ALPINE-APENNINE OPHIOLITIC PERIDOTITES: NEW CONCEPTS ON THEIR COMPOSITION AND EVOLUTION

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ABSTRACT

Ophiolites exposed in the Alpine-Apennine mountain range represent the oceanic lithosphere of the Ligurian Tethys, a small oceanic basin separating the Europe and Adria plates in Mesozoic times. Most of the peridotites represent former subcontinental mantle which was: (i) isolated from the convective mantle at different times (from Proterozoic to Permian); (ii) accreted to the thermal lithosphere, where it cooled along a conductive geothermal gradient under spinel peridotite facies conditions.

Our investigations reveal important records of melt/peridotite interaction and melt impregnation (i.e. formation of plagioclase peridotites), which were related to asthenosphere/lithosphere interaction occurred during lithospheric extension leading to rifting and drifting of the Jurassic Ligurian Tethys. The early asthenosphere/lithosphere interaction was caused by the reactive percolation of asthenospheric melts, which induced significant depletion, refertilization and heating of the lithospheric mantle peridotites. The plagioclase peridotites of the Alpine-Apennine ophiolites mostly derive from melt impregnation, whereas part of the depleted spinel peridotites result from reactive percolation of depleted MORB-type melts, rather than being solely refractory residua after near-fractional melting. The presence of large areas of impregnated peridotites indicates that significant volumes of melts were trapped in the lithospheric mantle. Subsequently, the asthenospheric melts reached the surface, both intruding as MORB gabbroic bodies or extruding as MORB lava flows.

These peridotites record two magmatic cycles: (1) An early magmatic, non-volcanic stage: the early diffuse porous flow percolation and impregnation by single melt increments, focused percolation in dunite channels and intrusion of MORB-type melts; (2) A late magmatic, volcanic stage: the late intrusion and extrusion of magmas deriving from aggregated MORB liquids.

The sequence of periods characterized by absence (non-volcanic or a-magmatic or magma-starved stages) and presence (volcanic or magmatic stages) of volcanism represents one of the most peculiar feature of slow and very-slow spreading ridges. Melt stagnation in the oceanic lithospheric mantle has been proposed as the dominant mechanism of peridotite impregnation and plagioclase peridotite formation along slow spreading systems. It could be that amagmatic periods of (ultra-) slow spreading ridges are characterized by melt stagnation in the thermal lithosphere, leading to plagioclase peridotite formation.

Our results evidence the great variability in terms of melt composition and regime of melt percolation during the rift evolution. They provide, moreover, a mechanism to explain non-volcanic and volcanic stages during the rift evolution of the Ligurian Tethys and might be equally applicable to modern slow spreading ridges, which are characterized by variable magmatic (volcanic) and amagmatic (non-volcanic) stages.

INTRODUCTION

The ophiolitic peridotites exposed along the Western Alps – Northern Apennine orogenic belt represent mantle sections of the oceanic lithosphere of the Piedmont-Ligurian ocean (or Ligurian Tethys) basin, which separated, during Late Jurassic – Cretaceous times, the Europe and Adria plates. The Ligurian Tethys opened by progressive divergence of the Europe and Adria blocks, in connection with the pre-Jurassic rifting and Late Jurassic opening of the Northern Atlantic (Dewey et al., 1973; Lemoine et al., 1987) (Fig. 1).

Structural and petrological evidence indicate that these mantle peridotites were exhumed, following a subsolidus tectonic-metamorphic evolution, from spinel-facies lithospheric mantle depths to shallow levels, were intruded by MORB-type gabbroic rocks and were exposed on the seafloor, where they were directly covered by MORB lava flows and Upper Jurassic radiolarian cherts, i.e. the first oceanic sediments. Accordingly, Alpine-Apennine ophiolites show a peculiar stratigraphy represented by an older serpentinized peridotite basement, with gabbroic intrusions, covered by an Upper Jurassic volcanic-sedimentary sequence.

Extensional allochthons of continental basement rocks and their pre- and syn-rift sedimentary cover locally overlie the exhumed mantle rocks in the Eastern and Central Alps (Froitzheim and Manatschal, 1996; Manatschal and Nievergelt, 1997). In the External Ligurides, olistoliths of pillowed MOR basalts and fertile mantle peridotites are locally associated with continental crust (Marroni et al., 1998). Petrologic, geochemical and isotopic evidence indicates that, in many areas of the Alps and the Apennines, the peridotite basement represents former subcontinental mantle (Piccardo 1976; Piccardo et al. 1990,1994; Trommsdorff et al. 1993; Rampone et al. 1995; Müntener and Hermann 1996; Rampone et al., 1998; Rampone and Piccardo, 2000; Müntener et al., 2004).

The peculiar stratigraphy and the presence of fertile peridotites derived from the subcontinental mantle led some authors to stress the diversity of the Alpine-Apennine ophiolites compared with mature oceanic lithosphere formed at mid-ocean ridges. Based on the atypical association of MORB magmatism and fertile subcontinental mantle, it was proposed that Alpine-Apennine ophiolites are different from mature oceanic lithosphere formed at mid-ocean ridges (Decandia and Elter, 1969, 1972; Piccardo, 1976). It was suggested (Piccardo, 1977; Beccaluva and Piccardo, 1978) that the Ligurian ophiolites were formed during early stages of opening of the Ligurian Tethys, following rifting, thinning, and break-up of the continental crust, and were therefore located in a marginal, peri-continental position of the Jurassic oceanic basin.

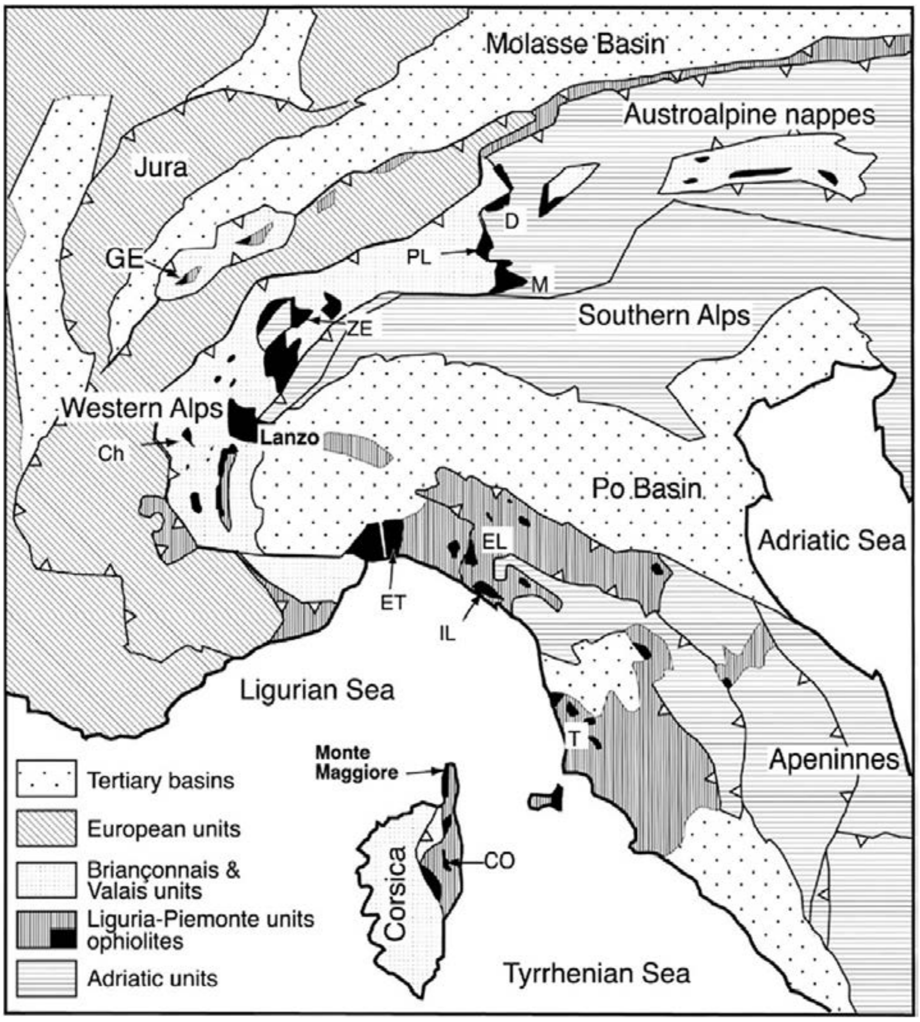

Fig. 1 - Generalized tectonic overview of the Alpine – Northern Apennine ophiolites (redrawn and modified after Schaltegger et al., 2002, Müntener and Piccardo, 2003). Abbreviations are: D = Totalp peridotite; Pl = Platta ophiolite; M = Malenco peridotite; ZE = Saas Zermat ophiolite; Ch = Chenaillet ophiolite; ET = Erro-Tobbio peridotite; EL = External Ligurides ophiolite; IL = Internal Ligurides ophiolite; T = Tuscan ophiolite; CO = Corsica ophiolite; GE = Gets ophiolite.

