The North Lanzo peridotite body (NW Italy): lithospheric mantle percolated by MORB and alkaline melts

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Abstract. — The North Lanzo peridotite body is mostly composed of fertile spinel lherzolites showing diffuse pyroxenite bands. These lithologies typically preserve older (lithospheric) spinel-facies assemblages, but most of them experienced a widespread recrystallization at plagioclase-facies conditions. In particular, spinel pyroxenites are deeply recrystallized to plagioclase+olivine-rich assemblages. The high pyroxenes modal contents of the lherzolites and the diffuse occurrence of pyroxenite banding indicate that this mantle section escaped important modifications by reactive interaction (i.e. pyroxene dissolution and olivine precipitation) of undersaturated MORB-type melts at spinel-facies conditions, prior to the subsolidus partial equilibration, as widespread in the South Lanzo peridotite body.

According to the petrographic evidence, the early plagioclase-bearing assemblages originated during subsolidus partial recrystallization, likely during the emplacement of the mantle sequence at relatively shallow levels. Field, structural and compositional features suggest that hectometre-scale areas of the North Lanzo peridotites were successively enriched in plagioclase + olivine + pyroxenes as a result of large diffuse percolation and impregnation mostly operated by aggregate MOR-type melts.

This indicates that asthenospheric melts migrated via porous flow through the North Lanzo peridotites when they had been already exhumed to plagioclase-facies conditions, i.e. to relatively shallow levels in the mantle lithosphere.

Replacive, strongly pyroxene-depleted, spinel harzburgites cut in the form of channels through both spinel-plagioclase peridotites and impregnated plagioclase peridotites. They have small interstitial magmatic pyroxenes showing clear alkaline affinity. This indicates that, after diffuse percolation and impregnation by MOR-type melts, the North Lanzo peridotites underwent focused percolation along strongly pyroxene-depleted channels of alkaline melts, deriving from garnet-bearing fertile mantle sources.

Available data indicate that the North Lanzo spinel-facies lherzolite protolith represent the ancient sub-continental lithospheric mantle, which was isolated from the convective mantle, as previously argued on the basis of Sr-Nd isotopic data.

These peridotites record a composite tectonic-metamorphic and melt-related evolution that indicates that this piece of sub-continental lithospheric mantle has been exhumed to shallow levels, it has been subsequently pervasively percolated and impregnated by asthenospheric MOR-type melts, and finally it has

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been percolated along focused channels by alkaline melts. Field and structural evidence indicates, thus, the close relationships between lithosphere extension, asthenosphere decompressional partial melting and lithosphere melt percolation during the rifting stages of the Ligurian Tethys basin.

Riassunto. — Il massiccio peridotitico di Lanzo Nord è principalmente composto di lherzoliti fertili ricche in clinopirosseno, caratterizzate dalla presenza di relitti di una più antica associazione mineralogica a spinello e abbondanti bande di pirosseniti a spinello. I dati disponibili indicano che i protoliti lherzolitici a spinello di Lanzo Nord rappresentano l'antico mantello litosferico sottocontinentale, che fu isolato dal mantello convettivo, come già sostenuto in precedenza sulla base di dati isotopici Sr-Nd. Le peridotiti mostrano una diffusa ricristallizzazione in condizioni di *subsolidus* alla transizione di facies spinello-plagioclasio. Consistentemente le bande di pirosseniti a spinello sono profondamente ricristallizzate in rocce "gabbriche" ricche in olivina e plagioclasio. Il loro elevato contenuto in clinopirosseno e la diffusa presenza di bande di pirosseniti indicano che questa sezione di mantello non fu soggetta a importanti modificazioni per interazione reattiva con fusi sottosaturi in condizioni di facies a spinello (dissoluzione dei pirosseni e cristallizzazione di olivina) in tempi precedenti alla parziale riequilibrazione di *subsolidus*, come invece diffusamente evidenziato dal massiccio peridotitico di Lanzo Sud.

Le peridotiti di Lanzo Nord presentano aree a scala ettometrica che mostrano caratteristiche strutturali e composizionali indicative di diffusa percolazione ed impregnazione (che si manifesta con arricchimenti in plagioclasio + olivina + pirosseni) da parte di fusi aggregati di tipo MORB successivamente alla parziale ricristallizzazione di *subsolidus* a condizioni di facies a plagioclasio. Questo indica che fusi astenosferici percolarono attraverso le peridotiti di Lanzo Nord quando queste erano già state esumate a livelli relativamente superficiali del mantello litosferico.

Harzburgiti a spinello di sostituzione, fortemente impoverite in pirosseni, tagliano sotto forma di canali sia le peridotiti a spinello-plagioclasio che le peridotiti impregnate a plagioclasio. Questi corpi sono caratterizzati dalla presenza di piccoli clinopirosseni magmatici interstiziali che presentano una composizione degli elementi in tracce ad affinità alcalina. Tale osservazione suggerisce un'importante variazione delle sorgenti mantelliche tra la fase di percolazione diffusa e l'impregnazione da parte di fusi MORB (assistita da una sorgente DMM) e quella di percolazione focalizzata di fusi alcalini, verosimilmente derivanti da sorgenti di mantello in facies a granato.

