.

Angiboust S., Wolf S., Burov E., Agard P. and Yamato P., 2012. Effect of fluid circulation on subduction interface tectonic processes: Insights from thermo-mechanical numerical modelling. Earth Planet. Sci. Lett., 357-358 (C): 238-248. http://doi.org/10.1016/j.epsl.2012.09.012 -

Austrheim H. and Andersen T.B., 2004. Pseudotachylytes from Corsica: fossil earthquakes from a subduction complex. Terra Nova 16: 193-197, doi:10.1111/j.1365-3121.2004.00551.x.

Basch V., Rampone E., Crispini L., Ferrando C., Ildefonse B. and Godard M., 2018. From mantle peridotites to hybrid troctolites: textural and chemical evolution during melt-rock interaction history (Mt.Maggiore, Corsica, France). Lithos, 323: 4-23.

Bayrakci G., Minshull T.A., Sawyer D.S., Reston T.J., Klaeschen D., Papenberg C., Ranero C., Bull J.M., Davy R.G., Shillington D.J., Perez-Gussinye M. and Morgan J.K., 2016. Fault-controlled hydration of the upper mantle during continental rifting. Nature, Geosci., 9: 384.

Beall A., Fagereng Å. and Ellis S., 2019. Strength of strained two-phase mixtures: application to rapid creep and stress amplification in subduction zone mélange. Geophys. Res. Lett., 46: 169-178, doi:10.1029/2018GL081252.

Beltrando M., Frasca G., Compagnoni R. and Vitale-Brovarone A., 2012. The Valaisan controversy revisited: Multi-stage folding of a Mesozoic hyper-extended margin in the Petit St. Bernard pass area (Western Alps). Tectonophysics, 579: 17-36.

Beltrando M., Manatschal G., Mohn G., Dal Piaz G.V., Vitale Brovarone A. and Masini E., 2014. Recognizing remnants of magma-poor rifted margins in high-pressure orogenic belts: The Alpine case study. Earth Sci. Rev., 131: 88-115, doi:10.1016/j.earscirev.2014.01.001.

Beltrando M., Rubatto D. and Manatschal G., 2010. From passive margins to orogens: The link between ocean-continent transition zones and (ultra)high-pressure metamorphism. Geology, 38: 559-562, doi:10.1130/G30768.1.

Bezzi A. and Piccardo G.B., 1971. Structural features of the Ligurian ophiolites: petrologic evidence for the "oceanic" floor of northern Apennines geosyncline. Mem. Soc. Geol. It., 10: 53-63.

Boudier F., 1978. Structure and petrology of the Lanzo peridotite massif (Piedmont Alps). Geol. Soc. Am. Bull., 89: 1574-1591.

Boutier A., Vitale Brovarone A., Martinez I., Sissmann O. and Mana S., 2021. High-pressure serpentinization and abiotic methane formation in metaperidotite from the Appalachian subduction, northern Vermont. Lithos, 396-397: 106190. http://doi.org/10.1016/j.lithos.2021.106190.

Brun J.-P., Sokoutis D., Tirel C., Gueydan F., Van Den Driessche J. and Beslier M.-O., 2017. Crustal versus mantle core complexes. Tectonophysics. https://doi.org/10.1016/j.tecto.2017.09.017.

Brunet C., Monié P., Jolivet L. and Cadet, J.P., 2000. Migration of compression and extension in the Tyrrhenian Sea, insights from ^{40}Ar/^{39}Ar ages on micas along a transect from Corsica to Tuscany. Tectonophysics, 321: 127-155.

Cannat M., Fontaine F. and Escartín, J., 2010. Serpentinization and associated hydrogen and methane fluxes at slow spreading ridges. In: Rona P.A., Devey C.W., Dyment J., Murton B.J., Diversity of hydroåthermal systems on slow spreading ocean ridges. Geophys. Monogr. Series. Am. Geophys. Union, Washington, p. 241-264, doi:10.1029/2008GM000760.

Carlson R.L., 2001. The abundance of ultramafic rocks in Atlantic Ocean crust. Geophys. J. Int., 144 (1): 37-48.

Charlou J.-L. and Donval J.-P., 1993. Hydrothermal methane venting between 12°N and 26°N along the Mid-Atlantic Ridge. J. Geophys. Res., 98: 9625-9642.

