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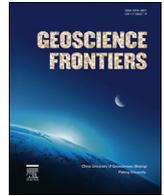


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Research Paper

Melt migration and melt-rock reaction in the Alpine-Apennine peridotites: Insights on mantle dynamics in extending lithosphere

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ABSTRACT

The compositional variability of the lithospheric mantle at extensional settings is largely caused by the reactive percolation of uprising melts in the thermal boundary layer and in lithospheric environments. The Alpine-Apennine (A-A) ophiolites are predominantly constituted by mantle peridotites and are widely thought to represent analogs of the oceanic lithosphere formed at ocean/continent transition and slow- to ultraslow-spreading settings. Structural and geochemical studies on the A-A mantle peridotites have revealed that they preserve significant compositional and isotopic heterogeneity at variable scale, reflecting a long-lived multi-stage melt migration, intrusion and melt-rock interaction history, occurred at different lithospheric depths during progressive uplift. The A-A mantle peridotites thus constitute a unique window on mantle dynamics and lithosphere-asthenosphere interactions in very slow spreading environments. In this work, we review field, microstructural and chemical-isotopic evidence on the major stages of melt percolation and melt-rock interaction recorded by the A-A peridotites and discuss their consequences in creating chemical-isotopic heterogeneities at variable scales and enhancing weakening and deformation of the extending mantle. Focus will be on three most important stages: (i) old (pre-Jurassic) pyroxenite emplacement, and the significant isotopic modification induced in the host mantle by pyroxenite-derived melts, (ii) melt-peridotite interactions during Jurassic mantle exhumation, i.e. the open-system reactive porous flow at spinel facies depths causing bulk depletion (origin of reactive harzburgites and dunites), and the shallower melt impregnation which originated plagioclase-rich peridotites and an overall mantle refertilization. We infer that migrating melts largely originated as shallow, variably depleted, melt fractions, and acquired Si-rich composition by reactive dissolution of mantle pyroxenes during upward migration. Such melt-rock reaction processes share significant similarities with those documented in modern oceanic peridotites from slow- to ultraslow-spreading environments and track the progressive exhumation of large mantle sectors at shallow depths in oceanic settings where a thicker thermal boundary layer exists, as a consequence of slow-spreading rate.

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1. Introduction

Studies on ophiolitic and abyssal peridotites have provided evidence that the compositional variability of the lithospheric mantle at extensional settings is largely caused by the reactive percolation, dissolution and crystallization of uprising melts in the thermal boundary layer and in lithospheric environments (e.g.

Piccardo et al., 1993, 2007; Boudier and Nicolas, 1995; Kelemen et al., 1995a,b; Van der Wal and Bodinier, 1996; Rampone et al., 1997, 2004, 2008; Seyler and Bonatti, 1997; Godard et al., 2000; Tartarotti et al., 2002; Bodinier and Godard, 2003; Dijkstra et al., 2003; Müntener and Piccardo, 2003; Niu, 2004; Seyler et al., 2004; Le Roux et al., 2007; Soustelle et al., 2009; Dick et al., 2010; Müntener et al., 2010; Higgie and Tommasi, 2012; Abily and Ceuleneer, 2013; Dygert et al., 2016; Varas-Reus et al., 2016; Warren, 2016). The reactive behaviour of percolating melts during their ascent from the melting region in the asthenosphere to the lithospheric mantle is related to their progressive oversaturation in olivine and undersaturation in pyroxenes (e.g. Kelemen, 1990; Kelemen et al., 1990, 1995a,b, 1997, 2000; Grove et al., 1992). This

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causes olivine crystallization and pyroxene dissolution at deeper and hotter spinel-facies mantle depths, originating repleve harzburgites and dunites. At shallower and colder lithospheric depths, percolating melts will crystallize plagioclase, together with pyroxenes and/or olivine, thus originating plagioclase-rich impregnated peridotites.

The percolation of melts by porous flow into mantle peridotites is therefore accompanied by melt-rock interactions, whose effects are mainly controlled by physical parameters (temperature, pressure), composition of the reacting melt, melt-rock ratio and grain-scale processes (Liang, 2003; Morgan and Liang, 2003, 2005). Such melt-rock interaction processes are capable to create significant modifications in large mantle sectors, including textures, mineral modes, major, trace element and isotopic compositions, and are believed to be responsible of peculiar chemical signatures of MORBs, observed at local to regional scale (e.g. Le Roux et al., 2002; Collier and Kelemen, 2010; Lambart et al., 2013).

In this context, considerable knowledge has resulted from last decade studies on the Alpine-Apennine (A-A) ophiolites, which are predominantly constituted by mantle peridotites, and are widely thought to represent analogues of the oceanic lithosphere formed at ocean/continental transition and slow- to ultraslow-spreading settings (e.g. Rampone and Piccardo, 2000; Manatschal and Müntener, 2009; Picazo et al., 2016). Structural and geochemical studies on the Alpine-Apennine mantle peridotites have revealed that they preserve significant small-versus large-scale textural, compositional and isotopic heterogeneity reflecting a long-lived multi-stage evolution, testified by: (i) records of old pre-Jurassic magmatic events, e.g. the diffuse occurrence of pyroxenite layers and/or bodies within the peridotites; (ii) metamorphic and deformation events related to tectonic exhumation, localized in extensional shear zones; (iii) multiple melt-rock interaction and intrusion events occurred at different lithospheric depths during progressive extension-related uplift (Hoogerduijn Strating et al., 1993; Rampone et al., 1993, 1995, 1996, 1997, 1998, 2004, 2005; Müntener and Piccardo, 2003; Piccardo et al., 2004; Tribuzio et al., 2004; Montanini et al., 2006; Borghini et al., 2007). Accordingly, the different styles and depths of melt percolation and melt-peridotite reaction stages allowed the direct observation of the origin and scale of structural, chemical and isotopic mantle heterogeneity, in extensional settings evolving from continental rifting to very slow spreading. Few available studies on pyroxenites have documented that they are witness of ancient events, possibly occurred in the asthenosphere and/or at the asthenosphere-lithosphere boundary (Montanini et al., 2006, 2012; Rampone and Borghini, 2008; van Acken et al., 2008, 2010a,b; Borghini et al., 2013, 2016; Montanini and Tribuzio, 2015). Structural and geochemical studies on pyroxenites in these mantle sectors can thus provide valuable insights on the chemical and isotopic signature of old recycled components in a MORB-type asthenospheric mantle and on deep-seated magmatic events related to MORB-type magma generation.

The Alpine-Apennine mantle peridotites therefore constitute a unique window on mantle dynamics and lithosphere-asthenosphere interactions in very slow spreading environments. This work aims to review field, microstructural and chemical-isotopic evidence on the major stages of melt percolation and melt-rock interaction recorded by the A-A peridotites, and discuss their consequences in creating chemical-isotopic heterogeneities at variable scales, and enhancing weakening and deformation of the extending mantle.

2. The Alpine-Apennine peridotites: distinct mantle domains in the extending lithosphere

The Alpine-Apennine ophiolites were formed during passive extension of the Europe-Adria continental lithosphere and opening

of the Jurassic Ligurian Tethys (or Alpine Tethys) ocean, a small slow-spreading oceanic basin with maximum estimated width of 800 km, an overall length of 1000 km, and spreading rate of 2 cm/year (see Rampone et al., 2014 and references therein).

Salient feature of the A-A ophiolites is the predominant association of old (pre-Jurassic) lithospheric mantle that was exposed at the sea floor and largely subordinate younger (Jurassic) oceanic crustal rocks (gabbroic intrusions and discontinuous basaltic cover). Accordingly, they were defined as “passive margin ophiolites”, sharing great similarities with modern non-volcanic passive continental margins and ultraslow-spreading ridges (Rampone and Piccardo, 2000; Piccardo et al., 2002; Marroni and Pandolfi, 2007; Manatschal and Müntener, 2009; Piccardo, 2009; Mohn et al., 2010; Piccardo and Guarnieri, 2010). This was indeed already described in pioneering studies (Elter, 1972; Lemoine et al., 1987) inferring mantle exhumation as a key process in the oceanic evolution of these ophiolites.

The ophiolitic units cropping along the Alpine-Apennine belt have been referred to different (pericontinental vs. intraoceanic) settings within the Jurassic Ligurian Tethys ocean (see Marroni and Pandolfi, 2007; Manatschal and Müntener, 2009; Mohn et al., 2010; Picazo et al., 2016) (Fig. 1). In recent review papers based on structural and petrologic studies on the Central and Western Alps

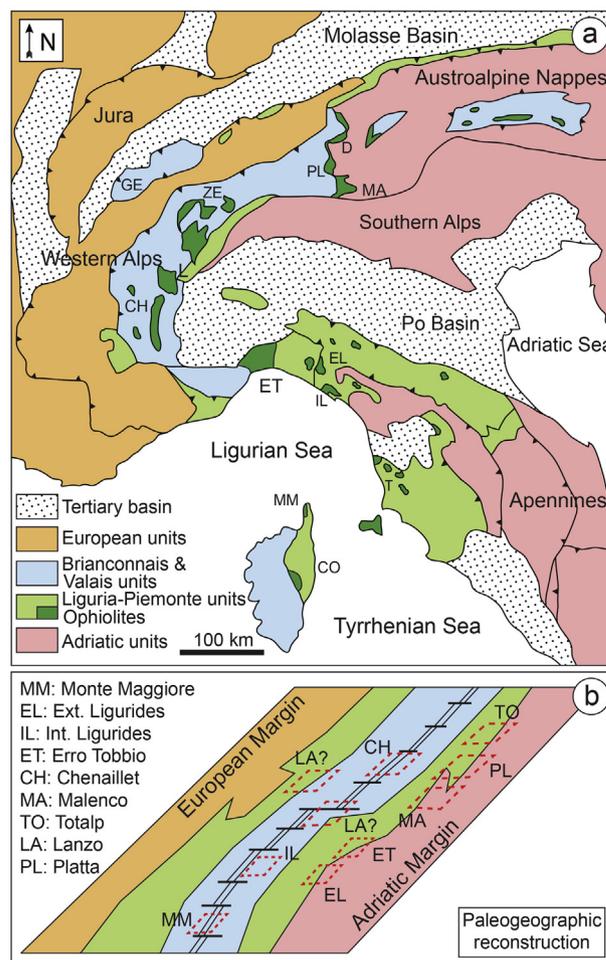


Figure 1. (a) Location of the major ophiolite massifs in the Central–Western–Ligurian Alps and Northern Apennines (and Corsica) (redrawn after Schaltegger et al., 2002). (b) Schematic palaeogeographic reconstruction of the Piemont–Ligurian oceanic basin during the Late Jurassic, with inferred location of the major ophiolite sequences (redrawn after Manatschal and Müntener, 2009).

ophiolites, Manatschal and Müntener (2009) and Picazo et al. (2016) provided a paleogeographic reconstruction of the Alpine Tethys oceanic lithosphere, with distinct mantle domains (from marginal to more intra-oceanic) corresponding to different melt-related and deformation processes recorded in the exhumed mantle: (i) old “inherited” subcontinental lithospheric mantle (mantle domains A in Fig. 2a) (primarily associated to continental crust) which was tectonically exhumed and did not experienced melting and/or melt migration events during Jurassic, (ii) more internal, “infiltrated” lithospheric mantle (mantle domains B in Fig. 2a) which was affected by multiple melt-rock interaction stages during exhumation and, eventually, partial melting to produce the Jurassic crust. The External Liguride (Northern Apennines), Lanzo North (Western Alps) and Malenco, Upper Platta, Totalp (Eastern Central Alps) peridotites are mostly reconcilable to subcontinental mantle domains (A), whereas the Erro-Tobbio (Ligurian Alps), Lanzo South, Mt. Maggiore (Alpine Corsica), Internal Liguride (Northern Apennines) peridotites largely represent mantle domains affected by melt infiltration events (B). Although being a simplified scheme, because interference and transition from “inherited” to “infiltrated” mantle domains are visible in a specific mantle unit at the outcrop scale, it is anyhow useful to introduce the different, partly overprinted, melt-rock reaction stages that these peridotites experienced during their long-lived mantle evolution.

