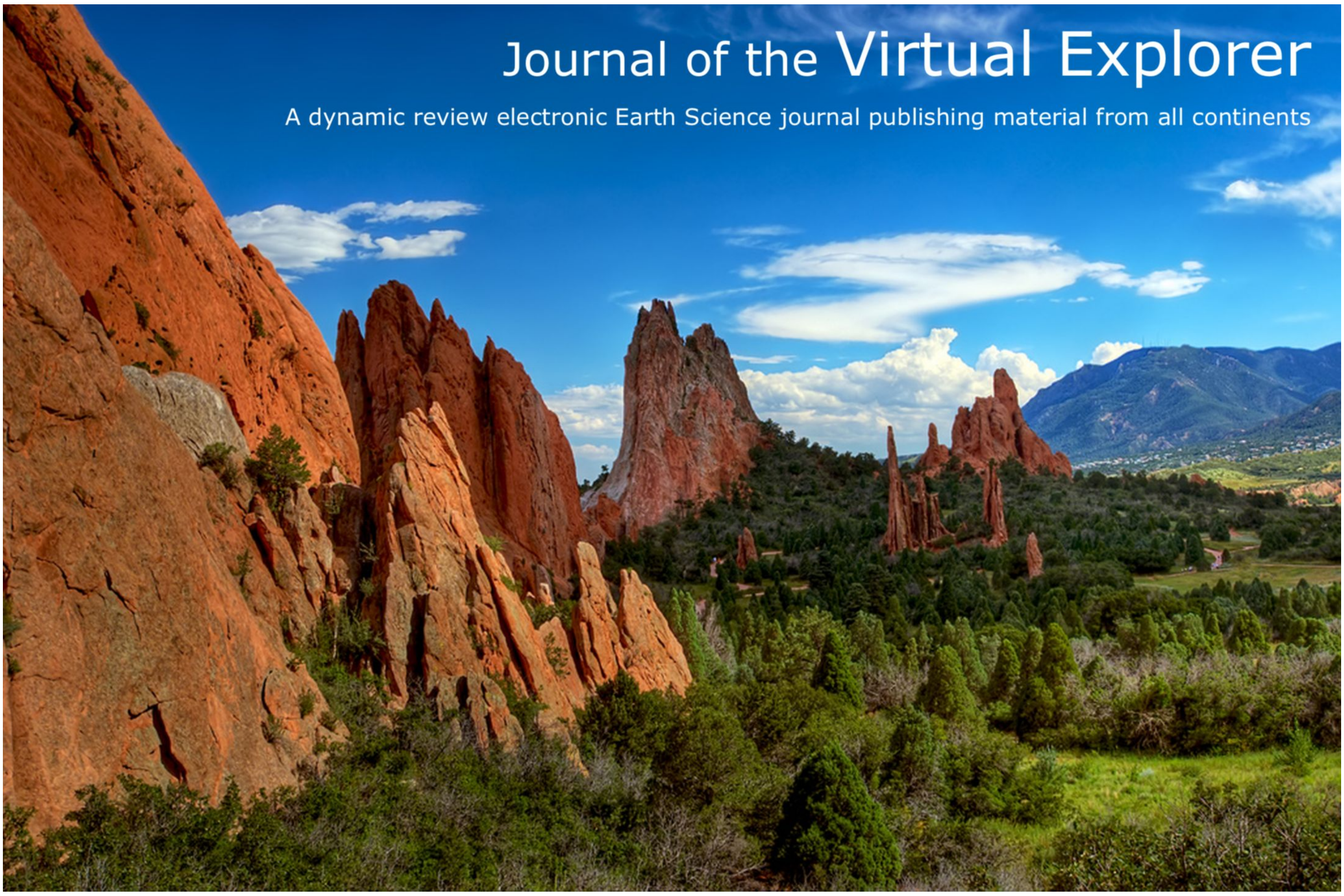

The Evolution of the Lithospheric Mantle during Mesozoic Rifting in the Ligure-Piedmontese Domain

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The Evolution of the Lithospheric Mantle during Mesozoic Rifting in the Ligure-Piedmontese Domain

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Abstract: Available structural, petrological, geochemical and geochronological data on the Alpine-Apennine ophiolitic peridotites allow to reconstruct from a mantle perspective the composite scenario of the evolution of the lithospheric mantle from the early continental extension to the formation of the Jurassic Ligure-Piemontese oceanic basin.

Continental extension by far field tectonic forces was already active during Triassic times and caused the progressive exhumation of the Europe-Adria sub-continental lithospheric mantle. Extension caused necking of the mantle lithosphere and adiabatic upwelling of the asthenosphere which underwent decompression melting along the axial zone of the extensional system.

Melt fractions from the asthenosphere percolated through, and interacted with the lithospheric mantle under spinel-facies conditions and formed reactive spinel peridotites. The percolating melts maintained their geochemical signature during reactive percolation and modified their composition from olivine- to orthopyroxene-saturated. Under plagioclase-facies conditions the rising melts impregnated by interstitial crystallization the percolated peridotites. The percolating melts were entrapped and stored into the shallow lithospheric mantle. These melts never reached the surface since lava flows with similar compositional characteristics did never erupt at the sea-floor of the basin.

Subsequently, aggregated MORBs migrated within replacive dunite channels and reached shallow levels forming gabbroic intrusions and basaltic extrusions which represented the Late Jurassic oceanic crustal rocks of the basin.

Mantle processes and geodynamics were strictly interconnected during the evolution of the Ligure-Piemontese realm. Mantle processes recorded in the mantle lithosphere are good indicators of the geodynamic evolution of the extensional continental system towards the opening of the oceanic basin.

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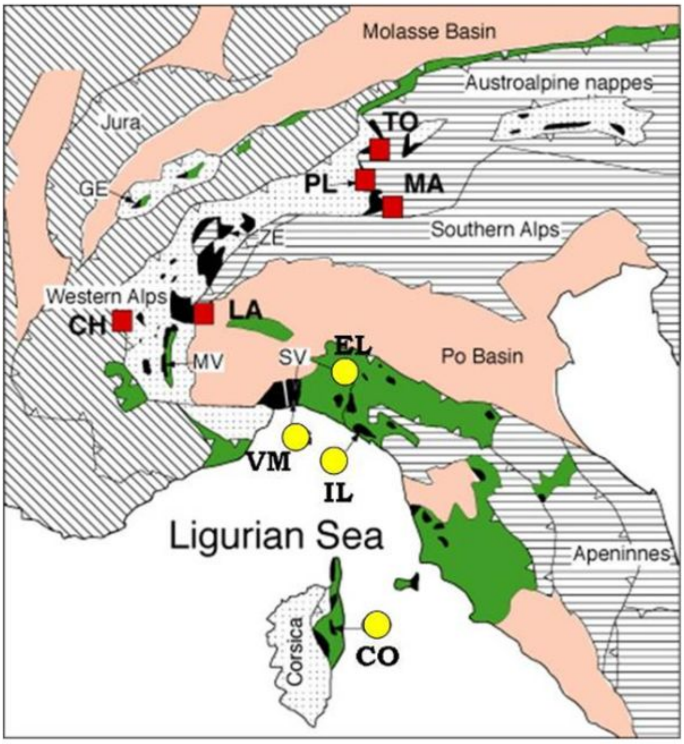
Introduction

The Alpine-Apennine mantle peridotites outcropping within ophiolite sequences in the Central and Western Alps, the Ligurian Alps, the Northern Apennines and Alpine Corsica (Fig. 1) derive from the oceanic lithosphere of the Ligure-Piemontese (Ligurian or Western Tethys) basin. This oceanic basin was formed by continental extension and break-up during late Jurassic times between the Europe and Adria continental margins (Fig. 2).

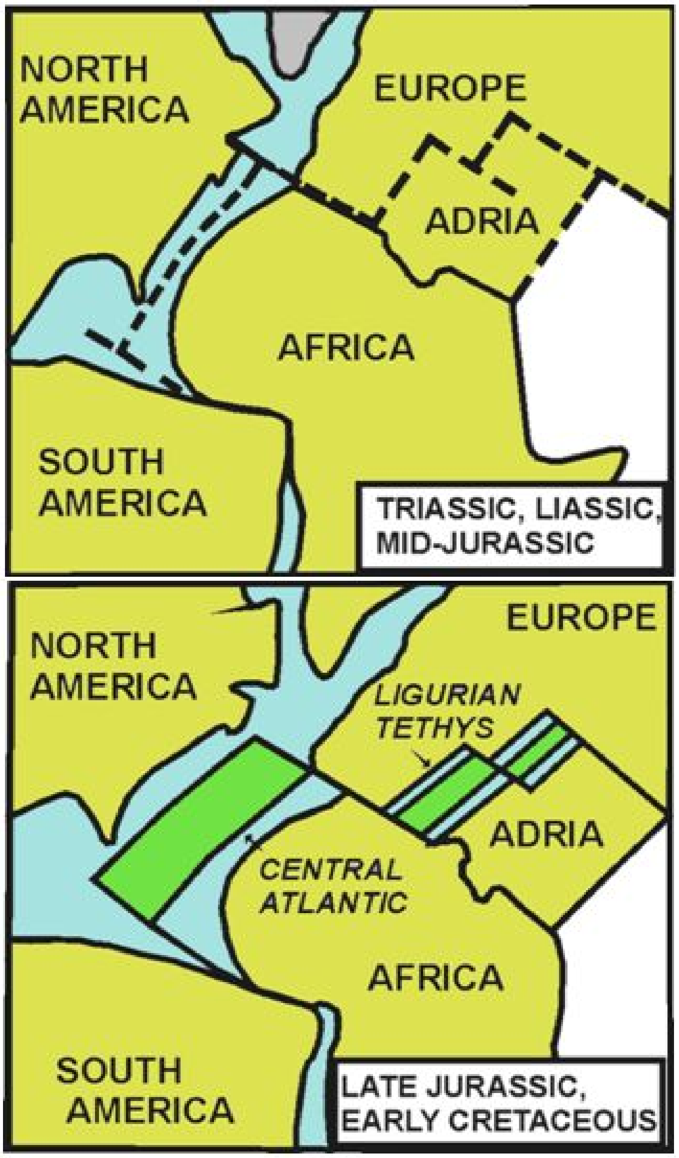
Figure 1. Location of the major ophiolite massifs



Location of the major ophiolite massifs (in black) in the Central-Western-Ligurian Alps and Northern Apennines (and Corsica) (pink = Tertiary basins; oblique lines = European Units; points = Brianconnais & Valais Units; Green = Liguria-Piemontese Units; horizontal lines = Adriatic Units) (Redrawn and modified after Schaltegger et al., 2002; Piccardo et al., 2009). Central Alps: TO= Totalp, MA=Malenco, PL=Platta; Western Alps: LA=Lanzo, CH=Chenaillet; Liguria: VM=Voltri Massif, EL=External Ligurides, IL=Internal Ligurides; Corsica = CO-Alpine Corsica.

Before the nineties, structural, petrologic and geochemical studies were done on some ophiolitic peridotite massifs from the Western Alps (Lanzo Massif), the Ligurian Alps (Erro-Tobbio Massif) and the Northern Apennines (External and Internal Ligurides) (Bezzi and Piccardo, 1971; Nicolas, 1974; 1986; 1989; Boudier, 1976; 1978; Boudier and Nicolas, 1972; Piccardo, 1976; Ernst, 1978; Ernst and Piccardo, 1979; Ottonello *et al.*, 1979; Beccaluva *et al.*, 1984; Ottonello *et al.*, 1984; Pognante *et al.*, 1985; Bodinier, 1988). The early studies recognized the presence of both fertile spinel lherzolites and depleted spinel peridotites.

Figure 2. Mesozoic evolution of the Central Atlantic and Ligurian Tethys oceans



Mesozoic evolution of the Central Atlantic and Ligurian Tethys oceans, from rifting to ocean formation (redrawn and modified after Lemoine *et al.*, 1987).