Decandia F.A. and Elter P., 1972. La zona ofiolitifera del Bracco nel settore compreso tra Levanto e la Val Graveglia (Appennino Ligure). Mem. Soc. Geol. It., 11: 503-530.

Deseta N., Andersen T.B. and Ashwal L.D., 2014a. A weakening mechanism for intermediate-depth seismicity? Detailed petrographic and microtextural observations from blueschist facies pseudotachylytes, Cape Corse, Corsica. Tectonophysics, 610: 138-149.

Deseta N., Ashwal L.D., Andersen T.B., 2014b. Initiating intermediate-depth earthquakes: Insights from a HP-LT ophiolite from Corsica. Lithos, 206-207: 127-146.

Emmanuel S. and Ague J.J., 2007. Implications of present-day abiogenic methane fluxes for the early Archean atmosphere. Geophys. Res. Lett. 34: L15810, doi:10.1029/2007GL030532.

Epin M.-E., Manatschal G., Amman M., Ribes C., Clausse A., Guffon T. and Lescanne M., 2019. Polyphase tectono-magmatic evolution during mantle exhumation in an ultra-distal, magma-poor rift domain: example of the fossil Platta ophiolite, SE Switzerland. Int. J. Earth Sci., 108: 2443-2467. https://doi.org/10.1007/s00531-019-01772-0.

Evans B.W., 2010. Lizardite versus antigorite serpentinite: Magnetite, hydrogen, and life(?). Geology, 38: 879-882, doi:10.1130/G31158.1.

Fabbri O., Magott R., Fournier M. and Etienne L., 2018. Pseudotachylite in the Monte Maggiore ophiolitic units (Alpine Corsica): a possible lateral extension of the Cima di Gratera intermediate-depth Wadati-Benioff paleo-seismic zone. Bull. Soc. Géol. Fr. - Earth Sci. Bull., 189, 18.

Ferrand T.P., Hilairet N., Incel S., Deldicque D., Labrousse L., Gasc J., Renner J., Wang Y., Green H.W.II and Schubnel A., 2017. Dehydration-driven stress transfer triggers intermediate-depth earthquakes. Nature Commun., 8: 1-11, doi:10.1038/ncomms15247.

Frasca G., Gueydan F., Brun J.-P. and Monié P., 2016. Deformation mechanisms in a continental rift up to mantle exhumation. Field evidence from the western Betics, Spain. Mar. Petrol. Geol., 76: 310-328.

Früh-Green G., Connolly J.A.D. and Plas A., 2004. Serpentinization of oceanic peridotites: implications for geochemical cycles and biological activity. In: The subseafloor biosphere at mid-ocean ridges. Wilcock W.S.D., Delong E.F., Kelley D.S.,. Baross J.A., Cary S.C.. Geophys. Monogr. Series, p. 119-136.

Giuntoli F., Vitale Brovarone A. and Menegon L., 2020. Feedback between high-pressure genesis of abiotic methane and strain localization in subducted carbonate rocks. Sci. Rep., 10: 1-15, doi:10.1038/s41598-020-66640-3.

Hacker B.R., 2003. Subduction factory 2. Are intermediate-depth earthquakes in subducting slabs linked to metamorphic dehydration reactions? J. Geophys. Res., 108: 2030, doi:10.1029/2001JB001129.

Hermann J., Müntener O. and Scambelluri M., 2000. The importance of serpentinite mylonites for subduction andexhumation of oceanic crust. Tectonophysics, 327: 225-238. https://doi.org/10.1016/S0040-1951(00)00171-2.

Jolivet L., Faccenna C., Goffé B., Mattei M., Rossetti F., Brunet C., Storti F., Funiciello R., Cadet P., Agostino N. and Parra T., 1998. Midcrustal shear zones in postorogenic extension: Example from the northern Tyrrhenian Sea. J. Geochem. Expl., 103: 12123-12160.

Kaczmarek M.-A. and Müntener O., 2010. The variability of peridotite composition across a mantle shear zone (Lanzo massif, Italy): interplay of melt focusing and deformation. Contrib. Miner. Petrol., 160: 663-679, doi:10.1007/s00410-010-0500-8.