The subcontinental mantle peridotites (domains A) still preserve the diffuse occurrence of pyroxenite layers, occurring as parallel layers, often displaying isoclinal folds, which are records of old deformation events. Available isotope-based chronological data have indicated Ordovician to Permian ages of pyroxenite emplacement (Montanini et al., 2006, 2012; van Acken et al., 2010a; Borghini et al., 2013, 2016). Detailed petrologic studies on peridotite-pyroxenite profiles in the External Liguride mantle units have shown that the host peridotites are modified by interaction with pyroxenite-derived melts, occurred during the pre-Jurassic emplacement of pyroxenites (Borghini et al., 2013, 2016). Such old melt-rock reaction events were totally preserved during the subsequent Jurassic tectonic exhumation of these mantle sectors, largely occurred at subsolidus conditions (Rampone et al., 1995; Borghini et al., 2011). Accordingly, such peridotite-pyroxenite associations are ideal case studies to investigate the chemical and isotopic changes induced by pyroxenite components in fertile lherzolites, proxy of MORB-type mantle sources.

On the other hand, the “infiltrated” mantle domains (B) experienced multiple stages of melt migration and melt-rock reaction at different lithospheric depths, during Jurassic exhumation, i.e. reactive porous flow percolation at deeper spinel-facies (Fig. 2b, sketch 1), melt impregnation and refertilization at shallower plagioclase facies depth (Fig. 2b, sketch 2) (e.g. Rampone et al., 1997, 2004, 2008; Müntener and Piccardo, 2003; Piccardo et al., 2004, 2007; Rampone and Borghini, 2008; Müntener et al., 2010; Sanfilippo and Tribuzio, 2011), focused melt flow through replacive dunite channels, both concomitant and/or subsequent to the previous melt migration stages (e.g. Piccardo and Vissers, 2007; Piccardo et al., 2007; Basch et al., 2018). These melt percolation events had a key role in creating chemical heterogeneities in the infiltrated mantle at variable scales and enhancing deformation along extensional shear zones (e.g. Ranalli et al., 2007; Kaczmarek and Müntener, 2008, 2010).

In the following, we will focus on three major stages: (i) the pyroxenite-peridotite interaction, which on a more general scale addresses the issue of small-scale mantle chemical-isotopic heterogeneity caused by pyroxenite components, (ii) the open-system reactive porous flow at spinel-facies depths, (iii) the melt impregnation, and the origin of plagioclase-enriched peridotites.

3. Pre-Jurassic events: pyroxenite-peridotite interaction

Isotopic studies on oceanic peridotites (by Nd, Os, Hf systematic) have shown that they record a large isotopic heterogeneity, much larger than in MORBs (e.g. Warren et al., 2009; Rampone and Hofmann, 2012, and references therein; Stracke et al., 2011; Stracke, 2012; Warren and Shirey, 2012; Lassiter et al., 2014; Mallick et al., 2014, 2015). This is evident in the Nd isotopic variation of oceanic peridotites (including both mid-ocean ridge abyssal and Iberian margin peridotites), compared to the major frequency (>90%) of Nd isotopic compositions in MORBs (Fig. 3a). The peridotites define a much larger interval, extending both towards more depleted and more enriched Nd isotopic values. Remarkably, the same output derives from studies on the Alpine-Apennine ophiolites, again showing much larger heterogeneity in mantle peridotites than in crustal, gabbroic and basaltic rocks (Fig. 3b; see Rampone and Hofmann, 2012 for complete compilation of data source references).

Isotopic heterogeneities in the oceanic mantle are presently considered to reflect, first of all, old depletion events unrelated to recent MORB melting and lithological heterogeneities in the mantle source, like pyroxenites (see Warren et al., 2009; Rampone and Hofmann, 2012, and quoted references). In this overall scenario, two major questions are still open: (i) the origin and significance of extremely depleted isotopic compositions, likely remnants of old (Archean) depletion events whose fingerprints are still preserved in the asthenospheric mantle and, (ii) the role of pyroxenite components in creating small-scale chemical and isotopic heterogeneities in the MORB mantle source. This has been largely invoked, but remains still controversial and poorly constrained, mostly due to the difficulty to link experimental and geochemical models with direct field observations.

Insights on the role of pyroxenite-peridotite interaction in creating a veined, chemically and isotopically heterogeneous, mantle repository, have resulted from recent field-controlled mineral trace-element and isotopic investigations in peridotites and associated pyroxenites from the External Liguride mantle sequences (Borghini et al., 2013, 2016). In the field, pyroxenites mostly occur as centimeter-scale layers within the host mantle peridotites (Fig. 4a). Peridotites locally display compositional banding (lherzolite, harzburgite and dunite) parallel to pyroxenite layers, and the whole layering is parallel to a well-developed foliation. Pyroxenite compositions range from spinel websterite to spinel clinopyroxenite and are partly recrystallized at plagioclase-facies conditions. In the whole mantle sequence, plagioclase is of truly metamorphic origin (Borghini et al., 2011), being confined to the most fertile lithologies (pyroxenite and lherzolite), and absent in harzburgite and dunite. Borghini et al. (2016) inferred that many of these pyroxenites originally contained garnet in the primary mineral assemblage, indicating that they originated by segregation of MORB-type melts at rather deep mantle levels ($P > 1.5$ GPa) (Borghini and Fumagalli, 2018).

Textural and chemical features in the wall-rock peridotites indicate interaction with pyroxenite-derived melt: (i) development of a thin orthopyroxene-rich layer at the pyroxenite-peridotite boundary (Fig. 5a), (ii) lower bulk Mg-values coupled to higher bulk Al_2O_3 , CaO contents, when compared to the “country” peridotites far from pyroxenite veins (Borghini et al., in preparation), (iii) progressive REE increase, and LREE enrichment (i.e. lowering of the Sm/Nd ratio) in both bulk-rock and clinopyroxene of wall-rock and host peridotites (up to 20 cm from the pyroxenite contact; Borghini et al., 2013). Such trace element variations are consistent with reactive percolation of pyroxenite-derived melts within the peridotite, at decreasing melt mass.

In an $^{87}Sr/^{86}Sr$ vs. initial (160 Ma) ϵ_{Nd} diagram (Fig. 6a), pyroxenites and peridotites (analyses performed on clinopyroxene

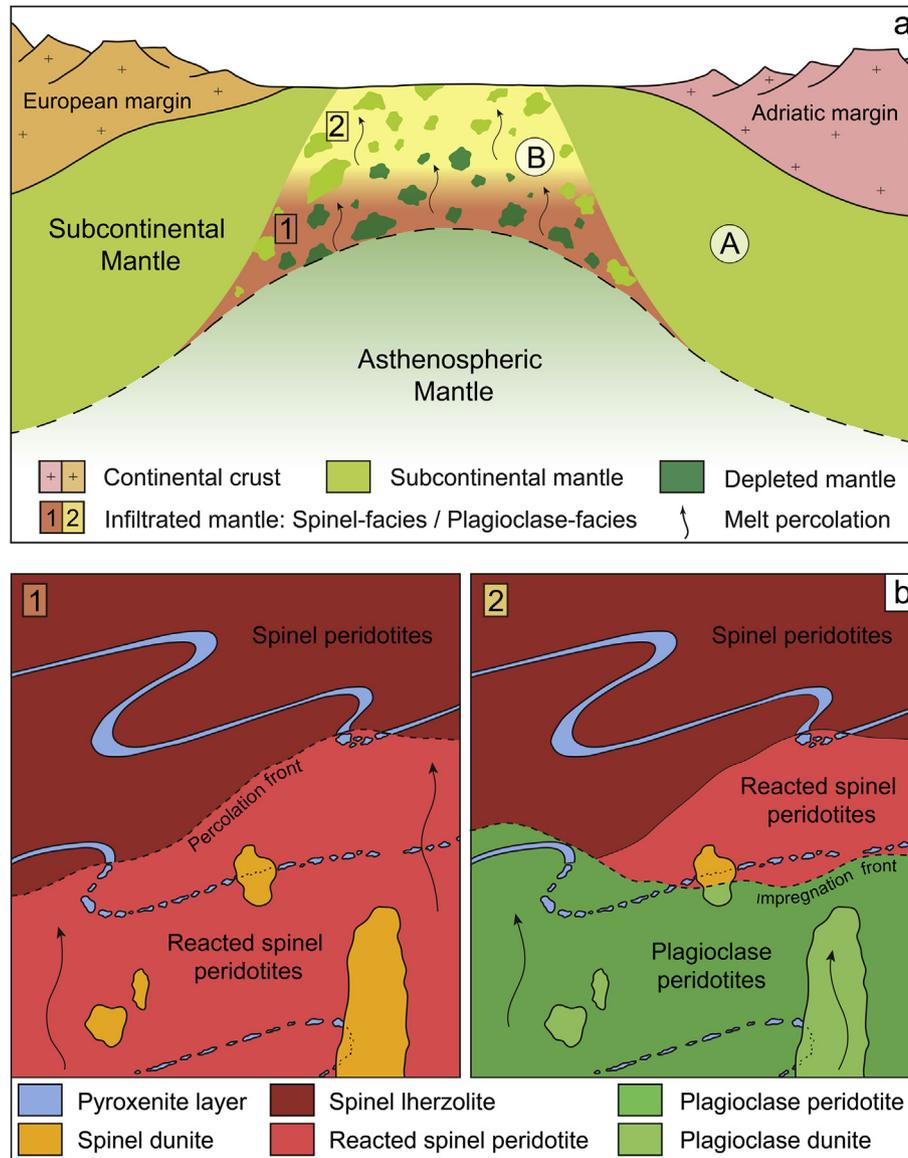


Figure 2. (a) Simplified schematic description of different mantle domains in the oceanic lithosphere of the Jurassic Piemont-Ligurian Basin (redrawn after Manatschal and Müntener, 2009). Mantle domains (A) correspond to old “inherited” subcontinental lithospheric mantle (primarily associated to continental crust) preserving diffuse occurrence of pyroxenite layers, and not affected by Jurassic melt infiltration. Mantle domains (B) correspond to more internal, “infiltrated” mantle affected by multiple melt-rock interaction stages during exhumation. Melt percolation and melt-rock reaction occurred at the expense of both “subcontinental mantle” (in light green) and “depleted mantle” (in dark green), this latter representing the residual mantle that produced the Jurassic crust (e.g. Mt. Maggiore - Corsica, Chenaillet; see text for more explanation). (b) Sketches [1] and [2] reported the most important field relations documenting melt-peridotite reaction stages at different depths (as indicated in the “infiltrated” mantle domain (B) of Fig. 2a), i.e. spinel-facies reactive porous flow [1] and plagioclase-facies melt impregnation [2].