The Ligurian ophiolitic peridotites from the Northern Apennine were recognized to derive from more peri-continental settings (the External Ligurides) and more intra-oceanic settings (the Internal Ligurides) of the Jurassic basin. On the basis of their fertile lherzolite composition and their tectonic-metamorphic evolution, the ophiolitic peridotites from the External Liguride Units were interpreted as deriving from the sub-continental lithospheric mantle (e.g. Bezzi and Piccardo, 1971; Piccardo, 1976). On the basis of their depleted compositions, the ophiolitic peridotites from the Internal Liguride Units were considered refractory residua after oceanic partial melting (e.g. Beccaluva *et al.*, 1984; Ottonello *et al.*, 1984).

Accordingly, it was inferred that the more fertile External Liguride lherzolites, that were exposed on the seafloor at more marginal, pericontinental settings of the basin, derived from the sub-continental lithospheric mantle and were not subjected to MORB-forming partial melting during the Triassic-Jurassic rifting. The more depleted Internal Liguride peridotites, that were exposed at more internal, oceanic settings, were believed to represent refractory residua after Jurassic asthenosphere partial melting and MORB extraction and to be similar to modern abyssal peridotites.

In summary, studies before the nineties evidenced the existence in the Ligurian sector of the Ligure-Piemontese basin of two main groups of mantle peridotites characterized by significantly different modal and chemical compositions, that were originated in the sub-continental lithosphere or in the oceanic asthenosphere.

Knowledge has been considerably improved as a result of the wealth of multidisciplinary studies performed during the last twenty years. The extreme heterogeneity of the ophiolitic peridotites of the basin has been evidenced and their genetic processes have been more carefully investigated. It has been, in particular, recognized the role of melt diffuse percolation through the mantle lithosphere and melt-peridotite interaction during the rifting stage of the basin. The mutual relationships between mantle processes and structural evolution of the lithosphere have been, thus, better recognized and the new results have been tentatively integrated in a composite geodynamic scenario.

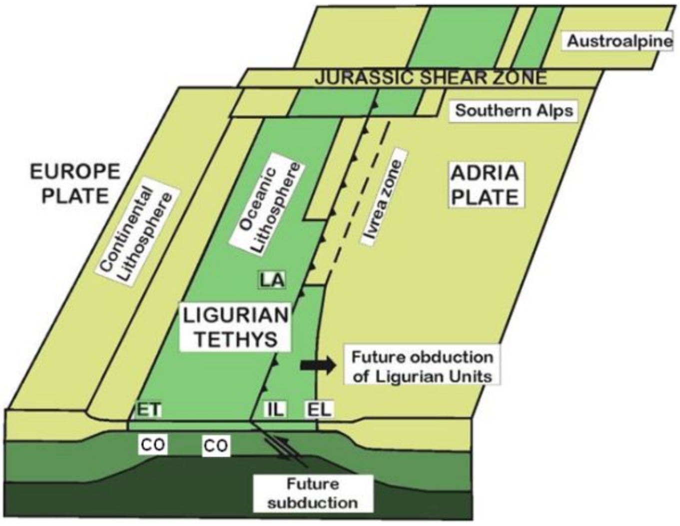
In this paper we present and discuss available structural, petrologic and geochronological knowledge on the Alpine-Apennine ophiolitic peridotites deriving from the different palaeogeographic settings of the Ligure-Piemontese basin. We show that the structural and compositional characteristics of the peridotites varied in space and time and that such variability was induced by both tectonic-metamorphic and magmatic processes. Mantle processes were induced in the lithosphere-asthenosphere system by continental extension. The asthenosphere underwent partial melting under decompression and the lithosphere was profoundly modified by the action of percolating asthenospheric melts. Mantle processes were strictly connected to geodynamics and were good indicators of the geodynamic evolution of the extensional continental system.

This work aims at presenting the composite evolution of the lithospheric mantle in relation with the geodynamic evolution the Ligure-Piemontese continental lithosphere.

The Ophiolitic Peridotites

In the frame of the palaeogeographic reconstruction of the Jurassic Ligure-Piemontese basin (Fig. 3), the various Alpine-Apennine ophiolitic peridotite bodies have been ascribed to different palaeogeographic settings of the basin, **marginal** and **distal**, with respect to the paired Jurassic Europe and Adria continental margins. The marginal peridotite massifs from the Eastern Central Alps (Malenco, Upper Platta, Totalp) and the Northern Apennines (External Ligurides) pertain to structural units originally located at pericontinental settings of the basin along the Adria margin. The distal peridotite massifs of the Eastern Central Alps (Lower Platta) and Western Alps (Chenaillet) and of the Northern Apennines (Internal Ligurides) pertain to structural units originally located at more internal settings of the basin (e.g. Marroni *et al.*, 1998; Schaltegger *et al.*, 2002; and references therein). The Lanzo peridotite massif (Western Alps) is composed of a marginal sector (the North Lanzo body), likely located close to the Adria margin, and a distal sector (the South Lanzo body), likely located at a more internal sector of the basin (Bodinier *et al.*, 1991; Piccardo, 2010b). The Erro-Tobbio massif (Ligurian Alps) is composed by marginal-type peridotites (north-east sector) and distal-type peridotites (south-western sector) (Piccardo and Vissers, 2007; Piccardo and Guarnieri, 2010a). The Monte Maggiore massif (Northern Corsica) is composed by distal peridotites from an internal setting of the basin (Rampone *et al.*, 2008; Piccardo and Guarnieri, 2010b).

Figure 3. Schematic palaeogeographic reconstruction of the Ligure-Piemontese basin during Late Jurassic



Schematic palaeogeographic reconstruction of the Ligure-Piemontese basin during Late Jurassic, with location of the main ophiolite sequences at marginal OCT settings [North Lanzo (LA), External Ligurides (EL), part of Erro-Tobbio(ET)] and at distal intra-oceanic settings [South Lanzo (LA), part of Erro-Tobbio (ET), Internal Ligurides (IL), Mt. Maggiore (MM)]. The position of the future subduction zone is also schematically reported (redrawn and modified after Piccardo *et al.*, 2009). Two major transects across the Adria margin, *i.e.* Lanzo and the Ligurides, are characterized by exhumed sub-continental peridotites at the marginal settings (*i.e.*, North Lanzo and External Ligurides) and melt-modified peridotites at the more distal settings (*i.e.*, South Lanzo and Internal Ligurides) (see text for explanation).

Accordingly, in the following we refer to the ophiolitic peridotite massifs of Malenco, Upper Platta, Totalp (in the Eastern Central Alps), North Lanzo (in the Western Alps), Erro-Tobbio (north-eastern part) (in the Ligurian Alps) and External Ligurides (in the Northern Apennines) as *marginal peridotites*, derived from the ocean-continent transition (OCT) zones of the Ligure-Piemontese basin, and we refer to the ophiolitic peridotite massifs of Lower Platta (in the Eastern Central Alps), South Lanzo (in the Western Alps), Erro-Tobbio (south-western part) (in the Ligurian Alps), Internal Ligurides and Tuscany (in the Northern Apennines) and Mt. Maggiore (in Northern Corsica) as *distal peridotites*, deriving from more internal oceanic settings of the basin.

Peridotite Petrology

Mantle peridotites from the Alpine-Apennine ophiolites are highly heterogeneous and show highly variable structural and compositional characteristics. They have been grouped into:

1) fertile spinel lherzolites;
2) depleted spinel harzburgites;
3) enriched plagioclase peridotites.

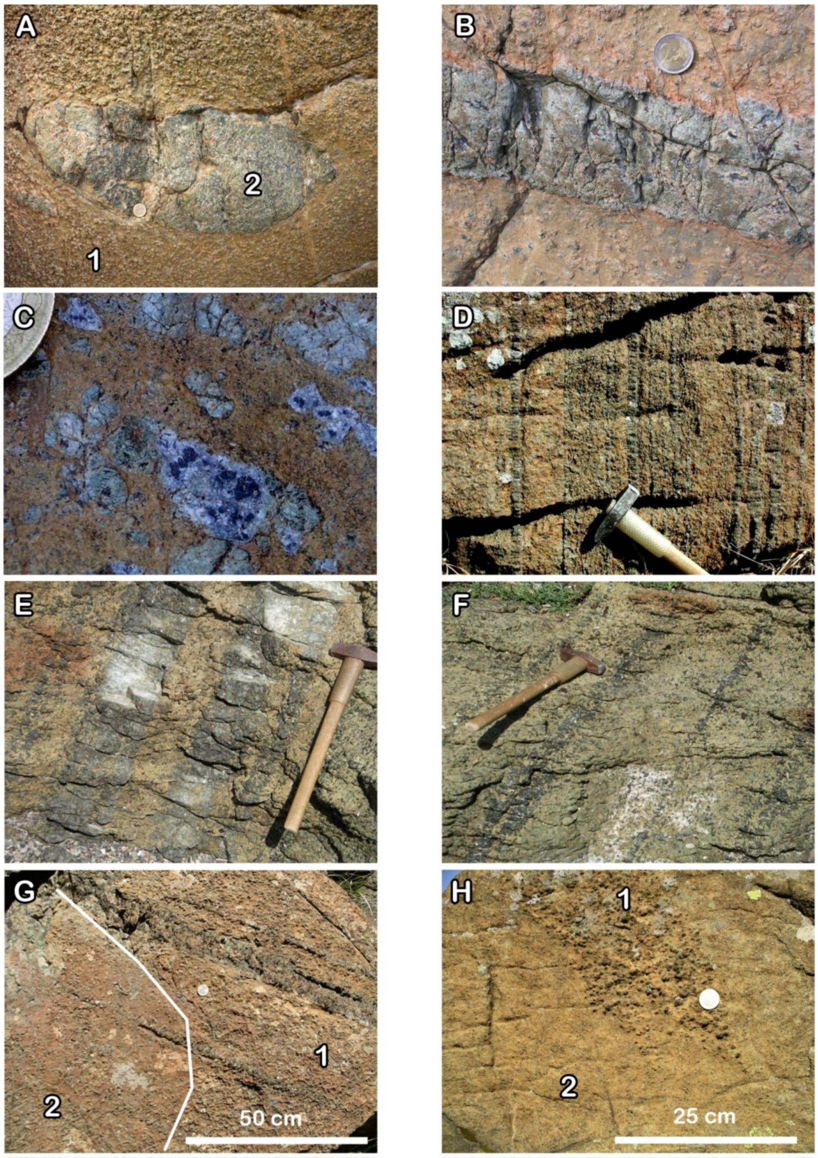
Fertile spinel lherzolites

The fertile lherzolites are clinopyroxene-rich, Ti-pargasite-bearing lherzolites that are usually veined by spinel(-garnet)-pyroxenite bands (Fig. 4) (e.g. Montanini *et al.*, 2006; Piccardo *et al.*, 2007b; Piccardo, 2008). They show porphyroclastic textures and spinel-facies assemblages and, in places, rounded spinel+orthopyroxene clusters suggesting spinel-facies recrystallization of precursor mantle garnet (Fig. 5A and B) (e.g. Hoogerduijn Strating *et al.*, 1993). Mineral assemblages and equilibration temperatures (mean 1000°C) indicate that these peridotites equilibrated at lithospheric mantle conditions to an average sub-continental geotherm.

These peridotites are considered upper mantle rocks that were uplifted from garnet peridotite-facies conditions (P > 2.5 GPa) and equilibrated at spinel peridotite-facies conditions (2.5 GPa <= P <= 1.0 GPa) in the sub-continental lithosphere where they were resident prior to inception of Triassic-Jurassic continental extension and rifting in the Ligure-Piemontese domain. On the basis of their structural and petrologic characteristics, that indicate provenance from, and composite evolution in the lithospheric mantle, these pyroxenite-bearing spinel lherzolites have been referred to as *lithospheric spinel lherzolites* (e.g. Piccardo *et al.*, 2007a, 2007b; Piccardo and Vissers, 2007).