Klein F., Bach W., Humphris S.E., Kahl W.A., Jons N., Moskowitz B. and Berquo T.S., 2014. Magnetite in seafloor serpentinite-Some like it hot. Geology, 42: 135-138, doi:10.1130/G35068.1.

Klein F., Bach W. and McCollom T.M., 2013. Compositional controls on hydrogen generation during serpentinization of ultramafic rocks. Lithos, 178: 55-69, doi:10.1016/j.lithos.2013.03.008.

Kodolányi J., Pettke T., Spandler C., Kamber B.S. and Gméling K., 2012. Geochemistry of ocean floor and fore-arc serpentinites: Constraints on the ultramafic input to subduction zones. J. Petrol., 53: 235-270, doi:10.1093/petrology/egr058.

Lagabrielle Y. and Cannat M., 1990. Alpine Jurassic ophiolites resemble the modern central Atlantic basement. Geology, 18: 319-322.

Lagabrielle Y., Vitale Brovarone A. and Ildefonse B., 2015. Fossil oceanic core complexes recognized in the blueschist metaophiolites of Western Alps and Corsica. Earth Sci. Rev., 141: 1-26, doi:10.1016/j.earscirev.2014.11.004.

Lahondère D., 1996. Les schistes bleus et les éclogites à lawsonite des unités continentales et océaniques de la Corse alpine. BRGM, Orléans., Doc. No. 240., 285 pp.

Lutz R., Franke D., Berglar K., Heyde I., Schreckenberger B., Klitzke P. and Geissler W.H., 2018. Evidence for mantle exhumation since the early evolution of the slow-spreading Gakkel Ridge, Arctic Ocean. J. Geodyn., 118: 154-165, doi:10.1016/j.jog.2018.01.014.

Magott R. Fabbri O. and Fournier M. 2016. Subduction zone intermediate-depth seismicity: insights from the structural analysis of Alpine high-pressure ophiolite-hosted pseudotachylyte (Corsica, France). J. Struct. Geol., 87: 95-114.

Magott R., Fabbri O. and Fournier M., 2017. Polyphase ductile/brittle deformation along a major tectonic boundary in an ophiolitic nappe, Alpine Corsica. Insights on subduction zone intermediate-depth seismicity. J. Struct. Geol., 94: 240-257.

Magott R., Fabbri O., Fournier M., 2020. Seismically-induced serpentine dehydration as a possible mechanism of water release in subduction zones. Insights from the Alpine Corsica pseudotachylyte-bearing Monte Maggiore ophiolitic unit. Lithos, 362:105-474.

Malvoisin B., 2015. Mass transfer in the oceanic lithosphere: Serpentinization is not isochemical. Earth Planet. Sci. Lett., 430: 75-85, doi:10.1016/j.epsl.2015.07.043.

Manatschal G., 2004. New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps. Int. J. Earth Sci. (Geol. Rundsch.), 93: 432–466, doi:10.1007/s00531-004-0394-7.

Manatschal G. and Müntener O., 2009. A type sequence across an ancient magma-poor ocean-continent transition: the example of the western Alpine Tethys ophiolites. Tectonophysics, 473: 4-19.

Manatschal G., Engström A., Desmurs L., Schaltegger U., Cosca M., Müntener O. and Bernoulli D., 2006. What is the tectono-metamorphic evolution of continental break-up: The example of the Tasna ocean-continent transition. J. Struct. Geol., 28: 1849-1869, doi:10.1016/j.jsg.2006.07.014.

Manatschal G., Sauter D., Karpoff A.M., Masini E., Mohn G. and Lagabrielle Y., 2011. The Chenaillet Ophiolite in the French/Italian Alps: An ancient analogue for an Oceanic Core Complex? Lithos, 124: 169-184, doi:10.1016/j.lithos.2010.10.017.

Marroni M. and Pandolfi L., 2007. The architecture of an incipient oceanic basin: a tentative reconstruction of the Jurassic Liguria-Piemonte basin along the Northern Apennines-Alpine Corsica transect. Int. J. Earth Sci. (Geol. Rundsch.), 96: 1059-1078, doi:10.1007/s00531-006-0163-x.

Martin C., Flores K.E. and Harlow G.E., 2016. Boron isotopic discrimination for subduction-related serpentinites. Geology, 44: 899-902, doi:10.1130/G38102.1.