separates) overall display a rather narrow Sr isotope variation, confined at depleted values (0.7017–0.7029), whereas they define a large Nd isotope range, especially the peridotites (Borghini et al., 2013). These latter range from very depleted ϵ_{Nd} values in the country peridotites, to much lower, “enriched” ϵ_{Nd} in the host and wall rocks peridotites, and such variation encompass the entire abyssal peridotite field (Borghini et al., 2013). The 160 Ma age represents the inferred timing of the emplacement at the ocean floor of the Ligurian ophiolitic mantle. Accordingly, Borghini et al. (2013) adopted such age to recalculate initial ϵ_{Nd} values, in order to compare the isotopic features of the Jurassic exhumed oceanic mantle of the Ligurian Tethys to those of modern oceanic peridotites.

Sm–Nd isotopic profiles through the peridotite-pyroxenite boundary also revealed systematic changes in the wall-rock and host peridotites. $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios in

clinopyroxene separates from the wall-rock and host peridotites are systematically shifted at lower values, relative to the country peridotites far (>2 m) from pyroxenite layers (Fig. 6b). Borghini et al. (2013) showed that such isotopic changes resulted from chemical interaction with LREE-enriched pyroxenite-derived melts percolating through the peridotites walls, combined to an age effect. Three investigated profiles indeed defined parallel $^{147}\text{Sm}/^{144}\text{Nd}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$ correlations yielding ages of 424–452 Ma, representing the age of pyroxenite emplacement. Such ages are much older than that the inferred Jurassic age of exposure at the seafloor of this mantle sector (160 Ma, Rampone and Hofmann, 2012).

Other few works on Alpine-Apenne mantle sequences documented pyroxenites originated by the interaction between peridotite and pyroxenite-derived melts (van Acken et al., 2010a; Montanini et al., 2012; Montanini and Tribuzio, 2015). A larger

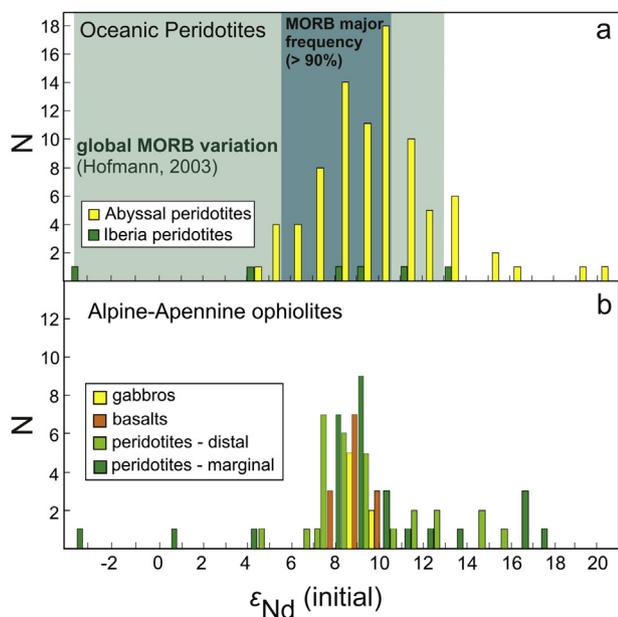


Figure 3. Initial ϵ_{Nd} histogram for: (a) abyssal peridotites (data from Snow et al., 1994; Kempton and Stephens, 1997; Salters and Dick, 2002; Cipriani et al., 2004; Warren et al., 2009) and Iberia Margin peridotites (computed at 120 Ma, data from Chazot et al., 2005). Also shown is the global MORB ϵ_{Nd} variation (Hofmann, 2003). (b) Alpine-Apennine ophiolites. Peridotite data are computed at 160 Ma (see Rampone et al., 2014 for more explanation) and distinguished in “marginal” (Platta, External Ligurides, Lanzo North, Lanzo South, Erro-Tobbio) and “distal” (Lanzo South, Internal Ligurides, Cecina, Mt. Maggiore) according to their inferred paleogeographic location in the Piemont-Ligurian ocean (see Fig. 1) (data from Bodinier et al., 1991; Rampone et al., 1995, 1996, 2005, 2009; Müntener et al., 2004; Tribuzio et al., 2004). Gabbroic and basaltic rocks from Borsi et al. (1996), Rampone et al. (1998, 2005, 2009), Schaltegger et al. (2002), Tribuzio et al. (2004).

number of field-controlled studies on orogenic ultramafic massifs have been dedicated to defining modal and chemical/isotopic modification of peridotite via pyroxenitic melt infiltration (e.g. Bodinier et al., 1990, 2004; Pearson et al., 1993; Rivalenti et al., 1995; Varfalvy et al., 1996; Zanetti et al., 1996; Mukasa and Shervais, 1999).

In summary, the above studies have shown that melt-rock reaction between peridotite and pyroxenite-derived melts can induce significant small-scale isotopic changes in the host mantle, which are even more extreme than the isotopic heterogeneity represented by the only pyroxenite component. This calls for the need of detailed field-base studies in spatially-controlled settings to unravel the size and distribution of upper mantle isotopic heterogeneity. Moreover, this motivates new experimental investigations focused on (i) petrologic processes (simple high-pressure crystallization versus melt-rock reaction) originating deep-seated mantle pyroxenites, and (ii) the role of such hybrid “pyroxenite-related” mantle sources in MORB formation (Lambart et al., 2013, 2016; Borghini et al., 2017, and quoted references).

4. The extension-related melt-rock reaction stages

Large, kilometre-scale sectors of A-A mantle peridotites experienced multi-stage melt infiltration during their extension-related lithospheric history ending with exposure at the Jurassic Ligurian Tethys ocean floor. Percolating melts were likely produced by the upwelling and melting of the underlying asthenospheric mantle, induced by passive lithosphere extension. In the following, we will provide an overview of the microstructural and chemical modifications that such melt infiltration caused on the extending

lithospheric mantle, focussing on two major events, i.e. the reactive porous flow percolation at spinel-facies and the melt impregnation at shallower plagioclase facies depths, and on three case studies, i.e. the Mt. Maggiore (Alpine Corsica), Erro-Tobbio (Ligurian Alps) and Lanzo (Western Alps) peridotite bodies. Large dunite bodies, crosscutting all previous spinel- and plagioclase-bearing peridotite structures have been described in all the peridotite massifs (e.g. Piccardo and Visers, 2007; Piccardo et al., 2007; Sanfilippo and Tribuzio, 2011; Sanfilippo et al., 2017). These dunites are mostly considered to represent late-stage focused melt flow channels generated by upwelling aggregated MORB melts (e.g. Sanfilippo et al., 2017). In this review, we will focus on the diffuse percolation stages occurred at spinel and plagioclase facies conditions.

4.1. Reactive porous flow at spinel facies

In the field, the clearest evidence of reactive melt percolation in spinel peridotites is the partial dissolution of pyroxenite layers, and replacement by olivine crystallization, as well as the formation of replacive harzburgites and dunites, i.e. olivine-enriched and pyroxene-depleted lithologies, at the expense of pristine lherzolites (Fig. 4a–c). Similar field relations have been extensively described in ophiolitic and orogenic peridotites worldwide and interpreted as the result of reactive melt percolation at spinel facies depths (e.g. Nicolas and Prinzhofer, 1982; Boudier and Nicolas, 1995; Kelemen et al., 1995; Godard et al., 2000; Soustelle et al., 2009; Hanghøj et al., 2010; Higgie and Tommasi, 2012; Abily and Ceuleneer, 2013; Dygert et al., 2016).

Consistently with the field evidence, the most salient microstructural feature in the reactive spinel peridotites and pyroxenites is the occurrence of olivine embayments in exolved mantle pyroxenes, indicating their partial dissolution and replacement by new olivine, and the crystallization of interstitial olivine between pyroxenes (ol_2 in Fig. 5b, c). Field and microstructural evidence thus point to a melt/rock interaction by reactive porous flow involving olivine crystallization and pyroxene consumption. Remarkably, very similar microstructures (interstitial olivine between pyroxenes) were documented in the Lena Trough pyroxenites (Arctic Ocean) (Laukert et al., 2014) but they were interpreted in the opposite way, i.e. as product of reactive crystallization driven by olivine dissolution and pyroxene precipitation. However, the authors highlighted that owing to the small sample size it was impossible to observe the contact relationships between pyroxenites and host peridotites, and this points to the importance of a proper understanding of microstructures, in possibly field-controlled settings, to unravel melt-peridotite reaction processes.

Reactive melt percolation also caused significant modal and chemical changes in spinel peridotites, as well as chemical contrasts between bulk and mineral compositions. In Fig. 7, we have reported the bulk-rock SiO_2 and FeO_{tot} vs. MgO abundances for the Erro-Tobbio, Mt. Maggiore and Lanzo spinel peridotites (Rampone et al., 2004, 2005; 2008; Piccardo et al., 2007), compared with the compositions of abyssal peridotites and various computed melting trends (Niu, 1997, 2004; Asimow, 1999). In the Lanzo massif, Piccardo et al. (2007) documented both granular reactive spinel peridotites, formed at the expenses of pristine foliated spinel peridotites, and late replacive spinel harzburgites and dunites, crosscutting plagioclase-bearing impregnated peridotites. In order to refer to a consistent set of data for all the peridotite massifs here considered, we will focus on the reactive spinel peridotites.