The lithospheric lherzolite masses are frequently cut by km-scale extensional shear zones showing tectonite-mylonite fabrics (Fig. 4D). The shear zones usually show progressive syntectonic recrystallizations, starting from the oldest spinel-facies assemblages, which vary from spinel- to plagioclase- to amphibole-(chlorite)-peridotite facies parageneses, followed by shallow serpentinization (e.g. Vissers *et al.*, 1991; Hoogerduijn Strating *et al.*, 1993). The presence of these shear zones and their progressive syntectonic recrystallizations from deep to shallow lithospheric levels indicate that extension and thinning of the Europe-Adria continental lithosphere was, most probably, driven by a network of extensional shear zones (e.g. Piccardo *et al.*, 2009). Accordingly, the pristine pyroxenite-bearing lherzolites from the sub-continental lithospheric mantle were progressively exhumed during continental extension and pre-oceanic rifting (e.g. Piccardo and Vissers, 2007).

Figure 4. Main features and field relationships of the sub-continental lithospheric spinel lherzolites and the reactive spinel harzburgites.



A) Pod of spinel pyroxenite (2) enclosed in lithospheric lherzolite (North Lanzo); B) Band of spinel pyroxenite enclosed in lithospheric lherzolite (North Lanzo); C) Cluster of orthopyroxene+spinel il lithospheric lherzolite: the cluster represents the breakdown of a precursor mantle garnet which indicate transition from garnet- to spinel-facies condition (Erro-Tobbio); D) Pyroxenite-rich tectonite-mylonite shear zone in lithospheric lherzolite which indicates that the sub-continental mantle underwent extension and exhumation (Erro-Tobbio); E) Lithospheric peridotite enriched in parallel pyroxenite bands (Monte Maggiore); F)Outcrop similar to E) where the diffuse percolation of a silica-undersaturated melt dissolved progressively the clinopyroxene of pyroxenites by melt-rock interaction (pyroxene dissolution/olivine crystallization), leaving out fanthoms of pyroxenites and strongly olivine-enriched reactive peridotites (Monte Maggiore);G) Primary contact between pyroxenite-bearing lithospheric lherzolite (1) and strongly pyroxene-depleted reactive spinel harzburgites (2). Harzburgite formed at the expense of lithospheric lherzolite by the reactive percolation of a undersaturated melt which dissolve pyroxenes (and pyroxenites) and crystallize olivine (Erro-Tobbio); H)Different types of reactive spinel harzburgites: 1) coarse granular spinel harzburgite; 2) fine-grained orthopyroxene-bearing dunite (South Lanzo).

Depleted spinel peridotites

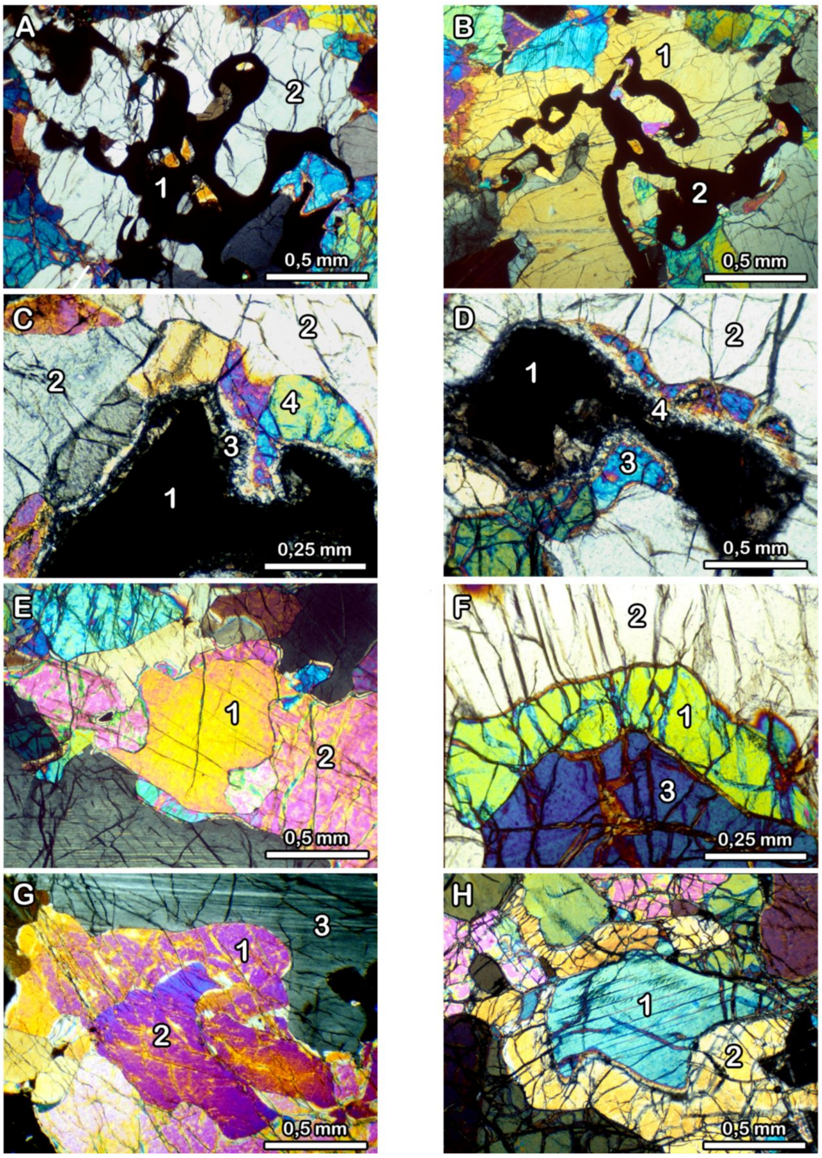
Km-scale masses of clinopyroxene-poor lherzolites and harzburgites are abundant in the distal ophiolitic peridotite massifs, and are characterized by coarse granular isotropic textures and spinel-facies assemblages (Fig. 4). They usually lack of pyroxenite banding and show peculiar micro-textures which indicate dissolution of the mantle pyroxene porphyroclasts and formation of new unstrained olivine. Characteristic micro-textures consist of grains, patches and coronas of new olivine which replaces the pyroxene porphyroclasts and crystallizes interstitially between the mantle porphyroclasts (Fig. 5). These micro-structural features are interpreted as records of melt/peridotite interaction processes during the diffuse and reactive porous flow percolation of an asthenospheric melt through the lithospheric mantle (e.g. Piccardo *et al.*, 2007a). Since these micro-textures indicate pyroxene-consuming/olivine-forming reactions, it is widely accepted that the percolating melt was silica(-pyroxenes)-undersaturated (e.g. Piccardo *et al.*, 2007a; Piccardo and Vissers, 2007; Piccardo and Guarnieri, 2010b).

Progressive pyroxene dissolution and olivine precipitation transformed the pristine mantle lherzolites into strongly pyroxenes-depleted and olivine-enriched peridotites. Mineral assemblages suggest that these earlier stages of melt percolation and interaction occurred under spinel-peridotite facies conditions. The resulting coarse granular spinel harzburgites, which are significantly depleted in pyroxenes, enriched in olivine and are characterized by reaction micro-textures, have been referred to as *reactive spinel harzburgites* (Piccardo, 2003, 2008; Müntener and Piccardo, 2003; Piccardo *et al.*, 2007a).

Enriched plagioclase peridotites

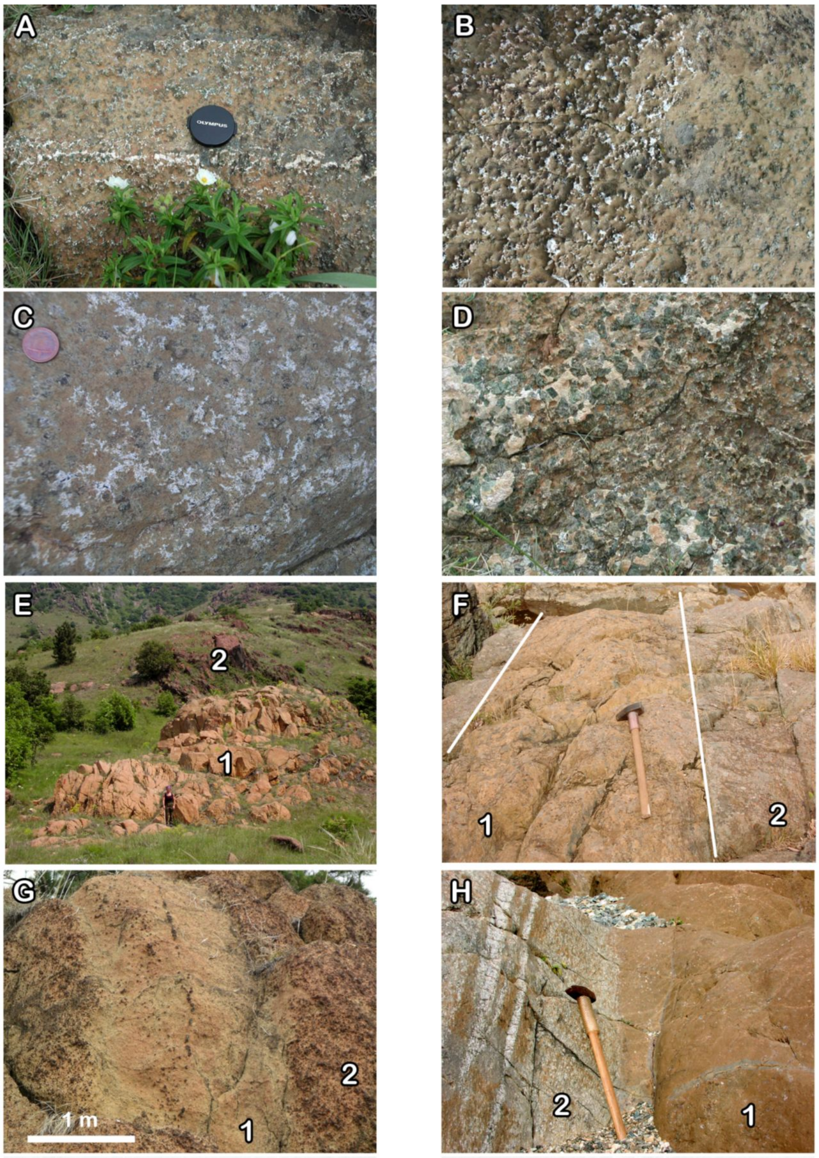
Km-scale bodies of plagioclase-bearing/rich peridotites are widespread within the distal ophiolitic peridotite massifs (Fig. 6). As a whole, these plagioclase-bearing rocks consist of an older, deformed and exsolved, spinel-facies assemblage and new mm-size, isolate plagioclase crystals and interstitial granular aggregates of plagioclase-rich gabbroic material. The most common micro-structural features are (Fig. 7): i) the presence of widespread undeformed plagioclase crystals which are interstitial or crosscutting deformed and exsolved mantle minerals; ii) the replacement of kinked mantle olivine by undeformed orthopyroxene patches; iii) the occurrence of mm-size plagioclase-rich gabbroic veins and pods, and symplectitic pyroxenes + plagioclase interstitial patches; and iv) rims of plagioclase surrounding the spinel crystals. These micro-structures are frequently coupled with clinopyroxene-dissolving/orthopyroxene+plagioclase-forming reactions (*i.e.* aggregates and coronas of orthopyroxene+plagioclase surrounding corroded clinopyroxene porphyroclasts) (Fig. 7) and interstitial crystallization of gabbro-noritic microgranular aggregates. Since these peridotites are characterised by olivine-consuming/orthopyroxene-forming micro-structures (Fig. 7), it is widely accepted that the percolating melt was silica(-orthopyroxene)-saturated (e.g. Piccardo *et al.*, 2007a; Piccardo and Vissers, 2007; Piccardo and Guarnieri, 2010b). Presence and abundance of plagioclase suggest that these melt infiltration and interstitial crystallization events occurred under plagioclase peridotite-facies conditions. The resulting peridotites, which are variably depleted in olivine and enriched in plagioclase and gabbroic material, have been referred to as *impregnated plagioclase peridotites* (Müntener and Piccardo, 2003; Piccardo *et al.*, 2004; 2007a; Piccardo and Vissers, 2007).