Rifting and opening of the Piedmont-Ligurian basin was driven by the passive extension of the Europe-Adria lithosphere. Rifting was recorded in the lithospheric mantle by development of extensional shear zones, leading to gradual upwelling of segments of the spinel-facies lithospheric mantle (Hoorgeduijn Strating et al., 1993; Müntener et al., 2000), and by incipient recrystallization under decompression to plagioclase-facies conditions (Piccardo, 1976; Rampone et al., 1993, 1995).

Extension and thinning of the lithosphere were accompanied by almost adiabatic upwelling of the underlying asthenosphere, which underwent partial melting under decompression.

New petrologic and geochemical evidence on the Alpine-Apennine ophiolitic peridotites (Piccardo, 2003; Müntener and Piccardo, 2003; Zanetti et al., 2003; Piccardo et al., 2004a) indicates that, during an initial stage, single melt increments derived from partial melting of the asthenosphere migrated upwards by diffuse porous flow through the overlying lithosphere. Melt/peridotite reaction and melt impregnation characterized the melt migration through the mantle lithosphere, enhancing asthenosphere/lithosphere interaction and causing chemical and thermal modifications of the lithospheric mantle.

The space-time evolution of melt migration processes in the lithosphere is particularly well preserved in the Alpine-Apennine ophiolitic peridotite massifs which were exhumed by extensional tectonics to shallow levels and were exposed on the sea-floor. After melt/peridotite interaction, ongoing cooling by conductive heat loss during progressive thinning of the lithosphere generally prevented subsequent partial melting and preserved large domains in the peridotites which maintain textural, petrologic and geochemical records of these early magmatic processes.

This paper presents recent results of an ongoing program of new field, textural, petrologic and geochemical studies on some Alpine-Apennine ophiolitic peridotite masses. We summarize recent field and microtextural observations, which outline the importance of melt/rock reaction processes in the interpretation of the Tethyan mantle lithosphere, and discuss several peridotite massifs by introducing more recent microstructural and petrologic-chemical observations. We will conclude that the temporal and spatial location of mantle processes is relevant for the evaluation of Alpine-Apennine peridotites and, in particular, the early history of rifting and opening of the Ligurian Tethys.

ALPINE - APENNINE OPHIOLITIC PERIDOTITES

Most peridotites from the Alpine – Northern Apennine ophiolites (Eastern-Central Alps, Lanzo, Liguria, Corsica) are lherzolites and cpx-bearing harzburgites, which can broadly be separated into two groups (Müntener and Piccardo, 2003): (1) variably depleted spinel peridotites (e.g. the Davos, Malenco and Upper Platta peridotites, and some of the External Liguride peridotites), showing abundant pyroxenite layers and locally phlogopite-hornblendite veins, diffuse LREE-depleted titanian pargasitic to kaersutitic amphiboles and, sporadically, thin plagioclase + olivine rims between spinel and pyroxenes (Peters, 1963; Piccardo, 1976; Rampone et al., 1995; Müntener and Hermann, 1996; Desmurs, 2001); (2) amphibole-free, spinel to plagioclase peridotites [e.g. Lower Platta, Chenaillet, Lanzo, Erro-Tobbio (Voltri Massif), Internal Ligurides, and Monte Maggiore (Corsica)], showing large areas where plagioclase is abundant, whereas plagioclase-free spinel peridotite is subordinate.

The Malenco, Totalp and Upper Platta units are fertile to moderately depleted spinel lherzolites, cut by several generations of pyroxenite dikes (both spinel websterites and garnet pyroxenites) and rare hornblendites (Peters, 1963; Müntener and Hermann, 1996; Desmurs, 2001). Plagioclase peridotites are only found in the Lower Platta unit (Müntener et al., 2004). Eastern Central Alpine peridotites consist of two domains: 1) peridotites exhumed close to the Mesozoic continental margin are dominated by spinel lherzolite compositions, whereas 2) peridotites exhumed further away from the continent are dominated by plagioclase-bearing peridotites (Müntener et al., 2004). Clinopyroxenes from spinel peridotites (Malenco, Davos, Upper Platta) show significantly higher contents in fusible components and lower equilibration temperatures of 850 to 950°C than clinopyroxenes from the plagioclase peridotites from the Lower Platta unit, which show equilibration temperatures up to 1200°C. Most clinopyroxenes from the spinel lherzolites have a weak LREE to HREE fractionation and no Eu anomaly, whereas clinopyroxenes from the plagioclase peridotites show generally convex upward REE patterns with high MREE contents and a significant negative Eu anomaly, indicating equilibration with plagioclase (Müntener et al., 2004). Clinopyroxenes with a strongly fractionated REE pattern, similar to that of depleted clinopyroxenes from abyssal peridotites, locally occur next to plagioclase-bearing peridotites in the same outcrop. These clinopyroxenes, possessing a strongly fractionated REE pattern show high Nd ratios, coupled with extremely high $^{147}Sm/^{144}Nd$, indicative of a Permian age of depletion (294±16Ma) (Müntener et al., 2004). Present knowledge indicate that the Eastern Central Alpine peridotites are mainly subcontinental spinel lherzolites. They have been partially refertilized by percolating MOR-type liquids, which caused reset of the Nd isotopic ratios to values similar to the composition of the infiltrating liquid, and transformed most of the former spinel lherzolites into plagioclase-bearing peridotites (Müntener et al., 2004).

The Lanzo peridotite massif is composed by plagioclase-free spinel peridotites and plagioclase-enriched peridotites. Both peridotites are cut by a younger suite of discordant dunite, replacive in origin (Boudier and Nicolas, 1972; Boudier, 1978), followed by various sets of gabbroic veins and dikes. The variably depleted spinel peridotites have been interpreted as mantle residua after partial melting. The plagioclase peridotites were thought to be formed either as the residuum of low-degrees of partial melting (Bodinier, 1988) or as a result of melt formation and incomplete melt extraction and crystallization in an upwelling diapir (Boudier and Nicolas, 1972; Boudier, 1978; Nicolas, 1986). Structural, as well as bulk-rock and isotopic data have been used to define two main domains: (i) The Northern Body, which is characterized by fertile lherzolitic composition, has been considered to represent a fragment of the sub-continental lithosphere which became isolated by the convective mantle at 400-700 Ma (Bodinier et al., 1991); (ii) The Southern Body, which displays more refractory compositions (Bodinier, 1988; Bodinier et al., 1991), has been interpreted as an asthenospheric diapir that rose from the garnet stability field and was emplaced in the early Mesozoic, during the opening of the Ligurian Tethys.