Martin C., Flores K.E., Vitale Brovarone A., Angiboust S. and Harlow G.E., 2020. Deep mantle serpentinization in subduction zones: Insight from in situ B isotopes in slab and mantle wedge serpentinites. Chem. Geol., 545: 119637, doi:10.1016/j.chemgeo.2020.119637.

Martin L.A.J., Rubatto D., Vitale Brovarone A. and Hermann J., 2011. Late Eocene lawsonite-eclogite facies metasomatism of a granulite sliver associated to ophiolites in Alpine Corsica. Lithos, 125: 620-640, doi:10.1016/j.lithos.2011.03.015.

Mateeva T., Wolff G.A., Manatschal G., Picazo S., Kusznir N.J. and Wheeler J., 2017. Preserved organic matter in a fossil Ocean Continent Transition in the Alps: the example of Totalp, SE Switzerland. Swiss. J. Geosci., 110: 457-478.

McCarthy A. and Müntener O., 2015. Ancient depletion and mantle heterogeneity: Revisiting the Permian-Jurassic paradox of Alpine peridotites. Geology, 43: 255-258, doi:10.1130/G36340.1.

Merdith A.S., Real P.G., Daniel I., Andreani M., Wright N.M. and Coltice N., 2020. Pulsated global hydrogen and methane flux at mid-ocean ridges driven by Pangea breakup. Geochem. Geophys., Geosyst., 21: 255-20, doi:10.1029/2019GC008869.

Miller D.J. and Christensen N.I., 1997. Seismic velocities of lower crustal and upper mantle rocks from the slow-spreading Mid-Atlantic Ridge, south of the Kane Transform Zone (MARK). In: J. A. Karson, M. Cannat, D. J. Miller, D. Elthon, Proc. ODP, Sci. Results 153: 437-456.

Michael P.J., Langmuir C.H., Dick H.J.B., Snow J.E., Goldstein S.L., Graham D.W., Lehnert K., Kurras G., Jokat W., Mühe R. and Edmonds H.N., 2003. Magmatic and amagmatic seafloor generation at the ultraslow-spreading Gakkel ridge, Arctic Ocean. Nature, 423: 956-961, doi:10.1038/nature01704.

Mohn G., Manatschal G., Müntener O., Beltrando M. and Masini E., 2010. Unravelling the interaction between tectonic and sedimentary processes during lithospheric thinning in the Alpine Tethys margins. Int. J. Earth Sci. (Geol. Rundsch.), 99: 75-101, doi:10.1007/s00531-010-0566-6.

Molli G. and Malavieille J., 2010. Orogenic processes and the Corsica/Apennines geodynamic evolution: insights from Taiwan. Int. J. Earth Sci. (Geol. Rundsch.), 100: 1207-1224, doi:10.1007/s00531-010-0598-y,

Morishita T. and Arai S., 2003. Evolution of spinel-pyroxene symplectite in spinel-lherzolites from the Horoman Complex, Japan. Contrib. Miner. Petrol., 144: 509-522, doi:10.1007/s00410-002-0417-y.

Mottl M.J., Komor S.C., Fryer P. and Moyer C.L., 2003. Deep-slab fluids fuel extremophilic Archaeaon a Mariana forearc serpentinite mud volcano: Ocean Drilling Program Leg 195. Geochem. Geophys. Geosyst. 4, n/a–n/a. doi:10.1029/2003GC000588.

Müntener O., Manatschal G., Desmurs L. and Pettke T., 2010. Plagioclase peridotites in ocean-continent transitions: refertilized mantle domains generated by melt stagnation in the shallow mantle lithosphere. J. Petrol., 51: 255-294, doi:10.1093/petrology/egp087.

Müntener O., Pettke T., Desmurs L., Meier M. and Schaltegger U., 2004. Refertilization of mantle peridotite in embryonic ocean basins: trace element and Nd isotopic evidence and implications for crust–mantle relationships. Earth Planet. Sci. Lett., 221: 293-308, doi:10.1016/S0012-821X(04)00073-1.

Müntener O. and Piccardo G.B., 2003. Melt migration in ophiolitic peridotites: the message from Alpine-Apennine peridotites and implications for embryonic ocean basins. Geol. Soc. London Spec. Publ., 218: 69-89, doi:10.1144/GSL.SP.2003.218.01.05.