Figure 5. Representative micro-textures of lithospheric spinel lherzolites and reactive spinel harzburgites.



A) B) Rounded spinel (1) +orthopyroxene (2) clusters, which derive from the breakdown to and equilibration at spinel-facies conditions of a precursor mantle garnet in mantle peridotite. This micro-texture indicates the transition from pristine garnet-facies conditions to final equilibrium recrystallization under spinel-facies conditions (P < 2.5 Gpa), that can be interpreted as exhumation from asthenospheric or deep lithospheric levelts in the mantle and accretion to the lithosphere at spinel-facies conditions. C) D) Coronas of olivine (4) + plagioclase (3) (altered) between pyroxenes (2) and spinel (1). This reaction forming plagioclase + olivine marks the transition from spinel-facies to plagioclase-facies conditions in mantle peridotite. This micro-textures marks the transition from spinel-facies to plagioclase-facies conditions which indicates further exhumation of the peridotite to shallow lithospheric levels (P < 1.0 Gpa). E) Reaction micro-texture where a relict clinopyroxene porphyroclast (1) is partially replaced by new olivine (2). This micro-texture indicate melt-pyroxene reaction (pyroxene dissolution and olivine crystallization) operated by the reactive porous flow percolation of a silica-undersaturated melt. F) Rim of new magmatic olivine (1) between mantle orthopyroxene (2) and olivine (3). This micro-texture indicates olivine crystallization during porous flow percolation of and olivine-saturated melt. G) Reaction micro-texture where a relict clinopyroxene porphyroclast (2) is partially replaced by new olivine (1). Note that the new olivine replaces also the exsolved orthopyroxene porphyroclast (3), indicating dissolution of both pyroxenes. H) Reaction micro-texture where a relict clinopyroxene porphyroclast (1) is partially replaced by new olivine (2).

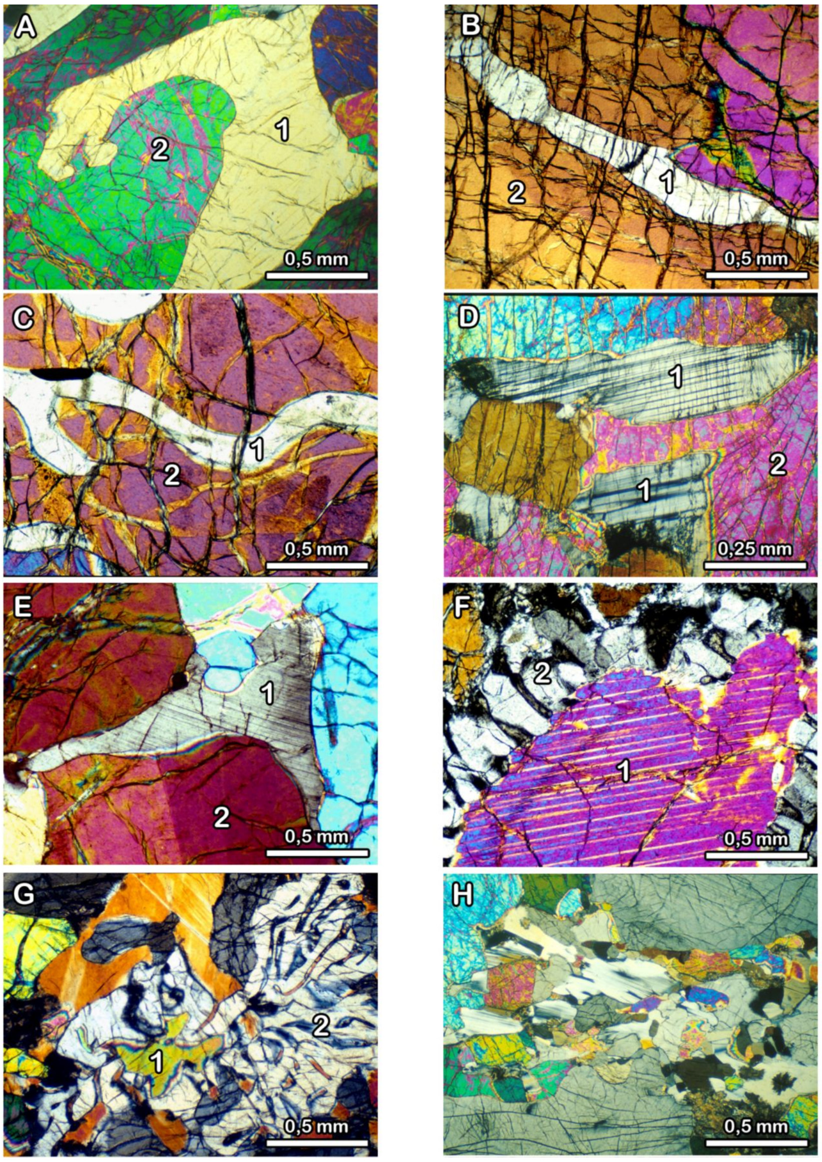
Figure 6. Main features and field relationships of impregnated plagioclase peridotites and replacive dunites.



A) Strongly plagioclase -impregnated peridotite: note the thin plagioclase-rich gabbroic vein (Monte Maggiore); B) Contact between a strongly plagioclase -enriched peridotite and a reactive spinel harzburgite (Monte Maggiore); C) Strongly plagioclase-enriched peridotite (Erro-Tobbio); D) Pod of gabbro-norite highly enriched in euhedral pyroxenes (Monte Maggiore); E) Replacive spinel dunite body (1) within impregnated plagioclase peridotite (2)(South Lanzo); F) Metric replacive spinel harzburgite channel (1) cutting spinel peridotite (2)(Erro-Tobbio); G) Metric replacive spinel harzburgite channel (1) cutting spinel peridotite: note the clinopyroxene vein crystallized in the center of the channel from the melt rising within the channel (South Lanzo); H) Part of a decametric spinel dunite channel (1) running inside a strongly deformed tectonite-mylonite shear zone (2), following this shear zone foliation (Erro-Tobbio). These high permeability, high porosity olivine-rich channels are believed to drive the asthenospheric MORB magmas to shallow oceanic crustal levels.

Decametric-hectometric intrusive pods, decimetric dykes and centimetric dykelets with pyroxene-rich gabbro-norite composition are widespread within the impregnated plagioclase peridotites of the distal ophiolite massifs (Fig. 6). They are composed of clinopyroxene, orthopyroxene and plagioclase, and sporadically olivine. Pyroxenes are always abundant and usually show euhedral shape against anhedral and interstitial plagioclase. Orthopyroxene is an abundant cumulus phase. Abundance and early crystallization of orthopyroxene suggests that parental magmas of the gabbro-norite suite were relatively high-SiO_2 basaltic liquids (Piccardo and Guarnieri, 2010c).

Figure 7. Representative micro-textures of the impregnated plagioclase peridotites.



A) Orthopyroxene (1) replacement on mantle olivine (2). This micro-texture indicates reaction of the mantle olivine with a silica-saturated melt, forming orthopyroxene (olivine dissolution and orthopyroxene precipitation); B) C) Veins of orthopyroxenes cutting mantle olivine (olivine dissolution and orthopyroxene precipitation), indicating migration and reaction of a silica-saturated melt. D) E) Undeformed plagioclase crystals (1) cutting through mantle porphyroclasts (2), indicating interstitial crystallization from a percolating melt. F) G) Exsolved clinopyroxene porphyroclasts (1) partially replaced by an orthopyroxene + plagioclase (altered) symplectitic aggregate (2), indicating reaction, at plagioclase-facies conditions, with an orthopyroxene-saturated melt. H) Micro-gabbroic aggregate crystallized between mantle porphyroclasts, indicating peridotite refertilization by interstitial crystallization of a basaltic liquid.

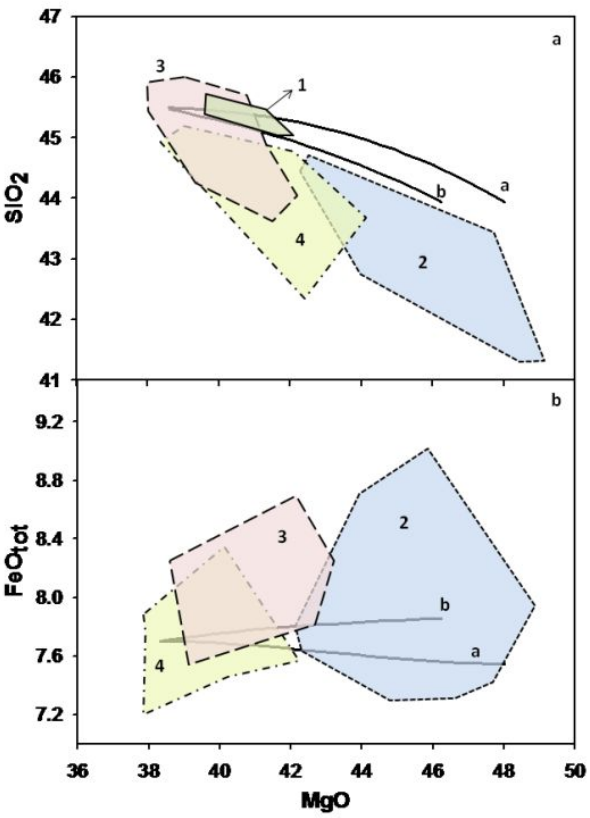
Replacive dunite channels

All the above peridotitic rocks were locally crosscut by channels of spinel harzburgites and dunites (Fig. 6). These strongly pyroxene-depleted/free peridotites have been interpreted as replacive channels formed by the complete reactive dissolution of mantle pyroxenes by focused percolation of silica-undersaturated melts along pre-existing compositional and structural discontinuities (e.g. Piccardo *et al.*, 2007a; Piccardo and Guarnieri, 2010a, and references therein). These rocks have been referred to as *replacive spinel peridotites*. In some peridotite massifs (e.g. South Lanzo, Erro-Tobbio, External Ligurides) these replacive harzburgite and dunite channels run concordantly inside tectonite-mylonite shear zones, indicating that the focused migration of melts was driven by these structural discontinuities (Fig. 6). The replacive channels sporadically host interstitial clinopyroxene grains, euhedral clinopyroxene megacrystals and gabbroic veins and dykelets, which are interpreted as products of initial crystallization of the melts percolating within the channels (Piccardo *et al.*, 2007a).

Some discriminant compositional features

The compositional characteristics of most Alpine-Apennine ophiolitic peridotite bodies have been compiled from the literature and discussed together to the processes responsible for their formation and evolution (sources of data reported in Piccardo and Guarnieri, 2010a, and references therein).

Figure 8. Some bulk rock major element characteristics of the Alpine-Apennine ophiolitic peridotites.



The data from the different sources have been grouped according to the palaeogeographic settings (*i.e.* marginal or distal peridotites) and petrologic features. 1) = Sub-continental lithospheric spinel lherzolites; 2) = Distal depleted spinel peridotites (reactive spinel peridotites); 3) = Marginal plagioclase peridotites (plagioclase peridotites impregnated by aggregated MORB melts); 4) = Distal plagioclase peridotites (plagioclase peridotites impregnated by MORB single melt fractions).

a) b) The various types of spinel peridotites are differently depleted in SiO_2 and enriched in FeO with respect to refractory residua after any kind of partial melting, as calculated by Niu (1997) (trends a-b). In fact, the spinel distal peridotites (2) fall at significantly lower SiO_2 contents and at significantly higher FeO contents with respect to the corresponding MgO values on the melting trends. In the MgO vs SiO_2 diagram (a) the lithospheric sub-continental spinel lherzolites (1) broadly align along the melting trends at low degrees of melting, evidencing their rather fertile composition. The impregnated plagioclase peridotites from the distal settings (4) plot below the melting trends, at lower MgO values and increasing SiO_2 contents than the distal spinel peridotites.