The Erro-Tobbio spinel peridotites consist of partly serpentinized cpx-poor lherzolites and harzburgites. Bulk-rock and mineral chemistry data on the Erro-Tobbio peridotites point to an overall depleted signature. The isotopic composition of the Erro-Tobbio mantle protolith is similar to other peridotites such as Lanzo and Internal Ligurides, and is indistinguishable from modern depleted MORB-source reservoirs (Romairone, 1999). Structural and petrological investigations have indicated that the oldest features are represented by granular texture and spinel-facies assemblage: they were overprinted by spinel-, to plagioclase-, to hornblende-bearing peridotite tectonites and mylonites forming composite km-scale shear zones (Ernst and Piccardo, 1979; Ottonello et al., 1979; Piccardo et al., 1990, 1992; Hoogerduijn Strating et al., 1990, 1993; Vissers et al., 1991). Thermometric estimates (Hoogerduijn Strating et al., 1993) suggested that the Erro-Tobbio peridotites underwent a progressive temperature decrease from spinel-facies (T ranging 1000-1100°C), to plagioclase-facies (T ranging 900-1000°C), to hornblende-facies (T lower than 900°C) conditions.

The Internal Liguride peridotites consist of cpx-poor (5-10 vol%) spinel lherzolites. They show depleted compositions that closely resemble those of abyssal peridotites; they show complete recrystallization under spinel-facies conditions at temperatures in the range 1150-1250°C (Ernst and Piccardo, 1979; Ottonello et al., 1979, 1984; Beccaluva et al., 1984; Rampone et al., 1996). Sr and Nd isotope ratios of some Internal Liguride (Mt. Fucisa) peridotites suggest a Permian age of depletion (Rampone et al., 1996). Microtextural and chemical features recording melt/peridotite interaction have been described by Rampone et al. (1997).

The External Ligurides peridotites are dominantly fertile spinel lherzolites with coarse granular to tectonite-mylonite textures. They display a complete static equilibrium recrystallization under spinel-facies conditions and T < 1100°C and the presence of disseminated kaersutite / titanian pargasite amphiboles, in equilibrium with the spinel-facies assemblage (Piccardo, 1976; Ernst and Piccardo 1979; Ottonello et al., 1979; 1984; Beccaluva et al., 1980, 1984; Piccardo et al., 1990; Rampone et al., 1993,1995). A spinel-lherzolite sample from the External Liguride (Suvero) peridotites displays extremely depleted isotopic composition and yields Sr and Nd model ages spanning from 2.1 to 2.4 Ga, which have been interpreted as the minimum ages of differentiation from the asthenospheric mantle (Rampone et al., 1995). The External Liguride spinel peridotites show incipient partial recrystallization to plagioclase-bearing assemblages, at relatively low temperatures (T = 900-950°C) conditions (Beccaluva et al., 1984; Rampone et al., 1995).

At Monte Maggiore (Corsica), both spinel peridotites and plg-enriched peridotites are present. Spinel peridotites are clinopyroxene-poor spinel lherzolites and have been interpreted as mantle residua after MORB-forming partial melting processes (Jackson and Ohnenstetter 1981; Rampone et al., 1997). A Jurassic age of depletion has been suggested by Rampone et al. (2003), on the basis of Sm/Nd isotope data. The presence of diffuse records of trapped mafic melts have been early described by Jackson and Ohnenstetter (1981); presence and abundance of plagioclase blebs, peculiar melt/peridotite reaction textures and chemical features (i.e. Ti, M-HREE, Zr, Y, Sc enrichment and Al depletion of mantle cpx) have been described and interpreted by Rampone et al., (1997) as evidence of trapped melts that probably consisted of unmixed depleted melt increments produced by 6-7% fractional melting of an asthenospheric mantle source.

The Alpine-Apennine ophiolitic peridotites are mostly derived from the subcontinental mantle lithosphere of the Europe-Adria system and preserve structural, petrologic and geochemical records of a composite evolution starting from their isolation from the convective asthenosphere and accretion to the subcontinental lithosphere, to their exposure at the sea-floor of the Jurassic Ligurian Tethys oceanic basin (as summarized by Rampone and Piccardo, 2000).

1) Partial melting

Alpine-Apennine ophiolitic peridotites are both fertile and cpx-poor lherzolites: the depleted rocks have compositional characteristics similar to those of refractory residua after fractional melting. Available Nd model ages which have been related to the melting event in the various peridotite masses seem to indicate that solely the residual peridotites of Monte Maggiore could record partial melting during Jurassic times (Rampone, 2002; Rampone et al., 2003). The Internal Liguride peridotites and some of the Platta peridotites show Permian model ages of depletion (Rampone et al., 1996; Müntener et al., 2004), which have been related to partial melting of upwelling asthenosphere during Permian extension of the continental lithosphere.

2) Lithospheric accretion / annealing recrystallization

Most of the investigated peridotite masses show a complete metamorphic recrystallization at spinel-facies conditions, and temperatures in the range 900-1100°C. This has been interpreted as the annealing recrystallisation of the different peridotite bodies during accretion to the subcontinental thermal lithosphere (e.g. Piccardo et al., 1990; Rampone and Piccardo, 2000). Available Sm-Nd DM model ages suggest that the different peridotite masses were isolated from the convective asthenosphere and accreted to the conductive lithosphere from Proterozoic to Mid-Jurassic times.

3) Subsolidus decompressional evolution

The passive extension of the Europe-Adria lithosphere and the inception of rifting in the Piedmont-Ligurian basin were recorded in the lithospheric mantle by development of km-scale extensional shear zones, leading to progressive unroofing of sectors of the subcontinental lithospheric mantle. These mantle sectors underwent exhumation through the plagioclase and/or amphibole-chlorite peridotite facies conditions, and later underwent widespread serpentinization while reaching shallow crustal levels. Thermometric estimates indicated that the temperature conditions were slightly to significantly decreasing during the subsolidus decompressional evolution (Piccardo, 1976; Hoorgeduijn Strating et al., 1993; Rampone et al., 1993,1995; Müntener et al., 2000).

4) Shallow level MORB gabbroic intrusion

The Alpine–Apennine ophiolitic peridotites are intruded by meter-wide gabbroic dykes and km-scale gabbroic bodies, showing sharp contacts and chilled margins to the country peridotite and cutting across all previous mantle structures. Mafic intrusives vary in composition from rather primitive troctolites to Mg-gabbros to Fe-Ti-gabbros, and rare plagiogranites. Computed liquids in equilibrium with clinopyroxene from the most primitive olivine gabbros are closely similar to average aggregated MORBs. Accordingly, MORB-type evolved magmas were intruded in the exhumed lithospheric mantle when it was already cold and brittle, at shallow levels in the conductive lithosphere.

5) Sea-floor exposure and MORB extrusion

Mantle exhumation led to sea-floor exposure of large masses of lithospheric peridotites, and their MORB gabbroic intrusions. The exhumed gabbro-peridotite basement was partially covered by ophicarbonates and, subsequently, by a discontinuous layer of pillowed basalts, punctuated lava flows and Upper Jurassic radiolarian cherts. Together, they built up the peculiar oceanic lithosphere of the Jurassic Ligurian Tethys basin.

RECENT STUDIES

New field, microtextural, petrological and geochemical investigations and reconsideration of previous data allow to recognize the existence of significant records of melt/peridotite interaction processes that modified significantly textural and compositional characteristics of these ophiolitic peridotites during their composite mantle evolution.

Field observations

Detailed field investigations show that many of the peridotite massifs have large areas consisting of plagioclase-enriched peridotites, which replace previous granular and tectonite spinel peridotites. The plagioclase-enriched areas are frequently associated with anostomosing networks of spinel dunite bodies. The spinel peridotites (including spinel pyroxenite banding), represent the oldest rock types which are replaced by the plagioclase-enriched parageneses. Dunite bodies and channels cut through both tectonitic spinel peridotites and plagioclase-enriched peridotites and show transitional contacts to the wall rock. Thin, cm-scale dikelets of gabbroic or gabbro-noritic compositions are associated with dunites and occasionally cut across the surrounding peridotites, showing fuzzy contacts with the enclosing ultramafic rocks.

