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Melt/peridotite interaction in the Southern Lanzo peridotite: Field, textural and geochemical evidence

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This paper is dedicated to Franca Cimmino, the wife of Giovanni, who died in silence to let Giovanni play the game of scientific research.

Abstract

This paper presents field, petrographic–structural and geochemical data on spinel and plagioclase peridotites from the southern domain of the Lanzo ophiolitic peridotite massif (Western Alps). Spinel lherzolites, harzburgites and dunites crop out at Mt. Arpone and Mt. Musinè. Field evidence indicates that pristine porphyroclastic spinel lherzolites are transformed to coarse granular spinel harzburgites, which are in turn overprinted by plagioclase peridotites, while strongly depleted spinel harzburgite and dunite bands and bodies replace the plagioclase peridotites. On the northern flank of Mt. Arpone, deformed, porphyroclastic (lithospheric) lherzolites, with diffuse pyroxenite banding, represent the oldest spinel-facies rocks. They show microstructures of a composite subsolidus evolution, suggesting provenance from deeper (asthenospheric) mantle levels and accretion to the lithosphere. These protoliths are locally transformed to coarse granular (reactive) spinel harzburgites and dunites, which show textures reminiscent of melt/rock reaction and geochemical characteristics suggesting that they are products of peridotite interaction with reactively percolating melts. Geochemical data and modelling suggest that <1–5% fractional melting of spinel-facies DMM produced the injected melts. Plagioclase peridotites are hybrid rocks resulting from pre-existing spinel peridotites and variable enrichment of plagioclase and micro-gabbroic material by percolating melts. The impregnating melts attained silica-saturation, as testified by widespread orthopyroxene replacement of olivine, during open system migration in the lithosphere. At Mt. Musinè, coarse granular spinel harzburgite and dunite bodies replace the plagioclase peridotites. Most of these replacive, refractory peridotites have interstitial magmatic clinopyroxene with trace element compositions in equilibrium with MORB, while some Cpx have REE-depleted patterns suggesting transient geochemical features of the migrating MORB-type melts, acquired by interaction with the ambient plagioclase peridotite. These replacive spinel harzburgite and dunite bodies are interpreted as channels exploited for focused and reactive migration of silica-undersaturated melts with aggregate MORB compositions. Such melts were unrelated to the silica-saturated melts that refertilized the pre-existing plagioclase peridotites. Finally, MORB melt migration occurred along open fractures, now recorded as gabbroic dikes.

Our data document the complexity of rock-types and mantle processes in the South Lanzo peridotite massif and describe a composite tectonic and magmatic scenario that is not consistent with the "asthenospheric scenario" proposed by previous authors. We envisage a "transitional scenario" in which extending subcontinental lithospheric mantle was strongly modified (both depleted

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and refertilized) by early melts with MORB-affinity formed by decompression partial melting of the upwelling asthenosphere, during pre-oceanic rifting and lithospheric thinning in the Ligurian Tethys realm.
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1. Introduction

The Lanzo ultramafic massif in the Western Alps (35 km west of Turin, Italy) has been divided into a southern body (55 km^2), a central body (90 km^2) and a northern body (5 km^2), separated by mylonitic and partially serpentinized shear zones (Boudier and Nicolas, 1972; Boudier, 1978) (Fig. 1). Along its margin and along major faults, the Lanzo massif is partially serpentinized (Boudier, 1976; Bodinier et al., 1986). In several places, peridotites are crosscut by pyroxenites, by a younger suite of discordant dunites and by various sets of gabbroic veins and dykes (Boudier and Nicolas, 1977; Bodinier et al., 1991). Dunite cuts and locally replaces earlier Sp-pyroxenites (Boudier and Nicolas, 1972; Boudier, 1978). Dunite bands and veins locally contain some feldspar and clinopyroxene, ascribed to trapped melt introduced during or after partial melting (Boudier and Nicolas, 1972, 1977; Nicolas and Dupuy, 1984). The Lanzo Sp-peridotites show Sp-facies granular assemblages and are Cpx-poor, refractory lherzolites. According to Boudier and Nicolas (1972), Boudier (1978) and Bodinier (1988), these rocks are mantle residua after partial melting. Refractory peridotites, harzburgites and dunites have been interpreted as bands of melt percolation at shallower levels (Bodinier et al., 1991). The Plg-peridotites are thought to be formed by melt formation and incomplete melt extraction and crystallisation in an upwelling diapir (Boudier and Nicolas, 1972; Boudier, 1978; Nicolas, 1986). The widespread occurrence of Plg was considered to be evidence of pervasive magma flow during the latest stage of decompression (Bodinier et al., 1986).

Several authors have interpreted the southern body as mantle asthenosphere that rose from the Gt-stability field as a high-temperature diapir, accompanied by a large degree of melt extraction (Nicolas, 1984, 1986; Bodinier et al., 1991). Bodinier (1988) proposed that the Plg-lherzolite body of Lanzo represents a residual piece of upper mantle, after MORB extraction from a primitive mantle. Melting occurred mainly in the Sp-stability field. The dunites were considered as preferential zones for magma tapping and circulation in the partially molten region. The northern body is considered to be a fragment of continental lithosphere, while the central body is interpreted as a hybrid containing components from the subcontinental lithosphere modified by small-volume melts from the asthenosphere. Bodinier et al. (1991) showed that the significant REE

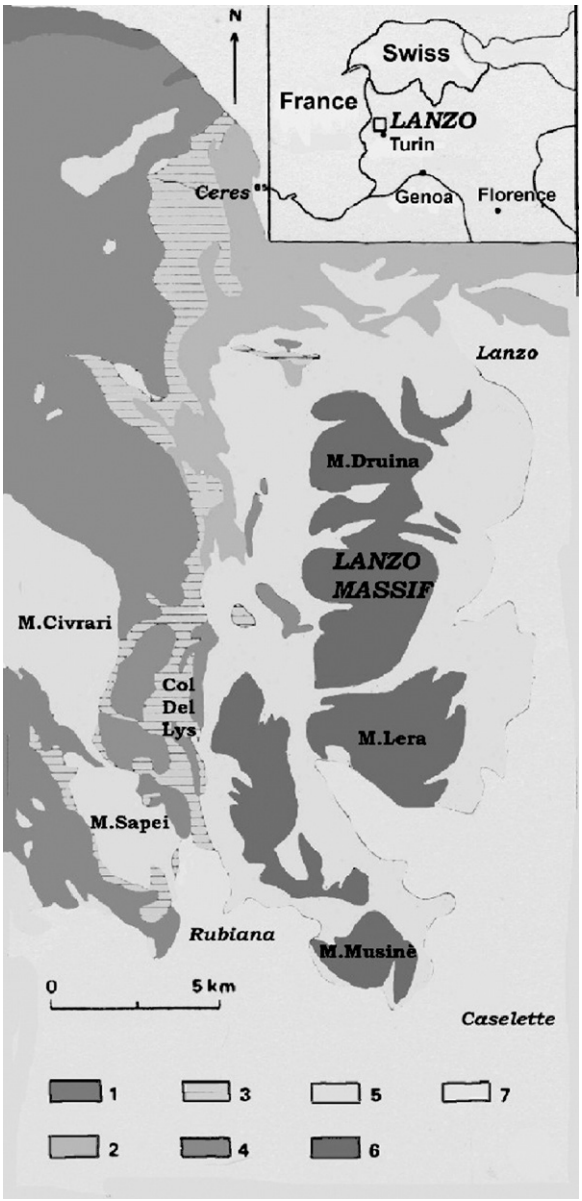


Fig. 1. Sketch map of the Lanzo peridotite massif, in the Western Alps. Legend: (1) Gran Paradiso orthogneiss; (2) Sesia–Lanzo Zone; (3) Schistes Lustres; (4) Pennine Ophiolites; (5) Pennine and Lanzo serpentinites; (6) Lanzo peridotites; (7) Late Cenozoic sediments (after Bodinier et al., 1986).

variations in Lanzo peridotites cannot be adequately explained by a single process. Four possible mechanisms were considered: (1) primary mantle heterogeneity; (2) polybaric melting; (3) melt extraction processes; (4) secondary Plg crystallisation. Bodinier et al. (1991) suggested that melting began at greater depths in the southern domain (Gt-stability field), consistent with the observation that the southern domain has suffered higher degrees of melt extraction. Melt extraction processes were considered to be responsible for local variations in REE coupled with mineralogical and compositional changes from Plg-lherzolites to refractory Sp-peridotites. It was suggested that the refractory peridotites underwent a single-stage process that was responsible for both their residual character and their high LREE/HREE ratios. This model implies that, during melt extraction, porous flow was concentrated into narrow regions now represented by the harzburgite bands. To explain the enriched Nd–Sr isotopic compositions in these refractory peridotites, Bodinier et al. (1991) suggested focused percolation of enriched melts in refractory porous-flow channels. Recently, Bodinier and Godard (2003) proposed that the high-temperature Plg-peridotites of Lanzo represent strongly "asthenospherized" mantle containing only sparse relics of lithospheric origin. In contrast, Pognante and coworkers (1985) suggested that Lanzo represents sub-continental lithosphere that suffered partial melting and decompression, during continental rifting and was intruded later by asthenospheric melts with N-MORB affinity.

This paper presents new field, structural, petrologic and geochemical data on the South Lanzo massif. These data reveal a composite scenario of melt/peridotite interaction and indicate that melt percolation and impregnation profoundly changed both whole rock and mineral chemistry of this peridotite section during its residence in the mantle lithosphere and the early stages of exhumation.

2. The South Lanzo peridotite body

2.1. Rock types, field relationships, petrographic and micro-structural features

Detailed field investigations show that the South Lanzo massif has large areas consisting of Plg-enriched peridotites that replace older Sp-peridotites and are crosscut by Sp-harzburgite and dunite bodies and channels. Prior to Plg-enrichment, the Sp-peridotites consisted of: (1) foliated porphyroclastic peridotites, hereafter referred to as "lithospheric" Sp-peridotites, with widespread Sp-pyroxenite bands; (2) coarse granular isotropic peridotites, hereafter referred to as "reactive" Sp-peridotites, varying from Sp-harzburgites to dunites. We have sampled lithospheric and reactive Sp-peridotites on the northern flank of Mt. Arpone, Plg-peridotites from the whole southern body, and replacive Sp-harzburgites and dunites and gabbroic dikes from the southern flank of Mt. Musinè (Fig. 2). Locally, the coarse granular fabrics of the reactive peridotites overprint the tectonite fabrics of the lithospheric peridotites. In these pyroxene-depleted reactive peridotites, the pyroxenite bands in the pre-existing Sp-lherzolites were almost completely dissolved, being solely marked by trains of relict spinel grains. Plg enrichment affected both lithospheric and reactive Sp-peridotites, and formed Plg-rich peridotites, hereafter referred to as "impregnated" Plg-peridotites. In these Plg-enriched peridotites, the pyroxenite bands in the pre-existing lithospheric Sp-lherzolites were transformed into Plg–Ol-rich "gabbroic" bands.

The northern flank of Mt. Arpone is a key area to unravel the field relationships and characteristics of the pre-impregnation Sp-peridotites. Here, hectometre-scale bodies of coarse granular Cpx-poor Sp-peridotites crop out replacing pre-existing deformed Sp-lherzolites and are in turn replaced by Plg-enriched peridotites. Decametre-size bodies of foliated, porphyroclastic Sp-lherzolites show a tectonite fabric (Plate IV-A) and widespread pyroxenite

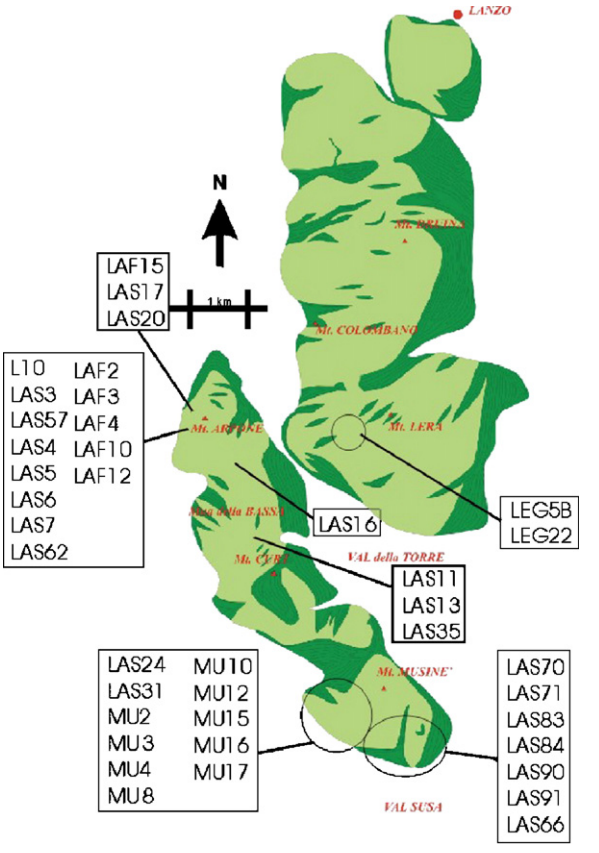
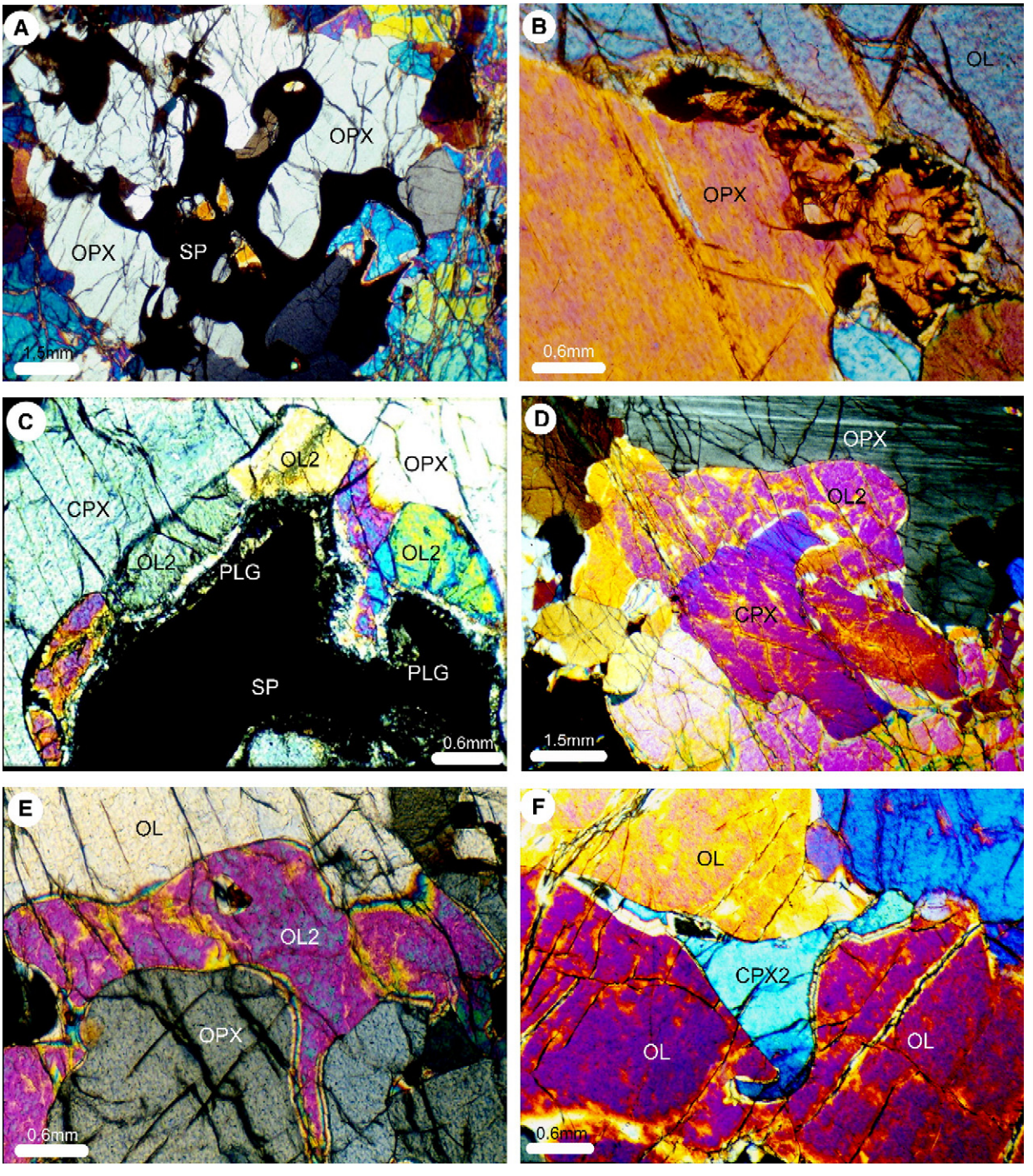


Fig. 2. Sample locations within the Lanzo peridotites.

banding. In thin section, the lherzolites show complete Sp-facies equilibration (i.e. Ol+Opx+Cpx+Sp assemblage) and are characterized by: (i) cm-scale exsolved and deformed Px porphyroclasts; (ii) subsolidus microtextures consisting of broadly rounded intergrowths (clusters) of Opx+Sp (±Cpx) (Plate I-A), and (iii) micro-symplectites of vermicular Sp located along the outer border of huge Opx porphyroclasts (Plate I-B). In most samples from Mt. Arpone, these textures are partially overprinted by reaction textures where rims of unstrained Ol developed surrounding the large Px porphyroclasts and, sporadically, new Ol grains formed interstitial to the porphyroclasts.