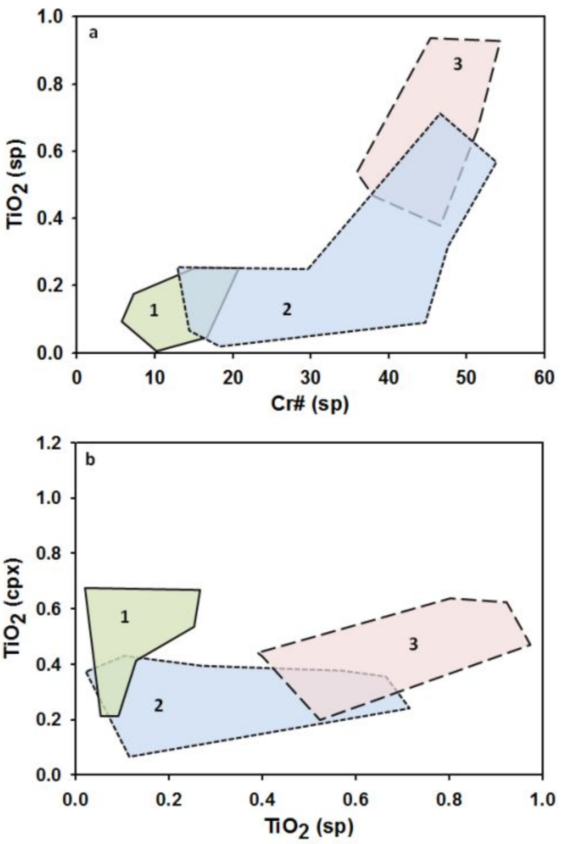
The samples from the different massifs have been grouped according to their different palaeogeographic settings (*i.e.* distal or marginal) and their structural-compositional characteristics. In the following, we present and discuss some discriminant compositional characteristics that are significant for giving indications on the petrogenetic processes recorded by the rocks (see a more complete discussion in Piccardo and Guarnieri, 2010a).

Bulk rock compositions of the Alpine-Apennine reactive spinel peridotites (Fig. 8) are differently depleted in SiO_2 and enriched in FeO with respect to refractory residua after any kind of partial melting, as calculated by Niu (1997); this indicates that a simple partial melting and melt extraction process can not be responsible of their compositional features. This compositional evidence, together with the presence of reactive micro-textures, supports the reactive origin of these depleted spinel peridotites (e.g. Piccardo *et al.*, 2007a; Piccardo and Vissers, 2007).

Bulk rock compositions of the Alpine-Apennine impregnated plagioclase peridotites (Fig. 8) plot at lower MgO contents than the reactive spinel peridotites, from which they derive, and at mostly higher SiO_2 contents, sometimes higher than the estimated contents of primary mantle composition. This suggests that silica-rich mineral phases (plagioclase, pyroxenes) should have been added to the pristine peridotites, supporting the indication that the plagioclase peridotites underwent a melt refertilization event (e.g. Piccardo *et al.*, 2004).

Spinel Cr# value spans over a wide range (6-50) and spinel TiO_2 content ranges from very low (0.04 wt%) to significantly high (up to about 1.0 wt%) (Fig. 9a). It is widely accepted (Dick, 1989; Dick and Bullen, 1984; Hellebrand *et al.*, 2002) that high Ti contents of spinel (*i.e.* TiO_2 > 0.1 wt%) in oceanic peridotites is a record of melt-peridotite interaction and it indicates equilibration with MORB melts. Accordingly, relatively high TiO_2 contents in spinel from the Alpine-Apennine distal reactive and impregnated peridotites confirm that they underwent reactive percolation of basaltic melts.

Figure 9. Some mineral chemistry characteristics of the Alpine-Apennine ophiolitic peridotites.



Peridotite groups as in Fig. 8.

a) Spinel Cr# spans over a wide range (6-50), the lowest values are shown by the fertile lithospheric subcontinental spinel lherzolites (1), the highest values are shown by the distal plagioclase peridotites (3). TiO_2 content in Sp ranges from very low (0.04wt%) up to about 1.0 wt%. Significantly high TiO_2 contents in spinel are shown by spinel and plagioclase distal peridotites (2-3) (Lower Platta, South Lanzo, Voltri Massif, Internal Ligurides, Mt. Maggiore).

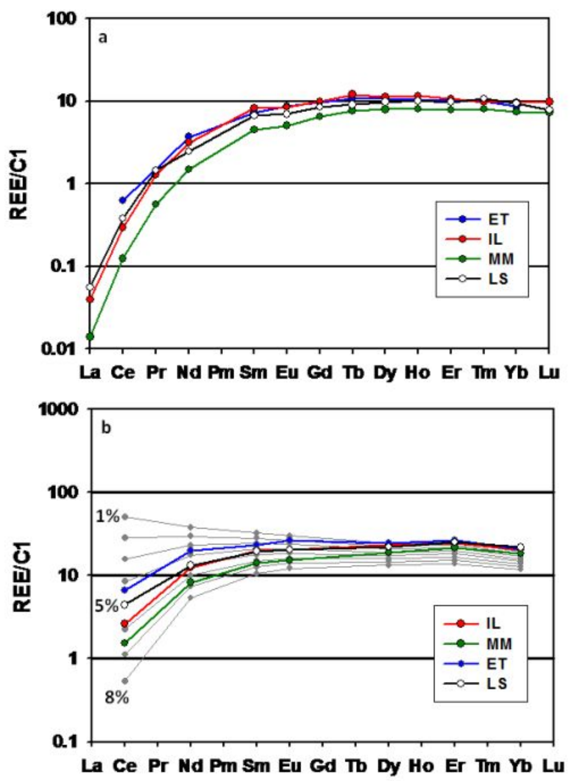
b) TiO_2 in Cpx ranges over a wide interval (0.12-0.98wt%). TiO_2 in clinopyroxene and TiO_2 in spinel show a broad positive correlation going from low-Ti, distal spinel peridotites (2) to high-Ti, distal plagioclase peridotites (3).

A broad positive correlation exists between TiO_2 in clinopyroxene and TiO_2 in spinel going from spinel to plagioclase peridotites (Fig. 9b). Parallel increase of Ti in clinopyroxene and spinel cannot represent the effect of closed-system metamorphic redistribution of Ti following spinel- to plagioclase-facies recrystallization, but must be more properly interpreted as due to an open-system process related to the progressive equilibration of both minerals with percolating Ti-bearing basaltic melts. Accordingly, the above compositional features support that the compositions of both Alpine-Apennine spinel and plagioclase peridotites were significantly influenced by melt-peridotite interaction processes.

Moreover, the different distal spinel peridotite masses are characterized by clinopyroxenes showing closely similar trace element compositions *i.e.*, strongly depleted incompatible trace elements and C1-normalized REE patterns strongly fractionated in the LREE and almost flat in the MREE-HREE region (at about 10xC1) (Fig. 10a) (see discussion in Piccardo and Guarnieri, 2010a, and references therein). The spinel peridotites of the ophiolite massifs usually show clinopyroxene modal contents varying in a wide range (from 2 up to 10% modal content) in the same massif. Notably, the clinopyroxene REE patterns are closely similar, at the scale of the peridotite massif, disregarding the strong variation in the clinopyroxene modal composition of the different samples. Clinopyroxenes do not show progressive incompatible trace element depletion/fractionation concordantly with progressive decrease of the clinopyroxene content, as expected in the case they were formed by progressive partial melting.

The micro-structural evidence of melt-peridotite interaction during melt reactive percolation favours the interpretation that clinopyroxenes, although present in highly variable modal contents in the different samples, attained the trace element equilibration with a remarkably similar percolating melt during open system migration at high melt-rock ratios (Piccardo *et al.*, 2007a). The close similarity of the clinopyroxene trace element composition in the different spinel harzburgite masses suggest, moreover, that the different harzburgites masses were equilibrated with percolating melts having closely similar geochemical affinities.

Figure 10. C1-normalized REE patterns of representative clinopyroxenes in distal reactive spinel peridotites and calculated equilibrium liquids.



a) C1-normalized REE patterns of representative clinopyroxenes in distal reactive spinel peridotites from South Lanzo (LS), Erro-Tobbio (ET), Internal Ligurides (IL) and Mt. Maggiore (MM). The REE patterns are strongly fractionated in the LREE and almost flat in the MREE-HREE. The representative clinopyroxenes from the different peridotite massifs show closely similar REE contents and C1-normalized REE patterns.

b) The C1-normalized REE patterns of liquids calculated in equilibrium with the representative clinopyroxene core compositions (using Cpx/liquid Kds of Hart and Dunn 1993), from the reactive spinel peridotites of the different peridotite massifs. The REE patterns of liquids calculated by the fractional melting model from Johnson *et al.* (1990) [mantle source from Johnson *et al.* (1990), Cpx/liquid Kds of Hart and Dunn (1993)] are also reported for comparison. The calculated equilibrium liquids are quite similar to those of single melt increments modelled by 4-7% fractional melting of spinel facies DM asthenospheric mantle source.

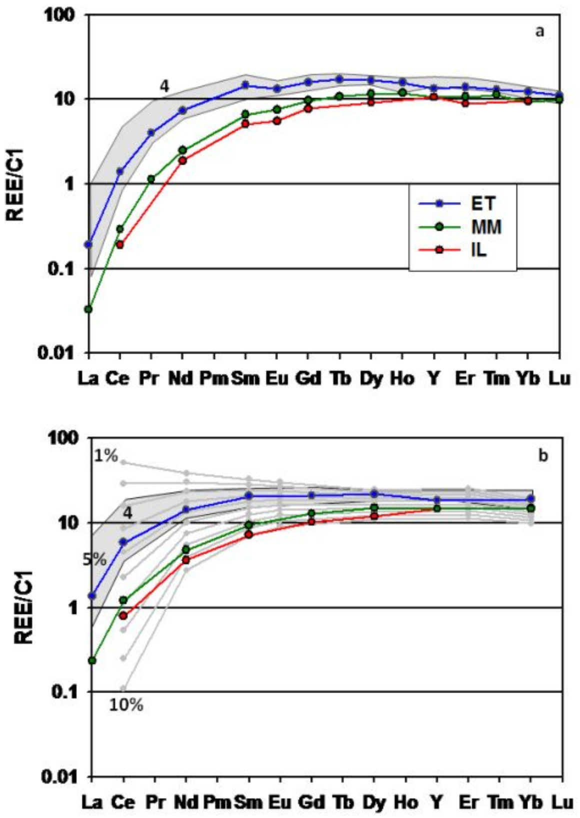
Magmatic affinity of percolating melts

Information on the compositional characteristics of the percolating melts have been obtained by the clinopyroxene trace element compositions, assuming that the mantle clinopyroxenes of the percolated peridotites and the percolating liquids attained the trace element equilibration during melt-peridotite interaction under the conditions of high melt-rock ratios and open system percolation.

Concerning the reactive spinel harzburgites from the different distal massifs the REE compositions and patterns have been calculated for the liquids in equilibrium with representative clinopyroxene core compositions using the clinopyroxene/liquid KDs of Ionov *et al.* (2002) (Fig. 10). Concerning the impregnated plagioclase peridotites from the distal massifs the REE compositions and patterns have been calculated for the liquids in equilibrium with representative clinopyroxene core compositions using the clinopyroxene/liquid KDs of Vannucci *et al.* (1998), useful for saturated basaltic systems (Fig.11). The computed melt compositions have been compared with the REE composition of single melt increments produced by a fractional melting process [fractional melting model of Johnson *et al.*, (1990), starting from the DMM (Depleted MORB Mantle) source of Johnson *et al.*, (1990)].