Microtextural investigations

Large areas of the spinel peridotites, associated in the field to the plagioclase peridotites, show a variety of microtextures (i.e. olivine rims surrounding mantle pyroxenes), which indicate partial dissolution of pyroxenes and formation of new olivine.

Plagioclase-enriched peridotites show a variety of microtextures (i.e. orthopyroxene + plagioclase aggregates surrounding and replacing mantle clinopyroxenes, mm-size pods of undeformed noritic or gabbroic aggregates, interstitial and crosscutting the deformed mantle minerals), which indicate the partial dissolution of mantle clinopyroxene and the interstitial crystallization of melts.

As described in details and discussed elsewhere (Piccardo, 2003; Müntener and Piccardo, 2003; Piccardo et al., 2004a and b), these microtextures indicate interaction between peridotites and asthenospheric melts, which vary in composition from pyroxene-undersaturated to pyroxene-(silica-)saturated.

Petrologic-geochemical investigations

New bulk rock and mineral major and trace element studies evidence that the compositions of peridotites and mantle minerals have been significantly modified during the melt/peridotite interaction, suggesting: (1) reactive porous flow circulation of pyroxene-undersaturated melts, melt/peridotite reaction and attainement of melt/mineral trace element equilibrium during reactive percolation (Müntener et al., 2004; Piccardo et al., 2004a and b; Rampone et al., 2004); (2) impregnation and refertilization (i.e. addition of basaltic components) by variably pyroxene(-silica)-saturated melts, which modified their compositions (attaining silica saturation and trace element enrichment) during deeper reactive porous flow percolation (Müntener and Piccardo, 2003; Zanetti et al., 2003; Müntener et al., 2004; Piccardo et al., 2004a and b).

On the basis of the differences in terms of field, petrographic and geochemical characteristics, three main groups of ultramafic rocks recording melt-peridotite interaction can be recognized within the Alpine-Apennine ophiolitic peridotites. These are: (1) the reactive spinel peridotites; (2) the impregnated plagioclase peridotites; (3) the replacive spinel dunites. In the following sections, a detailed report on the petrographic and geochemical features of these peridotites is furnished.

THE REACTIVE PERIDOTITES

These mantle ultramafics are clinopyroxene- and/or clinopyroxene-orthopyroxene-depleted, olivine-enriched peridotites. They have been, so far, recognized and studied in the Lanzo, Erro-Tobbio, Internal Liguride and Monte Maggiore (Corsica) massifs. These peridotites show reaction microtextures, indicating pyroxene dissolution and olivine crystallization, and contrasting bulk rock and mineral chemistries.

Mantle pyroxenes are deeply embayed and corroded, suggesting reaction of mantle pyroxenes with a pyroxene-undersaturated asthenospheric melt, whereas significant olivine crystallization during melt percolation is indicated by the formation of: i) broad rims of new, unstrained olivine around pyroxenes, ii) interstitial unstrained olivine grains between deformed, kinked and exsolved mantle minerals, and iii) euhedral olivine crystals within exsolved mantle pyroxenes (for textures, see: Müntener and Piccardo, 2003; Piccardo et al., 2004a and b).

The modal composition of these peridotites, although being strongly variable, is always characterized by low to very low clino- and orthopyroxene contents, anomalously high cpx/opx ratios (sometimes approaching unity) and high to very high olivine contents (up to 85% by volume). They generally show bulk rock compositions significantly SiO_2–depleted, at similar MgO contents, with respect to the estimated compositions of partial melting residua (Niu, 1997) (Fig. 2). Moreover, in the bulk rock Mg# vs. modal olivine diagram (after Bedini et al., 2002), their compositions do not plot along the calculated melting trends, but they plot along the calculate reactive porous flow trends (Fig. 3) (Piccardo et al. 2004b; Rampone et al., 2004).

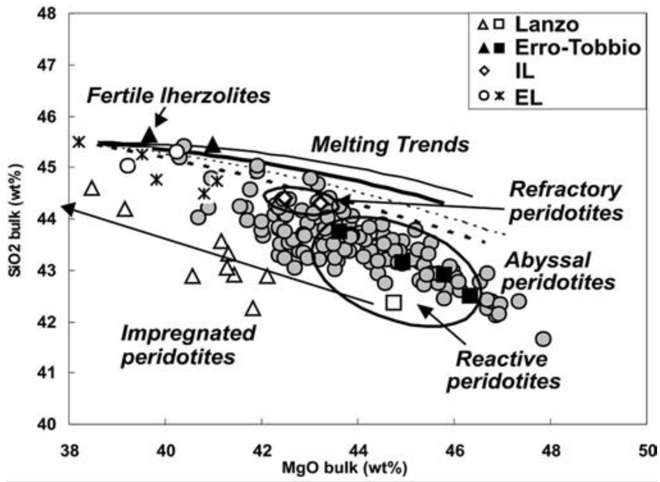

Fig. 2 - Bulk rock SiO_2 vs MgO diagram: melting trends and recalculate abyssal peridotite compositions are reporte from Niu (1997). Reactive spinel peridotites from Lanzo and Erro-Tobbio (data from Rampone et al., 2004) show bulk rock compositions significantly SiO_2–depleted, at similar MgO contents, with respect to the estimated compositions of partial melting residua (Niu, 1997). Similarly, the Lanzo South plagioclase peridotites generally show bulk rock compositions significantly SiO_2–depleted, at similar MgO contents, with respect to the estimated compositions of partial melting residua. They show, moreover, a broad trend of progressive bulk rock SiO_2 enrichment at decreasing MgO, starting from the composition of the LAS3 reactive spinel peridotite. This is consistent with the interpretation that they represent former reactive peridotites, similar to the LAS3 sample, which have been subjected by variable addition of basaltic components (i.e. plagioclase and pyroxenes) during impregnation. Note that the External Liguride plagioclase peridotites (data from Rampone et al., 1993) show a bulk rock trend similar to those of the impregnated Lanzo South samples, from lower to higher SiO_2 contents, at decreasing MgO contents, with respect to representative fertile spinel lherzolite compositions. Fertile lherzolite compositions from the Erro-Tobbio and External Liguride peridotites, together with refractory compositions from the Internal Liguride peridotites are also reported (data from Rampone et al., 1995,1996).

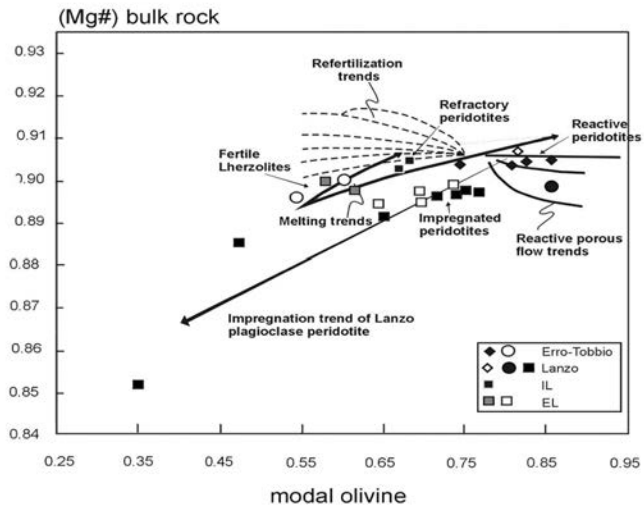

Fig. 3 - Bulk rock Mg# vs. modal olivine diagram; calculated melting trends, refertilization trends and reactive porous flow trends are from Bedini et al. (2002). The compositions of the Lanzo and Erro-Tobbio reactive peridotites (data from Piccardo et al. 2004b; Rampone et al., 2004) do not plot along the calculated melting trends, but they plot along the calculate reactive porous flow trends. The composition of the Lanzo impregnated peridotites plot along a trends of decreasing modal olivine, at decreasing bulk rock Mg# (Piccardo et al. 2004b). Note that the External Liguride plagioclase peridotites plot along the Lanzo impregnation trend (data from Rampone et al., 1995).