The foliated lithospheric Sp-peridotites are locally transformed to coarse granular reactive Sp-harzburgites,



characterized by low Cpx contents compared to the pre-existing foliated peridotites. The contact between foliated and granular rock-types is frequently sharp (Plate IV-A). The coarse granular, Cpx-bearing Sp-harzburgites (Plate IV-B) are locally cut by metre-wide bands of finer granular, opx-bearing Sp-dunites (Plate IV-D). Dunites also occur as decametre-size bodies that enclose elongated and rounded decimetre-size pods of coarse granular harzburgites (Plate IV-C). In the granular harzburgites and dunites, pyroxenite bands of the pre-existing lithospheric Sp-peridotites are almost completely dissolved and are solely recorded by aligned concentrations of Sp grains (Plate IV-E). In thin-section, the coarse granular Sp-harzburgites have microstructures indicating growth of new Ol on Px porphyroclasts, i.e.: (i) coarse rims of unstrained Ol surrounding and partially replacing the exsolved Px porphyroclasts (Plate I-D); (ii) crystallisation of less deformed Ol (Plate I-E); (iii) coarsening of the pre-existing mantle Ol, which encloses the broadly rounded Sp crystals. A subsequent stage is marked by interstitial crystallisation of small crystals of both Pxs (Plates 1-F and 2A). These rock-types preserve relics of the pristine lithospheric peridotites, i.e. Opx+Sp clusters and vermicular Sp in Opx porphyroclasts. In a few cases, thin Ol+Plg rims are present between Sp and Pxs (Plate I-C), predating Plg-enrichment.

The Plg-peridotites have high proportions of modal Plg (up to 20 vol.%), frequently concentrated in mm-scale aggregates and veins (Plate V-A). Most Plg-enriched peridotites preserve a former Sp-facies foliation. Plg is diffuse in the granular rock-types or aligned along the foliation in the foliated ones. In the Mt. Arpone area, Plg-rich peridotites are in contact with Plg-free reactive Sp-peridotites; the transition is rather sharp and can be followed continuously for tens of metres. A few cm-wide noritic veins, comprising rounded euhedral Opx and interstitial Plg, propagate from the Plg-peridotites inside the reactive Sp-peridotites. Ol in the peridotite around the vein is completely replaced by Opx, over a distance of >1 cm (Plate IV-F). In thin-section, Plg-peridotites consist of an older, deformed and exsolved, Sp-facies assemblage and a new, less deformed, mm-size granular aggregate of Plg-rich gabbroic material. Plg-peridotites are characterised by Opx-forming, Ol-dissolving microtextures. The most common features are: (i) widespread undeformed Plg crystals which are interstitial or crosscutting deformed and exsolved mantle minerals (Plate II-D); (ii) replacement of kinked Ol by undeformed Opx patches (Plate II-C); (iii) mm-size Plg-rich gabbroic veins and pods (Plate IIIA), and symplectitic Px+Plg interstitial patches; (iv) rims of Plg surrounding Sp. Plg-enrichment is linked to addition of gabbroic material and is coupled with replacement of unstrained Opx on kinked mantle Ol.

In the Plg-peridotites from Mt. Arpone these microstructures are coupled with Cpx-dissolving, Opx+Plg-forming reactions (i.e. symplectitic Opx+Plg coronas surrounding corroded Cpx) (Plate II-B) and interstitial crystallisation of Cpx-free noritic microgranular aggregates. In contrast, in the Plg-peridotites from Mt. Musinè, Cpx-dissolution microstructures are lacking and Opx-forming/Ol-dissolving microtextures are coupled with Plg+Px-forming microtextures, i.e. Px-rich veins cutting kinked mantle Ol (Plate II-F) and interstitial crystallisation of Cpx-bearing gabbroic microgranular aggregates. Small vermicular crystals of black Sp are sometimes widespread within the microgabbroic aggregates. Plg rims are usually formed between Sp and Ol; frequently, Ol shows Opx rims against Plg (Plate II-E). On the south flank of Mt. Musinè, Plg-peridotites are deformed along metre- to decametre-wide shear zones, where they acquire a strong foliation and tectonite fabric (Plate V-B), marked by strongly parallel Px+Plg aggregates and thin mylonitic bands. In thin-section, the Plg-rich magmatic association of the former Plg-peridotites is strongly deformed and recrystallised (Plate III-B). Mm-size shear bands are composed of very fine-grained Plg+Ol+Pxs that sporadically grade to extremely fine-grained bands (Plate III-C).

Plate I. Microtextures of pristine lithospheric spinel peridotite and granular, reactive spinel harzburgites from Mt. Arpone (South Lanzo).

Lithospheric spinel lherzolite:

(A). broadly rounded Opx+Sp cluster between Ol mantle porphyroclasts; this mineral aggregate represents the breakdown product, under spinel-facies conditions, of a precursor mantle Gnt;

(B). vermicular exsolutions of Al–Mg-rich Sp (i.e. Opx+Sp micro-symplectites) along the border of a porphyroclastic mantle Opx. This texture indicates that the former mantle Opx was an Al-rich, high *T* phase which underwent significant cooling (i.e. subsolidus exsolution of Mg-Tschemakitic components in form of Sp) under spinel-facies conditions;

(C). Ol+Plg (altered) corona surrounding Sp against mantle Pyroxenes: this texture is formed by the subsolidus metamorphic reaction Sp+Pxs=Ol+Plg, marking the transition between spinel- and plagioclase-facies conditions.

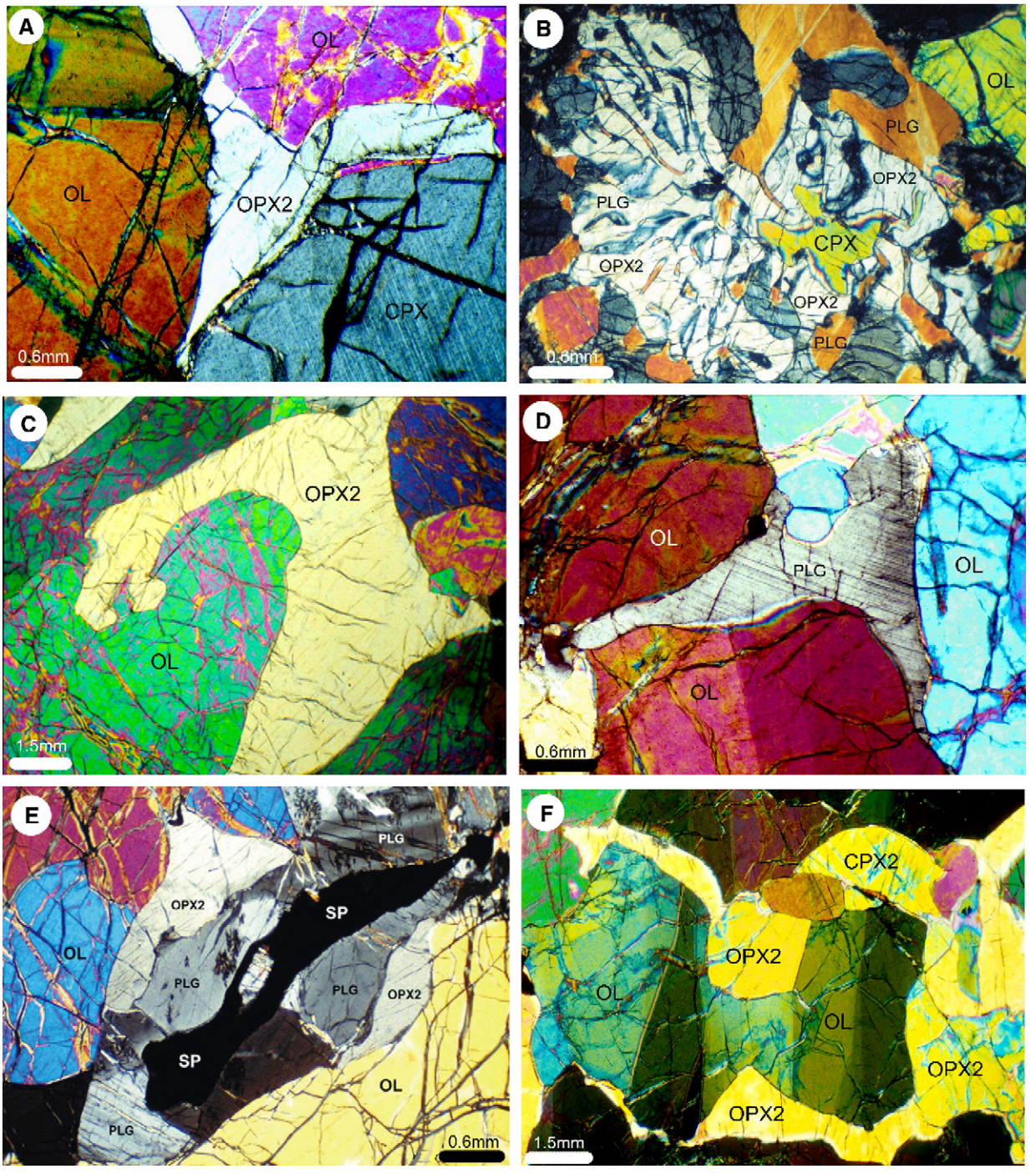
Reactive spinel harzburgite:

(D). wide corona of new unstrained magmatic Ol replacing a corroded relict of exsolved mantle Cpx and a large porphyroclast of exsolved mantle Opx;

(E). new unstrained magmatic Ol between mantle Ol and Opx porphyroclasts;

(F). unstrained interstitial Cpx crystal at triple junction between mantle Ol porphyroclasts.

At Mt. Musinè, Plg-peridotites and Plg-peridotite tectonites–mylonites are locally transformed to granular Sp-harzburgites and dunites, hereafter referred to as "replacive" Sp-peridotites (Plate V-D), which occur as: (i) elongated, metre-wide bands, within the tectonite–mylonite shear zones, concordant with the main foliation of the country rock; (ii) huge, decametre-wide, discordant dunite masses, crosscutting both the peridotite foliation and the concordant Sp-harzburgite and dunite bands. The concordant Sp-harzburgites are characterized by recovery of the tectonite fabrics to coarse granular textures (Plate V-E) and by the disappearance of Plg and Cpx. The granular harzburgites often preserve oriented relics of foliated Plg-bearing tectonites (Plate V-F). The



transition from country-rock Plg-bearing peridotite tectonite to granular Sp-harzburgite is marked by changes in both rock fabric and mineral modal composition. The thickness of the contact is variable, from rather sharp (Plate V-C) to transitional (dm-wide), with progressive modification of texture and modal composition. In thin-section, the granular Sp-harzburgites consist of kinked Ol and exsolved Opx, with some corroded relics of exsolved Cpx surrounded and partly replaced by new unstrained Ol (Plate III-D and F), which also crystallises between the Px porphyroclasts (Plate III-E). Small undeformed crystals of both Pxs are interstitial, sometimes at Ol triple junctions.

Some concordant bands consist of Sp-bearing dunites (concordant dunites) (Plate VI-A). The larger, metre-wide, bodies are frequently bordered by coarse granular Sp-harzburgites (transitional harzburgites), developed at the expense of the country-rock peridotite (Plate VI-B, C, D and E). These transitional harzburgites frequently have small crystals of new undeformed Cpx, grown interstitially at Ol triple points (Plate VI-F). The concordant dunite bands sporadically contain single crystals or trails of Cpx, up to a few cm in diameter and poikilitic on Ol (Plate VI-D). Cm-scale euhedral Cpx (Plate VI-C) and fuzzy gabbroic dikelets occasionally occur in the centre of the dunite bands (Plate VI-B).

Metre- to decametre-wide bodies and channels of Sp-dunites (discordant dunites) cut at high angles both the foliation of the Plg-peridotites, the strike of the Plg-tectonite shear zones and the concordant harzburgite–dunite bands. Sp-dunites often preserve relics of the foliation of the country-rock peridotites and of earlier Sp–pyroxenite bands, as oriented trains of Cr–Sp that are continuous with foliation and Sp–pyroxenite bands in the country-rock peridotite. These features indicate the replacive origin of these Sp-dunites (Boudier and Nicolas, 1972; Boudier, 1978), i.e. they have been formed by focused and reactive migration of Px-undersaturated melts (e.g. Kelemen et al., 1995a,b). Dunites and related harzburgites occasionally contain small interstitial and undeformed grains of Cpx, frequently crystallised at triple junctions between Ol crystals (Plate VI-F). The discordant dunite bodies contain cm-scale euhedral Cpx frequently concentrated in irregular 'pyroxenite' bands; euhedral Cpx and interstitial Plg form microgabbroic aggregates and veins, a few centimetres wide. These gabbroic veins show fuzzy contacts with the country rocks. Moreover, thin, cm-scale gabbroic or gabbro-noritic dikelets cut across dunites and the surrounding peridotites. Finally, the Lanzo South peridotites have later been cut by metre-wide gabbroic dikes, displaying sharp contacts and chilled margins to the country-rock peridotite.

Field and petrographic–structural observations provide information on the evolution of the South Lanzo massif. The Opx+Sp clusters in the lithospheric Sp-peridotites may be breakdown products of pre-existing mantle garnets (Gt) (e.g. Hoogerduijn-Strating et al., 1993; Vannucci et al., 1993), suggesting that pristine Gt-facies mantle peridotites underwent Sp-facies equilibration after decompression. The thin vermicular Sp in the outer border of the Opx porphyroclasts represent the subsolidus exsolution of an Al-rich Sp from a pre-existing, highly aluminous Opx, stable at higher temperatures under Sp-facies conditions. These features suggest that the pristine mantle peridotites: (i) upwelled from Gt- to Sp-facies conditions, (ii) were isolated from the convecting asthenosphere, and (iii) were accreted to the thermal lithosphere, where they completely recrystallised under cooling at Sp-facies conditions. The presence of Ol-forming reactions on Px porphyroclasts suggests that these rocks, although preserving structural, textural and mineralogical features referable to their lithospheric evolution, have been affected by melt percolation and incipient melt–peridotite interaction.

The microstructural features of reactive Sp-peridotites (Px-dissolving, Ol-forming microstructures and later interstitial crystallisation of both Pxs) are related to melt–rock reaction followed by Px interstitial crystallisation. They indicate that early percolating melts were

Plate II. Microtextures of reactive spinel harzburgites from Mt. Arpone and impregnated plagioclase peridotites from Mt. Musinè (South Lanzo).
Reactive spinel harzburgite:

(A). unstrained interstitial Opx crystal at triple junction between mantle Ol and exsolved Opx porphyroclasts.