In all ultramafic massifs, spinel peridotites define large bulk-rock compositional variations marked by SiO_2 decrease at increasing MgO (Fig. 7a). In most samples, the decrease in SiO_2 content is coupled to an increase in FeO abundance (Fig. 7b). Similar chemical variations were documented in abyssal peridotites by Niu

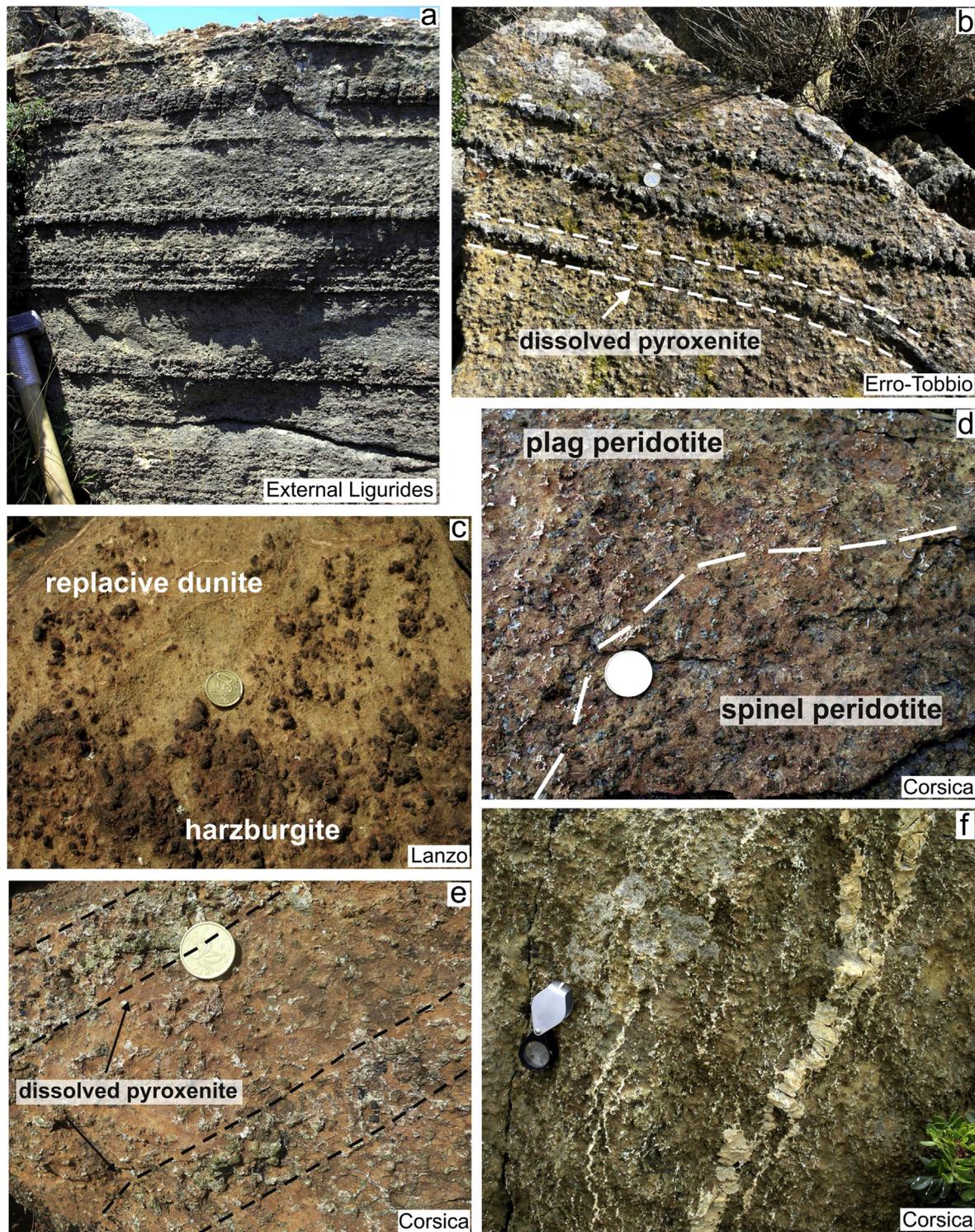


Figure 4. (a) Centimeter-thick pyroxenite layers embedded in the External Ligurides mantle peridotites (Northern Apennines). (b) Partially dissolved pyroxenite layers (substituted by olivine) in reactive spinel peridotites (Erro-Tobbio, Ligurian Alps). (c) Replacive dunite (including pyroxene relics) grading to harzburgite (Lanzo, Western Alps). (d) Spinel peridotite grading to impregnated plagioclase-bearing peridotite (Mt. Maggiore, Alpine Corsica). (e) Two parallel layers of partially dissolved spinel pyroxenites (substituted by olivine) embedded in spinel peridotites. Both peridotite and associate pyroxenites display subsequent plagioclase enrichment related to melt impregnation (see text for more explanation). (f) Plagioclase-rich iso-oriented veinlets in impregnated peridotite.

et al. (1997), who also showed their inconsistency with simple partial melting trends (see Fig. 7), especially for peridotite samples with high MgO contents (>43 wt.%). SiO₂ decrease and FeO enrichment in reconstructed abyssal peridotites bulk compositions were thus inferred to result from melt migration events, following

partial melting and incorporation in the Thermal Boundary Layer, which caused either olivine addition (Niu et al., 1997) or pyroxene dissolution/olivine dissolution reactions (Asimow, 1999).

In the Erro-Tobbio reactive spinel peridotites, Rampone et al. (2004) showed that constituent minerals have rather uniform

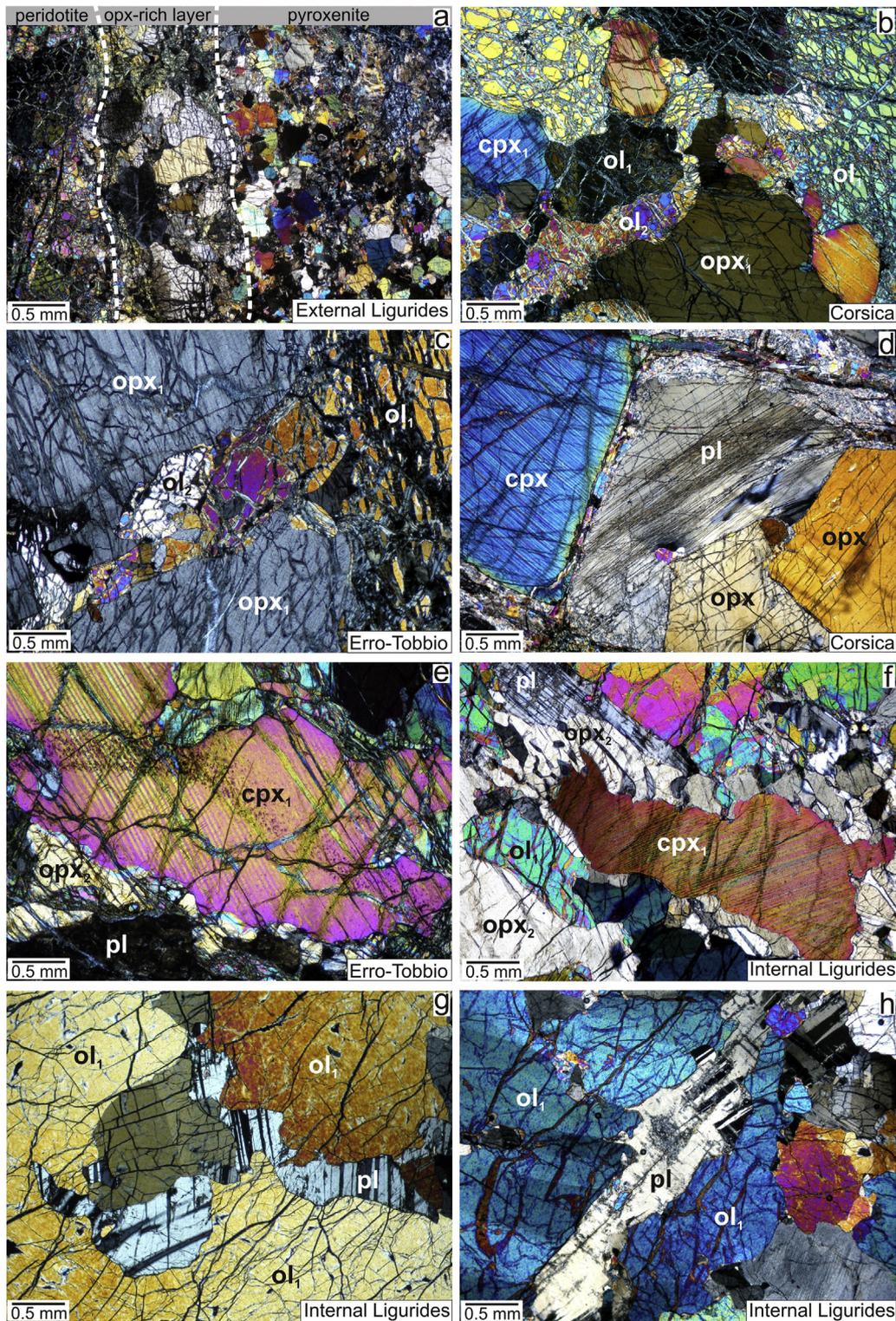


Figure 5. Main microstructural features testifying melt-rock reaction in the Alpine-Apennine peridotites. (a) Orthopyroxene-rich layer (contoured by white dotted lines) developed at the contact between peridotite (on the left) and pyroxenite (on the right) (External Liguride, Northern Apennines). (b) Orthopyroxene, clinopyroxene and kinked olivine porphyroclasts (opx_1 , cpx_1 , ol_1) showing embayments and partial dissolution by new interstitial olivine (ol_2) (Mt. Maggiore spinel peridotites, Alpine Corsica). (c) Orthopyroxene porphyroclasts (opx_1) partially dissolved and substituted by new interstitial olivine (ol_2) (Erro-Tobbio spinel peridotites, Ligurian Alps). (d) Idiomorphic orthopyroxene and clinopyroxene and interstitial plagioclase in gabbronitic veinlets associated to plagioclase-rich impregnated peridotites (Mt. Maggiore peridotite, Alpine Corsica). (e) Orthopyroxene (opx_2) and plagioclase (pl) altered rim corrodng exolved spinel-facies clinopyroxene porphyroclast (cpx_1) (Erro-Tobbio plagioclase peridotite, Ligurian Alps). (f) Orthopyroxene (opx_2) and plagioclase (pl) intergrowth partially substituting spinel-facies exolved clinopyroxene porphyroclast (cpx_1). The new orthopyroxene (opx_2) also forms a poikilitic grain (on the left) corrodng kinked olivine (ol_1) (Internal Liguride impregnated plagioclase peridotites, Northern Apennines). (g) Interstitial plagioclase (pl) crystallized between large olivine grains (ol_1) (Internal Liguride impregnated plagioclase peridotites, Northern Apennines). (h) Plagioclase veinlet (pl) crosscutting a large kinked olivine grain (ol_1) (Internal Liguride impregnated plagioclase peridotites, Northern Apennines).