Queste peridotiti registrano una complessa evoluzione tettonico-metamorfica e di interazione con fusi percolanti che indica che questo elemento di mantello litosferico sottocontinentale fu esumato a livelli superficiali, fu successivamente percolato in modo diffuso ed impregnato da fusi MORB e infine fu percolato lungo canali focalizzati da fusi alcalini. La combinazione delle evidenze di terreno e strutturali indicano gli stretti rapporti esistenti fra estensione ad assottigliamento della litosfera, la fusione parziale dell'astenosfera durante la decompressione e la percolazione di fusi astenosferici nel mantello litosferico, durante gli stadi di *rifting* pre-oceanico del bacino della Tetide Ligure.

Introduction

The Lanzo ultramafic body (~150 km^2) is located ~30 km northwest of Torino in the Western Alps and is bounded by the Po plain sediments to the East, the ophiolites with HP/LT metamorphism and schistes lustrés to the West, and the continental units of the Sesia-Lanzo Zone to the North (Nicolas, 1974; Pognante, 1989; Spalla *et al.*, 1983). The massif is characterized by a large proportion of fresh peridotites that predominantly consist of plagioclase lherzolites, with minor spinel lherzolites, pyroxenites and dunites, surrounded and partially overprinted by serpentinites (Boudier, 1978). Lithostratigraphic studies indicate that serpentinized peridotites are overlain by metabasites (partially with breccia textures), Mn-rich metaquartzites and calcschists (Lagabrielle *et al.*, 1989; Pelletier and Müntener, 2006), similar to other, less metamorphic successions in the Alps and Apennines. This strongly suggests that the Lanzo massif had to be exhumed to the seafloor of the Ligurian Tethys ocean.

The Lanzo ultramafic massif has been divided in a Southern Body (~55 km^2), a Central Body (~90 km^2) and a Northern Body (~5 km^2), separated by two partially serpentinized mylonitic shear zones

(Boudier, 1978). The Lanzo peridotites have an overall fertile composition with respect to primitive mantle abundances. Bodinier (1988) calculated melt extraction of about 6% in the Northern Body and 6 to 12 % in the Southern Body. The extracted melts was believed to have T-MORB and T- to N-MORB composition in the North and South, respectively (Bodinier, 1988). Several authors have interpreted the Southern Body as mantle asthenosphere that rose from the Grt-stability field (abbreviations after Bucher and Frey, 2002) as a high-temperature diapir, accompanied by a large degree of melt extraction (Nicolas, 1984, 1986; Bodinier *et al.*, 1991).

According to the conventional interpretation that plagioclase peridotites are residual peridotites impregnated by a N-MORB melt (e.g. Nicolas and Dupuy, 1984), Nicolas (1986) suggested that the Pl-peridotites of Lanzo were formed by "in situ" low pressure (plagioclase-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. On the basis of isotopic studies, Bodinier *et al.* (1991) interpreted the Northern Lanzo body as a fragment of the continental lithosphere which became isolated from the convective mantle 400-700 Ma.

Recent investigations on the South Lanzo peridotite (Piccardo *et al.*, 2007, and references therein) document the complexity of rock-types and mantle processes in South Lanzo and describe a composite tectonic and magmatic evolution that is not consistent with the asthenospheric scenario proposed by previous authors. On the basis of a wealth of field, petrologic and geochemical data, it has been envisaged that the extending subcontinental lithospheric mantle was strongly modified (both depleted and refertilized) by melts with MORB-affinity formed by decompression partial melting of the upwelling asthenosphere, during pre-oceanic rifting and lithospheric thinning in the Jurassic Ligurian Tethys basin.

This paper presents new field, petrographic-structural and compositional data on the North Lanzo peridotite massif. The data evidence that these peridotites derived from the subcontinental mantle lithosphere and reveal a composite scenario of subsolidus evolution and melt/peridotite interaction suggesting that melt percolation and impregnation profoundly changed both whole rock

and mineral chemistry of this peridotite section during exhumation.

On the basis of the new data on the North Lanzo peridotite and literature data on the South Lanzo peridotite, the evolution of the Lanzo mantle sections is discussed in the frame of the rifting processes related to the formation of the Late Jurassic Ligurian Tethys.

THE NORTH LANZO PERIDOTITE BODY

Petrography and field relationships

The Northern body of the Lanzo peridotite massif in the Western Alps is a small mass (5 km^2), separated by mylonitic shear zones from the main massif. It has been firstly considered as part of an asthenospheric mantle diapir emplaced during the early stages of opening of the Jurassic Ligurian Tethys (Nicolas, 1974, 1984). Bodinier *et al.* (1991) interpreted it as DMM material separated from the convective mantle and accreted to the sub-continental lithosphere near the Proterozoic-Phanerozoic boundary.