Mineral chemistry data shows that spinels have high Ti content, with respect to their Cr#, in comparison with those of spinel from refractory peridotites. Clinopyroxenes from the reactive peridotites of the different Alpine-Apennine bodies show very similar trace element contents. They have relatively low Na, Ti, very low Sr (0.5-1.0 ppm) and Zr (3.0-5.0 ppm) contents. The depleted character is also confirmed by the strong LREE-depletion of the C1-normalised patterns (La_N/Sm_N in the range 0.005-0.01), which are essentially flat in the M-HREE region (at 10xC1) and have no negative Eu anomaly (Fig. 4). Orthopyroxenes have strongly fractionated HREE-enriched patterns with Yb_N at about 2.0 and Nd_N at about 0.02. Thermometric estimates, based on the trace element (i.e. Sc and V) distribution between coexisting pyroxenes (Seitz et al., 1999), indicate that these cpx-poor spinel peridotites equilibrated at relatively high temperature conditions, in the range 1200-1300°C.

As previously outlined, many considerations indicate that the minerals of the reactive peridotites attained trace element equilibration with the percolating melts. Accordingly, the geochemical characteristics of the migrating melts have been modelled by assuming realistic solid/liquid (S/L) partition coefficients and the trace element composition of clinopyroxenes. Present knowledge suggests that early pyroxene-undersaturated percolating melts in all the studied reactive spinel peridotites were probably, depleted single melt increments formed by about 5% of near-fractional melting of an asthenospheric mantle source (Zanetti et al., 2003; Piccardo et al., 2004a).

Most probably, the reactive spinel peridotites derive from deep sectors of the lithospheric mantle column where rising asthenospheric melts were still pyroxene-undersaturated and the pyroxene dissolution / olivine precipitation processes were dominant.

THE IMPREGNATED PLAGIOCLASE PERIDOTITES

The plagioclase-enriched peridotites show both melt/mineral reaction and impregnation microtextures.
The plagioclase-forming microtextures indicate that plagioclase+pyroxene enrichment is produced by the interstitial crystallization of minerals from percolating melts. The widespread distribution of these microtextures suggests that melt migration occurred by diffuse porous flow (Piccardo, 2003; Müntener and Piccardo, 2003). The majority of impregnated peridotites preserve unambiguous textural features (i.e. relict pyroxene dissolution / olivine precipitation microtextures) indicating that they derive form previous reactive peridotites. Textural relationships (i.e. superposition of impregnation textures on reactive textures) clearly evidence that reactive pyroxene depletion and olivine enrichment preceeded melt impregnation and peridotite refertilization (Piccardo et al. 2004a and b).

The plagioclase-enriched peridotites of Erro-Tobbio, Internal Ligurides, Monte Maggiore, and a minority of Lanzo (Type 1), show melt/peridotite reactions; exsolved mantle clinopyroxene porphyroclasts are partially dissolved and unstrained orthopyroxene + plagioclase cotectic aggregates crystallize around and within the clinopyroxene crystals. Moreover, kinked mantle olivine is deeply embayed and corroded, and is replaced by new undeformed orthopyroxene. These peridotites show widespread interstitial crystallization and impregnation textures, as indicated by the diffuse presence of interstitial unstrained orthopyroxene and plagioclase crystals crystallized between the deformed mantle minerals and of mm-scale opx-rich, cpx-free noritic veins and pods. These reaction/impregnation features suggests that the percolating melts were already saturated in orthopyroxene(-silica) but not yet in clinopyroxene (see Piccardo et al., 2004a, with references therein).

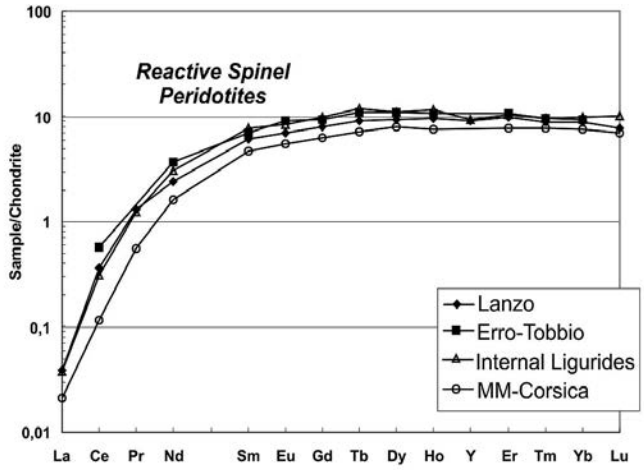

Fig. 4 - Chondrite-normalized REE patterns of average clinopyroxene compositions from reactive spinel peridotite (Lanzo, Erro-Tobbio, Internal Liguride and Corsica) (data from Piccardo et al., 2004a, and reference therein).

The plagioclase-enriched peridotites of Lower Platta, External Ligurides and the majority of Lanzo (Type 2) solely have reaction textures on kinked mantle olivine (olivine corrosion and orthopyroxene replacement), whereas the exsolved mantle clinopyroxene porphyroclasts do not show any reaction and new undeformed clinopyroxene grains crystallized as interstitial magmatic mineral between the deformed mantle assemblage. Frequently, the mantle pyroxene porphyroclasts are overgrown by unstrained pyroxene rims that, sometimes, propagate in form of vermicular apophyses beween and within mantle olivine porphyroclasts. These peridotites show widespread interstitial crystallization and impregnation textures in form of interstitial unstrained ortho- and clinopyroxene and plagioclase crystals between the deformed mantle minerals and of mm-scale opx-rich, cpx-bearing gabbroic veins and pods. The migrating melts thus did not react with mantle cpx suggesting that melts were saturated in both pyroxenes.

Pyroxene saturation indicates that melts, prior to their cooling to liquidus conditions leading to widespread crystallization, reacted extensively with the peridotite mantle column during their upward migration by diffuse porous flow towards the impregnation level. As discussed by Kelemen et al. (1995), the mineral saturation of pyroxene-undersaturated liquids, which reacted with mantle peridotite depends on the relative effects of reaction with the surrounding host rocks and cooling. For relatively rapid reactions and slow cooling, liquids might get saturated early in orthopyroxene (and silica), whereas slower pyroxene dissolution or more rapid cooling would produce less silica-rich liquid compositions. Continued melt/rock reaction and/or cooling finally led to saturation in two pyroxenes.

The Lanzo South plagioclase peridotites generally show bulk rock compositions significantly SiO_2–depleted, at similar MgO contents, with respect to the estimated compositions of partial melting residua (Niu, 1997) (Fig. 2). They show, moreover, a broad trend of progressive bulk rock

SiO_2 enrichment at decreasing MgO, starting from the composition of the LAS3 reactive spinel peridotite. In the bulk rock Mg# vs. modal olivine diagram of Bedini et al. (2002) (Fig. 3), their compositions plot along a trend of decreasing modal olivine, at decreasing bulk rock Mg# (Piccardo et al. 2004b). It must be noted that the External Liguride plagioclase peridotites from Mt. Nero, considered by Rampone et al. (1993) as the subsolidus plagioclase-facies recrystallization of previous spinel lherzolites under closed system conditions, show a similar bulk rock trend, from lower to higher SiO_2 contents, at decreasing MgO contents, with respect to representative fertile spinel lherzolite compositions. They follow, moreover, the Lanzo impregnation trend, on the bulk rock Mg# vs. modal olivine diagram of Bedini et al. (2002). The diffuse presence of reaction and impregnation textures in these plagioclase-enriched peridotites (Piccardo et al., 2004a), together with the above compositional evidence, suggest that they underwent variable melt impregnation under open system conditions.