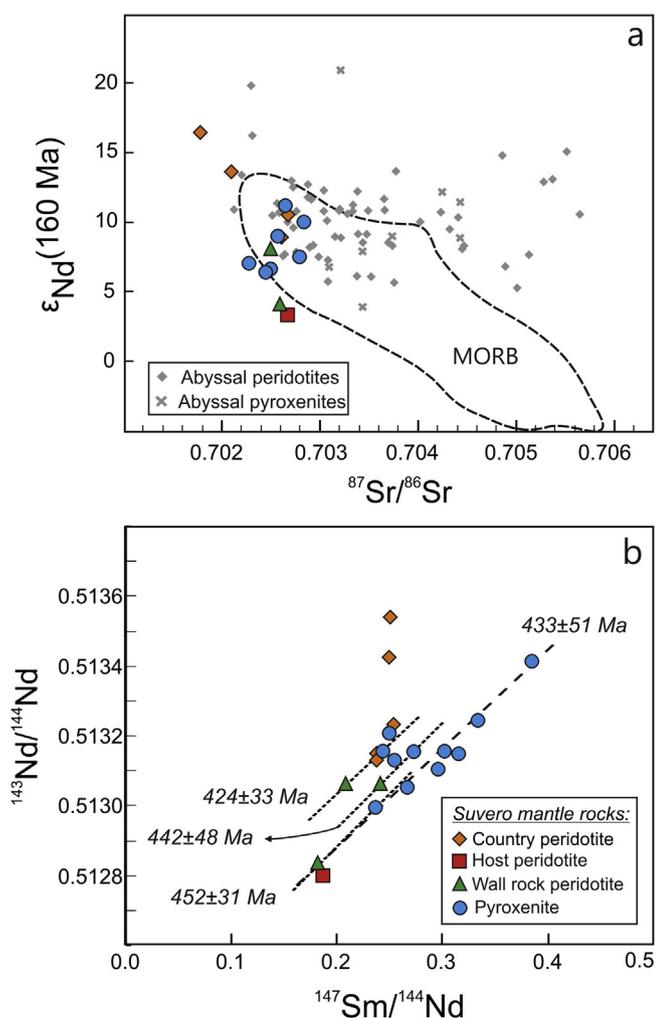


Figure 6. (a) Present-day $^{87}\text{Sr}/^{86}\text{Sr}$ vs. initial ϵ_{Nd} value (computed at 160 Ma, i.e. the inferred age of oceanic emplacement of this mantle sector) in clinopyroxenes of External Liguride (Suvero) pyroxenites and peridotites (data from Borghini et al., 2013). Gray symbols are present-day ϵ_{Nd} values of abyssal peridotites and pyroxenites (Snow et al., 1994; Kempton and Stephens, 1997; Salters and Dick, 2002; Cipriani et al., 2004, 2011; Warren et al., 2009). The mid-oceanic-ridge basalt (MORB) field (from data set downloaded in May 2013 from www.petdb.org) is shown for comparison. (b) Present-day $^{143}\text{Nd}/^{144}\text{Nd}$ vs. $^{147}\text{Sm}/^{144}\text{Nd}$ in clinopyroxenes of Suvero pyroxenites and peridotites (data from Borghini et al., 2013). Dotted lines refer to isochrones obtained for three pyroxenite – wall-rock peridotite profiles. Dashed line is the errorchron (433 ± 51 Ma) based on most pyroxenites and wall-rock and/or host peridotites, with an initial ϵ_{Nd} (433 Ma) = 4.3 ± 1.8 .

compositions (e.g. similar LREE fractionation in clinopyroxene), in spite of the observed whole-rock variations, thus pointing to a decoupling between bulk-rock and mineral chemistry. Similar contrasts, i.e. rather homogeneous mineral chemistry coupled to heterogeneous major and trace element bulk rock abundances, were documented in the Mt. Maggiore spinel peridotites (Rampone et al., 2008). In the Lanzo reactive peridotites, Piccardo et al. (2007) described considerable intra-sample variations in REE clinopyroxene compositions, most of them representing “transient geochemical gradients” acquired during reaction between a harzburgitic mantle and percolating melts with variable compositions. In addition, they also described a decoupling between the compositions of bulk peridotites and their constituent minerals, again inconsistent with a simple residual origin.

In the Erro-Tobbio, Corsica and Lanzo spinel peridotites, the observed bulk-rock chemical variations are coupled to systematic

modal changes, namely decrease in clinopyroxene and orthopyroxene, and increase in olivine, at increasing bulk MgO. Again, such modal variations can be only in part explained by partial melting. This is shown in Fig. 8, which report the modal olivine contents versus bulk Mg# [$= \text{Mg}/(\text{Mg} + \text{Fe}^{\text{I}})$] of peridotites, together with computed trends for partial melting, reactive porous flow and refertilization reactions, from Bodinier and Godard (2003) (see figure captions for more details on adopted parameters). Bedini et al. (2003) and Bodinier and Godard (2003) showed that the bulk-rock Mg# versus modal olivine variation can be significantly controlled by melt-rock reactions. Partial melting will generally produce a positive (modal olivine – bulk Mg#) correlation. On the other hand, reactive porous flow, involving olivine crystallization and pyroxene dissolution reactions, will cause significant increase in modal olivine combined to variable bulk Mg#, depending on the Mg-value of the percolating melts. Refertilization reactions, involving pyroxene crystallization, will produce modal olivine decrease, again coupled to variable bulk Mg#.

Fig. 8 clearly shows that most Alpine and Corsica spinel peridotites define an overall trend marked by significant increase in modal olivine (up to 90 vol.%), coupled to rather constant bulk Mg# (in the range 90–91 mol%), consistent with reactive porous flow trends. Some Lanzo peridotite samples deviate from this correlation, showing high modal olivine combined to an increase in bulk Mg#, still consistent with reactive percolation of melts with higher Mg# (77 mol%). Therefore, spinel peridotite bulk compositions do not reflect simple melting features, rather they are ruled by modal variations induced by the reactive melt percolation. The most “reacted” spinel peridotites are those with higher FeO and lower SiO_2 contents, coupled to higher olivine modal amounts. Remarkably, such peridotites also show the clearest evidence of melt/mineral reaction textures.

The above inference is corroborated by the comparison with experimental results on peridotite partial melting and basalt-peridotite interaction (e.g. Lambart et al., 2009; Van den Bleeken et al., 2010, 2011; Tursack and Liang, 2012) (Figs. 7 and 8). Lambart et al. (2009) studied the chemical consequences of reactive melt percolation on mantle lherzolite, over the pressure range of 1.25–0.75 GPa. In Fig. 7, it is evident that experimentally-derived peridotite compositions resulting from melt-rock interaction display similar FeO enrichment and SiO_2 depletion, as documented in the Erro-Tobbio, Mt. Maggiore and Lanzo peridotites. Moreover, reacted spinel peridotites exhibit almost constant bulk Mg# (around 90–90.5 mol%) at increasing modal olivine (up to 95 vol.%). Again, this is consistent with the chemical trends described above for the Alpine and Corsica peridotites, and with the results of theoretical studies of Mg-Fe partitioning during mantle melting and melt/rock interaction (Bedini et al., 2003), showing that the bulk-rock Mg# versus modal olivine relationship in residual mantle peridotites may be largely controlled by melt-rock reactions (see computed trends reported in Fig. 8, from Bodinier and Godard, 2003).

In summary, combined field, textural and chemical evidence indicates that large (km-scale) mantle sectors in the Alpine-Apennine realm were affected by reactive porous flow. The spinel-facies melt migration was an open system melt-rock interaction that caused bulk-rock depletion, transforming pristine spinel lherzolites in reactive olivine-rich harzburgites and dunites. The reactive nature of the percolating melts was related to the expansion of the olivine phase volume at low-pressure, causing progressive oversaturation in olivine and undersaturation in pyroxenes of an uprising basaltic melt (e.g. Kelemen, 1990; Kelemen et al., 1995a,b, 1997, 2000; Niu et al., 1997). Such process explains the observed decoupling between rather homogeneous mineral compositions (buffered by the migrating melts), and heterogeneous

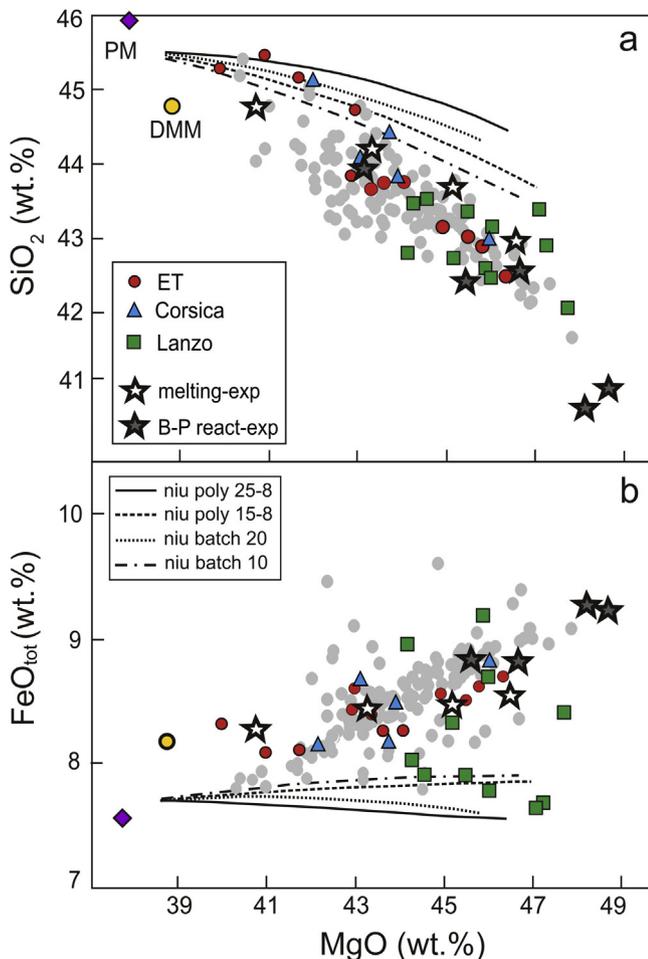


Figure 7. Whole-rock abundances of MgO vs. SiO₂ and FeO_{tot} (data on anhydrous basis in wt.%) in Erro-Tobbio (ET), Mt. Maggiore (Corsica) and Lanzo spinel peridotites (data from Rampone et al., 2004, 2005, 2008; Piccardo et al., 2007). Primordial mantle (PM) and depleted MORB mantle (DMM) estimates from Hofmann (1988) and Workman and Hart (2005), respectively. Also reported are: (1) estimated compositions (light gray dots) of abyssal peridotites from Niu et al. (1997) and Baker and Beckett (1999), (2) fractional and batch melting trends from Niu et al. (1997), (3) peridotite compositions resulting from partial melting (white stars) and melt-peridotite reaction (dark gray stars) experiments in the pressure range of 1.25–0.75 GPa (data from Lambart et al., 2009).

bulk-rock chemistry (resulting from modal variations caused by dissolution and precipitation reactions).

4.2. Melt impregnation at plagioclase facies

At shallower mantle depths, large, km-scale, volumes of variably reacted spinel peridotites were affected by melt impregnation, which originated plagioclase-rich peridotites. This is a ubiquitous process in modern oceanic mantle and it is mostly documented in peridotites from ocean-continent transition settings and slow-to ultraslow-spreading ridges (e.g. Seyler and Bonatti, 1997; Tartarotti et al., 2002; Chazot et al., 2005; Dick et al., 2010; Laukert et al., 2014; Martin et al., 2014; Harigane et al., 2016; Paquet et al., 2016), and is considered to play a key role in the refertilization and softening of the shallow extending mantle (e.g. Ranalli et al., 2007; Kaczmarek and Müntener, 2008).