Our ongoing field, petrologic and geochemical data indicate the presence and abundance of:

1) fertile lherzolites, showing abundant spinel pyroxenite banding, hereafter referred to as *subcontinental lithospheric lherzolites*;

2) 10-100 m wide bodies of strongly plagioclase-enriched peridotite, characterized by plagioclase-rich pyroxenite layers, replacing pristine fertile lherzolites, hereafter referred to as *impregnated plagioclase peridotites*;

3) 1-10 m wide bodies and channels of coarse granular cpx-bearing harzburgites and, less frequent, dunites, replacing lithospheric lherzolites and plagioclase peridotites, hereafter referred to as *replacive spinel harzburgites*.

Subcontinental lithospheric lherzolites

These peridotites are represented by porphyroclastic clinopyroxene-rich (12.0-14.5% by volume) lherzolite, with spinel-facies mineral assemblage and abundant cm- to dm-wide spinel pyroxenite banding (Plate 1a-b). They are characterized by coarse-granular (a few mm-wide) clinopyroxene porphyroclasts showing widespread fine vermicular spinel exsolution
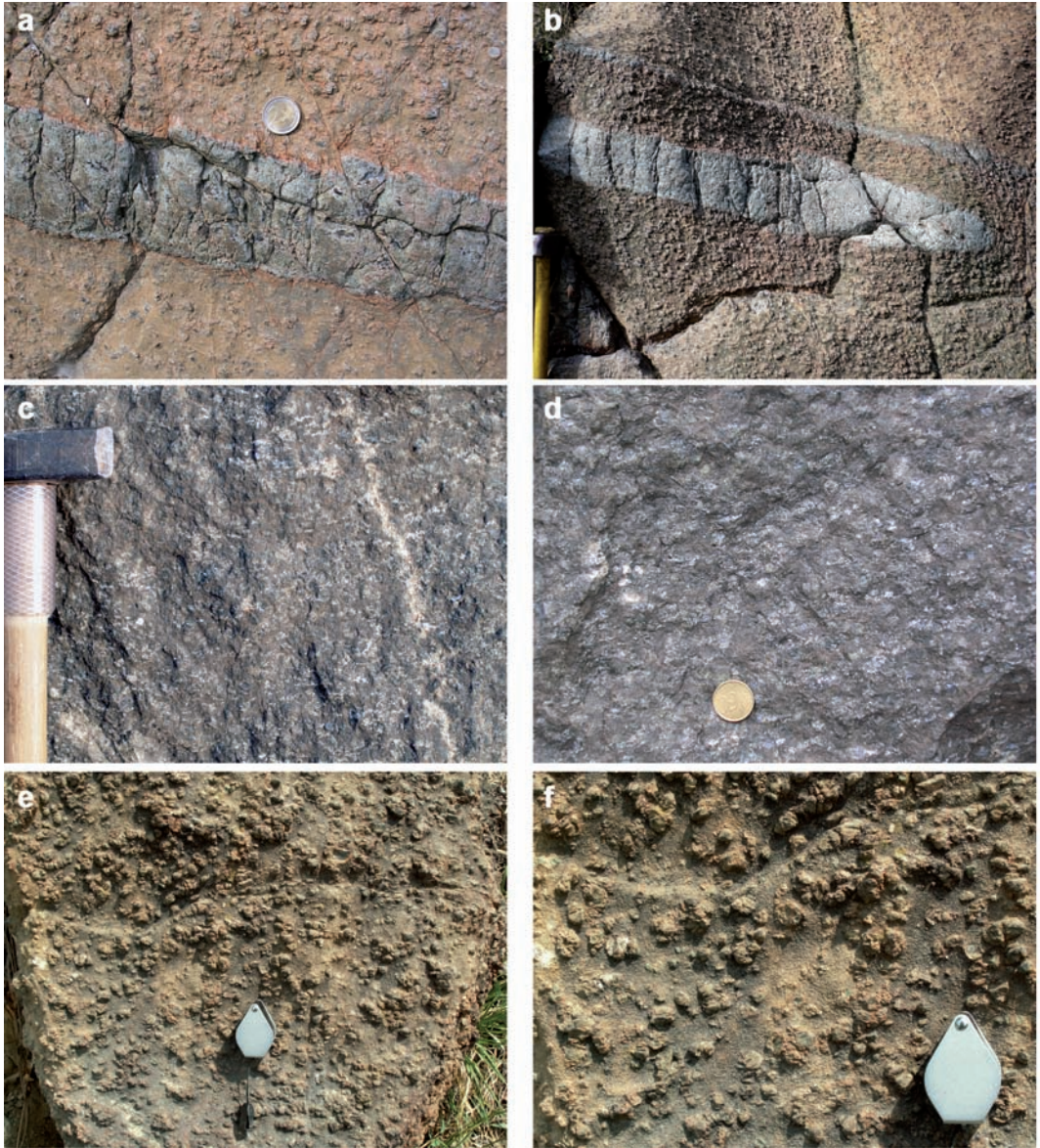
Plate 1 – (a) Spinel pyroxenite layer in lithospheric spinel lherzolite. Note the huge holy leaves spinel crystals within rounded orthopyroxene+spinel clusters, most probably derived by spinel-facies recrystallization of pristine mantle garnet. This indicates that the spinel assemblages in pyroxenites