Impregnated plagioclase peridotite:

(B). Opx+Plg symplectitic border surrounding and replacing a strongly corroded relic of mantle Cpx;

(C). new unstrained Opx plague partially replacing mantle Ol;

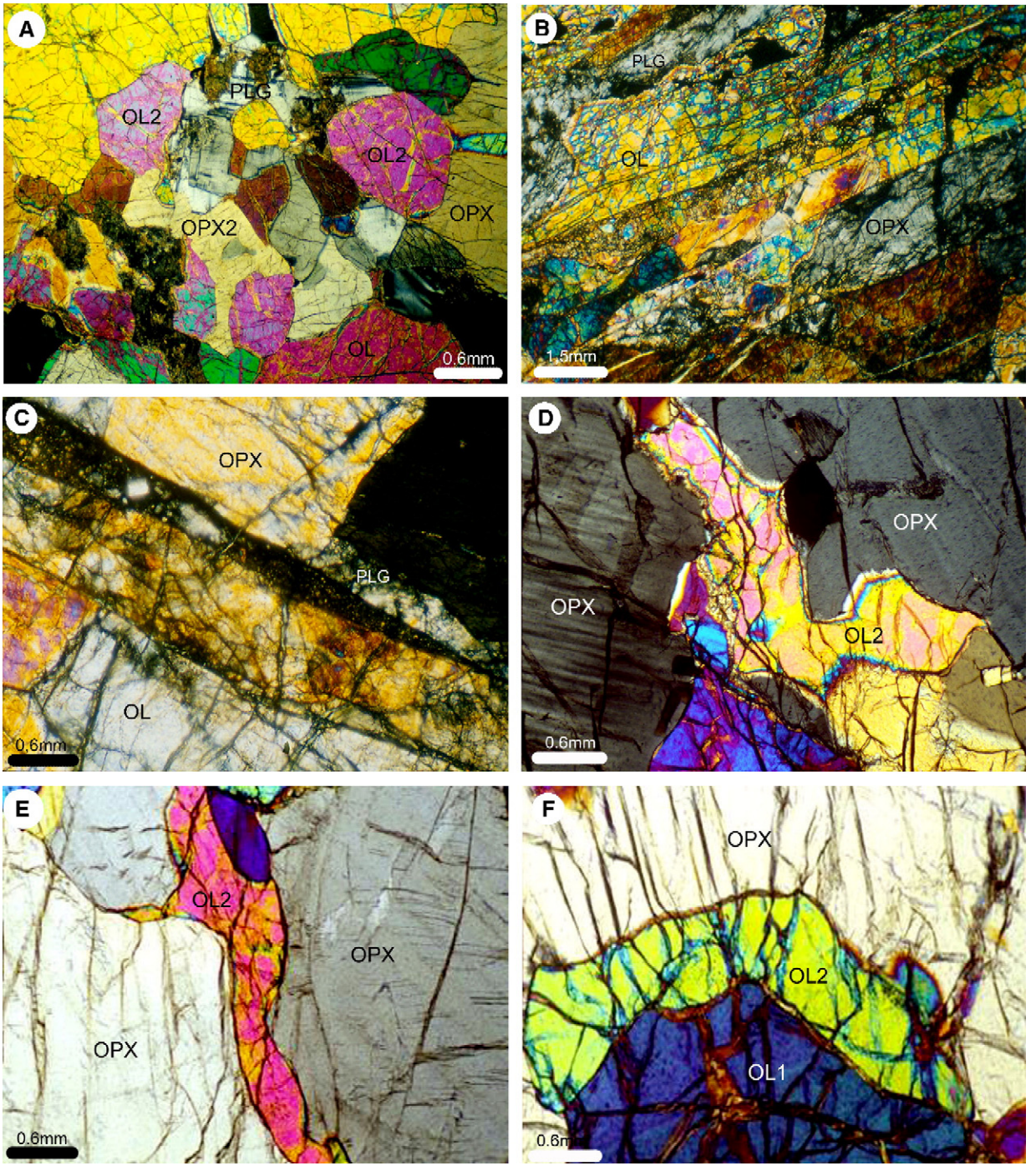
(D). unstrained crystal of Plg grown across kinked mantle Ol;

(E). Plg corona surrounding a corroded Sp crystal, developed in Sp and mantle Ol: note that Ol is replaced by Opx along the contact with Plg. This texture cannot represent a subsolidus feature, but, more probably, developed by the reactive melt percolation in between mantle Sp and Ol; the percolating melt reacted with Sp crystallising Plg, and reacted with Ol crystallising Opx. Accordingly, the percolating melt should have been silica-saturated. This texture seems to indicate that development of Plg can be assisted and enhanced by percolating melts, i.e. "the melt-assisted transition to plagioclase-facies compatibilities";

(F). veins of unstrained Opx and Cpx cutting across strongly kinked mantle Ol.

Px(-silica)-undersaturated and became progressively saturated in Pxs and silica. This compositional evolution indicates reactive melt migration within the lithospheric mantle column. In summary, the coarse granular Sp-harzburgites: (1) preserve micro-structural relics of pre-existing lithospheric peridotites; (2) are almost complete recovered to coarse granular textures; (3) record effects of interaction with Px-undersaturated melts; (4) show evidence of late interstitial crystallisation of Pxs, indicating that the percolating melt reached Px-saturation during the final stage of percolation.

Field and petrographic evidence suggest that the Plg-rich impregnation overprinted former Sp-peridotites, whilst Opx replacement on mantle Ol suggests that the



impregnating melts were silica-saturated. In the Plg-peridotites from Mt. Arpone, the presence of Cpx-dissolving, Opx+Plg-forming microtextures (Plate II-B) indicates that the percolating melts were undersaturated in Cpx, whilst in the Plg-peridotites from Mt. Musinè, the lack of Cpx dissolution microtextures, the presence of Px-forming microtextures (Plate II-F) and of Cpx-bearing gabbroic microgranular aggregates indicate that the percolating melts were saturated in both Pxs. In summary, structural and mineralogical features indicate that pre-existing Sp-peridotites were percolated by Opx(-silica)-saturated, and variably Cpx-saturated melts, suggesting progressive Px-saturation of the uprising melts. This evidence well matches with the progressive Px- and silica-saturation trend described by Kelemen et al. (1995a,b) for a Px-undersaturated melt migrating upwards via melt/peridotite interaction. Both reactive Sp-peridotites and impregnated Plg-peridotites locally show annealing of pre-existing tectonite fabrics to coarse granular textures (as described for the Ronda peridotite by Van der Wal and Bodinier, 1996). This suggests that high temperatures persisted during and after intergranular flow of melt through the peridotites.

A Plg rim is frequently present surrounding Sp (Plate II-E); this texture cannot be equated with the Plg+Ol rims between Sp and Px, which probably formed by metamorphic reaction (i.e. Sp+Pxs=Ol+Plg) from Sp- to Plg-facies mineral assemblage. Instead, it indicates that a silica-saturated melt percolated along the Sp rim, forming magmatic Plg and Opx at the expense of Sp and Ol, respectively (Plate II-E) (Piccardo et al., 2004b). Apparently, melt percolation in spinel peridotite can trigger "melt-assisted transition to plagioclase-facies mineral association". In contrast, the sporadic presence of thin Plg+Ol rims between Sp and Pxs (Plate I-C) in spinel peridotites suggests that, at least in some cases, pristine Sp-peridotites have been exhumed and underwent incipient subsolidus recrystallisation at plagioclase–facies conditions ($P<1.0$ GPa), prior to melt impregnation.

The Sp-harzburgite and dunite bands and bodies have microstructural features [i.e. (i) Cpx and Plg dissolution, (ii) abundant Ol crystallisation, (iii) recovery of the tectonite fabrics to granular structures; (iv) subsequent interstitial crystallisation of Cpx and Opx] which indicate an origin by reactive percolation of Px-undersaturated melts, followed by incipient interstitial crystallisation of Px-saturated melts. Field and petrographic–structural features indicate that focused and reactive melt percolation produced the mineralogical (chemical) and structural modification of pristine Plg-peridotite tectonites. Field evidence suggests that focused melt migration should have been enhanced by the deformation fabrics (i.e. the strongly reduced grain size and the preferred shape orientation of the Ol grains and mineral aggregates) of peridotite tectonite–mylonite shear zones i.e. melt migration was driven by pre-existing structural discontinuities. The presence of Cpx megacrysts in concordant and discordant dunites suggests incipient crystallisation of melts migrating along these high permeability channels (Müntener and Piccardo, 2003; Piccardo, 2003). The presence of gabbroic dikes, cutting through all older rock-types indicates that subsequent melts intruded and migrated along fractures when the conductive cooling modified the peridotite rheology from plastic to brittle, later and at shallower lithospheric levels during exhumation.

2.2. Compositional features

2.2.1. Analytical methods

Bulk rock major element compositions were determined by XRF at the University of Modena, on pressed pellets, using the methods of Leoni and Saitta (1976). Analyses are accurate within 2–5% for major elements and better than 10% for trace elements. Total iron oxide content is reported as FeO. Measurement of bulk rock

Plate III. Microtextures of impregnated plagioclase peridotites, plagioclase peridotite tectonites-mylonites and replacive spinel harzburgites from Mt. Musinè (South Lanzo).

Impregnated plagioclase peridotite:

(A). mm-size pod of gabbroic material, crystallised in between mantle porphyroclasts.

Plagioclase peridotite tectonite–mylonite:

(B). general aspect under the microscope of these peridotite tectonites–mylonites: the previous Plg-bearing assemblage of the plagioclase peridotite is strongly deformed. Plg, in particular, acquires undulate, "cloudy", extinction and mechanical twinning and is frequently recrystallised to very fine-grained aggregates. Minerals recrystallised in the mylonitic bands are Ol, Plg and Pxs, suggesting that the deformation event occurred under plagioclase-facies conditions;

(C). a very fine grained pseudo-tachylite band, preserving small crystals of Plg, within a peridotite tectonite–mylonite.

Replacive spinel harzburgite:

(D). unstrained magmatic Ol replacing corroded and exsolved porphyroclasts of mantle Opx;

(E). interstitial unstrained magmatic Ol between exsolved porphyroclasts of mantle Opx;

(F). corona of new unstrained magmatic Ol between porphyroclasts of mantle Ol and Opx.

trace element composition was performed by ICP-MS at the University of Montpellier II. Rock digestion on 100 mg of sample followed the procedure outlined by Ionov et al. (1992). Reproducibility and accuracy were checked by replicate analyses of both certified reference materials and samples. Bulk rock major element compositions are reported in Table 1; bulk rock trace element compositions are reported in Table 2. Major element compositions of minerals were determined by electron microprobe JEOL JXA-8600, at the University of Florence, according to the procedure described by Vaggelli et al. (1999). Trace elements in clinopyroxene, orthopyroxene and plagioclases were analysed by laser-ablation microprobe (LA-ICP-MS) at CNR-IGG, Pavia Section. Precision and accuracy (both better than 10% for concentration at ppm level) were assessed from repeated analyses of NIST SRM 612 and BCR-2 standards. Full details of the analytical parameters and quantification procedures can be found in Tiepolo et al. (2003). The mineral major element compositions are reported in Table 3; mineral trace element compositions are reported in Tables 4, 5 and 6.

2.2.2. Bulk rock composition

Reactive spinel peridotites have relatively low contents of fusible components (Al_2O_3 0.8–2.1 wt.%, CaO 0.8–2.2 wt.%, TiO_2 0.03–0.08 wt.%), the highest MgO (43.2–45 wt.%) and lowest SiO_2 (41.8–43.0 wt.%) contents. Their whole rock REE concentrations and patterns are significantly variable (Fig. 3). Harzburgite L10 shows a slightly LREE-depleted pattern but is almost flat in the M-HREE region. Lherzolites LAS3

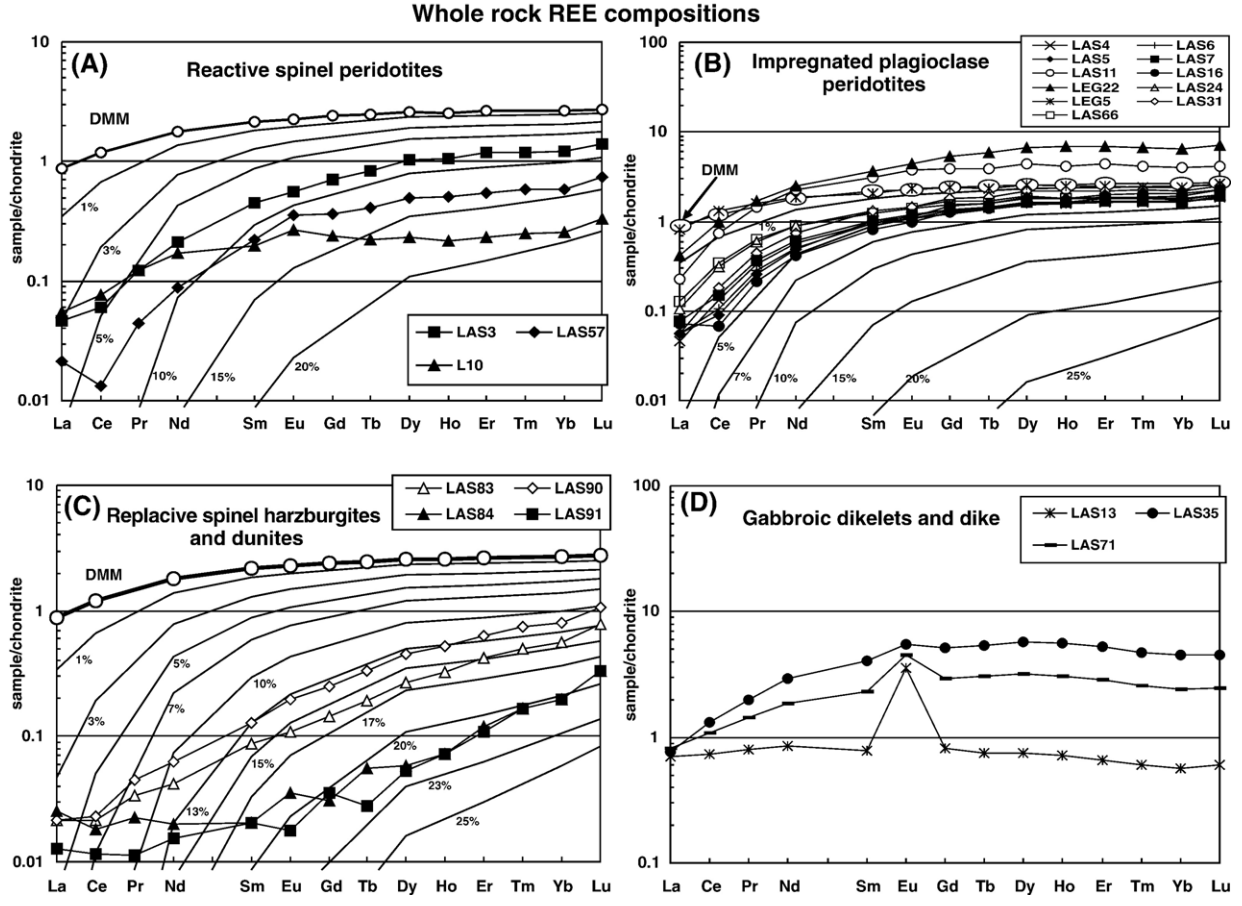


Fig. 3. Chondrite-normalised REE abundance in whole rocks: (A) reactive spinel peridotites; (B) impregnated plagioclase peridotites; (C) replacive spinel dunites and harzburgites; (D) gabbroic dikelets and an olivine gabbro dike from the South Lanzo peridotite body. C1-chondrite values are from Anders and Grevesse (1989). The chondrite-normalised REE abundance calculated for refractory peridotites after variable degrees of spinel-facies fractional melting of DMM are reported for comparison in (A), (B) and (C). Fractional melting equation was taken from Shaw (1970). Modal and geochemical composition of DMM were determined according to Hirschmann and Stolper (1996). Melting mode and solid/melt partition coefficients set were taken from Kinzler (1997; experiment at 1.5 GPa) and Ionov et al. (2002), respectively.

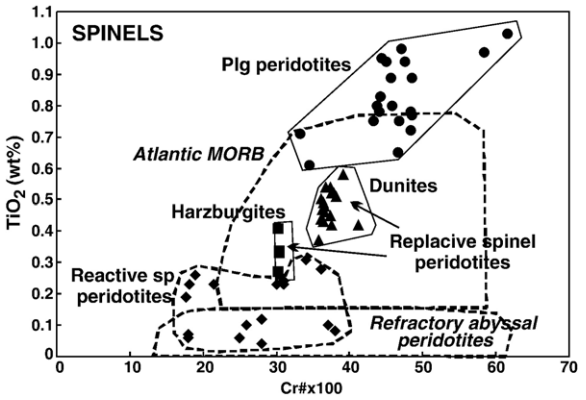


Fig. 4. TiO_2 vs. Cr# diagram of spinels from the Lanzo South reactive spinel peridotites, impregnated plagioclase peridotites, replacive dunites and transitional harzburgites, replacive dunites and harzburgites. Fields of refractory abyssal peridotites and Atlantic MORB are also reported after Kelemen et al. (1997). Note, in particular, that TiO_2 contents of spinel from dunites and harzburgites are remarkably higher than those of the refractory abyssal peridotites and fall inside the field of spinel compositions from MORB (Dick and Bullen, 1984).

and LAS57 show remarkably LREE fractionated patterns. HREE content is relatively large in LAS3 (Yb_N=1.3), whereas it is ~0.5×C1 in LAS57. Whole rock extended trace element patterns (Fig. 13) show slight to positive Sr anomalies, and negative to strongly positive $HFSE^{4+}$ anomalies.