Porphyroclastic mantle pyroxenes and new magmatic pyroxenes in plagioclase peridotites have, as a rule, trace element compositions that are significantly enriched in many trace elements (i.e REE, Ti, Sc, V, Zr, Y), with respect to clinopyroxenes in spinel lherzolites from the same peridotite body and to clinopyroxene crystals in equilibrium with MORB melts. Plagioclase is rather variable in composition ranging from An65 to An90, and shows a progressive decrease in Sr (from 154 to 5.7 ppm) at increasing An content. Clinopyroxenes of the impregnated peridotites shows convex-upward REE patterns with MREE up to 30x chondrite and a significant REE enrichment (with MREE up to 30xC1) (Fig. 5), and both orthopyroxenes and clinopyroxenes frequently show negative Eu_N anomalies.

Type 1 impregnated peridotites (Erro-Tobbio, Internal Liguride, Monte Maggiore) have strongly fractionated clinopyroxene LREE patterns, and plagioclase with negative LREE fractionation, suggesting a depleted nature of the percolating melt. Type 2 impregnated peridotites (External Liguride, Platta) have usually clinopyroxenes with a moderate LREE fractionation and plagioclases with positive LREE fractionation, suggesting a slightly enriched nature of the percolating melts. Most frequently, both mantle porphyroclasts and interstitial magmatic grains in the same sample show remarkably similar trace element compositions. These features suggest that pyroxenes in impregnated peridotites attained trace element equilibrium with the percolating melts (Piccardo, 2003; Müntener and Piccardo, 2003; Zanetti et al., 2003; Piccardo et al, 2004a).

At Lanzo, the composition of magmatic pyroxene and plagioclase in the interstitial gabbroic microgranular aggregates of the impregnated peridotites varies from sample to sample. Cpx shows a moderate to strong LREE depletion (La_N/Sm_N = from 0.19 to 0.01), which is mirrored by plg LREE fractionation (La_N/Sm_N = from 3.60 to 0.10; La_N/Pr_N = from 1.20 to 0.07) (Fig. 3A). This indicates that the composition of the impregnating melts changed during ongoing impregnation from strongly depleted to slightly enriched (Piccardo, 2003; Müntener and Piccardo, 2003; Zanetti et al., 2003; Piccardo et al., 2004b).

Trace element thermometry (Seitz et al., 1999) indicate temperatures higher than 1200°C for the porphyroclastic cores and new magmatic grains. These data suggest substantial higher temperatures of equilibration for the impregnated peridotites compared to the rather low temperature (in the range 950-1100°C) of spinel peridotites residence in the conductive lithosphere.

As previously outlined, many considerations indicate that mantle and magmatic minerals of the impregnated peridotites attained trace element equilibration with the percolating melts. In this hypothesis, the geochemical characteristics of the impregnating melts can be modelled by assuming realistic S/L partition coefficients and the trace element composition of clinopyroxenes. In particular, the LREE/HREE fractionations shown by both mantle and magmatic clinopyroxenes are consistent with their equilibration with fractional melts (Müntener and Piccardo, 2003; Piccardo, 2003; Zanetti et al., 2003; Piccardo et al., 2004a and b). However, the absolute content in moderately incompatible elements (e.g. HREE) of these clinopyroxenes is significantly higher with respect to those expected for cpx in equilibrium with these melts. This observation suggests that the impregnating melts of the plagioclase peridotites must have acquired compositions relatively enriched in incompatible trace elements (Zanetti et al., 2003).

Starting from this assumption, a numerical simulation of the melt evolution has been performed (Zanetti et al., 2003): preliminary results indicate that impregnating melts in the studied plg-enriched peridotites were single melt fractions of variable compositions, from slightly enriched to strongly depleted, derived from different degrees of near-fractional melting on the asthenospheric mantle source; these melts acquired pyroxene saturation and variable trace element en-

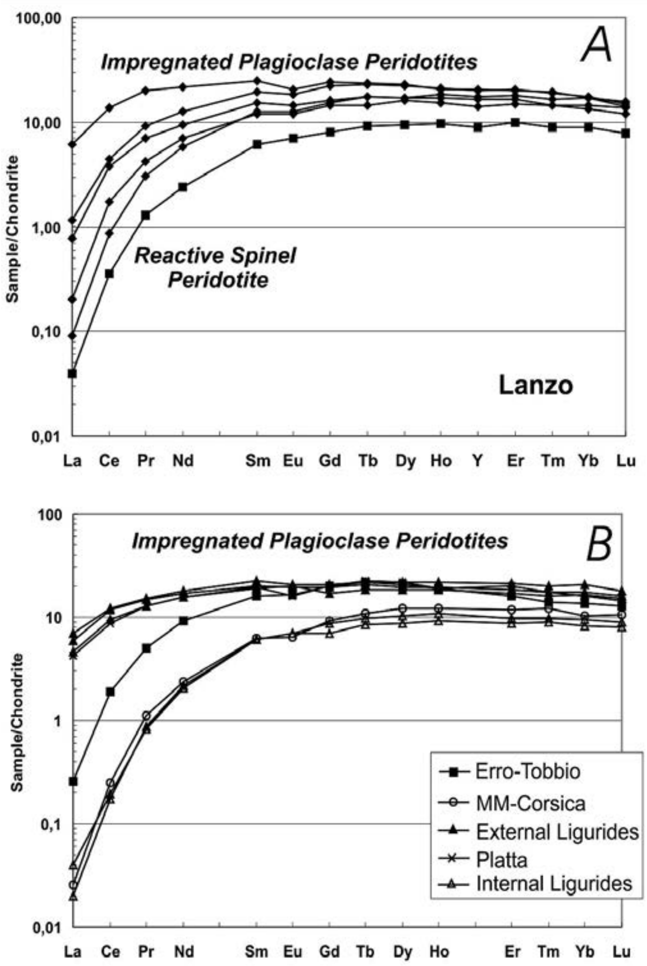

Fig. 5 - Chondrite-normalized REE patterns of average clinopyroxene compositions from impregnated plagioclase peridotites (Lanzo, Erro-Tobbio, Internal and External Liguride and Corsica) (data from Piccardo et al., and references therein).

richment during reactive percolation in the mantle column (Zanetti et al., 2003; Piccardo et al., 2004b).

THE REPLACIVE SPINEL DUNITES

Large areas of the Alpine-Apennine peridotite massifs are cut by a network of dunite channels and bodies, frequently accompanied by gabbroic veins and dikelets. The dunite channels and the gabbroic dikelets are present in both reactive and impregnated peridotites and in lithospheric peridotites, where they cut across the early spinel-facies foliation of the tectonite and mylonite fabrics (Piccardo et al., 2004a). The spinel foliation of the deformed peridotites and the trend of the spinel pyroxenite bands are continuous from peridotite into dunite. Spinel pyroxenite bands in peridotites can be followed as spinel trains into the dunites, as it has been observed in the Lanzo peridotite (e.g. Boudier and Nicolas, 1972; Müntener and Piccardo, 2003). These relationships indicate that plagioclase-enrichment and dunite formation postdate the lithospheric deformation under spinel-facies conditions.

In addition to the evidence that these spinel dunites are replacive in origin, they show significant overgrowth of the olivine crystals, typically enclosing the rounded spinel crystals, and new olivine crystallization, as indicated by the presence of euhedral olivine crystals inside the pyroxene porphyroclasts of the harzburgitic border (Piccardo et al., 2004b).