derive from precursor garnet bearing assemblages. (b) Hinge of an isoclinally folded spinel pyroxenite layer in lithospheric spinel lherzolite. (c) (d) Outcrop aspect of plagioclase enriched impregnated peridotites. (e) Outcrop aspect of coarse granular replacive spinel harzburgite. (f) Close up of the coarse granular replacive spinel harzburgite in (e)
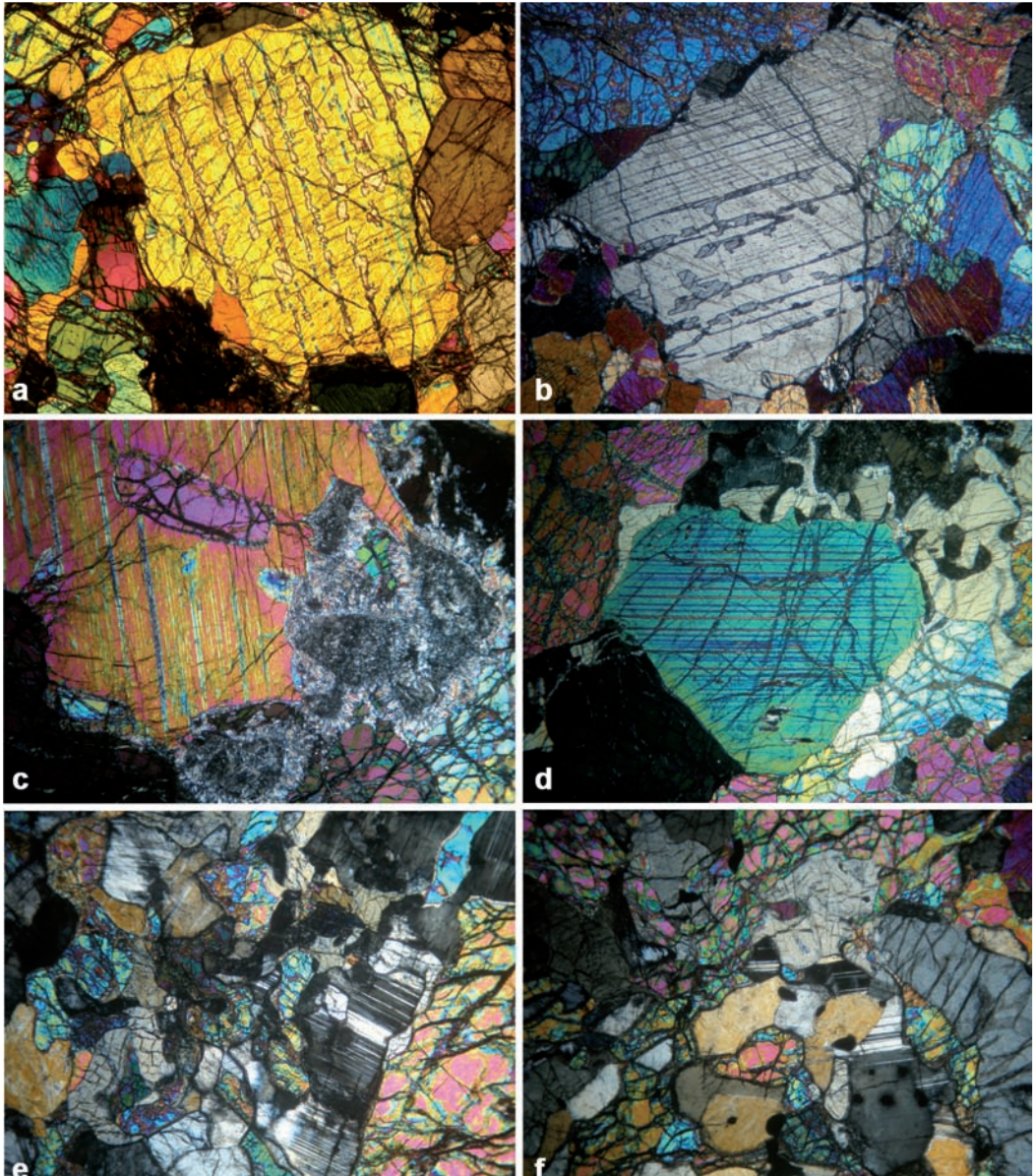
Plate 2 – (a) (b) Large clinopyroxene porphyroclasts in lithospheric spinel lherzolite, showing evident parallel exsolutions of orthopyroxene+plagioclase. (c) Type 2 impregnated plagioclase peridotite: note that a large exsolved clinopyroxene porphyroclast in partly replaced by new olivine and an aggregate of metamorphic chlorite+serpentine+talc (preserving small relics of olivine and plagioclase), replacing previous olivine+plagioclase aggregate. This texture indicates reaction between the exsolved clinopyroxene porphyroclast and an undersaturated melt, crystallizing olivine+plagioclase. (d) Type 1 impregnated plagioclase peridotite: note that a large exsolved clinopyroxene porphyroclast in partly replaced by a corona of new orthopyroxene and plagioclase (altered). This texture indicates reaction between the exsolved clinopyroxene porphyroclast and a silica saturated melt, crystallizing orthopyroxene +plagioclase. (e) (f) Mm-size troctolitic pockets in impregnated plagioclase peridotites and pyroxenites.