In the Alpine-Apennine peridotite massifs (e.g. Erro-Tobbio, Mt. Maggiore, Lanzo South, Platta), the spinel peridotites grade to plagioclase-bearing peridotites, which show clear impregnation

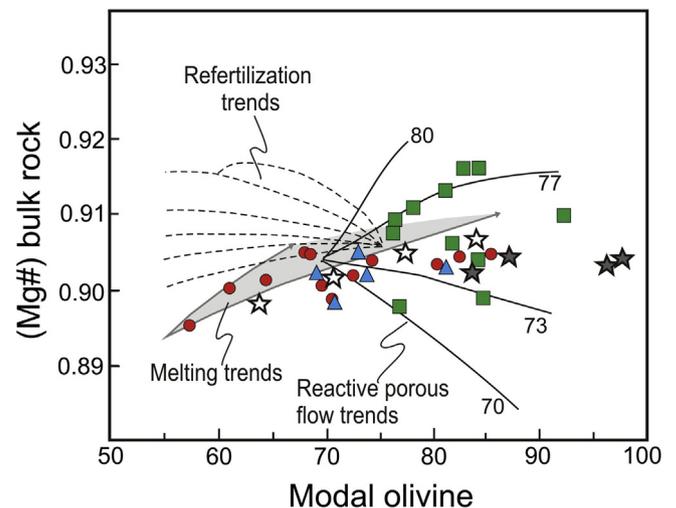


Figure 8. Modal olivine versus Mg# [= Mg/(Mg + Fe) cationic ratio] in bulk rocks, Erro-Tobbio, Mt. Maggiore (Corsica) and Lanzo spinel peridotites (data from Rampone et al., 2004, 2005, 2008; Piccardo et al., 2007). Symbols as in Fig. 7. The grey shaded field (“melting trends”) refers to simple partial melting trends, assuming different melting reactions in the spinel-facies stability field (from Bodinier and Godard, 2003). “Reactive porous flow trends” (thick lines) are computed assuming a reactive porous flow process (involving olivine crystallization and pyroxene dissolution and variable infiltrating melt compositions, Mg# = 70–80), whereas computed “refertilization trends” (dashed lines) involve pyroxene-forming reactions (all trends are from Bodinier and Godard (2003), see this reference for details on the model parameters). Also shown are peridotite compositions resulting from partial melting (white stars) and melt-peridotite reaction (dark gray stars) experiments in the pressure range of 1.25–0.75 GPa (data from Lambart et al., 2009) (same data as in Fig. 7).

textures, i.e. diffuse and heterogeneous plagioclase enrichment (Fig. 4d, e), plagioclase-rich gabbroic and gabbronoritic veinlets with irregular contact against the host peridotites, indicating local coalescence of impregnating melts (Fig. 4f). Remarkably, plagioclase enrichment also occurs at the expense of spinel peridotites showing clear evidence of the previous reactive percolation stage (e.g. spinel peridotites embedding partially dissolved pyroxenites, see Fig. 4e), thus indicating the temporal evolution and overprinting of melt-rock interaction stages during oceanic exhumation of these mantle sectors.

Melt impregnation in the peridotites is testified by the ubiquitous development of peculiar microstructures (Rampone et al., 1997, 2008; Rampone and Borghini, 2008; Piccardo et al., 2007): (i) partial dissolution and replacement of deformed mantle clinopyroxene by plagioclase and orthopyroxene intergrowths (Fig. 5e, f), (ii) large poikilitic orthopyroxene grains replacing deformed mantle olivines, (iii) plagioclase crystallizing as anhedral interstitial crystals between olivine grains (Fig. 5g), or crosscutting large olivines (Fig. 5h). In the gabbronoritic veinlets, ortho- and clinopyroxene occurs as idiomorphic to subidiomorphic crystals, whereas plagioclase is interstitial (Fig. 5d). Similar textures, specifically the occurrence of interstitial plagioclase lenses, orthopyroxene + plagioclase aggregates substituting mantle clinopyroxene, and rims of secondary orthopyroxene between olivine and plagioclase, have been documented in abyssal plagioclase peridotites (Romanche, Mid Atlantic Ridge, Tartarotti et al., 2002; Southwest Indian Ridge, Paquet et al., 2016) and pyroxenites (Lena Trough, Arctic Ridge, Laukert et al., 2014).

The crystallization of plagioclase (\pm pyroxenes) in spinel peridotites caused a re-enrichment in fusible components, marked by an increase in Al₂O₃ and CaO contents. This process of refertilization is evident in the MgO vs. Al₂O₃/CaO diagram of Fig. 9, which reports the bulk-rock compositions of spinel and plagioclase-rich peridotites from Erro-Tobbio, Corsica, Lanzo and Platta (see figure caption for references). Relative to the spinel-facies protoliths, the

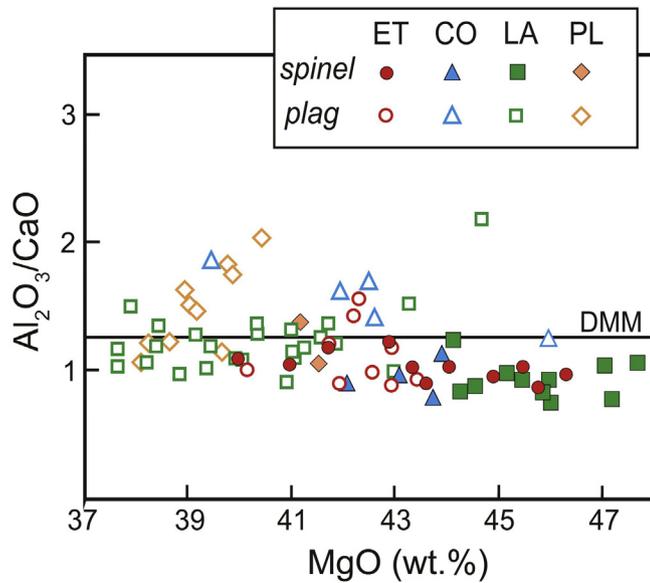


Figure 9. Bulk rock abundances of MgO vs. $\text{Al}_2\text{O}_3/\text{CaO}$ (data on anhydrous basis in wt.%), in the Erro-Tobbio (ET), Mt. Maggiore (CO), Lanzo (LA) and Platta (PL) spinel peridotites (solid symbols) and plagioclase peridotites (open symbols) (data from Rampone et al. (2004, 2005, 2008), Piccardo et al. (2007), Kaczmarek and Müntener (2010), Müntener et al. (2010); Depleted MORB mantle (DMM) estimate from Workman and Hart (2005), respectively.

plagioclase peridotites are systematically shifted at lower MgO and higher $\text{Al}_2\text{O}_3/\text{CaO}$ ratios, exceeding the $\text{Al}_2\text{O}_3/\text{CaO}$ value of the depleted mantle (DM). The role of such refertilization and melt focusing in the deformation and weakening of the extending lithosphere has been shown in a detailed study of a high-temperature mylonitic shear zone in the Lanzo plagioclase-rich peridotites (Kaczmarek and Müntener, 2008, 2010). In this work, the authors performed bulk compositional profiles from porphyroclastic to mylonitic peridotites and documented progressive chemical homogenization (in terms of Al and Ca contents) in the mylonites, indicative of melt accumulation in the shear zone. They thus claimed that melt migration and high- T deformation were juxtaposed in time and space, and that deforming peridotites may act as important areas of melt focusing in the upper mantle. This inference was further corroborated in a detailed microstructural study by Higgie and Tommasi (2014), who showed that plagioclase-rich layers in the impregnated peridotites resulted from synkinematic reactive melt percolation during which the melt distribution was mainly controlled by the deformation.

The plagioclase-bearing melt/rock interaction stage also caused significant chemical changes in mantle minerals, mostly marked by (i) higher Cr-number and TiO_2 abundances in spinel, (ii) Al decrease coupled to REE, Ti, Zr, Y increase in clino- and ortho-pyroxenes (Rampone et al., 1997, 2008; Piccardo et al., 2007; Kaczmarek and Müntener, 2008; Rampone and Borghini, 2008; Müntener et al., 2010; Sanfilippo and Tribuzio, 2011). Consistent compositional variations, at least for major elements, have been documented in melt impregnated abyssal plagioclase peridotites (e.g. Hellebrand et al., 2002; Tartarotti et al., 2002; Dick et al., 2010). In Fig. 10, we have reported the REE composition of reacted clinopyroxenes in plagioclase peridotites (i.e. the clinopyroxene relics, partly substituted by plagioclase \pm orthopyroxene intergrowths, see Fig. 5e, f), compared with the REE compositions of clinopyroxenes in the spinel peridotites, free of plagioclase, in the Erro-Tobbio, Corsica, and Lanzo massifs (see figure caption for references). In spite of an overall increase of the REE abundances, coupled to development of negative Eu_N anomalies, reacted clinopyroxene in

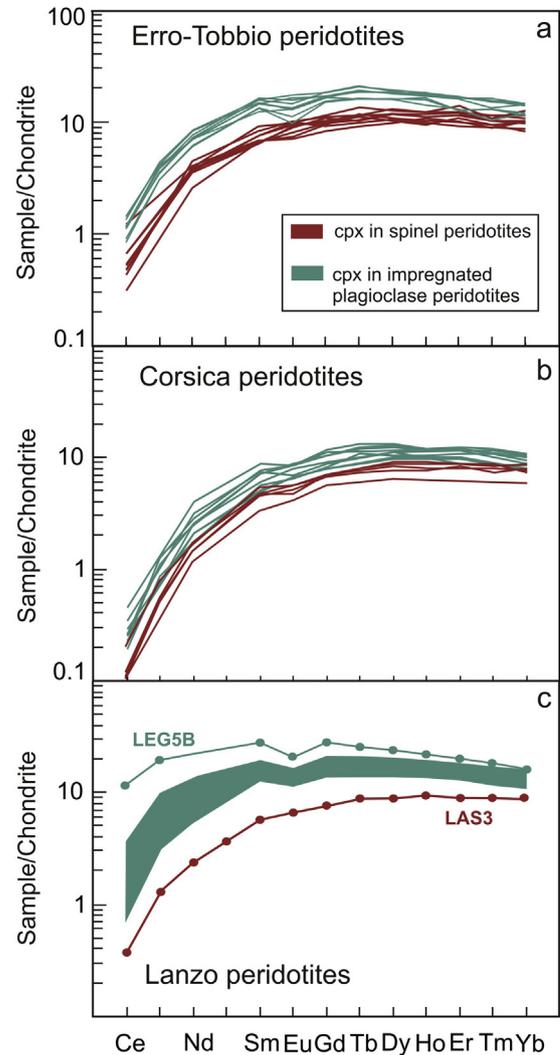


Figure 10. Chondrite-normalized REE abundances (normalized to Chondrite C1 after Anders and Ebihara, 1982) of clinopyroxenes in spinel peridotites (red patterns) and impregnated plagioclase peridotites (green patterns and field) from (a) Erro-Tobbio, (b) Mt. Maggiore, Corsica, (c) Lanzo (data from Rampone et al., 2004, 2005, 2008; Borghini et al., 2007; Piccardo et al., 2007).