The computed melts are almost coincident to MORB-type single melt increments after 4-7% of fractional melting of a spinel facies DM asthenospheric mantle source (Figs. 10b and 11b). It can be deduced that both the reactive spinel peridotites and the impregnated plagioclase peridotites were percolated at spinel- and plagioclase-facies conditions, respectively, by closely similar MORB-type single fractional melt increments showing closely similar geochemical affinities. It must be recognized that the early asthenospheric melts that infiltrated the lithospheric mantle at spinel- and plagioclase-facies conditions during continental extension and rifting were depleted single fractional melt increments that did not mixed with other melt increments and migrated isolated though the extending lithosphere (e.g. Piccardo and Guarnieri, 2010a, and references therein).

Figure 11. C1-normalized REE patterns of representative clinopyroxenes in distal impregnated plagioclase peridotites and calculated equilibrium liquids.



a) C1-normalized REE patterns of representative clinopyroxenes in distal impregnated plagioclase peridotites from Erro-Tobbio (ET), Internal Ligurides (IL) and Mt. Maggiore (MM) and South Lanzo (field 4). The distal plagioclase peridotites have clinopyroxene showing significant LREE fractionated C1-normalized REE patterns.

b) The C1-normalized REE patterns of liquids calculated in equilibrium with the representative clinopyroxene core compositions [using Cpx/liquid Kds of Vannucci *et al.* (1998), useful for saturated basaltic systems] from the impregnated plagioclase peridotites of the different peridotite massifs. The REE patterns of liquids calculated by the fractional melting model from Johnson (1990) [mantle source from Johnson (1990), Cpx/liquid Kds of Hart and Dunn (1993)] are also reported for comparison. The calculated equilibrium liquids are quite similar to those of single melt increments modelled by 4-7% fractional melting of spinel facies DM asthenospheric mantle source.

The Monte Maggiore study case

The compositional features of the Monte Maggiore peridotites furnish a scenario that well represents the evolution of the percolating melts (Piccardo and Guarnieri, 2010c).

Clinopyroxenes from the reactive spinel harzburgites are highly magnesian (Mg# 93-94), rich in Cr (Cr_2O_3 1.00-1.26 wt%) and strongly depleted in Na (Na_2O 0.11-0.55 wt%), Ti (TiO_2 0.29-0.34 wt%), Zr (1.38-2.78 ppm), Sr (0.80-2.01 ppm) and LREE (data from Rampone *et al.*, 2008; Piccardo and Guarnieri, 2010b). Clinopyroxenes from the impregnated plagioclase peridotites are highly magnesian (Mg# 91), rich in Cr (Cr_2O_3 1.01-1.30 wt%) and strongly depleted in Na (Na_2O 0.11-0.33 wt%), Ti (TiO_2 0.27-0.47 wt%), Zr (2.83-5.60 ppm), Sr (1.00-5.17 ppm) and LREE (data from Rampone *et al.*, 1997, 2008; Piccardo and Guarnieri, 2010c). Plagioclases are highly anorthitic (An 88-94) and strongly depleted in Sr (6.3-28.6 ppm) with respect to plagioclase in equilibrium with aggregated MORBs. Clinopyroxenes from the gabbro-norite suite are highly magnesian (Mg# 90.5-93.7), rich in Cr_2O_3 (1.18-1.42 wt%) and strongly depleted in TiO_2 (0.28-0.43 wt%) and Na_2O (0.17-0.30 wt%). They have very low LREE (La_NO = 0.04-0.28), Sr (0.8-3.5 ppm) and Zr (2.2-7.4 ppm) contents. Their C1-normalized REE patterns are rather flat in the HREE-MREE region (at about 8-15xC1) and are strongly LREE fractionated (La_NO/Sm_NO = 0.007-0.025). Plagioclase has very low LREE (e.g. Ce_N = 0.013-0.03) and Sr (15.6-30.4 ppm): C1-normalized REE patterns show a negative LREE fractionation (La_NO/Sm_NO = 0.07-0.96).

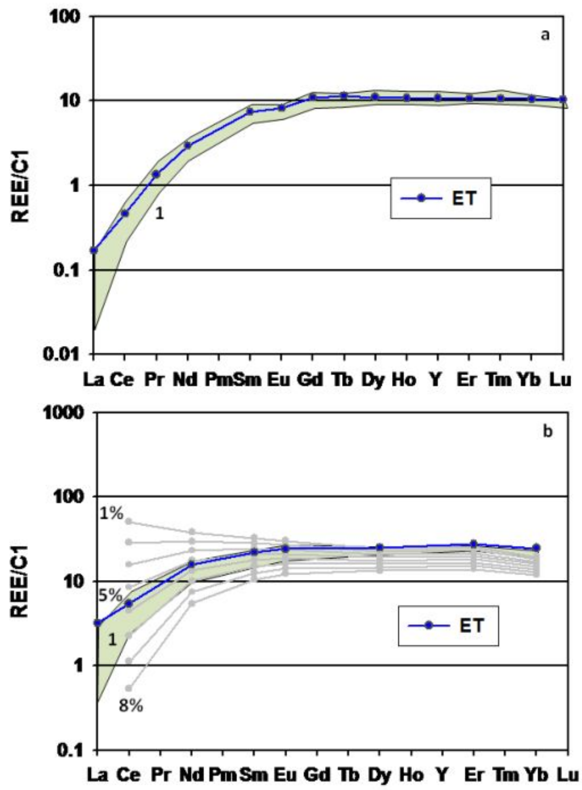
The compositional characteristics of minerals from reactive spinel harzburgites, impregnated plagioclase peridotites and gabbro-norite intrusives indicate that they equilibrated with strongly depleted melt fractions with MORB affinity. The computed melts in equilibrium with clinopyroxenes of peridotites and gabbro-norites show identical geochemical affinities and correspond to MORB-type depleted single melt increments formed by 5-7% of fractional melting of a spinel-facies DM asthenospheric mantle source (Piccardo and Guarnieri, 2010c).

Accordingly, at Monte Maggiore the melt migration and early crystallization stages were characterized by asthenospheric melts having almost identical LREE and incompatible trace element compositions, consistent with depleted single melt fractions. These melt increments infiltrated the lithospheric mantle at spinel-facies conditions at high melt/rock ratios and open system conditions and the peridotite minerals attained trace element equilibration with the percolating melts. Structural evidence indicate that during reactive percolation pyroxenes were progressively dissolved and olivine crystallized, causing progressive silica(-orthopyroxene)-saturation of the melts. It can be argued that the percolating melts maintain their primary strongly depleted geochemical signature, as recorded in the equilibrium minerals, during the reactive percolation at spinel-facies conditions but they were progressively modified from olivine-saturated to orthopyroxene-saturated compositions by pyroxene assimilation and olivine precipitation. The resulting strongly depleted, silica saturated basaltic liquids impregnated the mantle lithosphere at plagioclase-facies conditions and were later collected in dykelets and pods to form the gabbro-norite intrusive suite.

The replacive spinel harzburgite-dunite channels show sporadically interstitial and megacrystic clinopyroxenes and gabbroic veinlets that have been considered the early crystallization products of the melts migrating within the focused channels (e.g. Piccardo *et al.*, 2007a). In some massifs (Erro-Tobbio, Mt. Maggiore), these magmatic clinopyroxenes show strongly fractionated LREE patterns and depleted incompatible trace element contents, suggesting crystallization from depleted melts fractions (Piccardo and Vissers, 2007; Piccardo and Guarnieri, 2010c) (Fig. 12).

In other massifs (e.g. South Lanzo) the magmatic clinopyroxenes from spinel dunite channels shows moderately fractionated LREE patterns that are more compatible with clinopyroxenes in equilibrium with aggregated N-MORB melts (Fig. 13) (Piccardo *et al.*, 2007a). This evidence suggests a change in the melt dynamics after the early percolation of single melt fractions. The migration of aggregated MORBs within the replacive dunite channels indicate that the single melt fractions in the asthenosphere were more completely aggregated and mixed to form aggregated MORBs and that the dunite channels were exploited for delivery of the aggregated MORBs to shallow lithospheric levels. It can be argued that the aggregated MORB magmas passed through the mantle lithosphere migrating within these high porosity dunite channels, reached shallow lithospheric levels where they were intruded forming ephemeral gabbroic intrusions and were extruded at the sea-floor forming pillowed basaltic flows.

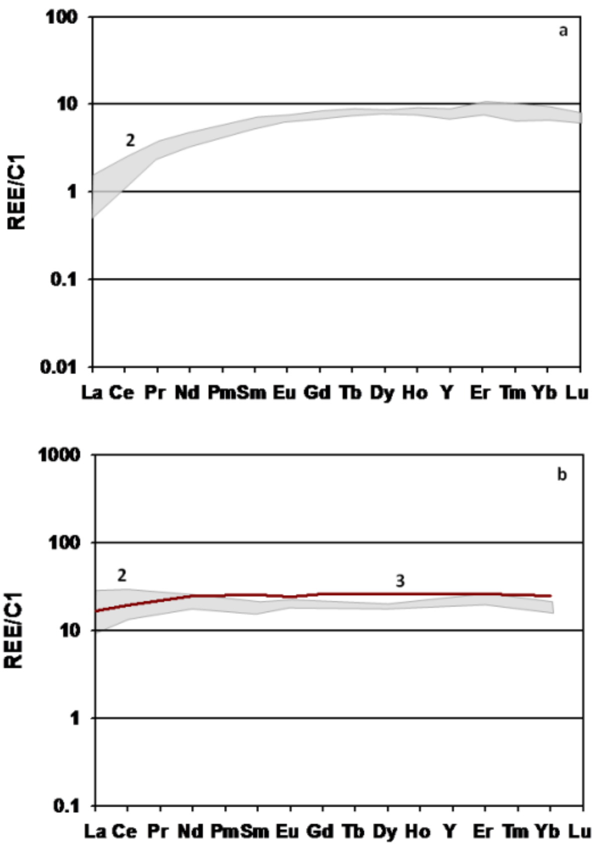
Figure 12. C1-normalized REE patterns of representative clinopyroxenes in distal replacive dunite channels of Erro-Tobbio (ET) and Mt. Maggiore (field 1) and calculated equilibrium liquids.



a) The distal replacive channels have magmatic interstitial clinopyroxenes showing strongly LREE fractionated C1-normalized REE patterns.

b) The liquids calculated in equilibrium with the representative clinopyroxene core compositions [using Cpx/liquid Kds of Hart and Dunn (1993)] are quite similar to those modelled for liquids formed by 4-7% fractional melting of spinel facies DM asthenospheric mantle source.

Figure 13. C1-normalized REE patterns of representative clinopyroxenes in distal replacive dunite channels of South Lanzo (field 2) and calculated equilibrium liquids.



a) The distal replacive channels of South Lanzo have magmatic clinopyroxenes showing slightly LREE fractionated C1-normalized REE patterns (field 2).

b) The REE patterns of liquids calculated in equilibrium with the representative clinopyroxene compositions [using Cpx/liquid Kds of Hart and Dunn (1993)] (field 2) are quite similar to those of aggregated N-MORB melts. The REE pattern of N-MORB from Hofmann (1988) is also reported for comparison (3).

Peridotite Distribution and Paleogeography

Field relationships

In the field, pyroxenite-bearing lithospheric lherzolites and deformed peridotites of the shear zones locally show primary contact with the reactive spinel harzburgites (Fig. 4). The contact is usually transitional in a few decimetre-wide zones: the deformed textures, the widespread pyroxenite banding and the clinopyroxene-rich compositions of the former rocks are rapidly modified passing to the reactive spinel harzburgites (e.g. Erro-Tobbio Massif, Piccardo and Vissers, 2007; Mt. Maggiore, Piccardo and Guarnieri, 2010b). In fact, the transition to the depleted rock type is marked by development of isotropic coarse granular textures, strong clinopyroxene depletion and olivine enrichment and disappearance of the spinel pyroxenite bands. At Monte Maggiore the spinel pyroxenite bands in the lithospheric lherzolites are progressively replaced by spinel dunite bands in the reactive harzburgites (Piccardo and Guarnieri, 2010b). Clinopyroxene-consuming and olivine-forming reactions, causing progressive clinopyroxene dissolution in peridotites and pyroxenites, are clearly evidenced by the presence of olivine replacement micro-textures on clinopyroxenes. Frequently, the reactive spinel harzburgites and the spinel dunite bands preserve structural relics, *i.e.* rounded spinel+orthopyroxene clusters, inherited from the pristine lithospheric lherzolites and pyroxenites that they replace.