from orthopyroxene porphyroclasts: this texture indicates exsolution of an Al-rich Tschermakitic component during progressive cooling under spinel-facies conditions.

Clinopyroxene porphyroclasts show abundant exsolution lamellae of orthopyroxene and plagioclase (Plate 2a-b), while spinel is rimmed by plagioclase + olivine coronas when in contact with spinel-facies pyroxenes. These microstructures indicate the incipient recrystallization under decompression from spinel to plagioclase-facies (P < 1.0 GPa) conditions. Thus, in the following these rocks will be referred to as spinel-plagioclase lherzolites (according to Bodinier *et al.*, 1991), to indicate that their plagioclase was mainly formed by subsolidus recrystallization.

Impregnated plagioclase peridotites

Hectometre-scale masses of peridotites are strongly enriched in plagioclase (up to 15% by volume) (Plate 1c-d): they have frequently preserved pyroxenite bands that are enriched in gabbroic material and transformed to "gabbroic" rocks.

Both peridotites and pyroxenites are characterized by the presence of relatively large clinopyroxene porphyroclasts showing abundant exsolution lamellae of plagioclase and orthopyroxene, which testify for a preexisting decompressional evolution with concomitant cooling from spinel- to plagioclase-facies conditions. These older exsolved clinopyroxene porphyroclasts are frequently corroded and partially replaced by plagioclase-rich symplectites and granular aggregates, suggesting melt interaction. Olivine-bearing, plagioclase-rich micro-gabbroic patches are widespread interstitially between the large mantle porphyroclasts (Plate 2e-f).

Two types of impregnated peridotites have been identified, on the basis of their different microstructures (which are coupled to microchemical differences, see below).

i) Type 1, represented by sample LN25, shows orthopyroxene + plagioclase coronas surrounding clinopyroxene porphyroclasts (Plate 2d), suggesting interaction with a opx-saturated but cpx-undersaturated liquid.

ii) Type 2, represented by samples LN11, LN12, LN13, LN15 and LN47, shows olivine +

plagioclase coronas surrounding clinopyroxene porphyroclasts (Plate 2c), suggesting interaction with an Ol-saturated and silica-undersaturated liquid. Pyroxenite bands (samples LN26a and LN26b) are enclosed in these peridotites and show, similarly, profound reaction and impregnation of plagioclase-rich gabbroic material.

The textural and compositional features of these peridotites indicate that they experienced a strong interaction with percolating melts and were affected by the interstitial crystallization of large melt volumes (melt impregnation). Accordingly, they consist of an older spinel-facies assemblage and a new interstitial, magmatic fine-grained aggregate, mostly consisting of olivine + plagioclase.

Replacive cpx-bearing spinel harzburgites

In places, meter- to decameter-wide masses and elongated bands of spinel harzburgites crop out, which are strongly depleted in pyroxenes (samples LN22, LN41 and LN45). They are characterized by coarse granular isotropic texture, mostly formed by rounded orthopyroxene aggregates (Plate 1e-f), replacing the foliated textures of the spinel and plagioclase peridotites they cut. Their modal composition, as represented by sample LN22, is: Cpx = 6.7%, Opx = 7.1%, Ol = 82.5%, Spl = 3.7% (by volume), pointing to a strong olivine enrichment coupled with a significant depletion in pyroxenes (mainly orthopyroxene). In thin section, replacement structures of new unstrained olivine on exsolved pyroxene porphyroclasts are widespread, suggesting that these refractory channels were formed by focused and reactive percolation of pyroxene(-silica)-undersaturated melts which dissolved pyroxenes and precipitated olivine. The percolating melts crystallized small interstitial clinopyroxene crystals.