Erro-Tobbio and Corsica plagioclase peridotites preserve strong LREE depletion (Fig. 10a, b). In the Lanzo plagioclase peridotites, REE spectra in clinopyroxenes are more heterogeneous, the significant REE enrichment being associated, in a few samples, to a decrease of the LREE depletion (Fig. 10c).

Consistent with clinopyroxenes, plagioclase in the Corsica peridotites also shows REE depleted compositions, significantly lower than computed REE compositions of plagioclase in equilibrium with variably depleted (D- and N-) MORBs (Hofmann, 1988; Jenner and O'Neil, 2012) (Fig. 11a). Plagioclase also exhibits very high anorthite contents ($\text{An} = 87\text{--}94$ mol%; data from Rampone et al., 1995, 2008), similar to what documented in various suites of plagioclase-bearing abyssal peridotites (e.g. Tartarotti et al., 2002; Dick et al., 2010; Warren and Shimizu, 2010; Paquet et al., 2016). In the Southern Lanzo impregnated peridotites, plagioclase displays larger REE variability, similar to what described above for clinopyroxenes, indicating plagioclase-clinopyroxene equilibration (Fig. 11a). In spite of such larger heterogeneity, Lanzo plagioclases still exhibit more fractionated (i.e. LREE depleted) patterns relative to plagioclase compositions in equilibrium with MORBs (data from Jenner and O'Neil, 2012; see figure caption for more details).

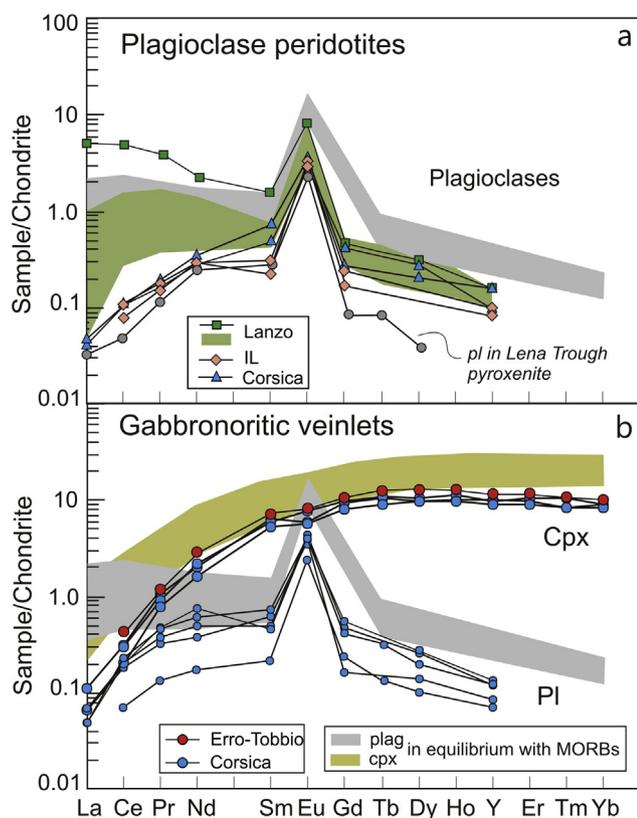


Figure 11. (a) Chondrite-normalized REE abundances of plagioclases in impregnated plagioclase peridotites from Mt. Maggiore (Corsica), Lanzo and Internal Ligurides (IL) (data from Piccardo et al., 2007; Rampone et al., 1997, 2008; Piccardo and Guarnieri, 2011). Also shown is the composition of plagioclase in Lena Trough pyroxenite (sample 256-6; from Laukert et al., 2014). The gray field refers to computed compositions of plagioclase in equilibrium with variably depleted D- to N-MORBs (data from Hofmann, 1988; Jenner and O'Neill, 2012). (b) Chondrite-normalized REE abundances of clinopyroxenes and plagioclases in the Erro-Tobbio and Mt. Maggiore gabbro-noritic veinlets (data from Piccardo et al., 2004; Rampone et al., 2008; Piccardo and Guarnieri, 2011). The gray and mustard-colored field refer to computed compositions of plagioclase and clinopyroxenes in equilibrium with variably depleted D- to N-MORBs (data from Hofmann, 1988; Jenner and O'Neill, 2012). Normalization factors as in Fig. 10.

Exception is shown by one single sample (LEG5B), showing high LREE concentrations in both plagioclase and clinopyroxene (see Figs. 10c and 11a). According to the LREE signature, Lanzo plagioclases also exhibit more heterogeneous anorthite values ($An = 68.5\text{--}88.8\text{ mol}\%$), with the lowest An content found in plagioclase from LEG5B peridotite (Piccardo et al., 2007).

As mentioned above, small (cm-size) gabbroic and gabbro-noritic veinlets are often associated to plagioclase-rich peridotites (Piccardo et al., 2004; Rampone et al., 2008; Piccardo and Guarnieri, 2011). Field evidence clearly indicates that these veinlets crystallized from the same melts impregnating the host peridotites (Fig. 4f). Microstructural observations point that ortho- and clinopyroxenes (subidiomorphic) preceded plagioclase (interstitial) in the crystallization sequence (Fig. 5d). In Fig. 11b, we have reported the REE compositions of clinopyroxene and plagioclase in gabbro-noritic veinlets from Erro-Tobbio and Corsica. As described for peridotites, minerals in the plagioclase-rich veins have LREE-depleted geochemical signature, more depleted than plagioclase and clinopyroxene in equilibrium with variably depleted MORBs. Plagioclase is also very anorthite-rich ($An = 84\text{--}91\text{ mol}\%$; data from Rampone et al., 2008; Piccardo and Guarnieri, 2011). In modern oceanic settings, similar highly anorthitic plagioclase was documented in some primitive oceanic gabbro-norites (Elthon et al., 1992; Ross and Elthon, 1993; Nonnotte et al., 2005).

In summary, textural and chemical features in the Alpine-Apennine plagioclase peridotites indicate that this melt-rock interaction stage was related to cooling and crystallization of fractionating melts, differently from the open-system reactive porous flow process that modified the spinel peridotites. The crystallization of plagioclase (together with pyroxenes \pm olivine) indicates that melt impregnation occurred when the spinel peridotites reached shallower and cooler lithospheric levels, where melt-rock reaction was dominated by closed-system crystallization.

5. Origin of impregnating melts and analogy with abyssal peridotites at slow-spreading environments

Different hypotheses have been inferred to explain the origin of the observed trace element enrichment in minerals of the Alpine-Apennine impregnated plagioclase peridotites. Some authors (Rampone et al., 1997, 2008; Piccardo et al., 2004; Rampone and Borghini, 2008) emphasized the role of closed-system trapped melt crystallization (to explain within-mineral chemical zoning), whereas Piccardo et al. (2007) in the Lanzo South peridotites invoked the role of increased $K_{d}^{solid/liquid}$, consistent with the silica-rich composition of impregnating melts. In the Platta (Central Alps) plagioclase peridotites, Müntener et al. (2010) concluded that the trace element signature of clinopyroxenes are better reproduced by assuming variable amounts (5%–12%) of fractional melts crystallizing within previously depleted peridotite, followed by equilibrium trace element redistribution.

In spite of different processes invoked to explain the within-sample and/or within-mineral chemical variations observed in plagioclase peridotites, many studies outlined that the impregnating melts in many Alpine-Apennine peridotites (Corsica, Erro-Tobbio, Internal Liguride, Lanzo South) had a peculiar chemical signature, characterized by orthopyroxene saturation and trace element depletion, different from the composition of MORB-type melts, and more closely resembling unaggregated depleted melt fractions (Rampone et al., 1997, 2008; Piccardo et al., 2004, 2007; Rampone and Borghini, 2008; Sanfilippo and Tribuzio, 2011). In these studies, the depleted signature was considered to reflect either an origin as last depleted melt increments produced by underlying ascending and melting mantle, or extensive interaction with percolated depleted peridotite during ascent. This latter process (reactive percolation ruled by olivine crystallization and pyroxenes dissolution) was also considered responsible of chemical modification of impregnating melts towards Si-rich orthopyroxene-saturated compositions. Similar SiO_2 -rich and LREE-depleted chemical fingerprints of impregnating melts were documented in plagioclase-rich peridotites of the Othris Massif (Greece) by Barth et al. (2003) and Dijkstra et al. (2003), who inferred an origin by shallow (uppermost spinel lherzolite field) melting of an already depleted mantle source.

Although impregnated plagioclase peridotites are widely documented in modern passive margins and slow-to-ultraslow-spreading environments, few studies combining microstructural observations and a detailed major and trace element chemistry of minerals (particularly, plagioclase) are available. This is due to the frequent diffuse alteration of oceanic peridotites, which normally results in a very rare preservation of fresh plagioclase crystals in these rocks (e.g. Tartarotti et al., 2002; Dick et al., 2010; Laukert et al., 2014; Paquet et al., 2016). Based on the evidence that pyroxenes in plagioclase-bearing abyssal peridotites frequently show Ti, Na, and Fe enrichment, Dick et al. (2010) inferred an origin by migration of partially to fully aggregated MORB-like melts through the shallow mantle. Similarly, Paquet et al. (2016) proposed melt-rock interaction and impregnation by aggregated melts in the Southwest Indian Ridge plagioclase peridotites. A few studies, however, have documented a

more refractory and orthopyroxene-saturated chemical signature of melts migrating at mid-ocean ridge settings, either impregnating abyssal peridotites and pyroxenites (e.g. [Laukert et al., 2014](#)), or forming gabbronorites (e.g. [Nonnotte et al., 2005](#)).

In the Lena Trough (Arctic Ocean) pyroxenites, [Laukert et al. \(2014\)](#) documented a second-stage melt-rock interaction, occurring at shallower depth (relative to the spinel-facies reactive crystallization described in the previous chapter), evidenced by crystallization of plagioclase + orthopyroxene ($\pm\text{cpx}_2$) at the expense of primary clinopyroxene (cpx_1). Plagioclase in these pyroxenites is very Anorthitic (An_{90}) and display LREE-depleted composition (see [Fig. 11b](#)). These features were interpreted to reflect impregnation of refractory melts modified towards orthopyroxene saturation by significant amount of melt-rock reaction and pyroxene dissolution. On the other hand, [Nonnotte et al. \(2005\)](#) inferred that the parental melts of primitive, depleted orthopyroxene-rich gabbronorites from DSDP Site 334 (Mid Atlantic Ridge) originated by re-melting of shallow residual mantle, caused by interaction with hydrothermal fluids. The hydrous chemical signature of parental melts would account for the early appearance of orthopyroxene in the crystallization sequence and

the high An contents (An_{87-89}) of plagioclase. In Site 334 cumulates, an origin by seawater-contaminated melts was mainly inferred by the occurrence of highly radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7034–0.7067) in depleted gabbronorites ([Nonnotte et al., 2005](#)).