At Lanzo spinel dunites contain both small interstitial clinopyroxene crystals, which are found along olivine triple junctions, huge euhedral clinopyroxene megacrysts (more than 1 cm in diameter), which are generally associated with plagioclase, and pyroxene-rich or gabbroic veinlets showing fuzzy contacts with the country rocks [the “pyroxenites” and “indigenous” gabbroic dikes of Boudier and Nicolas (1972) and Boudier (1978)] (Müntener and Piccardo, 2003; Piccardo et al., 2004b). Interstitial and megacrystic clinopyroxene grains and spinels show compositions that are similar to crystals in equilibrium with MORB melts (Piccardo, 2003; Müntener and Piccardo, 2003; Piccardo et al., 2004a and b) (Fig. 6). At Monte Maggiore, the percolating melt in dunites crystallized as a network of mm-scale films of plagioclase and pyroxenes in dunites and were sporadically aggregated to form cm-scale gabbro-noritic veinlets, having Cr-Mg-rich pyroxenes (Mg# around 90-92), with strongly LREE fractionated patterns and Ca-rich plagioclases (around An90) (Piccardo, 2003; Müntener and Piccardo, 2003).

Present knowledge indicate that the dunite channels were percolated by asthenospheric melts with different compositions, from significantly depleted single melt fractions to already aggregated MORB-type melts (Piccardo, 2003; Zanetti et al., 2003; Piccardo et al., 2004a and b), which escaped melt/peridotite reaction during their channeled migration towards shallow levels.

The formation of interstitial clinopyroxene and plagioclase-pyroxene films and finally cm-scale gabbroic veins, indicate that the interconnected melt network in dunite channels becomes progressively clogged with crystallization products. This suggests that melt migration changed from focused porous flow in dunite channels to intrusion into narrow cracks and fractures, produced by substantial hydrostatic overpressure: melts initiated to be expelled in dykes (Nicolas, 1986; Kelemen et al., 1997; Kelemen and Aharonov, 1998).

Noritic and gabbroic dikelets, showing fuzzy contacts to the surrounding ultramafic rock, are widespread in the studied peridotite massifs: as a rule, they are formed inside the dunite channels and propagate into the surrounding peridotites. The gabbroic veins and dykelets, and the mafic-ultramafic cumulate pods at Monte Maggiore, are rather primitive (Mg# of olivine and pyroxenes of about 90). Clinopyroxenes from dikelets show REE patterns variably fractionated in the LREE, and almost flat patterns in the M-HREE region (Fig. 4); slightly LREE fractionated patterns are show by clinopyroxenes from Lanzo and Internal Liguride samples, whereas strongly LREE fractionated patterns are shown by the Erro-Tobbio and Monte Maggiore (Corsica) samples. The variable trace element composition of liquids in equilibrium with clinopyroxene from early dykelets and cumulate pods indicate that both depleted and enriched single melt increments migrated in the lithospheric mantle without undergoing significant melt/peridotite reaction within the mantle column.

In conclusion, present knowledge (Piccardo et al., 2004a) suggest that melts migrating within the dunite channels and intruding as early dikes were both depleted single melt fractions similar to those which impregnated the surrounding peridotites (as for the Erro-Tobbio and Monte Maggiore massifs), and MORB-type liquids (as for the Lanzo and Internal Liguride massifs).

In places, spinel peridotites, plg-enriched peridotites and spinel dunites are all deformed and show porphyroclastic to tectonite-mylonite fabrics along km-scale extensional shear zones: the spinel foliation in dunites is parallel to the main foliation of the country peridotites. Porphyroclasts with clear relict impregnation textures are embedded in a mylonitic matrix consisting of olivine, pyroxenes, plagioclase, spinel and rarely titanian hornblende. These shear zones indicate the progressive localization of deformation during continuous exhumation. This deformation, postdating plagioclase-enrichment and dunite formation, occurred in the plagioclase-facies peridotite stability field, as indicated by incipient formation of olivine+plagioclase rims between relict pyroxenes and spinel in the tectonite peridotites. Trace element thermometric calculations (Seitz et al., 1999) on recrystallized pyroxenes of deformed plagioclase peridotite from the External Ligurides provide temperatures in the range 900-1150°C, indicating decreasing temperature during post-impregnation metamorphic recrystallization. Fluid-

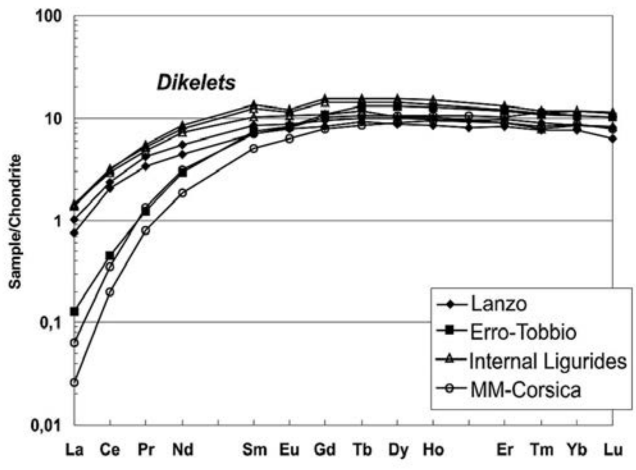

Fig. 6 - Chondrite-normalized REE patterns of average clinopyroxene compositions of replacive dunites, gabbroic veins and dikelets from Lanzo, Erro-Tobbio, Internal and External Liguride and Corsica) (data from Piccardo et al., 2004a, and references therein).

assisted recrystallization produced low-K titanian pargasites, in equilibrium with plagioclase. Subsequent partial recrystallization of amphibolite- and green-schists-facies assemblages indicates decreasing temperature and pressure conditions during progressive exhumation. All the above tectonic and magmatic structures are cut by later MORB-type Mg-rich and Fe-Ti-rich gabbroic and MOR basaltic dikes, which show sharp contacts and chilled margins to the enclosing peridotites. Exposure on the sea-floor is documented by widespread serpentinization and rodingitization, and by the emplacement of post-serpentinization chilled basaltic dikes, which crosscut all previous magmatic and metamorphic fabrics (Piccardo et al., 1990).

DISCUSSION

Presence and abundance of reactive pyroxene-poor peridotites, impregnated plagioclase-rich peridotites and replacive spinel dunites indicate that the studied Alpine-Apennine ophiolitic peridotites experienced important asthenosphere/lithosphere interaction by melt reactive percolation before their tectonic denudation at the sea-floor of the Jurassic Ligurian Tethys.

Field and textural evidence suggests that melt/peridotite interaction occurred when the pristine mantle sections were residing at lithospheric mantle depths (spinel-peridotite-facies conditions and T in the range 900-1100°C). Field relationships between rocks showing reaction/impregnation textures and pristine granular and tectonite/mylonite spinel peridotites allow the relative spatial and temporal location of the processes of melt/peridotite interaction, within the exhumation evolution of these ophiolitic peridotites. Some main features must be recalled (see: Müntener and Piccardo, 2003; Piccardo et al., 2004a and b, for a more detailed discussion):

1) Reactive/impregnated/replacive ultramafic rocks always show crosscutting relationships to the extensional structures formed under spinel-peridotite-facies conditions (i.e. the tectonite-mylonite foliation of the km-scale shear zones) within the “lithospheric” peridotites; accordingly, asthenosphere/lithosphere interaction occurred after the initial stages of lithospheric extension;
2) Microtextural evidence indicates that reactive peridotites are the relatively early products of reactive melt percolation and were formed at the expense of “lithospheric” peridotites, which show clear thermal, compositional and structural features indicative of their long residence in the thermal lithosphere;
3) ‘Reactive’ peridotites were formed by the reactive percolation of pyroxene-undersaturated melts, rising upwards from deep asthenospheric levels; during their reactive migration in the lithospheric mantle column these melts became progressively orthopyroxene- and clinopyroxene-saturated and trace element enriched;
4) Refertilized plagioclase-rich peridotites were mostly formed at the expense of peridotites which had already experienced the reactive percolation of asthenospheric melts; they were impregnated by modified asthenospheric melts which had already experienced the reactive percolation at deeper levels of the lithospheric mantle column;
5) Replacive dunites were formed by complete pyroxene (+plagioclase) dissolution along channels within the spinel and plagioclase peridotites; these high porosity olivine-rich channels allowed the direct upward migration of asthenospheric melts, which escaped reactive porous flow percolation through the lithospheric peridotites and melt/peridotite interaction;
6) The competing effects of heating by melt percolation and cooling by progressive exhumation led to crystallization of the migrating melts, clogging of the migration pathways and hydrofracturing, forcing melt expulsion along cracks and fractures, i.e the first generation of “indigenous” veins and dikes.