COMPOSITIONAL FEATURES

Analytical methods

Bulk rock major and trace element compositions were analyzed by XRF and ICP-MS at the ACTLAB (Toronto, Canada). Major element compositions of minerals were determined by EMPA at the IGG-CNR of Padova. Trace elements in clinopyroxenes, orthopyroxenes and plagioclases were analyzed by

TABLE 1
Bulk rock major (wt%) and trace element (ppm) compositions of the North Lanzo ultramafics.

Sample	LN11	LN12	LN13	LN15	LN22	LN25	LN26a	LN26b	LN38	LN41	LN45	LN46	LN47
Rock Type	1	1	1	1	2	1	3	3	1	2	2	4	1
SiO_2	45.12			45.50			47.75	49.17	44.21	42.98	43.34	45.25	45.43
TiO_2	0.096			0.125			0.277	0.393	0.143	0.046	0.024	0.041	0.146
Al_2O_3	2.54			3.54			7.41	10.87	3.52	1.02	1.26	2.77	4.13
Fe_2O_3Tot	8.22			7.90			7.45	6.18	9.10	8.91	8.87	8.27	8.30
MnO	0.13			0.13			0.13	0.13	0.13	0.12	0.12	0.12	0.12
MgO	40.21			38.57			30.23	22.75	39.31	46.04	45.38	40.68	37.80
CaO	2.54			3.03			5.93	9.37	3.22	0.65	0.84	2.52	3.64
Na_2O	0.22			0.44			0.81	1.11	0.32	0.16	0.14	0.33	0.42
Total	99.07			99.23			99.98	99.98	99.96	99.93	99.99	99.98	99.99
Sc	13	14	17	14	8	14	26	38	15	6	7	14	16
V	53	58	69	59	26	58	137	201	79	29	41	73	94
Cr	2290	3000	3020	2570	2470	3090	1910	1720	2220	1850	2010	3110	2850
Rb	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Sr	11	8	13	9	4	3	20	32	7	4	3	8	13
Y	2.6	3.2	4.3	3	0.6	2.7	8.9	14.2	3.8	< 0.5	0.7	1.8	4.4
Zr	< 4	< 4	5	< 4	< 4	< 4	13	15	8	5	< 4	< 4	4
Nb	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Cs	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.2	< 0.1	< 0.1	< 0.1	< 0.1
Ba	3	4	5	< 3	5	4	< 3	< 3	< 3	< 3	< 3	< 3	< 3
La	0.1	0.09	0.17	0.1	0.07	< 0.05	0.25	0.43	0.11	0.07	0.07	0.1	0.18
Ce	0.35	0.34	0.68	0.41	0.19	0.07	0.95	1.64	0.46	0.19	0.19	0.38	0.72
Pr	0.07	0.07	0.14	0.08	0.03	0.03	0.19	0.31	0.11	0.03	0.03	0.07	0.14
Nd	0.48	0.48	0.84	0.57	0.16	0.29	1.31	2.13	0.7	0.19	0.18	0.44	0.97
Sm	0.19	0.19	0.32	0.23	0.06	0.16	0.55	0.91	0.27	0.06	0.06	0.14	0.35
Eu	0.08	0.089	0.145	0.101	0.02	0.077	0.257	0.398	0.123	0.019	0.018	0.054	0.149
Gd	0.29	0.34	0.51	0.37	0.06	0.27	0.83	1.37	0.43	0.06	0.07	0.18	0.55
Tb	0.06	0.07	0.1	0.08	0.01	0.06	0.21	0.33	0.09	0.01	0.01	0.04	0.1
Dy	0.42	0.51	0.7	0.54	0.09	0.42	1.44	2.32	0.61	0.07	0.1	0.26	0.66
Ho	0.10	0.11	0.15	0.11	0.02	0.09	0.31	0.50	0.13	0.02	0.02	0.06	0.14
Er	0.31	0.33	0.45	0.36	0.08	0.29	0.97	1.55	0.39	0.05	0.08	0.2	0.46
Tm	0.048	0.05	0.07	0.055	0.013	0.045	0.151	0.238	0.059	0.009	0.015	0.033	0.074
Yb	0.31	0.35	0.47	0.36	0.09	0.30	1.01	1.62	0.39	0.06	0.11	0.23	0.48
Lu	0.049	0.057	0.07	0.053	0.016	0.044	0.16	0.253	0.061	0.01	0.017	0.038	0.072
Hf	0.1	0.1	0.2	0.1	< 0.1	< 0.1	0.4	0.6	0.2	0.1	< 0.1	< 0.1	0.3
Ta	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Pb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5
Th	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
U	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.16	0.72	0.03	0.1	0.08	0.02	0.06