Impregnated plagioclase peridotites show significant major element variations. In particular, samples LAS11 and LEG22 are enriched in fusible components (Al_2O_3 9.3–12.8 wt.%, CaO 8.6–8.9 wt.%, TiO_2 0.18–0.34 wt.%) and silica (SiO_2 45.2–45.9 wt.%) and depleted in Mg (MgO 22.5–28.4 wt.%), compared to the other Plg-peridotites (Al_2O_3 3.1–4 wt.%, CaO 2.3–3.3 wt.%, TiO_2 0.08–0.14 wt.%, MgO 38.4–41.7 wt.%, SiO_2 42–44.5 wt.%). The incompatible trace element content of LAS11 and LEG22 ($HREE_N$=4–7) is thus significantly higher than that of other Plg-bearing samples ($HREE_N$=1.7–2.7). The bulk rock trace element composition of these rocks are LREE-depleted (Fig. 3). Sr content ranges from 0.75 to 12 ppm and follows LREE

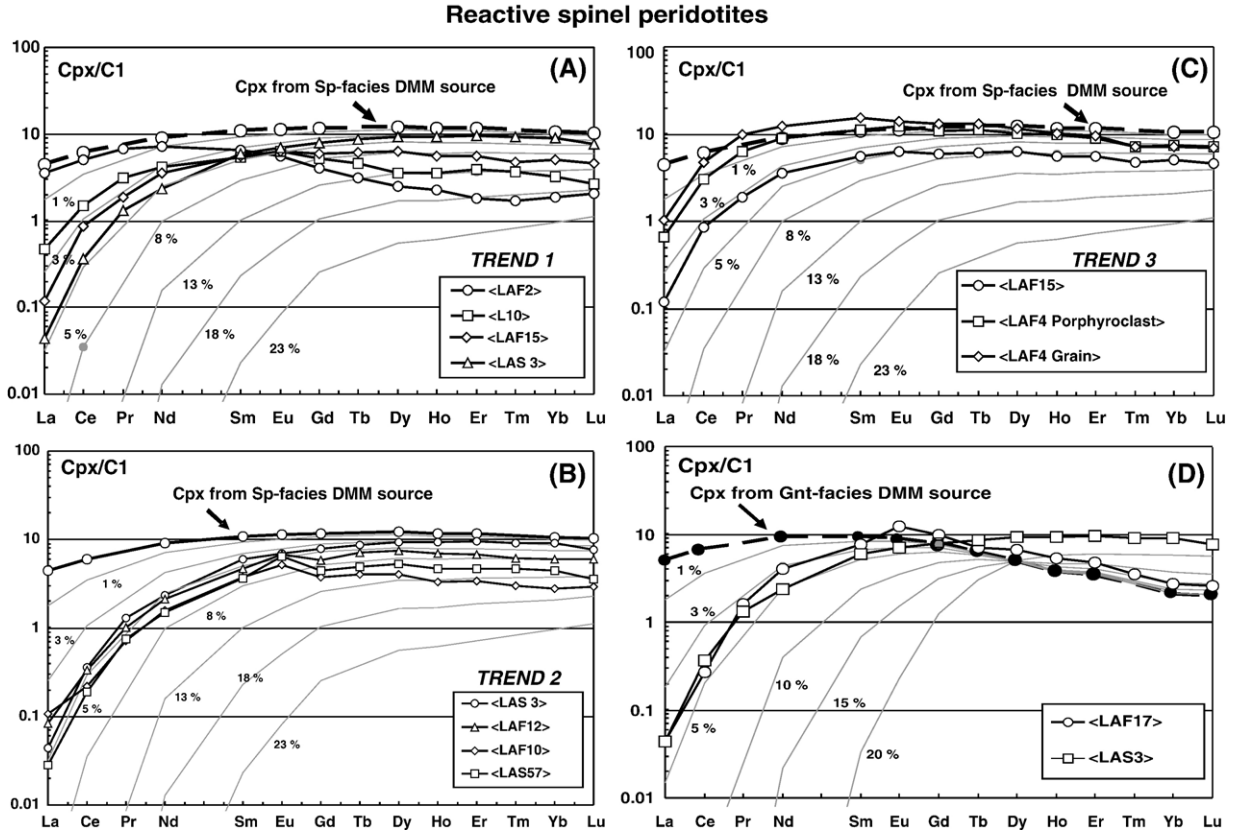


Fig. 5. Chondrite-normalised REE average abundance in clinopyroxenes (Cpx) of the analysed South Lanzo reactive spinel peridotites. (A) Trend 1; (B) Trend 2; (C) Trend 3; (D) LAF17 Cpx. See text for explanation. The chondrite-normalised REE abundance calculated for Cpx from refractory peridotites after variable degrees of spinel-facies (A–B–C) and garnet-facies (D) fractional melting of DMM is reported for comparison. Fractional melting equation according to Johnson et al. (1990). Primitive melt composition, melting mode and solid/melt partition coefficients as in Fig. 3. Differently, garnet-facies residual Cpx composition were calculated using the garnet peridotites melt modes from Walter (1998).

concentrations. Similarly, $HFSE^{4+}$ content, which shows either no anomaly or a slight negative anomaly, is correlated with that of REE (Fig. 13).

Replacive spinel harzburgites have strongly fractionated LREE-depleted patterns, with low HREE contents. REE contents are lower in the *replacive spinel dunites* ($Yb_N = 0.2$). The fractionation of the REE patterns is strong for M-HREE, but modest in the LREE region (Fig. 3). Extended patterns are characterised by positive Sr and $HFSE^{4+}$ anomalies (Fig. 13).

Gabbroic dikelets LAS13 and LAS35 and the olivine *gabbro dike* LAS71 have variable REE concentrations. LAS13 shows major and trace element characteristics indicative of large Plg accumulation, such as high Al and Na contents, low REE contents but with slight LREE-enrichment, marked positive Eu, Sr and Ba anomaly, and negative Zr and Hf anomaly (Fig. 3 and 13). Sample LAS35 and LAS71 shows LREE-depleted patterns at higher REE contents, consistently with higher Cpx modal content. Plg accumulation is reflected by a positive anomaly in Sr, sometimes associated with large Eu and Ba contents, and relative depletion in $HFSE^{4+}$.

2.2.3. Mineral composition

2.2.3.1. Reactive spinel peridotites. These contain highly magnesian (expressed as molar $Mg/(Mg+Fe_T)\times 100$) mafic minerals (Ol Mg# = 90.7–91.8, Opx Mg# = 90.7–92, Cpx Mg# = 90–92.3). Sps are relatively magnesian (Mg# = 67–81) and have low chrome (Cr# = 18–45) and high TiO_2 (up to 0.31 wt.%) (Fig. 4). Pxs have high Al contents (Al_2O_3 up to 6.9 wt.% in core of Cpx porphyroclasts). Na_2O in Cpx is mostly 0.4–0.5 wt.%, but up to 0.8 wt.% in L10 harzburgite. Modal compositions, obtained by mass balance calculations using bulk rock and mineral major element compositions, indicate that these rocks are poor in Px and enriched in Ol (Ol = 76–92%, Opx = 3–15%, Cpx = 3–10%, Sp = 0.5–2.4%), compared to residual peridotites (e.g. Kinzler, 1997; Niu, 1997). Pxs in reactive Sp-peridotites have variable major element compositions as a function of the different microstructural sites (i.e. porphyroclastic cores and rims, interstitial magmatic grains). As a rule, Al_2O_3 is higher in the porphyroclast cores, and decreases in the rims, whilst it increases again in the magmatic grains. As an example, Al_2O_3 in Cpx LAS3 is up to 6.7 wt.% in the cores, 5.9 wt.% on average in the rims, and rises again to 6.4 wt.% in the interstitial grains. Opx shows similar Al_2O_3 compositional trends: interestingly, also the CaO contents follow these trends, reaching 1.70 wt.% in the porphyroclastic cores and decreasing to 1.25 wt.% in the rims, whilst the magmatic grains have CaO contents up to 1.70 wt.%.

However, Pxs have rather homogeneous trace element concentrations among the different microtextural sites of the same sample, while there is considerable intra-sample variation. In particular, in a series of samples (i.e. LAF2, LAF15, LAS3 and L10) (Fig. 5A), the REE composition of Cpx defines a trend (**Trend 1**) varying from L/MREE-enriched sinusoidal patterns with low HREE content to strongly LREE-depleted patterns with higher HREE contents. A group of samples (i.e. LAF12, LAF20 and LAF10) defines a sub-trend (**Trend 2**) characterised by strongly fractionated LREE-depleted patterns, having LREE fractionation similar to that of LAS3 Cpx (Fig. 5B) but with variable HREE contents and fractionation. A further sub-trend (**Trend 3**) is shown by Cpx from LAF15 (that belongs also to **Trend 1**) and LAF4 samples (Fig. 5C), which share very similar patterns, with pronounced negative $HFSE^{4+}$ anomalies, but with very different absolute concentrations. Cpx from LAF17A show a peculiar composition with strongly humped REE patterns with maximum at Eu (Fig. 5D). LREE and HREE contents are low and significantly fractionated compared to MREE.

2.2.3.2. Impregnated plagioclase peridotites. Ols from the Plg-peridotites have rather low Fo contents (89.6–90.1, with the exception of LAS11 that shows Fo = 88.7), similar to that found in other Plg-peridotites from ophiolites (e.g. Barth et al., 2003). Fo is roughly correlated with Mg# [expressed as molar $Mg/(Mg+Fe_T)\times 100$] of Pxs (89.2–90.6 and 88–91.3 in Opx and Cpx, respectively). Porphyroclast rims and interstitial Pxs have Mg# similar to slightly higher than the porphyroclast core, with the relevant exception of LAS 11 Opxs. The latter show a progressive decrease of Mg# from porphyroclast cores to interstitial grains through porphyroclast rims. Al and Ca are usually heterogeneous among the different microtextural positions, but show rather variable zoning patterns. Some samples (e.g. LAS4) display Al and Ca variation in Pxs as described for reactive Sp-peridotites. In others (e.g. LAS16), Pxs show a steady Al decrease from porphyroclastic core to rim to interstitial grains. CaO in Opx shows, in some cases, a more systematic variation from relatively higher contents (up to 1.75 wt.%) in cores to lower contents (down to 1.12 wt.%) in rims, and it became higher (up to 1.60 wt.%) in the magmatic grains. Sps have high TiO_2 contents (0.66–1.0 wt.%) (Fig. 4), as commonly observed in Plg-bearing abyssal peridotites, similar to those in equilibrium with MORB (Dick and Bullen, 1984). A positive correlation occurs between Ti and Fe contents in Sp. Plgs show An contents of 68.5–88.8, being slightly to highly Ca-enriched with respect to those in equilibrium with N-MORB (e.g. Cortesogno et al., 2000). An content

of Plg is positively correlated with Ca/(Ca+Na) content in Cpx. Nicolas (1986) reported that An content steadily decreases from the grain dispersed in the peridotites to those filling up tension gashes. However, in our samples, there is no clear correlation between the An composition and the extension of the "magmatic" areas, roughly correlated with the modal Plg content.

Trace element compositions of porphyroclasts and interstitial magmatic Pxs are homogeneous to slightly zoned within the same sample, but variable from sample to sample. Minor systematic zoning is provided by REE in Cpxs, with interstitial grains enriched in MREE (with the exception of Eu) and depleted in LREE and HREE relative to porphyroclastic cores (e.g. Cpx from LEG5B). As a result, a pronounced "hump" in the REE pattern in the interstitial grains is observed, with a negative Eu anomaly. Sometimes, interstitial Cpx shows a Sr decrease. Normalized REE patterns of Cpx (Fig. 6A) are usually characterized by high M-HREE contents associated with a strong to moderate LREE depletion. A relatively M-HREE depleted composition is only shown by LAS11 Cpx. The latter have MREE, HREE, $HFSE^{4+}$, Y, V and Sc content very similar to those in Cpx from the reactive Sp-peridotite LAS3, but higher LREE and lower Sr (0.4–0.5 ppm). All Cpx show negative $HFSE^{4+}$ anomalies, with the exception of LEG5B Cpx, in which Zr and Hf are very close to the adjacent REE. In general, REE/HFSE fractionation decreases with increasing LREE contents (Fig. 14A). The trace element variability documented here for Cpx from Plg-peridotites of South Lanzo is significantly larger than that reported by Bodinier et al. (1991). However, Cpx from the Plg-peridotites have more fractionated REE patterns than those in equilibrium with N-MORB (Cortesogno et al., 2000), with only the exception of LEG5B Cpx. Opx and Plg trace element compositions vary consistently with that of the associated Cpx (Fig. 6B and C, 14B and C). Plg patterns vary strongly. The An decrease is matched by a decrease in Sr (from 154 to 5.7 ppm), LREE and LREE/M-HREE ratios. REE patterns are also characterized by large positive Eu anomalies. Ba content is very low. Similar geochemical features have been reported for interstitial Cpx from Plg-peridotites from ophiolites (Barth et al., 2003; Dijkstra et al., 2003; Spadea et al., 2003).

2.2.3.3. Replacive spinel harzburgite and dunite bands and bodies. Interstitial and megacrystic Cpx from these rocks show extremely variable compositions (Fig. 7A and 15A); on the basis of Cpx trace element composition, the investigated samples can be divided into 3 groups, hereafter called A, B and C: (i) Group A: Cpx with a depleted to strongly depleted incompatible trace element composition; (ii) Group B: Cpx having MORB s.l. signatures; (iii) Group C: Cpx showing large enrichments in highly incompatible trace elements.

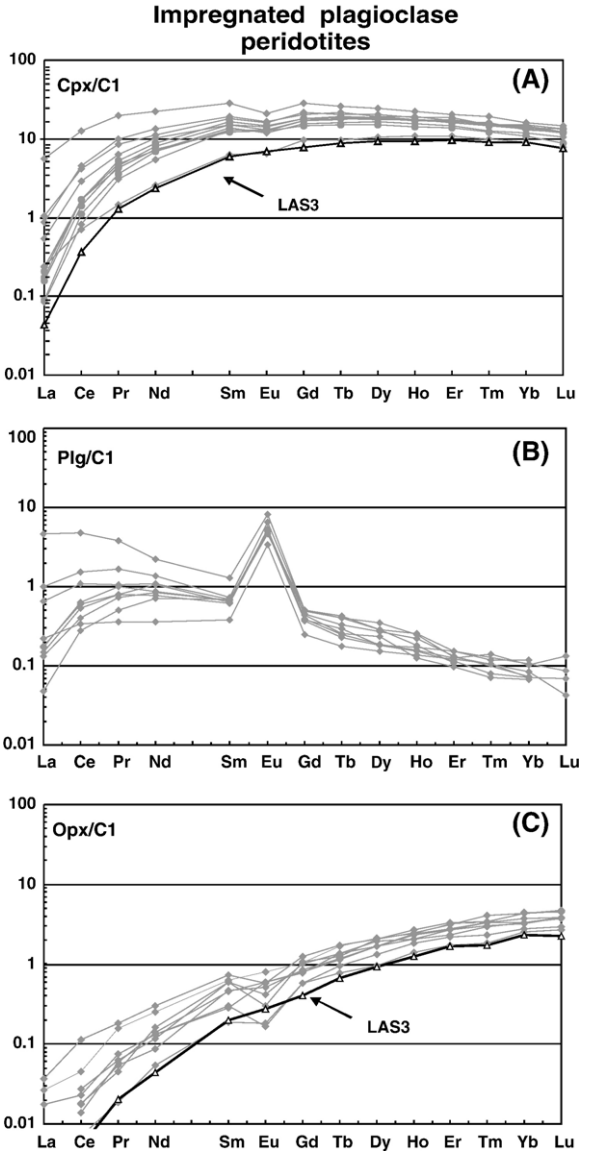


Fig. 6. Chondrite-normalized REE average abundance in the minerals from South Lanzo plagioclase peridotites: (A) interstitial, magmatic, Cpx, (B) plagioclase, and (C) orthopyroxene. Compositions of Cpx and Opx from the reactive spinel peridotite LAS3 are shown for comparison in (A) and (C), respectively.