The recognized stages of melt diffuse porous flow (melt/peridotite reaction and melt impregnation), followed by focused flow in dunite channels and finally intrusion of mafic dykes reflect the dynamics of the lithosphere extension, in which mantle lithosphere is continuously exhumed to shallower levels. Thus, the reactive spinel peridotites, formed at deeper levels in the lithospheric mantle column, were progressively exhumed to shallower levels were they were impregnated by pyroxene-saturated liquids which were rising from deeper levels and became saturated in silica by the reactive percolation. These impregnated (once reactive) peridotites were subsequently cut by dunite channels where the melt migration was focused. Later, these peridotites were exhumed to shallow levels, were cooled to lower temperatures and were intruded by MORB type gabbroic dykes.

The MORB affinity of melts involved in the reaction/impregnation processes imply that they were, most probably, produced by asthenosphere partial melting under decompression related to thinning of the lithosphere, during continental extension and rifting. Geochemical data indicate that melt fractions were produced by the upwelling asthenosphere by different degrees of near-fractional melting, from initial to more advanced melting stages. Melt composition was changed from enriched/depleted melt increments to aggregated MORB. The asthenospheric melts produced during the initial stages migrated through the overlying lithospheric mantle column via porous flow (Piccardo, 2003; Müntener and Piccardo, 2003). Melt/peridotite interaction (pyroxenes dissolution and olivine precipitation) by depleted single fractional melts most probably transformed the percolated spinel lherzolites to cpx-poor spinel peridotites, forming a lower zone of reactive, pyroxene-depleted peridotites (similar to Xu et al., 2003) at the expense of the percolated lithospheric mantle. The reactive porous flow through the lower lithospheric mantle caused progressive pyroxene saturation of the migrating melts. At shallower levels, melt crystallization produced pervasive impregnation of the lithospheric mantle. Melt reactive migration thus produced depletion of the lower lithospheric mantle, whereas melt impregnation produced refertilization of the mantle lithosphere at shallower levels. This process was accompagnied by advective heat transport. Thermometric estimates indicate substantial heating of the lithospheric mantle up to > 1250°C; the thermochemical erosion of the mantle lithosphere was thus an important process during the rifting stages of the Ligurian Tethys (Piccardo, 2003; Müntener and Piccardo, 2003). Focused melt flow and significant increase in the melt/peridotite ratio at high temperature conditions produced almost complete pyroxene dissolution within preferred channels, forming high permeability zones for rapid melt migration. Subsequent melts migrating in dunite channels escaped melt/peridotite interaction and were delivered unmodified towards the surface: they were both depleted melt increments (Monte Maggiore, Erro-Tobbio) and MORB-type liquids (Lanzo, Internal Ligurides).

Infiltration of asthenospheric magmas in the lower lithosphere has been considered as being important during the early stages of continental rifting (Bedini et al., 1997), which may accomplish the thermomechanical erosion of the lithosphere (Davies, 1994). Evidence of km-scale melt porous flow in the Ronda peridotites, related to pervasive infiltration of asthenospheric melts, has been regarded as a volumetrically important process accompanying the thermomechanical erosion of the lower lithosphere by the upwelling asthenosphere (Van der Wal and Bodinier, 1996). Heating combined with the chemical modification of the mantle rocks has been inferred for the asthenosphere-lithosphere interaction during early continental rifting (Menzies et al., 1987; Bedini et al., 1997).

The thermal softening of the extending lithosphere could have played an important role in the dynamics of the rifting system during transition from passive lithosphere extension to active oceanic drifting in a slow spreading system (Piccardo, 2003; Müntener and Piccardo, 2003).

CONCLUDING REMARKS

The recognition that many peridotites massifs of the Alpine-Apennine ophiolites represent depleted/refertilized and thermally modified lithospheric mantle significantly changes the "classical" subsolidus model of evolution of the ophiolitic peridotites, from their lithosphere accretion to their sea-floor exposure during Upper Jurassic. In fact, a "cold" subsolidus exhumation history during opening of the Ligurian Tethys ocean is solely shown by peridotites in the eastern Central Alps and, in some cases, the External Liguride, which are still associated with the lower continental crust (Müntener et al., 2000; Müntener and Hermann, 2001; Piccardo et al., 2004a), indicating a considerable distance from the upwelling asthenosphere. On the contrary, a "hot" exhumation history, in which modification of lithospheric peridotite by asthenospheric melts was dominant, might illustrate the other extreme evolution of peridotites exhumed close to the upwelling asthenosphere (the Lower Platta Unit, Lanzo, Erro-Tobbio, most Ligurides and Corsica peridotites) (Piccardo, 2003; Müntener and Piccardo, 2003; Piccardo et al., 2004a) .

The investigated Alpine-Apennine ophiolitic peridotite massifs reveal presence of large areas of "hot" impregnated mantle rocks. This suggests that important volumes of melts did never reach the surface, since they underwent reactive percolation and were captured in the lithospheric mantle at rather deep levels (around 30 km depth). Later melts migrated through the mantle lithosphere within isolated dunite channels or along fractures, reached unmodified shallow lithospheric levels where they underwent crystal fractionation, forming variably evolved Mg- and Fe-Ti-rich magmas which intruded (MORB-type gabbroic bodies) or extruded at the sea-floor (MOR basaltic flows). Accordingly, the Alpine-Apennine ophiolitic peridotites record two distinct magmatic stages:

1) an early magmatic event, where initial asthenosphere decompressional melting produced melt increments which were completely captured in the lithospheric mantle and did not reach the surface: this represents a magmatic, but non-volcanic stage;
2) a later magmatic event, where more advanced asthenosphere partial melting produced aggregated MORB melts that intruded in shallow magma chambers or extruded at the sea-floor: this represents a magmatic and volcanic stage.

The sequence of periods characterized by absence (non-volcanic or a-magmatic or magma-starved stages) and presence (volcanic or magmatic stages) of volcanism represents one of the most peculiar feature of slow and very-slow spreading ridges. Melt stagnation in the oceanic lithospheric mantle has been proposed as the dominant mechanism of peridotite impregnation and plagioclase peridotite formation along slow spreading systems (e.g. Dick, 1989; Elthon, 1992; Cannat and Casey, 1995; Cannat et al., 1997). It could be that amagmatic periods of (ultra-)slow spreading ridges (e.g. Tucholke et al., 1998) are characterized by melt stagnation in the thermal lithosphere, leading to plagioclase peridotite formation.

Our studies on the ophiolitic peridotites of the Alpine-Apennine system evidence the important role of melt/peridotite interaction during extension and rifting of the Jurassic Ligurian Tethys ocean.

Accordingly, the origin and magmatic evolution of the Alpine-Apennine ophiolitic peridotites must be reconsidered on the basis on detailed investigations on their microtextural and geochemical features. The majority of the plagioclase-bearing peridotites of the Alpine-Apennine ophiolites derive from melt impregnation and refertilization whereas a great part of the associated depleted spinel peridotites result from melt/peridotite interaction during reactive percolation of depleted melt fractions, rather than being simple refractory residua after near-fractional partial melting.

Records of melt percolation, melt/peridotite reaction and melt impregnation are commonly found in ophiolitic peridotites and present day oceanic mantle lithosphere. Our results provide a mechanism to explain non-volcanic and volcanic stages during the rift evolution of the Ligurian Tethys and might be equally applicable to modern slow and ultra-slow spreading ridges, which are characterized by variable magmatic (volcanic) and amagmatic (non volcanic) stages.

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