Obata M., and Karato S.., 1995. Ultramafic pseudotachylite from the Balmuccia peridotite, Ivrea-Verbano zone, northern Italy. Tectonophysics, 242: 313-328. http://doi.org/10.1016/0040-1951(94)00228-2

Padrón-Navarta J.A., Hermann J., Garrido C.J., López Sánchez-Vizcaíno V. and Gómez-Pugnaire M.T., 2009. An experimental investigation of antigorite dehydration in natural silica-enriched serpentinite. Contrib. Miner. Petrol., 159 (1): 25-42. http://doi.org/10.1007/s00410-009-0414-5.

Pelletier L. and Müntener O., 2006. High-pressure metamorphism of the Lanzo peridotite and its oceanic cover, and some consequences for the Sesia-Lanzo zone (northwestern Italian Alps). Lithos, 90: 111-130, doi:10.1016/j.lithos.2006.01.006.

Pennacchioni G., Scambelluri M., Bestmann M., Notini L., Nimis P., Plümper O., Faccenda M. and Nestola F., 2020. Record of intermediate-depth subduction seismicity in a dry slab from an exhumed ophiolite. Earth Planet. Sci. Lett., 548: 116490, doi:10.1016/j.epsl.2020.116490.

Peters D., Bretscher A., John T., Scambelluri M., and Pettke T., 2017. Fluid-mobile elements in serpentinites: Constraints on serpentinisation environments and element cycling in subduction zones. Chem. Geol., 466: 654-666,oi:10.1016/j.chemgeo.2017.07.017.

Péron-Pinvidic G. and Manatschal G., 2009. The final rifting evolution at deep magma-poor passive margins from Iberia-Newfoundland: a new point of view. Int. J. Earth Sci. (Geol. Rundsch.), 98: 1581-1597, doi:10.1007/s00531-008-0337-9

Picazo S., Müntener O., Manatschal G., Bauville A., Karner G. and Johnson C., 2016. Mapping the nature of mantle domains in Western and Central Europe based on clinopyroxene and spinel chemistry: Evidence for mantle modification during an extensional cycle. Lithos, 266-267: 233-263, doi:10.1016/j.lithos.2016.08.029.

Piccardo G.B. and Guarnieri L., 2010. Alpine peridotites from the Ligurian Tethys: an updated critical review. Int. Geol. Rev., 52: 1138-1159, doi:10.1080/00206810903557829.

Piccardo G.B., Ranalli G. and Guarnieri L., 2010. Seismogenic shear zones in the lithospheric mantle: ultramafic pseudotachylytes in the Lanzo Peridotite (Western Alps, NW Italy). J. Petrol., 51: 81-100. http://doi.org/10.1093/petrology/egp067.

Piccoli F., 2017. High-Pressure carbonation: a petrological and geochemical study of carbonated metasomatic rocks from Alpine Corsica. PhD thesis. Université Pierre et Marie Curie (UPMC), 309 pp.

Piccoli F., Hermann J., Pettke T., Connolly J.A.D., Kempf E.D. and Duarte J.F.V., 2019. Subducting serpentinites release reduced, not oxidized, aqueous fluids. Sci. Rep., 9: 1-7. http://doi.org/10.1038/s41598-019-55944-8.

Piccoli F., Ague J.J., Chu X., Tian M. and Vitale Brovarone A., 2021. Field-based evidence for intra-slab high-permeability channel formation at eclogite-facies conditions during subduction. Geochem. Geophys. Geosyst., 22, e2020GC009520. http://doi.org/10.1029/2020GC009520.

Pinto V.H.G., Manatschal G., Karpoff A.M., Ulrich M. and Viana A.R., 2017. Seawater storage and element transfer associated with mantle serpentinization in magma-poor rifted margins: A quantitative approach. Earth Planet. Sci. Lett., 459: 227-237.

Pinto V.H.G., Manatschal G., Karpoff A.M. and Viana A., 2015. Tracing mantle-reacted fluids in magma-poor rifted margins: The example of Alpine Tethyan rifted margins. Geochem. Geophys. Geosyst., 16: 3271-3308.