Group A: This group is defined by some concordant Sp-harzburgites (samples MU3, MU8, MU10 and MU15) in which Cpx shows a "depleted" composition. They have moderately incompatible trace element contents (e.g. HREE, Y, Ti and V) that are significantly lower than those of Cpx from the country-rock Plg-peridotites (e.g. $Yb_N = 7.1–1.9$) and those in equilibrium

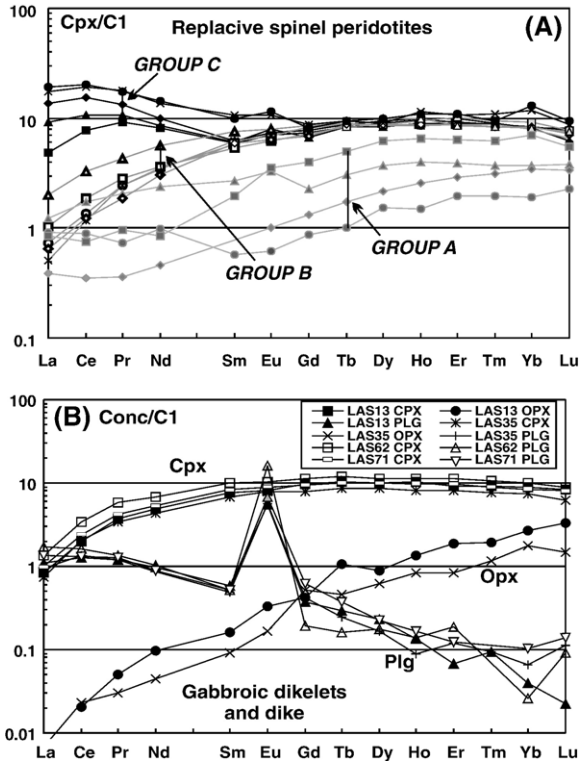


Fig. 7. Chondrite-normalized REE patterns of: (A) Cpx from concordant and discordant replacive spinel harzburgites and dunites (Group A=Cpx with depleted composition; Group B=Cpx with MORB s.l. affinity; Group C=LREE-HFSE-enriched Cpx from concordant dunites=thick, black, lines); (B) Cpx, Opx and Plg from the South Lanzo gabbroic dikelets and the gabbro dike LAS71.

with MORB. The LREE content is low (e.g. La_N=1.2–0.4). Nevertheless, highly incompatible elements are less depleted and fractionated than that expected on the basis of the HREE concentration level.

Group B: Most Cpx from replacive Sp-harzburgites and dunites show a trace element composition consistent with those crystallised by N-MORB to slightly LILE-enriched MORB. This signature is shared by discordant and concordant bodies. Trace element content in Opx is that expected on the basis of two-pyroxene partitioning (Garrido and Bodinier, 1999; Witt-Eickschen and O'Neill, 2005). Ol is uniformly Fo=90. The Sps are enriched in TiO_2 (0.27–0.58 wt.%) relatively to their Cr# (30–41), compared to those in refractory peridotites after partial melting, and are remarkably similar to Sps from MORB (Dick and Bullen, 1984) (Fig. 4). Opx from transitional harzburgites have high Mg# (91), CaO (~1.2 wt.%), Al_2O_3 (4.1–3.3 wt.%) and Cr_2O_3 (0.9–0.7 wt.%). Interstitial Cpx from transitional harzburgites are highly chromian (Cr_2O_3=1.21–1.54 wt.%) and have high Mg# (90–91), Al_2O_3 (5.3–4.8 wt.%) and Na_2O (0.8–1 wt.%) very similar to those of the dunitic bands (Cr_2O_3=1.10–1.56 wt.%, Mg#=91–92, Al_2O_3=4 wt.% and Na_2O=1.3 wt.%).

Group C: Small interstitial Cpx from metre-wide concordant dunite bands from Mt. Musinè (samples MU12 and LAS84: the latter associated with harzburgite LAS83) have patterns characterized by HREE and Y contents like those of Group 2 Cpx, but with strong enrichment in highly incompatible elements, such as LREE, Nb, Ta, Zr, Hf, Sr, Th and U (Fig. 15A). Relatively high concentrations are also shown by moderately

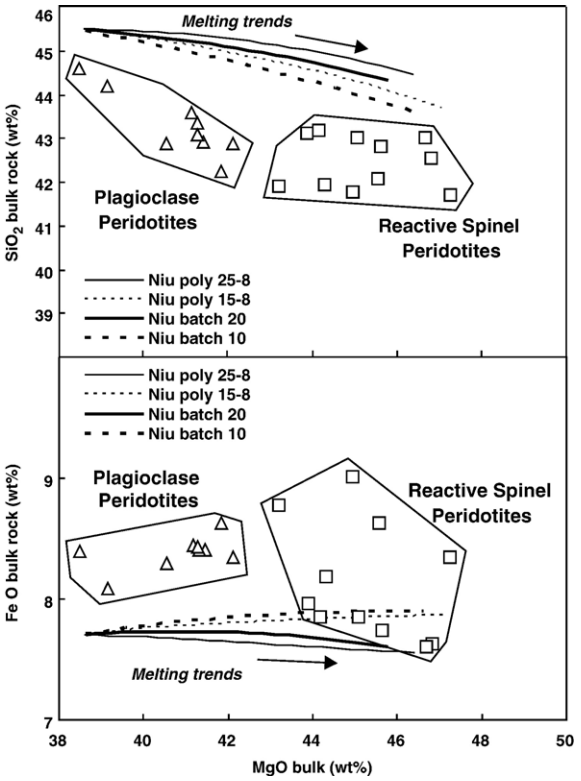


Fig. 8. Bulk rock SiO_2 and FeO vs. MgO diagrams (after Niu, 1997) of the analyzed reactive spinel peridotites (squares) and impregnated plagioclase peridotites (triangles) from South Lanzo. Melagabbroic samples LEG22 and LAS11 are not plotted because of their extremely MgO and FeO depleted composition, which also characterised by large SiO_2. Note that reactive spinel peridotites show, at a given MgO content, significantly lower SiO_2, and frequently higher FeO, contents than partial melting residua. Moreover, plagioclase peridotites define a trend, starting from the compositional field delimited by reactive spinel peridotites, which is characterised by a progressive MgO depletion, accompanied by SiO_2 enrichment and FeO depletion. Such a trend consistent with progressive enrichment in magmatic pyroxenes and plagioclase documented in these rocks by petrographic investigation. Melting trends are reported from Niu (1997). Legend: Niu poly 25–8 and Niu poly 15–8 are trends related to fractional melting in the range of 2.5–0.8 and 1.5–0.8 GPa, respectively; Niu batch 10 and Niu batch 20 are the trends related to batch melting at constant *P*, i.e. 1 and 2 GPa, respectively.

incompatible elements, such as Ti, Sc and V. In particular, REE patterns are concave-upward with an abrupt change of slope at Sm or Gd.

2.2.3.4. Gabbroic dikelets and olivine gabbro dike. Mafic minerals of the gabbroic dikelets and dikes have Mg# of 89–91. Al and Cr contents are close to those of Cpx megacrysts in dunite, whereas Na is slightly lower. Cpx shows LREE-depleted patterns, almost flat in the HREE region at about 10×C1, with no Eu anomaly (Fig. 7B). As with the major elements, they are similar to the interstitial Cpx of LREE-depleted dunites and to Cpx megacrysts LAS70. Plgs in the gabbroic veins and dikelets are relatively rich in Na (An 54–66) and Sr (500–750 ppm). Their REE patterns show a positive LREE fractionation and a marked positive Sr and Eu anomaly (Fig. 7B and 15B).

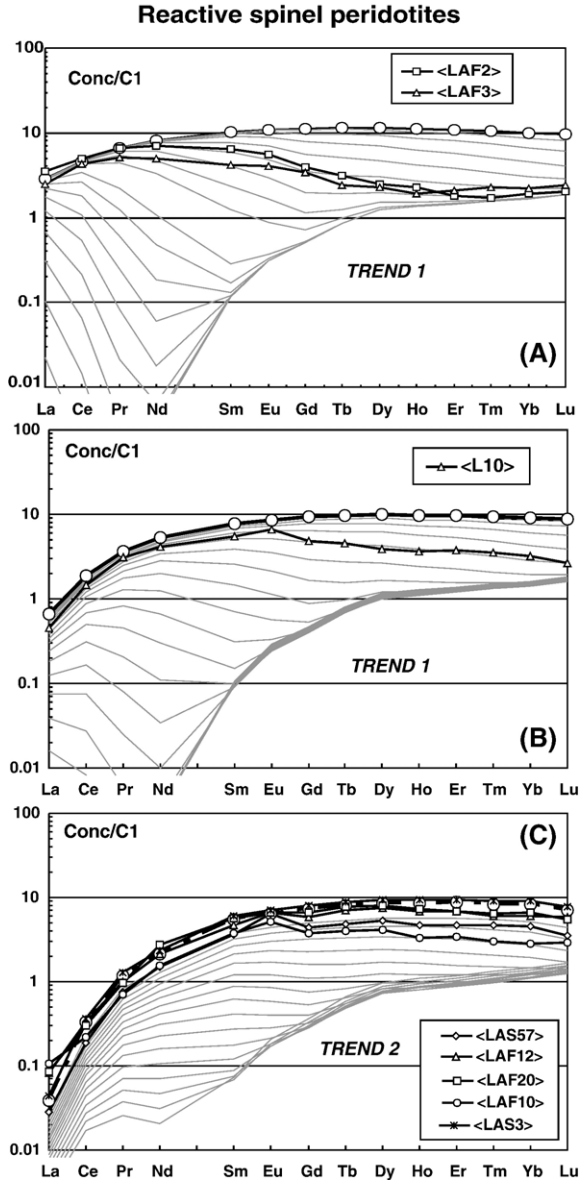


Fig. 9. Chondrite-normalised REE abundance in clinopyroxenes modelled by numerical simulation (Plate Model, Vernières et al., 1997) of reactive porous flow of melts into a depleted peridotite. The latter was considered the refractory product after 20% basalt removal via spinel-facies fractional melting of DMM, according to the mean partial melting degree estimated on the basis of bulk rock major composition and the HREE depletion level shown by some Cpx from the reactive spinel peridotites (i.e. Cpx LAF2, LAF3 and L10: Trend 1). Weight fraction of the minerals in the country peridotites was as follows: Ol:Opx:Cpx:Sp=0.65:0.27:0.07:0.01. The mantle column was divided in 20 cells and 20 process increments were run. According to Kelemen et al. (1995a,b), it was regarded that, during each process increment, peridotite pyroxenes were assimilated in the following weight fraction: Opx:Cpx=0.8:0.2. For sake of simplicity, fractional crystallisation was not allowed and starting porosity was fixed to 1%. The assimilation rate of peridotite minerals is set to 1‰ throughout the column. Cell compaction was set for melt/rock ratio larger than 0.03. At the end of the simulation, the porosity decreases progressively from the bottom to the top of the mantle column, in the range of 3–1.1%. Solid/melt partition coefficients set were taken from Ionov et al. (2002). The simulation result show that the REE fractionation of the Trend 1 Cpx (e.g. LAF2, L10 and LAS3) from reactive spinel peridotites can be interpreted as transient geochemical gradients induced by the reactive migration of different melt increments. In particular, melt increments by 0.5, 2 and 5% fractional melting of spinel facies DMM can explain the REE fractionation of Cpx LAF2 (and LAF3), L10 and LAS3, respectively. The fractionation of a melt increment by 5% fractional melting of spinel facies DMM can also account for the overall REE fractionation variability of the Trend 2 Cpx. In all simulations, the modal composition of the mantle peridotite does not show significant changes in terms of modal composition as a consequence of the relatively low assimilation rate and of the limited number of process increments.

3. Interpretation

3.1. Geochemical constraints on the petrologic evolution of the Lanzo South peridotites

3.1.1. Reactive spinel peridotites

Bulk rock modal and major element compositions of Sp-peridotites from Mt. Arpone do not correspond to those expected for refractory residua after either polybaric fractional and isobaric batch melting, as compiled by Niu (1997). In particular, most of them show significantly lower SiO_2 and higher FeO contents than those expected on the basis of Niu's calculations (Fig. 8). Although Asimow (1999) demonstrated that the SiO_2 and FeO trends of abyssal peridotites can be accounted for by polybaric batch melting, the "reactive" nature of the coarse granular Sp-peridotites from Mt. Arpone is definitely highlighted by their peculiar

reaction microtextures, which point to an early main stage characterised by Px dissolution and Ol precipitation, followed by a late subordinate stage of interstitial Px crystallisation. Thus, modal compositions of these Sp-peridotites do not match those calculated for simple refractory residua after partial melting. In fact, they show relatively low modal Pxs and high Ol contents, sometimes associated with anomalously large Cpx/Opx ratios. The geochemical consequences of melt percolation and reaction with the peridotite are apparent from monitoring the consistency of the major and trace element composition of bulk rock with the corresponding mineral chemistry in terms of estimation of refractory degree. In particular, the occurrence of a significant "decoupling" between bulk rock and mineral chemistry is clear in Sp-peridotite LAS3. When compared with compositions modelled for residual Cpxs after partial melting, the REE pattern of LAS3 Cpx well matches the composition modelled for residual Cpx after about 5% fractional melting of Sp-facies DM (~7% partial melting of Primitive Mantle, PM). Such a degree of partial melting is also consistent with the large Al content of Pxs and Sp (the Cr# of Sp points to 7% partial melting, according to Hellebrand et al., 2001), but is dramatically different compared to 20–22% partial melting estimated using Niu's modelling and MgO bulk rock content. This decoupling can be explained only by assuming that the chemistry of LAS3 minerals was completely equilibrated with a percolating melt formed by 5% fractional melting of a DM mantle. Rampone et al. (2004) and Piccardo et al. (in press) envisaged a similar scenario for reactive Sp-peridotites from Erro-Tobbio (Voltri Massif, Ligurian Alps).

Trace element compositions of hypothetical liquids in equilibrium with Cpx from other reactive Sp-peridotites using Cpx-liquid partition coefficients appropriate for high-T, silica-undersaturated, systems (e.g. Hart and Dunn, 1993; Ionov et al., 2002) do not fit those of melt increments produced either by Sp-facies or by Gt-facies DMM, with the relevant exception of the putative parental melt of LAF17 Cpx. The latter shows REE fractionation strictly consistent with that modelled for melt increments produced by 5% fractional melting of Gt-facies DMM. The occurrence of $MREE_N/HREE_N > 1$ in Cpx from Sp-facies abyssal and ophiolitic peridotites is not straightforwardly evidence of partial melting and/or melt evolution under Gt-facies conditions, because this feature can be also produced by interaction between melts and refractory Sp-facies peridotites (Suhr et al., 1998; Hellebrand et al., 2002). Nevertheless, specific numerical simulations documenting the interaction of melt increments produced by a Sp-facies source and refractory Sp-peridotites, systematically fail to reproduce the very large $MREE_N/LREE_N$ and $MREE_N/HREE_N$ values shown by LAF17 Cpx. Therefore, it is concluded that LAF17 Cpx composition was related to equilibration with melts that actually recorded petrologic processes that originated in the presence of Gt. As for the bulk rock compositions and mineral chemistry of the other reactive Sp-peridotites, according to the numerical modelling of metasomatic processes in Sp-facies peridotites from the oceanic realm s.l. (Suhr et al., 1998; Hellebrand et al., 2002), as well as in subcontinental mantle lithosphere (e.g. Ionov et al., 2002; Rivalenti et al., 2004), they can be referred to transient geochemical gradients developed as a consequence of reaction between migrating melts and ambient peridotite.

Plate Model numerical simulations (Vernières et al., 1997) have been performed with the aim of understanding the nature of the percolating melts, and the chemical and physical parameters governing their interaction with the ambient peridotite. Modelling (Fig. 9) excludes the possibility that the very large LREE variation defining Trend 1 could have been produced by injection of a unique LREE-depleted melt (e.g. in equilibrium with LAS3 Cpx). In turn, transient geochemical gradients consistent with Trend 1 can be accounted for by percolation and reaction of relatively LREE-enriched melts, similar to those in equilibrium with LAF2 and LAF3 Cpx, through a Sp-facies mantle column having LAS3 composition. Nevertheless, such a model requires injection of large volumes of liquids with a marked alkaline affinity, the occurrence of which is unexpected in view of the considered geodynamic environment. Besides, the observation that the degree of fractional melting estimated on the basis of the heaviest REE content in Cpx LAS57 and Cpx L10 (14% and 19% fractional melting of Sp-facies DMM for LAS57 and L10, respectively) is close to that estimated according to Niu's modelling and major element composition (15–16% and 21–23% partial melting for LAS57 and L10, respectively) (Fig. 9) indicates that, before the last melt injection, the mantle was significantly more depleted in trace elements than in LAS3, thus making this scenario rather unlikely.