Insights on the origin of primitive, SiO_2 -rich, orthopyroxene-saturated melts have resulted from recent experimental studies on melt impregnation and the origin of plagioclase peridotites by melt-rock reaction. [Saper and Liang \(2014\)](#) performed dissolution-crystallization step-cooling experiments by reacting a primitive mid-ocean ridge basalt with a melt impregnated lherzolite at 1300–1050 °C and 0.7–1 GPa, and produced hybrid lithologies (i.e. products of melt-rock reaction processes) including gabbro, plagioclase-bearing wehrlite and plagioclase-bearing peridotite. In the plagioclase peridotite, they observed the growth of large poikilitic orthopyroxene grains, with inclusions of olivine and clinopyroxene. The authors ascribed this specific textural feature to relatively high melt-rock ratios and/or fast cooling rates used in the experiments, compared to natural settings. However, we have shown above that very similar microstructures are indeed observed in many ophiolitic and oceanic impregnated plagioclase peridotites, thus linking this feature to the chemical evolution of percolating

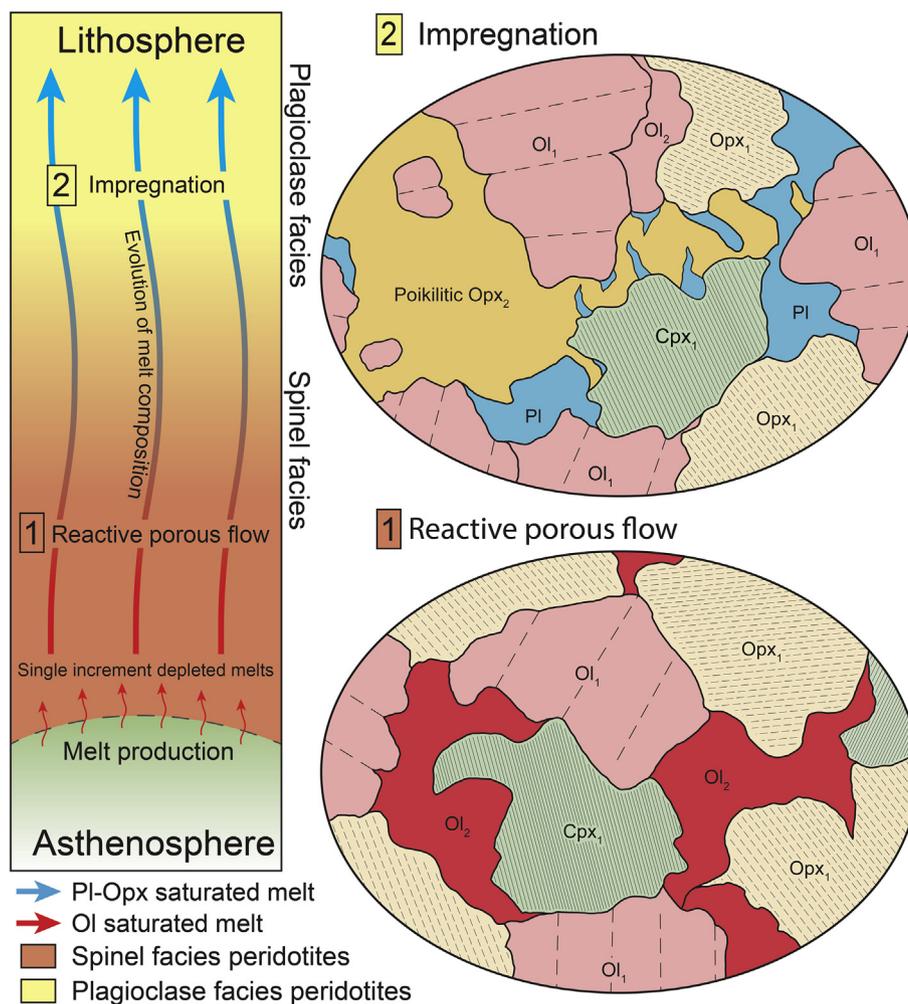


Figure 12. Progressive evolution of the microstructures in mantle peridotites during their extension-related upwelling and associated melt-rock interaction history from spinel-facies to shallower plagioclase facies depths. Left: the composition of the percolating melt is progressively modified from olivine-saturated to orthopyroxene- (and plagioclase-) saturated, by the reactive porous flow occurring at spinel facies in a mantle column. [1] Representative microstructures characterizing the spinel-facies reactive porous flow, with corrosion of exsolved mantle clinopyroxene1 (Cpx_1) and orthopyroxene1 (Opx_1), and crystallization of interstitial olivine2 (Ol_2); [2] representative microstructures characterizing the plagioclase-facies melt impregnation, with corrosion of pre-existing olivine1–2 (Ol_{1-2}), exsolved clinopyroxene1 (Cpx_1) and orthopyroxene1 (Opx_1), and crystallization of interstitial to poikilitic orthopyroxene and plagioclase intergrowths. It is noteworthy that in places the microstructures indicative of the reactive porous flow occurring at spinel facies (olivine2 (Ol_2) corroding mantle clinopyroxene and orthopyroxene) are still observed in the impregnated plagioclase peridotite.

melts towards Si-rich compositions, during reactive dissolution and crystallization. In this respect, significant inputs have come from the experimental work by Van den Bleeken et al. (2011) who studied the reactive migration of tholeiitic melts in the upper mantle by infiltration reaction experiments at 1170–1290 °C and 0.65–0.8 GPa. At the lowest temperatures investigated, the authors documented SiO₂-enriched, Ca-depleted melts produced by reactive percolation and pyroxene dissolution, and inferred that such modified melts, upon progressive cooling, would dissolve clinopyroxene (due to CaO-undersaturation) and crystallize orthopyroxene + plagioclase, thus explaining the microstructural features described above and frequently observed in ophiolitic and oceanic impregnated plagioclase peridotites.

In summary, different hypotheses are presently available about the origin of impregnating melts in many ophiolitic and abyssal peridotites, especially concerning two major aspects: (i) the depleted signature, either acquired by extensive reaction with depleted peridotite, or inherited by their origin as non-aggregated depleted melt fractions, and (ii) the primitive Si-rich composition, again either acquired by reactive porous-flow migration, or reflecting a primary chemical feature (e.g. melting of hydrous depleted peridotites).

In a recent combined EBSD (Electron Backscatter Diffraction)-geochemical study on the Mt. Maggiore peridotites, aimed at defining the origin of hybrid troctolites from mantle peridotites by melt-rock interaction, Basch et al. (2018) performed plate model numerical simulations (Vernières et al., 1997) of the spinel- and plagioclase-facies reactive percolation stages, using variably depleted melts. They showed that an aggregated MORB composition cannot explain the strong LREE-depletion found in minerals of plagioclase peridotite and troctolite, thus corroborating the inference (Rampone et al., 2008) that the percolating melts had a primary LREE-depleted composition, and acquired their M-HREE-enriched signature from previous spinel-facies melt-rock interaction. The primary depleted signature of impregnating melts can also explain the high anorthite contents of plagioclase and the high Mg-values of pyroxenes in the gabbronorites, whereas the early crystallization of ortho- and clino-pyroxenes can be consequence of the chemical modification of percolating melts by reactive dissolution of mantle pyroxenes. As discussed by Nonnotte et al. (2005), similar textural and chemical features could be accounted by crystallization from hydrous melts. Experimental studies on the crystallization of hydrous tholeiitic melts (e.g. Berndt et al., 2005; Husen et al., 2016) showed that the addition of water has indeed the effect to enhance early pyroxene saturation and increase the anorthite content of plagioclase. However, hydrous melts are characterized by low saturation temperature of plagioclase and clinopyroxene (<1100 °C for melts containing more than 2 wt.% H₂O) and this is in contrast with thermometric estimates on impregnated peridotites and gabbronorites, generally yielding high crystallization temperatures (1150–1250 °C; Piccardo et al., 2007; Rampone et al., 2008; Müntener et al., 2010).

Based on present knowledge, we thus favor the hypothesis that percolating melts in the Alpine-Apennine peridotites mostly originated as unaggregated depleted melt fractions and were progressively modified from olivine-saturated to orthopyroxene- (and plagioclase-) saturated composition by the reactive porous flow migration from spinel- to plagioclase-facies depths in a mantle column (Fig. 12).

As discussed above, many textural and chemical features of melt-rock reaction processes recorded by the Alpine-Apennine peridotites are comparable to those documented in modern oceanic peridotites from slow-to ultraslow-spreading environments. Warren (2016), in a recent study on global compositional variations in abyssal peridotites, outlined that the occurrence of melt impregnated peridotites increases at decreasing spreading

rates. This is thought to be a consequence of more pronounced conductive cooling at slow (<40 mm/yr) spreading environments, which in turn limits the degree of melting and favors the freezing of melts into the shallow lithospheric mantle (e.g. Cannat, 1996; Dick et al., 2003; Müntener et al., 2010; Sleep and Warren, 2014). Remarkably, this is consistent with studies on the composition of MORB glasses on a global scale, pointing to a greater role for reactive crystallization (i.e. crystallization influenced by chemical modifications of MORB melts by previous melt-peridotite reaction; Collier and Kelemen, 2010) at slow-spreading ridges, characterized by thicker thermal lithosphere. Melt impregnation and refertilization thus appear to be ubiquitous and prominent features observed in the slow-spreading exhumed oceanic mantle.

6. Concluding remarks

In the Alpine-Apennine mantle, melt-peridotite interactions played a key role in creating chemical and isotopic changes in infiltrated peridotites at variable scales and depths. At deep spinel-facies conditions, old (pre-Jurassic) pyroxenite emplacement and reactive percolation of pyroxenite-derived melts caused significant small-scale chemical and isotopic modifications in the host mantle, even more extreme than the isotopic heterogeneity represented by the pyroxenite component. This points to the importance of such processes in generating the hybrid “pyroxenite-related” mantle sources increasingly invoked to explain the global compositions of MORBs.

During extension-related Jurassic mantle exhumation, the Alpine-Apennine peridotites experienced open-system reactive porous flow at spinel facies depths originating reactive harzburgites and dunites, and shallower melt impregnation forming plagioclase-rich peridotites. We infer that migrating melts largely originated as shallow, variably depleted, melt fractions, and acquired Si-rich composition by reactive dissolution of mantle pyroxenes during upward migration.

The melt-peridotite reaction processes here documented track the progressive exhumation at shallow depths of large mantle sectors in oceanic settings where a thicker thermal boundary layer exists, as a consequence of slow-spreading rate.

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