1: impregnated plagioclase peridotites, 2: replacive spinel harzburgites, 3: impregnated pyroxenites, 4: lithospheric spinel lherzolite
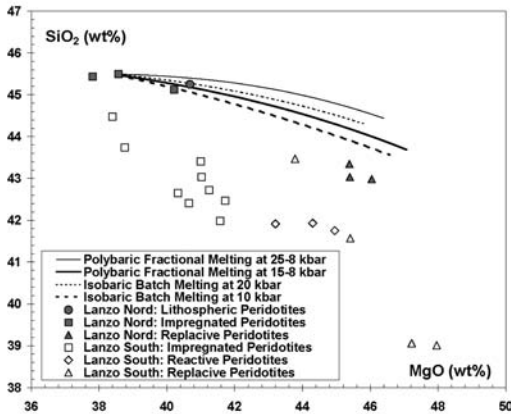
Fig. 1 – Bulk-rock SiO_2 *vs.* MgO diagram for the North Lanzo mantle peridotites. The bulk rock compositions of the South Lanzo peridotites from Piccardo *et al.* (2007) are reported for comparison, as well the isobaric and polybaric

means of Laser-Ablation Inductively-Coupled-Plasm Mass-Spectrometry (LA-ICP-MS) at the IGG-CNR of Pavia. Data reduction was performed using NIST SRM 610 and CaO as external and internal standards, respectively. Precision and accuracy (both better than 10% for concentration at ppm level) were assessed from repeated analyses of NIST SRM 612 and BCR-2g standards.

Bulk rock major and trace element compositions

Subcontinental lithospheric lherzolites have rather fertile compositions. The sample LN46 (Table 1; Fig. 1) is characterized by relatively high SiO_2 (45.3 wt%), Al_2O_3 (2.8 wt%) and CaO (2.5 wt%) and relatively low MgO (40.7 wt%). C1-normalized REE pattern is only slightly LREE-depleted ($La_N/Sm_N = 0.45$; $La_N = 0.43$) and show a positive slope in the MREE-HREE region (maximun at $Lu_N = 1.6$ xC1). HREE content fits that expected for refractory residua after 7% fractional melting of a spinel-facies DM (Fig. 2a).

With respect to lithospheric spinel-plagioclase lherzolites, impregnated plagioclase peridotites Type 2 have comparable SiO_2 (45.1-45.4 wt%), basically higher Al_2O_3 (2.5-4.1 wt%) and CaO (2.5-3.6 wt%), and lower MgO (37.8-40.2 wt%), consistently with large plagioclase addition (Fig. 1). They are also richer in incompatible trace elements

(e.g. REE) than the lithospheric lherzolites. C1-normalized patterns are moderately depleted in LREE ($La_N/Sm_N = 0.26-0.33$; $La_N = 0.38-0.77$), with a slight positive slope in the MREE-HREE region (in the range 2-3 xC1). The plagioclase peridotites Type 2 with the highest trace element content have the REE pattern fitting the DM one, estimated according to Zanetti *et al.* (2006) (Fig. 2b).

The LREE in the impregnated plagioclase peridotites Type 1 are strongly fractionated and depleted ($Ce_N/Sm_N = 0.11$; $Ce_N = 0.12$), with a slight positive slope in the MREE-HREE region (~1.8 xC1). The overall REE pattern of the LN25 sample fits that modelled for refractory residua after 4% fractional melting spinel facies DM (Fig. 2b).

Impregnated plagioclase pyroxenites are relatively rich in SiO_2 (47.8-49.2 wt%), Al_2O_3 (7.4-10.9 wt%) and CaO (2.5-3.6 wt%), and poor in MgO (22.8-30.2 wt%). The REE content is extremely large ($HREE_N$ up to 10 xC1) (Fig. 2b).

Replacive spinel harzburgites have relatively low SiO_2 (43.0-43.3wt%), Al_2O_3 (1.0-1.3 wt%) and CaO (0.65-0.84 wt%) and high MgO (45.4-46.0 wt%) contents (Fig. 1), and are strongly depleted in incompatible trace elements with respect to lithospheric and impregnated peridotites. The C1-normalized REE patterns are broadly concave (minimum at Tb 0.28 xC1), with LREE and HREE concentrations always lower than 0.40 and 0.68 xC1, respectively. HREE contents fit that expected for refractory residua after 13-17% fractional melting of spinel-facies DM (Fig. 2a).