In the distal peridotite massifs, decametric-hectometric remnants of pyroxenite-veined lithospheric lherzolites are preserved within the km-scale masses of reactive spinel harzburgites (e.g. Piccardo and Vissers, 2007; Piccardo and Guarnieri, 2010b). The replacement relationships of the reactive spinel harzburgites on the pyroxenite-bearing lithospheric lherzolites provide clear field evidence that the pristine subcontinental lithospheric mantle was early diffusely percolated by silica(-pyroxene)-undersaturated melts. It was significantly modified as for its structural and compositional characteristics and it was transformed into clinopyroxene-depleted reactive spinel harzburgites (e.g. Piccardo, 2003).

In the distal peridotite massifs, both pyroxenite-bearing lithospheric lherzolites and pyroxene-depleted reactive harzburgites show primary contacts with the enriched plagioclase peridotites (Fig. 6). Plagioclase-free and plagioclase-rich domains are usually in sharp contact and, locally, plagioclase-rich veins propagate from the plagioclase-rich peridotites inside the plagioclase-free spinel peridotites (e.g. Piccardo *et al.*, 2007a). Field relationships evidence that plagioclase enrichment occurred on km-scale masses of pre-existing reactive spinel harzburgites: this indicate that plagioclase enrichment represents a further process of melt diffuse percolation accompanied by early interstitial crystallization of plagioclase (and micro-gabbroic aggregates).

Palaeogeographic distribution

The Alpine-Apennine ophiolitic peridotites were exposed during Jurassic times at the sea-floor of the Ligure-Piemontese oceanic basin following continental break-up and formation of the paired Europe and Adria non-volcanic passive margins. These peridotites derived from the sub-continental lithosphere of the pre-Triassic Europe-Adria system that was exhumed starting from Triassic times as a consequence of passive extension of the Europe-Adria continental lithosphere (see discussion in Piccardo *et al.*, 2009, and references therein).

Present knowledge indicates that mantle peridotites of the marginal ophiolite sequences deriving from ocean-continent transition (OCT) zones of the Jurassic Ligure-Piemontese basin mostly consist of pyroxenite-bearing lithospheric spinel lherzolites, which show effects of subsolidus evolution and non-adiabatic exhumation from sub-continental spinel-facies mantle depths to the seafloor (e.g. Hoogerduijn Strating *et al.*, 1993; Montanini *et al.*, 2006; Piccardo and Vissers, 2007). Mantle peridotites of the distal ophiolite sequences deriving from more internal oceanic (MIO) settings of the basin mostly consist of reactive spinel harzburgites and impregnated plagioclase peridotites, which record significant effects of interaction with percolating asthenospheric melts (e.g. Müntener and Piccardo, 2003; Piccardo *et al.*, 2004, 2007a; Piccardo and Vissers, 2007). This indicates that the sub-continental mantle that was exhumed close to the continental margin escaped significant percolation and interaction of asthenospheric melts, whereas the sub-continental mantle that was exhumed at the more internal setting of the basin was profoundly percolated and interacted by the MORB-type melts rising from the melting asthenosphere.

Discussion

The wealth of structural and petrologic studies on the ophiolite sequences from the Alpine and Apennine terrains allow to reconstruct the main characteristics of formation, composition and evolution of the oceanic lithosphere of the basin of provenance, the Jurassic Ligure-Piemontese basin.

The palaeogeographic distribution of the different peridotite massifs indicate that continental break-up exposed at the sea-floor the sub-continental mantle, variably modified by melt-peridotite interaction. During progressive opening of the basin, shallower lithospheric mantle levels that had largely escaped melt percolation were exposed at the ocean floor earlier along the proximal margins, whereas deeper lithospheric mantle levels profoundly modified by melt percolation and melt-rock interaction were exposed in the more distal parts of the basin later on.

The heterogeneity of the Alpine-Apennine peridotites

Alpine-Apennine ophiolitic peridotites show strong compositional heterogeneity and exhumed sub-continental peridotites and melt-modified peridotites characterize, respectively, the ophiolite sequences deriving from marginal and distal settings of the basin.

The marginal Cpx-rich fertile lherzolites preserve structural and paragenetic features that indicate that these peridotites: i) were uplifted from garnet-facies conditions (P >= 2.5 GPa) and ii) were equilibrated at pressures compatible with spinel-facies conditions and mean temperatures of 1000°C, to an average continental geotherm. They are in places strongly deformed in up to km-scale shear zones, showing spinel- to plagioclase- to amphibole-(chlorite)-peridotite facies syn-tectonic metamorphic assemblages, followed by shallow serpentinization. The marginal peridotites maintain, accordingly, rather fertile compositions and spinel-facies assemblages that characterized the sub-continental lithospheric mantle protoliths and record the composite structural-compositional evolution that took place under progressive exhumation during pre-oceanic lithosphere extension and rifting.

The distal peridotites show extreme compositional heterogeneities, varying from pyroxene-depleted spinel harzburgites to plagioclase-enriched peridotites to spinel dunites. Their structural and compositional features indicate the effects of significant melt-rock interaction processes. Geochemical evidence indicates that impregnating melts were fractional melt increments showing MORB affinity, formed under Sp-facies conditions by fractional melting of a DM asthenospheric mantle source, suggesting that melting conditions were attained in the asthenosphere after significant adiabatic upwelling. Reactive and impregnated peridotites were strongly deformed in extensional shear zones that were exploited for the upward focused and reactive migration of MORB-type melts.

Compositional evidence (*i.e.* transition from early silica-undersaturated to late silica-saturated melts) suggests that the asthenospheric melts which percolated and interacted at spinel-facies conditions were progressively saturated by the reactive interaction (pyroxene dissolution/olivine precipitation) with the host peridotite, and were subsequently entrapped by interstitial crystallization at plagioclase-facies conditions within the lithospheric mantle.

A fundamental role in producing the extreme heterogeneity of the Alpine-Apennine ophiolitic peridotites was played by the upward migration by diffuse porous flow through the lithospheric mantle of MORB melts formed in the underlying melting asthenosphere during the rifting stage in the Ligure-Piemontese system. Depending on the melting process and melt dynamics in the melting source (fractional vs aggregate melts), the melt composition (silica-undersaturation vs saturation) and the depth and mode of percolation (spinel- or plagioclase-facies conditions, diffuse vs focused percolation, open system migration, high melt-rock ratios, low time-integrated melt-rock ratios), strongly different rock types are formed, both depleted and enriched in basaltic components, that cannot be formed by simple partial melting and melt extraction processes on a DM asthenospheric mantle.

The oceanic lithospheric mantle of the Ligure-Piemontese basin

The marginal peridotites consist of sub-continental fertile spinel lherzolites and remnants of these protoliths are preserved within the distal peridotites, nothwithstanding their profound structural and compositional modification by melt-peridotite interaction.

The marginal peridotites, that were exposed at the sea-floor at ocean-continent transition zones, derived from shallower lithospheric levels where they were only sporadically reached by the percolation fronts. The distal peridotites, that were exposed at the sea-floor at more intra-oceanic settings, were exhumed from deeper lithospheric levels where they were more profoundly modified by melt percolation and interaction. Present knowledge indicate that the whole oceanic lithospheric mantle was derived by the sub-continental mantle and was exhumed in different positions in the developing oceanic basin depending on its original location in the extending lithosphere.

Since the early eighties, the distal depleted spinel peridotites of the Internal Liguride ophiolites were considered refractory residua after extraction of the associated N-MORB (*i.e.* the Internal Liguride ophiolitic basalts) (e.g. Beccaluva *et al.*, 1984). The distal depleted spinel peridotites from the Internal Liguride Units and Corsica were considered similar to modern abyssal peridotites, having experienced an “oceanic-type” evolution, namely asthenospheric upwelling and MORB-type melting (e.g. Rampone *et al.*, 1996, 1997).

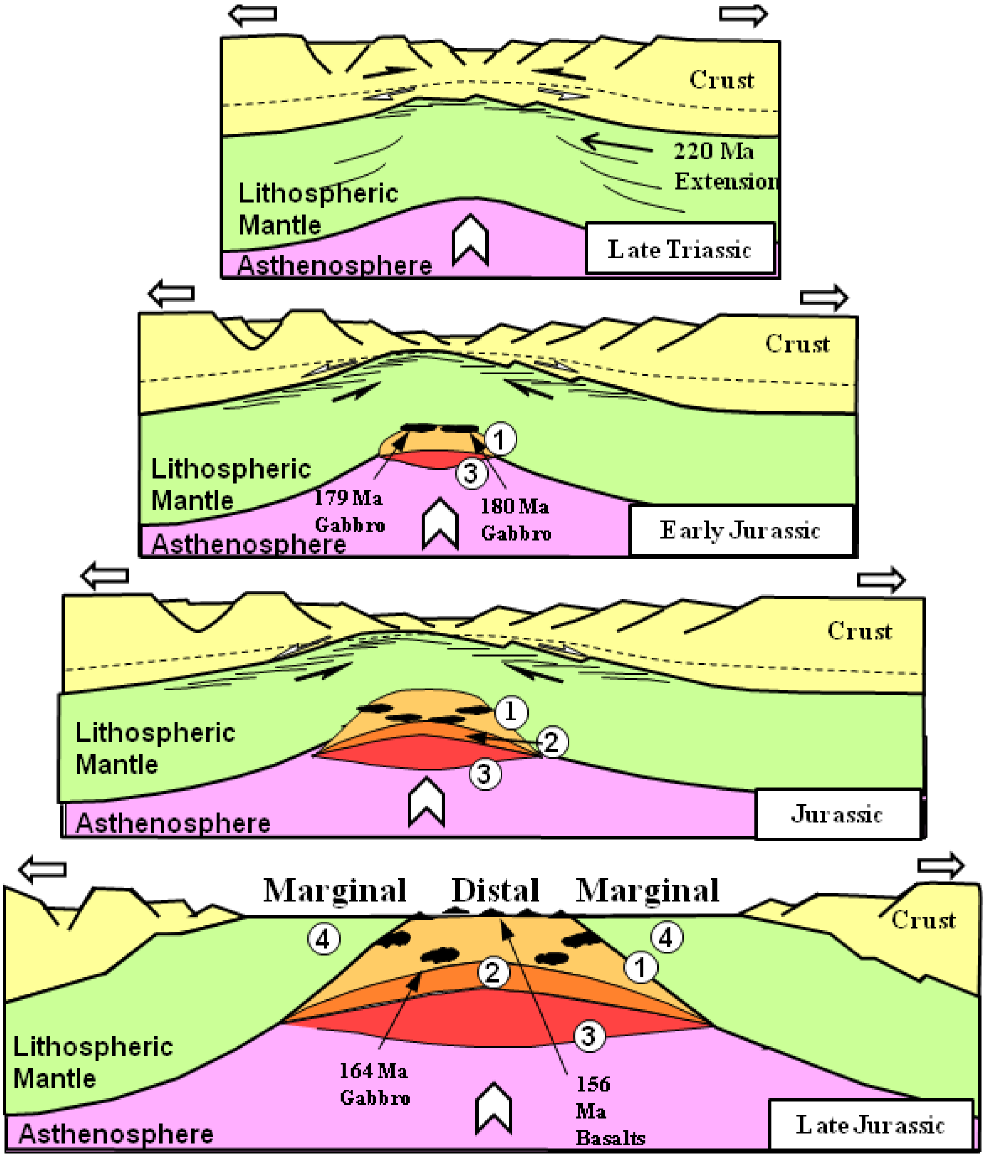
Recent studies (e.g. Piccardo, 2003; Rampone *et al.*, 2004; Piccardo *et al.*, 2007a; Piccardo and Vissers, 2007; Piccardo and Guarnieri, 2010a and 2010b) revealed that the depleted distal peridotites record contrasting bulk and mineral chemistry characteristics that cannot be simply induced by oceanic partial melting and melt extraction. They moreover show diffuse olivine-forming/pyroxene-dissolving melt-peridotite reaction micro-textures. The bulk of compositional and structural features of these depleted peridotites support their origin as reactive spinel harzburgites formed by melt-peridotite interaction at the expenses of sub-continental lithospheric protoliths.