The only alternative possibility is to envisage that Trend 1 is the product of injection of melt increments with different trace element compositions, which re-equilibrated to different extents with an already strongly refractory mantle. Thus, according to the major and trace element composition of bulk rock and the HREE level content in Cpx from several reactive Sp-peridotites (e.g. LAF2, LAF3 and L10), in all the specific numerical simulations, a refractory residuum after 20% fractional melting of Sp-facies DMM has been used as ambient peridotite.

According to solid–liquid partition coefficients, modelling indicates that the variable composition of the injected liquids can be argued on the basis of the fractionation of the highly incompatible elements (e.g. LREE) in Cpx, whereas the variability of the moderately incompatible elements (e.g. HREE) is the product of the more efficient chemical buffering exerted by the ambient peridotites. In particular, the composition of the most LREE-enriched Cpx (i.e. LAF2 and LAF3 Cpx) has been successfully approached by model Cpxs from a harzburgitic mantle produced by interaction between a melt degree of 0.5% fractional melting of Sp-facies DMM), assuming that the melt composition was mainly modified during its migration under low instantaneous melt/mass ratio (i.e. porosity) by chemical exchange with mantle peridotite (Fig. 9A). The same model is capable of approaching the geochemical features of the rest of Trend 1 Cpx using as injected melts those produced by 2% to 5% fractional melting of Sp-facies DMM (Fig. 9B and C). The best fit to the REE composition of L10 and LAF15 Cpx is obtained by taking into account the effects of Px-dissolving reactions, a feature clearly documented by petrographic investigations. The Plate Model numerical simulations indicate that Trend 2 Cpx reflect transient geochemical gradients that affected a melt produced by 5% fractional melting of a DMM source (namely, the same recorded by LAS3 Sp-peridotite). Finally, Trend 3 (i.e. an overall increase of the trace element content from Cpx LAF15 to Cpx LAF4, in presence of very similar fractionation) is an anticipation of what characterises the trace element composition of minerals from Plg-peridotites and, as discussed in the next

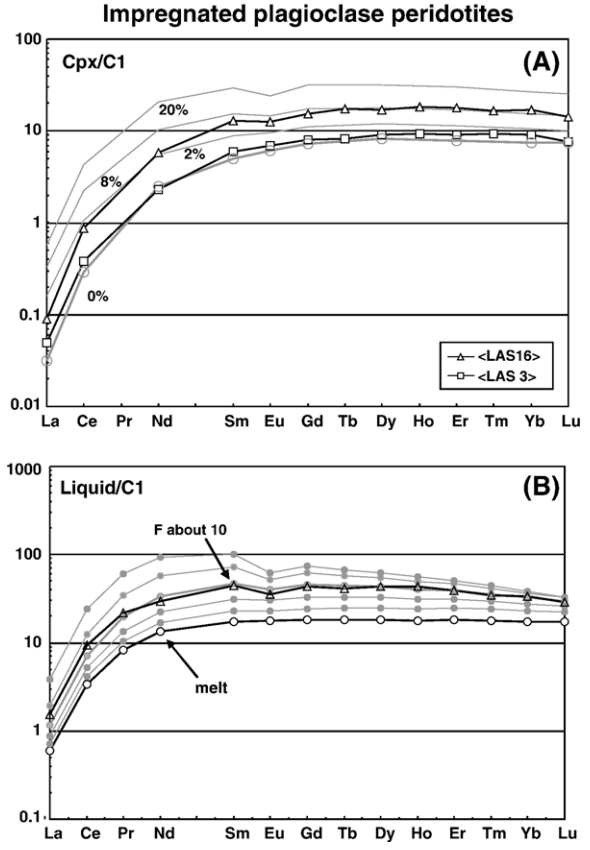


Fig. 10. (A) Numerical simulation of the geochemical consequences, in terms of Cpx REE composition, of the entrapment of different melt volumes into spinel peridotites. The numerical simulation has been designed to document the effects of the entrapment a melt increment produced by 5% fractional melting of spinel-facies DMM into the reactive spinel peridotites LAS3 (modal proportion: Ol:Opx:Cpx:Sp=0.811:0.098:0.074:0.017), whose Cpx have REE composition in chemical equilibrium with the putative trapped melt. Solid/melt partition coefficients set were taken from Ionov et al. (2002). Volume fraction of the minerals crystallised from the interstitial melt was as follows: Opx:Cpx:Plg=0.25:0.25:0.50. As expected, modelling results show that the increase of the trapped melt volumes determines an overall increase of the REE content in the Cpx, at which is associated (according to the solid/liquid partition coefficients) an increase of the $LREE_N/HREE_N$ value. As a consequence, Cpx crystallised in presence of trapped melt will have $LREE_N/HREE_N$ value always higher than those segregated by the melt via fractional crystallisation, at parity of $^{Cpx/Liquid}D$. Focusing on South Lanzo data, such a fractionation trend implies that the significant difference of the absolute REE content between Cpx LAS3 Cpx (from a reactive spinel peridotite) and Cpx the from plagioclase peridotites, showing the same REE fractionation (e.g. LAS16), cannot be accounted for by the entrapment of a melt with which they are in apparent chemical equilibrium (namely, a melt increment by 5% fractional melting of spinel facies DMM). Besides, it can be noted that the increase of the $LREE_N/HREE_N$ ratio is insufficient to document the trace element heterogeneity shown by minerals from plagioclase peridotites. These observation suggest that the generation of plagioclase peridotites: (i) was not governed by melt entrapment processes; (ii) was related to migration of different melts. (B) Chondrite-normalised REE abundance in liquids calculated by numerical simulation (Plate Model, Vernières et al., 1997) of the melt impregnation process dominated by fractional crystallisation under open system conditions. Injected melt (the heavy pattern with empty circles) and ambient peridotite as in Fig. 10(A). Initial melt/rock ratio was fixed to 0.1. According to petrographic evidence, mineralogical reaction scheme involved olivine assimilation (assimilation rate: 0.1 each run increment) and Opx+Plg precipitation (Opx:Plg=0.50:0.50; residual melt fraction after each run increment varying from 0.99 in the first cell to 0.4 in the last cell). Plagioclase/liquid partition coefficients have been estimated using the average Plg/Cpx trace element partitioning documented in the plagioclase peridotites and the clinopyroxene/liquid partition coefficients from Ionov et al. (2002). All the other modelling parameters as in Fig. 10(A). At the end of the simulation, the melt/rock ratio decreases from the bottom to the top of the mantle column, in the range of 0.099–0.011. Numerical simulation shows that the large absolute REE content estimated for the putative liquid in equilibrium with the Cpx from plagioclase peridotite LAS16 (the heavy pattern with empty triangles) with respect to that in equilibrium with the Cpx from the reactive spinel peridotite LAS3 can be approached for very small residual melt fraction ($F \sim 10$).

section, is related to petrologic processes occurring in presence of large solid–liquid partition coefficients.

The evidence that in Trend 1 Cpx, the highest LREE contents are coupled with the lowest HREE (the latter still reflecting the depleted character acquired by the peridotite before the last melt injection), suggests that the migration of the melt increments produced by lowest degrees of partial melting preceded that of the most LREE-depleted ones. In other words, the progression of melt injection was accompanied by an increase of LREE-depletion of the injected melts and by a progressive re-equilibration of the moderately incompatible elements (e.g. HREE).

Summing up, the apparent decoupling between bulk rock major element compositions and major and trace element mineral chemistry agrees well with an origin of these Sp-peridotites as reactive rocks, which interacted and partially to completely equilibrated with percolating melts produced by different degrees of partial melting of a deep-seated source. They most probably derive from the zone of the percolated lithospheric mantle, where rising asthenospheric melts were Px-undersaturated and Px-dissolution–Ol-precipitation processes were dominant.

3.1.2. Impregnated plagioclase peridotites

Our field and petrographic investigations at Mt. Arpone document that the Plg-bearing mineral assemblage overprints a heterogeneous mantle consisting of foliated (lithospheric) Sp-lherzolites, intercalated with pyroxenite bands, and coarse granular (reactive) Sp-harzburgites to dunites. The former have been partially transformed to the latter, which testifies to the occurrence of stages of pervasive and reactive melt percolation (see previous section) predating Plg enrichment. Cores of Px porphyroclasts in Plg-peridotites have major element compositions very close to those in the (reactive) Sp-peridotites. Therefore, the same high *T* conditions can be estimated for porphyroclasts in both Sp- and Plg-peridotites. On the other hand, the marked differences in terms of mineralogical, petrographic and geochemical features between early reactive Sp-peridotites and the Plg-peridotites point to dramatic changes of the intensive and extensive parameters governing these two different stages of melt migration. The origin of the contrasting petrochemical features exhibited by the reactive Sp-peridotites of Mt. Arpone and the Plg-peridotites of South Lanzo will be addressed next.

3.1.2.1. Nature of the impregnating melts. REE fractionation of melts calculated to be in equilibrium with the magmatic Cpxs suggests a strong affinity with melt increments generated by <1–5% fractional melting of Sp-facies DMM (Fig. 16), analogous to what we argued for the reactive Sp-peridotites. Nevertheless, widespread replacement of kinked mantle Ol by newly-formed Opx, along with the early crystallisation of Opx with respect to Plg and the abundance of Opx in the magmatic patches, indicate that the parental melts of the Plg-bearing mineral assemblages were more silica-rich than typical MORB, in which Opx is the last mineral to appear at liquidus conditions (e.g. Kelemen et al., 1995a). Silica-rich melts have been interpreted as the last melt fractions produced by low pressure partial melting of depleted peridotites underneath mid-ocean ridges (e.g. Dijkstra et al., 2001, 2003). On the other hand, open system upwelling of melts can cause a progressive Px(-silica) saturation as result of the early mineralogical reactions involving assimilation of mantle Pxs and segregation of Ol (Kelemen et al., 1993, 1995a). Indeed, the occurrence of progressive Px-saturation of early Ol-saturated melts is argued on the basis of the petrographic features of reactive Sp-peridotites of Mt. Arpone, as well as in many Mediterranean ophiolitic peridotites (Rampone et al., 1997; Dijkstra et al., 2001, 2003; Piccardo, 2003; Müntener and Piccardo, 2003; Müntener et al., 2004; Piccardo et al., 2004a,b) and in peridotite xenoliths (e.g. Zinngrebe and Foley, 1995; Rivalenti et al., 2004).

Thus it can be concluded that there are several lines of evidence that the silica-rich composition of the melts impregnating the Lanzo South Plg-peridotites was acquired during open system migration through the lithospheric mantle. Consequently, the very different evolution degree manifested by the melt increments circulating through the Sp-peridotite sequence of Mt. Arpone and the Plg-peridotites of southern-central Lanzo represents a further important argument against the hypothesis that the spatial distribution of Plg-bearing assemblages could be the result of a heterogeneous melt concentration during in situ melting.

3.1.2.2. Geochemical constraints on the melt impregnation process. As a rule, the Plg-peridotites are more "fertile" than the Sp-peridotites, sometimes exceeding PM composition (PM by Hofmann, 1988). The bulk rock composition of the Plg-peridotites defines a trend of increasing SiO_2, Al_2O_3 and CaO at decreasing MgO, which starts from the field delimited by the reactive Sp-peridotite compositions and points to the melagabbroic samples (Fig. 8). As in the reactive Sp-peridotites, the bulk rock major element composition and mineral chemistry are not strictly correlated as would be expected in the case of simple partial melting. Conversely, a significant correlation is apparent between the major and

trace elements of Plg and interstitial Cpx (e.g. the striking correlation between REE fractionation and albite content in Plg). Therefore, it can be concluded that the composition of these rocks was fully reset by the percolating melts. This observation supports the petrographic evidence that new magmatic Pxs and Plgs were added to the rock by the interstitial crystallisation of the percolating melts. Insights into the petrologic processes governing crystallisation of the Plg-bearing assemblages can be provided by the mineral chemistry. In particular, the absolute trace element concentrations of Pxs and Plgs from the Plg-peridotites are significantly higher with respect to those equivalent in terms of REE fractionation modelled in equilibrium with fractional melt increments using solid–liquid partition coefficients relevant for SiO_2-undersaturated systems at high P–T conditions (e.g. Hart and Dunn, 1993; Ionov et al., 2002). Furthermore, these minerals are enriched, at least in moderately incompatible elements, with respect to the same minerals from the other mafic and ultramafic lithologies of South Lanzo (namely, reactive Sp-peridotites, replacive harzburgites and dunites, gabbroic dikelets and dikes) and to those in equilibrium with MORB (e.g. Cortesogno et al., 2000). Such a difference is exemplified by Cpx from reactive Sp-peridotite LAS3 and Plg-peridotite LAS16 (Fig. 10A) that possess the same REE fractionation (pointing to equilibrium with melt increments produced by 5% fractional melting of Sp-facies DMM), but the absolute concentration of REE in Cpx LAS16 are around twice those in LAS3. The SiO_2-saturation argued for the melts assisting the formation of Plg-peridotites and the peculiar geochemical features of their component minerals are not confined to the Lanzo South Plg-peridotites, but have been documented in all Plg-peridotites of the Alpine–Apennine ophiolite massifs (Rampone et al., 1997; Müntener et al., 2004; Piccardo et al., 2004a,b), and other ophiolitic Plg-peridotites (e.g. Spadea et al., 2003), as well as in transitional (Chazot et al., 2005) and abyssal peridotites (e.g. Cannat et al., 1990).

In the literature, the trace element enrichment of Plg-peridotite mineral assemblages has been related to the following petrologic processes/interaction parameters: (1) effect of subsolidus redistribution in presence of Plg (e.g. Bodinier et al., 1991; Rampone et al., 1993); (2) crystallisation of trapped melts (e.g. Rampone et al., 1997; Dijkstra et al., 2003); (3) occurrence of large solid–melt partition coefficients during the impregnation process and/or trace element enrichment of the melts, accompanying progressive Px(-silica)-saturation, during their pre-impregnation, reactive migration in the lithospheric mantle column (Piccardo et al., 2004a,b). Subsolidus re-equilibration can cause an increase of the high-charge transition elements in Cpx due to the decrease of modal Cpx in the frame of the mineralogical reaction describing the spinel - to plagioclase-facies transition (Sp+Cpx1=Plg+Ol+Cpx2) and the larger affinity of Cpx for such elements with respect to Plg and Ol (Rampone et al., 1993). Nevertheless, subsolidus Plg-forming reaction in Lanzo South peridotites is very subordinate (and related to the pre-impregnation evolution), compared to crystallisation of magmatic Plg from the melts. Thus, given that the observed Cpx/Plg modal ratios have been basically inherited by melt crystallisation, it seems very unlikely that subsolidus adjustment of major element composition can account for the observed REE and HFSE enrichments, which are, anyway, not only shown by Cpx, but also by the associated Plg and Opx. Thus, it is concluded that the large high-charge transition elements concentration in the Plg-peridotite minerals must have been produced as a consequence of other petrochemical mechanisms, such as melt entrapment and/or open system percolative fractional crystallisation. Apparently consistent with the melt entrapment hypothesis is the absence of marked positive Sr (and Eu) anomalies in the bulk rock composition of the Lanzo Plg-peridotites. This feature is basically the result of the negative Sr (and sometimes Eu) anomalies of Pxs associated with peridotite Plgs showing a less pronounced positive Sr and Eu anomaly than expected for those crystallised in equilibrium with melts. Trace element equilibrium compositions instead characterises the Pxs and Plg from gabbroic dikelets and dykes.

The possible geochemical consequences of the occurrence of variable volumes of trapped melts have been constrained on the basis of a specifically modified version of the numerical method developed by Cawthorn (1996). A reactive Sp-peridotite (i.e. LAS3) has been considered as the ambient peridotite and trace elements were partitioned among the different minerals on the basis of the same solid–liquid partition coefficients (relevant for high-T, SiO_2-undersaturated, systems) previously used for the numerical simulation of the geochemical gradients shown by the Cpx from reactive Sp-peridotites (Fig. 10A). Modelling indicates that melt entrapment induces an increase of REE content in Cpx, accompanied by a progressive increase of $LREE_N/HREE_N$ ratio. Specifically, modelled Cpx compositions have $LREE_N/HREE_N$ value steadily higher than that defined by Cpx–liquid partition coefficients during open system fractional crystallisation.