Plümper O., King H.E., Geisler T., Liu Y., Pabst S., Savov I.P., Rost D. .and Zack T., 2017. Subduction zone forearc serpentinites as incubators for deep microbial life. PNAS, 114: 4324-4329, doi:10.1073/pnas.1612147114.

Rampone E., Piccardo G.B., Vannucci R., Bottazzi P. and Ottolini L., 1993. Subsolidus reactions monitored by trace element partitioning: the spinel- to plagioclase-facies transition in the mantle peridotites. Contrib. Miner. Petrol., 115: 1-17.

Rampone E., Romairone A., Abouchami W., Piccardo G. B., Hofmann A. W., 2005. Chronology, petrology and isotope geochemistry of the Erro-Tobbio peridotites (Ligurian Alps, Italy): Records of Late Palaeozoic lithospheric extension. J. Petrol., 46: 799-827, doi:10.1093/petrology/egi001.

Rampone E., Piccardo G.B. and Hofmann A.W., 2008. Multi-stage melt-rock interaction in the Mt. Maggiore (Corsica, France) ophiolitic peridotites: microstructural and geochemical evidence. Contrib. Miner. Petrol., 156: 453-475, doi:10.1007/s00410-008-0296-y.

Rampone E. and Borghini G., 2008. Melt migration and intrusion in the Erro-Tobbio peridotites (Ligurian Alps, Italy): Insights on magmatic processes in extending lithospheric mantle. Eur. J. Miner., 20: 573-585, doi:10.1127/0935-1221/2008/0020-1807.

Rampone E., Hofmann A.W. and Raczek I., 2009. Earth Planet. Sci. Lett., 288: 601-610, doi:10.1016/j.epsl.2009.10.024.

Rampone E., Borghini G. and Basch V., 2020. Melt migration and melt-rock reaction in the Alpine-Apennine peridotites: Insights on mantle dynamics in extending lithosphere. Geosci. Front., 11: 151-166, doi:10.1016/j.gsf.2018.11.001.

Ranero C.R., Morgan J.P., McIntosh K. and Reichert C., 2003. Bending-related faulting and mantle serpentinization at the Middle America trench. Nature, 425: 367-373.

Ribes C., Petri, B., Ghienne J.-F., Manatschal G., Galster F., Karner G.D., Figueredo P.H., Johnson C.A. and Karpoff A.-M., 2019. Tectono-sedimentary evolution of a fossil ocean-continent transition: Tasna nappe, central Alps (SE Switzerland). GSA Bull., 132: 1427-1446. https://doi.org/10.1130/B35310.1.

Rossi P., Durand-Delga M., Caron J.M., Guieu G., Conchon O., Libourel G. and Loÿe-Pilot M.-D., 1994. Notice esplicative, Carte géologique de France (1/50000), feuille Corte (1110). Orléans: BRGM.

Roumejon S., Cannat M., Agrinier P., Godard M. and Andréani M., 2015. Serpentinization and fluid pathways in tectonically exhumed peridotites from the southwest Indian Ridge (62-65 E). J. Petrol., 56: 703-734, doi:10.1093/petrology/egv014.

Sanfilippo A. and Tribuzio R., 2013. Building of the deepest crust at a fossil slow-spreading centre (Pineto gabbroic sequence, Alpine Jurassic ophiolites). Contrib. Miner. Petrol., 165 (4): 705-721. http://doi.org/10.1007/s00410-012-0831-8.

Scambelluri M., Strating E.H.H., Piccardo G.B., Vissersa R.L.M. and Rampone E., 1991. Alpine olivine- and titanian clinohumite-bearing assemblages in the Erro-Tobbio peridotite (Voltri Massif, NW Italy). J. Metam. Geol., 9: 79-91, doi:10.1111/j.1525-1314.1991.tb00505.x.

Scambelluri M. and Tonarini S., 2012. Boron isotope evidence for shallow fluid transfer across subduction zones by serpentinized mantle. Geology, 40: 907-910, doi:10.1130/G33233.1

Scambelluri M., Pennacchioni G., Gilio M., Bestmann M., Plümper O. and Nestola F., 2017. Fossil intermediate-depth earthquakes in subducting slabs linked to differential stress release. Nature Geosci., 10: 960-966. http://doi.org/10.1038/s41561-017-0010-7.