The Triassic-Jurassic evolution of the Ligure-Piemontese realm

Passive continental extension, already active during Triassic times, caused the formation of extensional shear zones in the sub-continental lithosphere that was progressive exhumed to shallow lithospheric levels. Extension caused lithosphere necking and asthenosphere upwelling. After significant adiabatic upwelling, asthenosphere underwent decompression partial melting along the axial zone of the extensional system, most probably during Early Jurassic times (Fig. 14) (see discussion in Piccardo *et al.*, 2009, and references therein).

Asthenospheric melts percolated by porous flow through the lower lithospheric mantle, under spinel-facies conditions. Shear zones could have acted as preferential ways for initial focused percolation. Percolating melts were strongly depleted single melt fractions that interacted with the lithospheric mantle starting under spinel-facies conditions and formed pyroxene-depleted/olivine-enriched reactive spinel peridotites. They maintained their geochemical signature during reactive percolation but they were modified from olivine-saturated to orthopyroxene-saturated (Piccardo and Guarnieri, 2010d).

Figure 14. Schematic scenario of the geodynamic evolution of the Ligure-Piemontese basin (from top to bottom) (redrawn and modified after Brunn and Beslier, 1996, and Piccardo *et al.*, 2009).



Late Triassic times - Extension of the continental lithosphere by far field tectonic forces, tectonic exhumation of lithospheric mantle and adiabatic upwelling of the asthenosphere. Lithosphere extension was already active during Triassic (220-225 Ma), and was accomodated by km-scale extensional shear zones, as recorded in the subcontinental lithospheric peridotites exposed at the marginal settings of the basin during Late Jurassic continental break-up; Early Jurassic times - The adiabatically upwelling asthenosphere underwent decompressional partial melting (1). The asthenospheric melts infiltrated by porous flow mechanisms through the extending lithospheric mantle (2), most probably facilitated by the presence of extensional shear zones, and formed sporadic gabbroic intrusions (black bodies); Jurassic times - Ongoing extension caused further lithosphere exhumation and significant asthenosphere upwelling. Refractory residua after Jurassic partial melting were accreted to the base of the lithosphere (3); Late Jurassic times - The continental crust underwent complete break-up and failure, the non volcanic passive margins were formed and the sub-continental lithospheric mantle was exhumed and exposed at the sea-floor. The sub-continental lithospheric mantle peridotites (4), deriving from shallower mantle levels, were exposed at marginal OCT settings of the basin, close to the continental margins, whereas the deeper sub-continental lithospheric mantle, profounfly modified by melt-peridotite interaction processes, was exhumed and exposed at more distal intra-oceanic settings of the basin.

The strongly depleted, silica saturated melt fractions reached shallower, plagioclase facies conditions. They underwent interstitial crystallization in the percolated peridotites, forming impregnated plagioclase peridotites.

The percolation pathways in peridotites were clogged by interstitial crystallization and pods and dykelets of gabbro-norite intrusives were formed (Piccardo and Guarnieri, 2010c). These strongly depleted, variably silica-saturated melts were, accordingly, entrapped and stored into the shallow lithospheric mantle. This early fractional melts stagnated and refertilized the shallow lithospheric mantle forming widespread impregnated plagioclase peridotite bodies. These melts never reached the surface since lava flows with similar compositional characteristics did never erupt at the sea-floor of the extending basin (Piccardo *et al.*, 2009).

All the pre-existing rock types and, particularly, the impregated plagioclase peridotites were deformed along km-scale shear zones that acted as structural discontinuities for further upward migration of MORB melts (e.g. Piccardo and Vissers, 2007), that were in many cases aggregated MORB magmas. These aggregated MORB melts were delivered to shallow lithospheric depths, where intruded as ephemeral gabbroic intrusions, or extruded at the sea-floor as pillowed basaltic lava flows. These intrusive and extrusive products of the upwelling aggregated MORBs constituted the oceanic crustal rocks of the Ligurian lithosphere.

From diffuse continental extension to focused oceanic spreading

The Ligure-Piemontese oceanic basin was formed by passive stretching by far field tectonic forces of the pertinent Europe-Adria lithosphere (see discussion in Piccardo and Vissers, 2007). The extension of the lithospheric mantle was, most probably, an ultra-slow process and was accommodated by a network of shear zones. As discussed by Piccardo *et al.* (2009), continental extension in the Europe-Adria system was already active, most probably, during Triassic times (around 220-225 Ma, e.g. Montanini *et al.*, 2006; Muentener and Hermann, 2001) and the onset of major rifting occurred in Liassic times (around 190 Ma, e.g. Capitanio and Goess, 2006), whereas only minor amount of extension was contributed by earlier very slow continental extension and rifting (e.g. Dercourt *et al.*, 1986; Froitzheim and Manatschal, 1996).

Continental extention and stretching facilitated the progressive adiabatic upwelling of the asthenosphere which underwent partial melting under decompression and MORB melt extraction after more than 40 Ma of passive lithosphere extension. Information on the inception of asthenosphere melting under decompression are furnished by the first appearance of asthenospheric MORB melts intrusions into the extending lithospheric mantle. The oldest gabbroic bodies yielded Early Jurassic intrusion ages (180-179 Ma) (Tribuzio *et al.*, 2004; Borghini *et al.*, 2007).

Asthenospheric melts infiltrated through, and were entrapped in the mantle lithosphere. The spinel-facies lithospheric mantle protoliths record temperatures in the range 900-1100°C that are related to their residence in the subcontinental lithosphere, whereas the melt-modified peridotites of the distal ophiolites record peak temperatures of 1250-1300°C (Piccardo *et al.*, 2009, and references therein). This indicates that significant heating by asthenosphere upwelling and melt percolation induced asthenospheric thermal conditions in the percolated lithospheric mantle. This implies that significant rheological modifications were induced in the extending “cold” mantle lithosphere along the axial zone of the extending system in connection to asthenosphere upwelling and melt percolation. Accordingly, abundance of “hot” melt-modified peridotites in the distal ophiolites indicates that: 1) substantial volumes of melts from the asthenosphere were entrapped in the lithospheric mantle, and 2) significant portions of lithospheric mantle underwent thermo-chemical erosion.

The thermal erosion of the lithosphere along the axial zone of the extending system induced the rapid decrease in the total strength of the lithosphere. The significant rheological modification of the mantle lithosphere should have caused a significantly faster extension and have played an important role in the geodynamic evolution of the system, enhancing transition from ultra-slow diffuse continental extension to localized oceanic spreading (Ranalli *et al.*, 2007). Accordingly, the entrapment of asthenospheric melts in the shallow mantle lithosphere during the rifting stages of the system played a crucial role in the geodynamic evolution of the extensional system, enhancing the transition from ultra-slow diffuse lithosphere extension to focused oceanic spreading.

The oceanic stage in the Ligurian Tethys

It is widely accepted that the “oceanic stage” in the Jurassic Ligure-Piemontese basin was characterized by the complete removal of the continental crust, the formation of non-volcanic passive continental margins, and the exposure at the sea floor mantle peridotites bearing gabbroic intrusions. The new oceanic crust was characterized by a discontinuous basaltic cover on top of the exposed mantle peridotites, and by the deposition of oceanic sediments. Present knowledge on depleted spinel peridotites from the distal peridotite massifs evidence that they represent reactively modified, former sub-continental lithospheric mantle, and not refractory residua after MORB-forming asthenosphere partial melting. Shallow sub-continental lithospheric mantle was exhumed and exposed at marginal settings of the basin, whereas deeper lithospheric mantle, strongly modified by interaction with percolation asthenospheric MORB-type melts, was exhumed and exposed at more distal intra-oceanic settings during more advanced oceanization stages. Accordingly, the oceanic basin was floored by mantle peridotites deriving from the sub-continental mantle.

The lack of Jurassic oceanic refractory residua within the peridotite massifs exposed in distal settings poses a basic question about the meaning of the “oceanic stage” in the Ligurian Tethys, since the oceanic lithosphere of the basin, as represented by the distal ophiolites, was not formed by the products of asthenosphere partial melting, *i.e.* basalts and gabbros derived from the melt fraction, and abyssal peridotites representing mantle refractory residua. The transition from marginal peridotites to distal peridotites does not represent the transition from exposed sub-continental mantle to oceanic mantle (*i.e.* Jurassic refractory residua).

Accordingly, on the basis of present knowledge, it can be envisaged that the “oceanic stage”, frequently related in the past to the distal ophiolites of the Ligure-Piemontese basin, was characterized mainly by the failure of the continental crust. Although the lithosphere was drastically softened and thinned, complete break-up of the sub-continental mantle lithosphere did not occur in the Ligurian Tethys basin, and a complete oceanic lithosphere, consisting of magmatic rocks and peridotite refractory residua, deriving from Jurassic asthenosphere partial melting, was not formed.

The lack of refractory residua after oceanic partial melting within the known distal Alpine-Apennine ophiolitic peridotites and, accordingly, the lack of associated refractory residua and produced melts, evidence that the basin did not reach a “mature” stage in the classic sense.

Conclusive Remarks

Present knowledge on structure and petrology of the Alpine-Apennine ophiolitic peridotites from the Jurassic Ligurian Tethys basin shows that the evolution of the lithosphere-asthenosphere system during the rifting stages of the basin was driven by interdependent and mutually enhancing tectonic and magmatic processes. Far-field tectonic forces, already active during Triassic times, caused the progressive extension and thinning of the continental lithosphere and the adiabatic upwelling and decompression melting of the asthenosphere starting from early Jurassic times. The subcontinental lithospheric mantle underwent significant extension by means of a network of extensional shear zones that caused its progressive exhumation and final sea-floor exposure at the marginal OCT settings of the basin.

MORB melts from the asthenosphere percolated by porous flow through the mantle lithosphere along the axial zone of the extending system. Melt-peridotite interaction caused significant modification of the lithospheric mantle and the migrating melts were entrapped in the lithosphere by interstitial crystallization. Melt reactive percolation and entrapment in the lithospheric mantle during Jurassic times was responsible for the extreme heterogeneity of the lithospheric mantle which was exhumed and exposed during more advanced Late Jurassic oceanization stages at more distal intra-oceanic settings of the basin.

The entrapment of asthenospheric melts in the shallow lithospheric mantle during the rifting stages prevented melt extrusion during the continental break-up, which resulted in the non-volcanic nature of the passive rifted margins. Lithosphere melt impregnation and asthenosphere-lithosphere interaction induced significant reduction of the total strength of the sub-continental mantle along the axial zone of the extending system that, most probably, enhanced the transition from ultra-slow diffuse lithosphere extension to focused oceanic spreading.

The known ophiolite sequences from the distal intra-oceanic settings are still characterized by sub-continental lithospheric upper mantle, strongly modified by the melt-peridotite interaction they experienced during pre-oceanic rifting. In fact, the depleted spinel peridotites of the distal settings are reactive peridotites formed by melt-peridotite interaction and do not represent refractory residua after oceanic-type asthenosphere partial melting.

Acccordingly, the Ligure-Piemontese basin most probably did not reach a mature oceanic stage characterized by the sea-floor exposure of cogenetic refractory residua after Jurassic oceanic melting and the related melts.

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