The first evidence is that the large variability of the REE composition exhibited by Cpx from Plg-peridotites cannot be accounted for by entrapment of a unique melt. Secondly, it is apparent that the large trace element content of Cpx cannot be reproduced by assuming entrapment of the putative melts with which they are apparently in

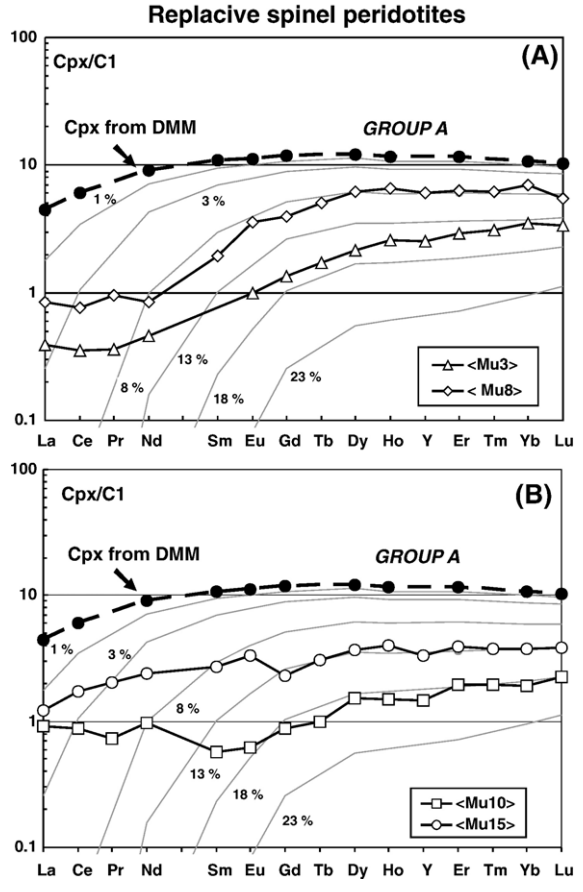


Fig. 11. Chondrite-normalised REE abundance in clinopyroxenes from refractory replacive spinel harzburgites compared to model Cpx from refractory peridotites after variable degrees of fractional melting of spinel facies DMM.

equilibrium through Cpx–liquid partition coefficients. Specifically, it means that the trace element composition of Cpx LAS16, which is among the most LREE-depleted so far documented, cannot be formed by assuming entrapment of melt increments produced by 5% fractional melting of Sp-facies DMM. On the other hand, modelling indicates that REE composition of Cpx LAS5 and LAS16 cannot be constrained by entrapment of hypothetical more refractory melts. This evidence introduces serious doubts about the role of melt entrapment during crystallisation of Plg-bearing assemblages, which is further reinforced by the observation that the most Plg-enriched, Ol-poor sample, namely LEG22, has Fo content very similar to those of the Ol from the other Plg-peridotites and of the cumulus gabbro dikes. Furthermore, LEG22 Cpx share the same trace element mineral chemistry of other less Plg-enriched peridotites, such as LAS24 and LAS66. Such features suggest that the very large modal Plg and Cps content of LEG22 was more likely determined by dissolution of peridotite minerals (in particular, Ol) under open system conditions rather than entrapment of large melt volumes. The only sample showing petrochemical features (i.e. low Fo and relatively large $LREE_N$/$HREE_N$ in minerals: Fig. 16) possibly related to some trapped melt is LAS11. However, the abundance of relic exsolved porphyroclastic Cpx suggests that this sample was originally a Sp-pyroxenite band produced during an ancient magmatic event. This observation makes interpretation of its compositional features doubtful, as they could to some extent be an imprint of the pre-impregnation lithology.

Thus, it is concluded that the major and trace element mineral chemistry excludes the significant incidence of trapped melt in the generation of Plg-peridotites in South Lanzo. This is consistent with petrographic observations which indicate that crystallisation of Plg-bearing mineral assemblage was mostly due to percolative open-system fractional crystallisation. Thus, the increase of the mineral trace element contents can have been caused by a strong decrease of the melt volume (e.g. Xu et al., 1998). This process requires that the crystallisation rate had to be larger than the assimilation rate (e.g. Vernières et al., 1997) and that the melt volume decreased during segregation of Plg-bearing assemblages. From a geochemical point of view, the predominance of fractional crystallisation in controlling the melt is also shown by the overall trace element composition of the Cpx, which show nearly constant HREE, magmatic-like, fractionation, unlike Cpx from the reactive Sp-peridotites. Plate Model simulations, which documents the interaction between melt increments and refractory peridotites using solid–liquid partition coefficients for SiO_2-undersaturated anhydrous systems at relatively high T and P (e.g. Hart and Dunn, 1993; Ionov et al., 2002), indicate that the decrease of melt mass needed to reach the concentration level calculated for the putative liquids is ~90% (Fig. 10B). This result would indicate that nearly all the melt mass actually crystallised inside the Plg-peridotites.

The main problem to consider reliable such a very large degree of melt crystallisation is again the Mg# value; it is difficult to believe that it was so perfectly buffered by the ambient peridotite. Lower degrees of melt entrapment and degrees of crystallisation can be estimated if an increase of solid–liquid partition coefficients is considered. It has been demonstrated that, during melt migration through non-adiabatic mantle, the $^{solid/Liquid}D$ can be significantly higher, $^{Cpx/Liquid}D$ for HREE becoming even >1 (e.g. Vannucci et al., 1998; Laurora et al., 2001). Similar D_{REE} values have been experimentally determined by Blundy et al. (1998) for near-solidus melting of

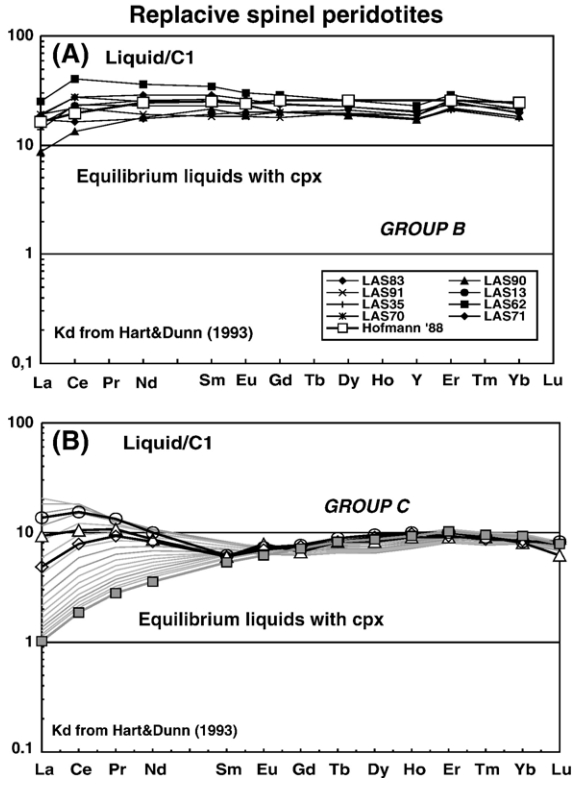


Fig. 12. (A) Calculated chondrite-normalized REE abundance in equilibrium liquids with magmatic clinopyroxenes in different rocks: (i) interstitial Cpx in replacive dunites (LAS91); (ii) Cpx megacrysts in replacive dunites (LAS70); (iii) interstitial Cpx in transitional harzburgites (LAS83–LAS90); (iv) euhedral Cpx in gabbroic dikelets (LAS13–LAS35–LAS62) and in olivine gabbro dike (LAS71). REE pattern of N-MORB is also reported (after Hofmann, 1988). (B) Chondrite-normalised REE abundances in clinopyroxenes calculated by numerical simulation (Plate Model, Vernières et al., 1997) of the consumption process of an aggregate MORB into a dunite conduit through fractional crystallisation. Trace element composition of the dunite channel was calculated according LAS91 Cpx composition, assuming Ol:Cpx mass ratio of 0.94:0.06 and partition coefficients from Ionov et al. (2002) and Zanetti et al. (2004). Initial porosity was fixed to 4%. No assimilation was allowed throughout the reaction column and residual liquid was set 100% in the first cell and 0.01% in the last cell. Cell compaction occurred for melt/rock ratio larger than 0.03. At the end of the simulation, the melt/peridotite ratio decreases from the bottom to the top of the mantle column, in the range of 3–0.03. Numerical simulation shows that the exhaustion of the interstitial melt via fractional crystallisation associated with the chemical exchange with the country rock can actually determine the progressive increase of LREE content and fractionation shown by Group C Cpx, being the HREE buffered at the Cpx composition of the host rock. The REE composition of the Cpx from the concordant dunite LAS84 are reported for comparison.

fertile Sp-peridotite and by Green et al. (2000) in hydrous tholeiite system. Fig. 17 shows as the apparent REE compositional ratio between interstitial LAS16 Cpx and melt increment by 5% fractional melting closely matched Cpx/liquid partition coefficients determined experimentally for basaltic to andesitic systems from Skulski et al. (1994) and Klein et al. (2000), as well as those obtained by Cpx/glass from mantle xenoliths (Rivalenti et al., 2004). In other words, if these solid/liquid partition coefficients assisted the crystallisation of Plg-bearing assemblage, they could cause the observed REE-enrichment in the Plg-peridotite minerals without the need to invoke a similar enrichment in the percolating melt or the occurrence of melt entrapment.

The increase of $^{\text{solid/Liquid}}D_{\text{REE}}$ could be mainly the result of an increase in Al content of the minerals, the polymerisation degree of the melt and the T decrease (e.g., Vannucci et al., 1998; Green et al., 2000 and reference therein). A higher polymerisation degree of melts percolating the Plg-peridotites compared to normal MORBs is expected according to the relatively large silica contents estimated on the basis of the mineral assemblage (i.e. Opx replacement of Ol) and the conductive regime at which Plg crystallisation occurred. Therefore, we conclude that a relevant part of the trace element enrichment documented in minerals from Plg-peridotites can be reasonably related to the occurrence of relatively high solid–liquid partition coefficients during crystallisation.

In conclusion, petrographic and geochemical data suggest that the Plg-peridotites of South Lanzo record peridotite interaction and interstitial crystallisation of melt increments, which were produced by near-fractional melting of spinel-facies asthenospheric source and acquired progressive Px(-silica)-saturation during open-system migration in the lithospheric mantle. Geochemical modelling suggests that percolative melt crystallisation was assisted by progressively larger solid–melt partition coefficients that, along with the decrease of melt volume and some melt entrapment, produced large incompatible trace element concentrations in the peridotite minerals.

3.1.3. Replacive spinel harzburgite and dunite bands and bodies

The micro-analytical data on interstitial and megacrystic Cpx from Sp-harzburgite and dunite bands and bodies replacing Plg-peridotites allowed us to unravel the presence of a significant geochemical heterogeneity, which can be interpreted as the result of different stages of melts evolution during their channelled migration. The compositions of Group A Cpx are significantly depleted compared to those of Cpx in equilibrium with aggregate MORB, whilst they approach those modelled for Cpx in refractory residua after large degrees of fractional melting under Sp-facies conditions. For instance, the REE pattern of Cpx from MU15 is, in MREE–HREE range, strictly consistent with that calculated for residual Cpxs after 13%

fractional melting of Sp-facies DMM (Fig. 11). Thus, the HREE contents in Cpx from Sp-harzburgites MU8 and MU10 are consistent with a percentage of ~8 and 18% fractional melting of Sp-facies DMM, respectively (Fig. 11A and B). The content of highly incompatible trace elements is low (e.g. La_N=1.2–0.4), but, in general, it is less depleted and fractionated than that expected on the basis of the HREE concentration level and fractional melting modelling (Fig. 11). REE patterns of Cpx MU3 are steeper in the M-HREE region (namely, they have higher $HREE_N/MREE_N$ values) than that expected for residual Cpx after fractional melting in Sp-facies DMM. The depleted character associated with variable, but sometimes strong, $MREE_N/HREE_N$ fractionation in interstitial dunite Cpx from the Bay of Islands Ophiolite (Batanova et al., 1998; Suhr et al., 1998; Suhr, 1999; Suhr et al., 2003) has been interpreted as the result of the late migration of refractory melts through peridotite channels formed by MORB (Suhr et al., 1998; Suhr, 1999). Conversely, the field, petrographic and petrologic features of these harzburgites suggests that the trace element composition of Group A Cpx can be interpreted as a transient geochemical feature produced by melt-assisted near-fractional melting of the ambient Plg-peridotite.

The geochemical evidence for the presence of a Plg component in the melts circulating along these replacive Sp-harzburgites is not straightforward. It is suggested by compositional features shown by some interstitial Cpx, like those from MU15 harzburgite, which are characterized by (Fig. 7A and 15A): (i) large absolute Sr content (higher than that documented in Cpx in equilibrium with N-MORB), which determines a marked positive Sr anomaly in the C1-normalised patterns; (ii) slight positive Eu anomaly; (iii) large LREE content and $LREE_N/MREE_N$ values; (iv) marked negative Zr anomaly. The documented petrochemical features indicate that this kind of interaction was capable of producing "refractory" harzburgitic peridotites with "depleted" geochemical compositions. The extensive modification of the ascending melt recorded by "depleted" replacive harzburgites can be reasonably ascribed to the early stages of "opening" of the migration pathways and/or of lateral "growth" of the channels. It can be argued that, in such bands, channelled melt migration had an ephemeral character, failing too early to allow the attainment of chemical equilibration with the injected melt of MORB s.l. composition (see next section).

Group B Cpx composition characterises both concordant and discordant replacive Sp-harzburgites and dunites that attained the chemical equilibrium with N-MORB to slightly LILE-enriched MORB (Fig. 12A). The hypothesis is also supported by the major element mineral chemistry. This observation indicates that the change of the mechanism of melt migration marked by the replacive bodies (from pervasive to channelled) caused mixing of the single melt increments produced by fractional melting of deeper sources. Some geochemical heterogeneity, relevant to describe the petrochemical evolution of the chanelled melt migration, is displayed by some concordant harzburgite–dunite bands, where a dm-wide harzburgitic zone makes transition to the country-rock Plg-peridotite. For example, the hypothetical liquids calculated in equilibrium with interstitial Cpx from some transitional Sp-harzburgites (LAS90 and LAS 83) (Fig. 12A) are strictly similar to N-MORB (Ross and Elthon, 1997). Conversely, the liquids in equilibrium with interstitial Cpx from the central dunitic part of these composite bands are slightly to extremely enriched (LAS91 and LAS84, respectively; the latter is a Group 3 replacive body) in highly incompatible elements. Some concordant replacive harzburgites (e.g. MU4) show relatively LILE-enriched Cpx compositions, which ubiquitously characterise the later Cpx megacrysts forming trails in both concordant and discordant dunite bodies (MU16, MU17 and LAS70), as well as the cumulate ones in gabbroic dikelets and dikes (MU7 and LAS71) (Fig. 12A). Although fractional crystallisation and/or melt entrapment can have locally biased the Cpx compositions, the systematic increase in LILE concentration documented in the Cpx going from the earlier concordant harzburgite and dunite bands to the later Cpx megacrysts in dunites and Cpx in gabbro dikes is consistent with a progressive change of the geochemical affinity of the upraising asthenospheric melts, from N-MORB to T-MORB. In conclusion, all the petrochemical features indicate that these replacive bodies could have efficiently acted as melt feeder of ocean-floor magmatism.

Cpx from LAS84 and MU12 dunites (Group C) record a more complex history. Similar geochemical compositions are commonly observed in lithospheric peridotites (e.g. Xu et al., 1998; Ionov et al., 2002), but cannot be related either to some kind of primary melt or to simple crystallisation/melting processes. Alternatively, the geochemical modelling (Fig. 12B) indicates they can be transient geochemical features produced by percolation of progressively small volumes of exhausting melts that become extremely evolved in composition as a consequence of large rate of fractional crystallisation accompanied by chemical exchange with the ambient peridotite (e.g. Xu et al., 1998; Rivalenti et al., 2007). Therefore, the enrichment in highly incompatible element documented by Cpx from Group C dunites can be interpreted as the record of the late migration of small aliquots of highly fractionated melts through early dunite channels formed by N-MORB percolation (Fig. 12B). The significant

heterogeneity shown by sample LAS84 Cpx also suggests that the temperature of the system rapidly decreased, in such a way to prevent subsolidus homogenisation. The appearance of a negative Sr anomaly in the MU12 sample is a marker of the chemical buffering of Plg. Such ephemeral melts can be considered the last breath of the melt migration in small dunite channels, which likely escaped significant compaction.