Secchiari A., Montanini A., Bosch D., Macera P. and Cluzel D., 2019. Origin of the spinel-pyroxene symplectites in the harzburgites from the New Caledonia Peridotite. Ofioliti, 4: 31-42, doi:10.4454/ofioliti.v44i1.463.

Seyfried W.E. Jr., Foustoukos D.I. and Fu Q., 2007. Redox evolution and mass transfer during serpentinization: An experimental and theoretical study at 200°C, 500 bar with implications for ultramafic-hosted hydrothermal systems at Mid-Ocean Ridges. Geochim. Cosmochim. Acta, 71: 3872-3886. http://doi.org/10.1016/j.gca.2007.05.015.

Souquière F., and Fabbri O., 2010. Pseudotachylytes in the Balmuccia peridotite (Ivrea Zone) as markers of the exhumation of the southern Alpine continental crust. Terra Nova, 22: 70-77.

Stanton N., Manatschal G., Autin J., Sauter D., Maia M. and Viana, A., 2016. Geophysical fingerprints of hyper-extended, exhumed and embryonic oceanic domains: the example from the Iberia-Newfoundland rifted margins. Marine Geophys. Res., 37: 185-205. https://doi.org/10.1007/s11001-016-9277-0.

Sutra E., Manatschal G., Mohn G. and Unternehr P., 2013. Quantification and restoration of extensional deformation along the Western Iberia and Newfoundland rifted margins. Geochem. Geophys. Geosyst., 14: 2575-2597. https://doi.org/10.1002/ggge.20135.

Tarling M.S., Smith S.A.F., Viti C. and Scott J.M., 2018. Dynamic earthquake rupture preserved in a creeping serpentinite shear zone. Nature Comm., 1-8, doi:10.1038/s41467-018-05965-0.

Ueda T., Obata M., Di Toro G., Kanagawa K. and Ozawa K., 2008. Mantle earthquakes frozen in mylonitized ultramafic pseudotachylytes of spinel-lherzolite facies. Geology, 3 (8): 607-610. http://doi.org/10.1130/G24739A.1

Vieira Duarte J.F., Kaczmarek M.-A., Vonlanthen P., Putlitz B, and Müntener O., 2020. Hydration of a mantle shear zone beyond serpentine stability: a possible link to microseismicity along ultraslow spreading ridges? J. Geophys. Res. Solid Earth, 125. https://doi.org/10.1029/2020JB019509.

Vitale Brovarone A., Alard O., Beyssac O., Martin L. and Picatto M., 2014a. Lawsonite metasomatism and trace element recycling in subduction zones. J. Metam. Geol., 32: 489-514, doi:10.1111/jmg.12074.

Vitale Brovarone A., Beltrando M., Malavieille J., Giuntoli F., Tondella E., Groppo C., Beyssac O. and Compagnoni R., 2011. Inherited ocean-continent transition zones in deeply subducted terranes: Insights from Alpine Corsica. Lithos, 124: 273-290, doi:10.1016/j.lithos.2011.02.013.

Vitale Brovarone A., Beyssac O., Malavieille J., Molli G., Beltrando M. and Compagnoni R., 2013. Stacking and metamorphism of continuous segments of subducted lithosphere in a high-pressure wedge: The example of Alpine Corsica (France). Earth Sci. Rev., 116: 35-56, doi:10.1016/j.earscirev.2012.10.003.

Vitale Brovarone A. and Herwartz D., 2013. Timing of HP metamorphism in the Schistes Lustrés of Alpine Corsica: New Lu-Hf garnet and lawsonite ages. Lithos, 172-173: 175-191, doi:10.1016/j.lithos.2013.03.009.

Vitale Brovarone A., Picatto M., Beyssac O., Lagabrielle Y. and Castelli D., 2014b. The blueschist-eclogite transition in the Alpine chain: P-T paths and the role of slow-spreading extensional structures in the evolution of HP-LT mountain belts. Tectonophysics, 615-616: 96-121, doi:10.1016/j.tecto.2014.01.001

Vitale Brovarone A., Sverjensky D.A., Piccoli F., Ressico F., Giovannelli D. and Daniel I., 2020. Subduction hides high-pressure sources of energy that may feed the deep subsurface biosphere. Nature Comm. 11, 3880, doi:10.1038/s41467-020-17342-x

Received, February 1, 2021
Accepted, May 22, 2021