3.1.3.1. Conditions of thermal equilibration. Diffuse porous flow of basaltic melts (at $T>1250$ °C) in the originally rather cold pristine mantle lithosphere of South Lanzo (about 1000–1100 °C, according to Müntener and Piccardo, 2003; Piccardo, 2003; Piccardo et al., 2004a) requires that the thermal lithosphere was significantly heated by the rising asthenosphere and melt percolation. This thermal effect should have caused the major and trace element equilibrium of all mineral phases at these high temperatures. However, systematic major element variation between core and rim of Px porphyroclasts, and between porphyroclasts and magmatic Pxs demonstrates that major element homogenization was not achieved (Piccardo et al., 2004a). For instance, the highest Al contents are shown by the core of Px porphyroclasts, the lowest occur in the corresponding rims, whereas the magmatic grains have frequently intermediate concentrations. Ca, Mg and Fe all show similar behaviour. This zoning could results from both subsolidus re-equilibration under decreasing *P–T* conditions (i.e. the Al decrease from porphyroclast cores to rims) and equilibration with the percolating melt (i.e. Al in magmatic grains). In contrast, most trace elements in Pxs are remarkably homogeneous, independent of microstructural sites, indicating that near complete trace element equilibration was attained during melt percolation, most probably in response of the high temperatures attained during melt percolation.

Thus, in order to discuss a consistent data set of temperature estimates referable to the thermal pick conditions of the melt percolation events, we calculated equilibration temperatures of the South Lanzo spinel and plagioclase peridotites by applying the empirical thermometers of Seitz et al. (1999), based on the partitioning of trace elements between coexisting Opx and Cpx. Results indicate that very high equilibration *T* are recorded by the mineral trace element distribution of the reactive Sp-peridotites (T_{Sc} in the range 1150–1306 °C, frequently above 1220 °C; T_V in the range 1170–1285 °C, frequently above 1220 °C) and the Plg-peridotites (T_{Sc} in the range 1145–1250 °C, frequently around 1200 °C; T_V in the range 1140–1250 °C, frequently around 1200 °C). Equilibrium *T* estimated for replacive Sp-peridotites are slightly lower (T_{Sc} in the range 1100–1200 °C, frequently above 1150 °C; T_V in the range 1140–1200 °C, frequently above 1150 °C). Closely similar results have been obtained by applying the empirical thermometer of Witt-Eickschen and O'Neill (2005), similarly based on the partitioning of trace elements between coexisting Opx and Cpx. High equilibrium *T*s for Plg-peridotites from Lanzo have been also reported by Pognante et al. (1985) and Bodinier et al. (1986).

The high equilibration *T*s recorded by reactive Sp-peridotites indicates that they reached thermal conditions close to the anhydrous peridotite solidus, under Sp-facies pressure conditions, during the reactive melt infiltration. Analogously, the high *T*s recorded by the Plg-peridotites confirm that the melt interstitial crystallisation occurred at high *T*s under Plg-facies pressure conditions. The slightly lower *T*s recorded by the replacive spinel peridotites could be indicative, according to Zanetti et al. (1996), that in the melt-rich zones of focused percolation the cooling rates were lower than in peridotites which suffered melt percolation and impregnation.

Notwithstanding the variability of major element contents of the same mineral in the different structural positions of the same sample, which suggests that complete major element equilibrium redistribution have not been achieved during the high temperature melt percolation, the Ca-in-Opx geothermometer by Brey and Köhler (1990) has also been applied to the different Opx compositions from the different structural sites. In some reactive peridotites, Opxs do not have significant Ca variations and, accordingly records similar, rather high *T*s (e.g. LAF15). In most reactive peridotites, the significant Ca variations in Opxs from the different sites (i.e. higher in the cores, lower in the rims and higher again in the magmatic grains) is reflected by higher *T*s recorded by the porphyroclastic cores (up to 1205 °C, in the range 1136–1205 °C), with respect to rims (in the range 1110–1165 °C) whilst relatively higher *T*s are recorded by the magmatic grains (up to 1204 °C, in the range 1135–1204 °C).

In the hypothesis that these systematic major element variations of minerals cannot be due to subsolidus equilibration subsequent to melt percolation, which should have homogenized the mineral major element compositions, they could record evolution stages preceding melt percolation. Solely *T*s recorded by the magmatic grains could give indication on the thermal state during melt percolation. In fact they indicate Ca-in-Opx *T*s in magmatic grains that are significantly high, approaching those obtained with Seitz et al. (1999) method.

The preservation of mostly equilibrated trace elements and variable major elements requires that

trace element distribution might be faster than major element distribution. Experimental and natural studies (Sneeringer et al., 1984; Griffin et al., 1996; Ionov et al., 2002; Van Orman et al., 2002) suggest that the diffusion velocity of many trace elements including REE in Pxs is significantly increased at increasing *T*, becoming higher than that of many major elements at about 1200 °C. The preservation of these characteristics also indicates that subsolidus re-equilibration subsequent cooling during progressive exhumation was not able to significantly alter the mineral transition element contents.

4. Discussion

According to the conventional interpretation that Plg-peridotites are residual peridotites impregnated by a N-MORB melt (e.g. Nicolas and Dupuy, 1984), Nicolas (1986) suggested that the Plg-peridotites of Lanzo were formed by "in situ" low pressure (Plg-facies) partial melting during the adiabatic upwelling of an asthenospheric diapir and by redistribution and entrapment of part of the produced melt within the peridotite. It was suggested that the upwelling asthenospheric mantle departed from the adiabatic regime at ~15 km depth (0.5 GPa) and that the total melt fraction formed in the Plg-lherzolite was around 18%. Bodinier (1988) interpreted the Plg-lherzolite body of Lanzo as a residual piece of upper mantle after MORB extraction from a primitive mantle source. Melting occurred mainly in the Sp-stability field, up to the transition between Sp- and Plg-peridotite facies. The estimated percentage of melt extracted varied from 6 to 12% and the expelled magmas were thought to have T- to N-MORB compositions. Bodinier et al. (1991) documented a large-scale chemical heterogeneity within the massif, on the basis of whole rock and Cpx trace element and Sr–Nd isotope data.

Our field observations indicate that Sp-facies lherzolites, harzburgites and dunites predated the Plg-enrichment. In the "in situ" partial melting hypothesis (e.g. Nicolas, 1986; Bodinier, 1988), these heterogeneous, Sp-facies peridotites should represent either the mantle protolith pre-existing to the in situ partial melting or the refractory residua after the melting event. In particular, the strongly Px-depleted, Sp-harzburgites and dunites should represent the refractory residua after the partial melting event. Our structural and compositional data do not support the hypothesis that these rocks are refractory residua after any kind of partial melting and, in contrast, indicate that they were formed by interaction with reactive, silica-undersaturated liquids with MORB affinity, upwelling from deeper mantle sources.

Our data show that these Sp-facies ultramafic rocks were "enriched" by addition of Plg-bearing mineral assemblages. This scenario is confirmed by the trends defined by bulk rock major element composition of the Plg-peridotites, which denote "refertilization" of early refractory peridotites, and by the strict correspondence in terms of major element compositions of the core of porphyroclastic mineral assemblages between the pre-enrichment reactive Sp-peridotites and the enriched Plg-peridotites. Most Plg-peridotites from Lanzo record migration of depleted melt increments produced by 1–5% fractional melting of Sp-facies DMM. The mineralogical reactions exhibited by the Plg-peridotites indicate that the parental melts of the Plg-bearing mineral assemblages were SiO_2-saturated. This finding indicates that these melts were more "evolved", likely due to reactive melt–peridotite interaction involving Ol-crystallisation and Px-dissolution at a mantle level deeper than that documented by Plg-enrichment. Such mineralogical reactions are furthermore not consistent with the melting reaction (Opx + Cpx + Al − Sp = Liquid + Ol + Cr − Sp) postulated to have affected the Lanzo peridotite at moderate *P* (Bodinier, 1988). Segregation of the Plg-bearing mineral assemblage marks the interstitial fractional crystallisation of large time-integrated melt volumes. This process produced the complete geochemical resetting of the peridotite mass and a significant change of both intensive and extensive parameters of the system with respect to the melt migration stage recorded by the reactive Sp-peridotites. In particular, porosity and/or mineral–melt partition coefficients had to progressively increase to account for the large trace element content shown by both bulk rock and mineral chemistry.

In the southern area of Mt. Musinè the Plg-peridotites are locally transformed to granular Sp-harzburgites and dunites, which occur as elongated, concordant metre-wide bands or huge, decametre-wide discordant dunite masses. The Cpx-poor Sp-lherzolites and harzburgites ("the refractory peridotites") studied by Bodinier et al. (1991) derive from the southern flank of Mt. Musinè and the western flank of Mt. Lera, where they "are hosted in the plagioclase lherzolites" and, particularly for sample L212, it "formed a poorly defined layer of unknown extension within the plagioclase peridotites" (p. 203, Bodinier et al., 1991). Thus, it is highly probable that the refractory Sp-peridotites studied by Bodinier et al. (1991) correspond to our replacive Sp-harzburgites and dunites, which postdate Plg-enrichment and melt impregnation. Bodinier et al. (1991) suggested that these refractory peridotites have undergone a single-

stage process that is responsible for both their residual character and their high LREE/HREE ratios, possibly consisting of percolation of melts produced by moderate degrees of melting leaving residual lherzolites.

Our data indicate that the concordant Sp-harzburgite bodies record a large chemical heterogeneity. Most of the interstitial Cpx from replacive Sp-harzburgites and dunites show a trace element composition consistent with segregation from Normal to slightly LILE-enriched MORB. Concordant and discordant bodies share this compositional feature, whereas interstitial Cpx from the large discordant dunite bodies record geochemical features consistent with the migration of melts just slightly LREE-enriched with respect to N-MORB. Moreover, interstitial Cpx from some concordant spinel harzburgites show a "depleted" geochemical composition, being characterized by sinusoidal REE patterns. We interpret the trace element composition of these Cpx as the record of a transient geochemical feature of the migrating MORB-type melt, acquired during interaction with the ambient Plg-peridotite. Thus, we suggest that these Px-depleted peridotite bodies were formed by the focused reactive migration of melt with aggregate MORB s.l. compositions.

Bodinier et al. (1991) found that these refractory peridotites show the highest $^{87}Sr/^{86}Sr$ ratios (>0.7035) and the lowest $^{143}Nd/^{144}Nd$ ratios (<0.5131): samples L210 and L212 show the highest $^{87}Sr/^{86}Sr$ ratio = 0.7045. The refractory facies, which show much higher $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ values than the associated plagioclase lherzolites, plot close to CHUR values. Bodinier et al. (1991) inferred that two extreme types of refractory peridotites could be distinguished from field evidence and isotope data. The first type (L212 and L210), which is not closely associated with dunites, is characterized by much higher Sr and lower Nd isotopic ratios than the host Plg-lherzolites. According to Bodinier et al. (1991), this indicates that the Plg-peridotites have been percolated, along these depleted channels, by magmas unrelated to the massif, which were clearly of deeper origin. These refractory peridotites have been interpreted as early percolation bands associated with the pre-rift stage, when magmas of deep asthenospheric origin may have circulated through the massif. The second type (L120) is closely associated with dunites and is isotopically indistinguishable from the Plg-lherzolites.

As previously described, a significant geochemical heterogeneity is displayed by some concordant, composite harzburgite–dunite bands, where a dm-wide harzburgite zone makes transition to the country-rock Plg-peridotite. The hypothetical liquids calculated in equilibrium with Cpx from the transitional Sp-harzburgites are strictly similar to N-MORB. Conversely, the liquids in equilibrium with interstitial Cpx from the central dunitic part of these composite bands are slightly enriched in highly incompatible elements. Similar heterogeneity has been found by Bodinier et al. (1991) in the isotopic markers; Sr and Nd isotopes vary from high $^{87}Sr/^{86}Sr$ to low $^{143}Nd/^{144}Nd$ ratios (much higher Sr and lower Nd isotopic ratios than the host Plg-lherzolites) near the border of the thick refractory bands (L210) and in the thin bands (L212) toward "normal" Lanzo values in the centre of the thick bands, where dunites are also found. Bodinier et al. (1991) attributed such a variation to the rise of melts, which were progressively shallower in origin, as a consequence of rifting, being the latter melts possibly related to MORB asthenosphere. Moreover, the occurrence in the centre of the thick bands of refractory Sp-peridotites of Cpx showing Sr and Nd isotope compositions similar to those of the Plg-peridotites, is consistent with the documented compositional heterogeneity in the composite replacive harzburgite–dunite bands. According to Bodinier et al. (1991), Cpx from the gabbro veins have REE patterns and Sr–Nd isotopes identical to Cpx of the second type of refractory peridotites; this has been interpreted as evidence that they are both related to circulation of melts produced by partial melting of mantle sources with identical chemical and isotopic characters (i.e., MORB asthenosphere). This is consistent with our evidence that late Cpx megacrysts in dunites and Cpx of gabbro dikes share very similar geochemical characteristics. On the Nd vs. Sr correlation diagram, gabbro veins from the southern body and second type of refractory peridotites plot in the centre of the field of Atlantic MORB.

On the basis of the above data and discussion, it is highly improbable that the refractory peridotites of Mt. Musinè (i.e. "a few depleted spinel lherzolites with enriched Nd–Sr isotopic composition") can be considered "sparse relics of lithospheric origin" preserved within the high temperature, Plg-peridotites (i.e. the strongly "asthenospherized" mantle) of Lanzo, as suggested by Bodinier and Godard (2003).

5. Conclusions

Spinel and plagioclase peridotites from South Lanzo record the interplay of tectonic–metamorphic and melt-related events, and their relative timing, thus allowing us to infer the following scenario:

1) pristine Gt-bearing lherzolites were fully equilibrated at Sp-facies conditions in the mantle lithosphere;
2) these mantle protoliths underwent different stages of melt–peridotite interaction, from reactive percolation

at Sp-facies conditions to melt impregnation at Plg-facies conditions;
3) migrating melts had MORB-affinity and were formed by partial melting of MORB asthenosphere;
4) asthenosphere partial melting most probably was induced by near-adiabatic decompression of the MORB asthenosphere, which upwelled in response to lithospheric extension and thinning;
5) the uprising hot asthenosphere caused heating of the extending mantle lithosphere whilst the upward migration of the asthenospheric melts produced the compositional modification (both depletion and enrichment) of the extending lithospheric mantle, which underwent thermo-chemical erosion, i.e. it was "asthenospherized" (Bodinier and Godard, 2003; Piccardo, 2003; Piccardo et al., 2004a,b, 2005; Müntener et al., 2005).

The documented complexity of rock types and mantle processes describes a composite tectonic and magmatic evolution that cannot be reconciled with an "asthenospheric scenario", i.e. the interpretation of the South Lanzo peridotite as a mantle domain which upwelled adiabatically from the asthenosphere, suffered in situ partial melting and in situ redistribution and crystallisation of part of the produced melt.

We propose here a "*transitional scenario*", where the extending lithospheric mantle is strongly modified by asthenospheric MORB melts.

The proposed scenario is based on the recognition of remnants of lithospheric spinel-facies mantle rocks which suffered significant rheological and compositional modifications by variable melt–rock interaction (both depletion and refertilization) processes operated by diffusely percolating MORB-type melts. This scenario envisages that pristine subcontinental lithospheric mantle was progressively exhumed during pre-oceanic stages of lithosphere extension, and was significantly modified by interaction with migrating MORB melts which were formed in the asthenosphere by decompression partial melting during near-adiabatic upwelling, in response of ongoing lithosphere extension and thinning.

This composite melt-related evolution of the mantle lithosphere was followed by the upward migration of aggregate MORBs by focused percolation within dunite channels and by intrusion in open fractures, and this mantle section was progressively exhumed towards the sea-floor of the opening Jurassic Ligurian Tethys.

This transitional scenario implies, accordingly, that pristine subcontinental, lithospheric mantle is "asthenospherized" by the thermo-chemical erosion produced by lithosphere/asthenosphere interaction at an extensional, pre-oceanic setting.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.lithos.2006.07.002.

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