Major and trace element mineral chemistry

In all the lithologies, olivine and pyroxenes are highly magnesian (Table 2). Na_2O in Cpx is lower in Type 1 impregnated peridotites (0.3-0.4 wt%) than in Cpx Type 2 (mostly 0.5-0.7 wt%): the highest Na_2O content (0.77 wt%) is shown by the Cpx grain in the replacive harzburgites LN22. In the impregnated peridotites, spinels are relatively magnesian, have large Cr_2O_3 content (>30 wt%) and high TiO_2 (up to 0.47 wt%). Pyroxenes have large Al contents ($Al_2O_3 > 6$ wt% in core of Cpx porphyroclasts), which usually vary as a function of the different microstructural sites (i.e. porphyroclastic cores and rims, interstitial
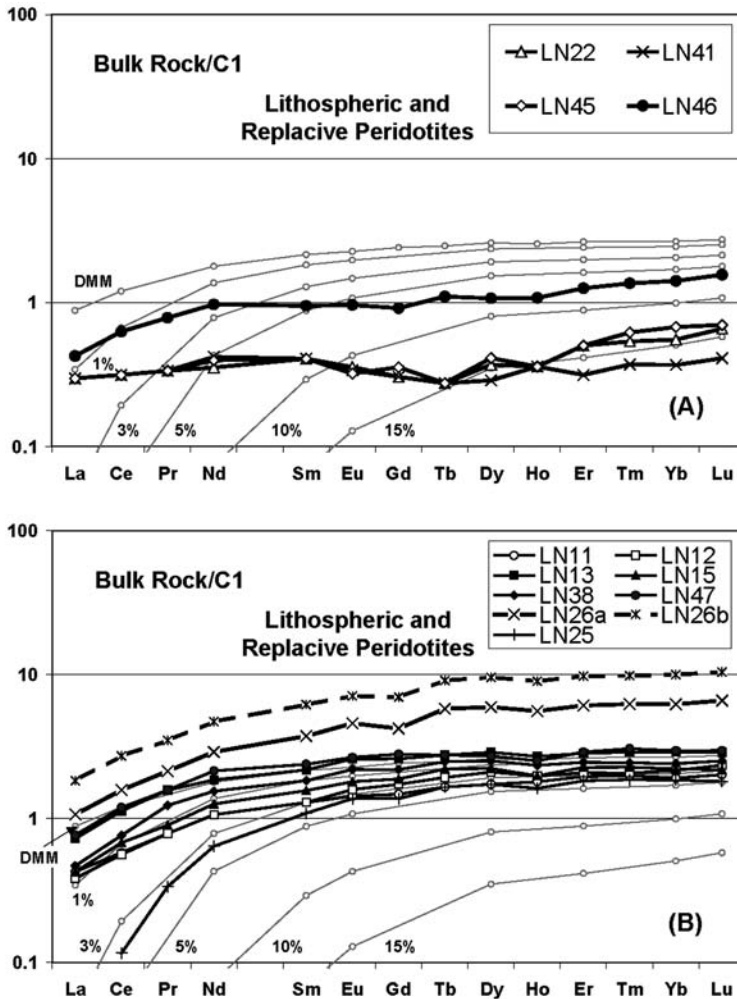
Fig. 2 – Bulk-rock C1-normalized REE content of the mantle ultramafics from the North Lanzo body: (a) lithospheric (i.e. LN46) and replacive peridotites; (b) impregnated peridotites and pyroxenites (the latter are LN26a and LN26b). Modelled compositions calculated after different degrees of spinel-facies fractional melting of a DMM source are reported for comparison. See text for further explanations.

magmatic grains). For instance, Al_2O_3 in Cpx LN25 is up to 6.0 wt% in the cores, 5.2 wt% on average in the rims, and 4.8 wt% in the interstitial grains. The Al variation is broadly inversely correlated to Ca content. Opx shows similar compositional trends. Anorthite content in plagioclase is mostly between 60-70. As a whole, the major element mineral chemistry of the North Lanzo samples is similar to what documented for the South Lanzo by Piccardo *et al.* (2007).

The determination of trace element composition has been carried out on clinopyroxene, orthopyroxene and plagioclase (Table 3). The trace element compositions of the minerals in the same sample are pretty homogeneous (with some exception mainly related to Sr zoning) disregarding the microstructural site (i.e. porphyroclast core and rim, interstitial grain).

Clinopyroxenes of the lithospheric lherzolite sample LN46 show a REE normalized pattern

TABLE 2

Major element mineral chemistry (wt%) of selected mantle ultramafics from the North Lanzo body.

Sample	LN 25							LN 11	
Rock Type	Impregnated Peridotite (Type 1)							Impregnated Peridotite (Type 2)	
Occurrence	Cpx Porf Core	Cpx Porf Rim	Cpx Grain	Opx Porf Core	Opx Porf Rim	Opx Grain	Ol	Cpx Porf Core	Cpx Porf Rim
SiO_2	51.14	51.89	51.68	55.92	56.80	56.75	41.70	51.16	52.08
TiO_2	0.48	0.46	0.51	0.19	0.17	0.22	0.02	0.77	0.65
Cr_2O_3	1.22	1.36	1.26	0.85	0.72	0.63	0.03	1.17	1.21
Al_2O_3	6.03	5.21	4.75	3.42	2.53	2.33	0.00	5.79	4.98
FeOTot	3.24	3.03	3.03	6.82	6.30	6.46	10.05	2.93	2.76
MnO	0.11	0.12	0.08	0.18	0.14	0.17	0.13	0.06	0.13
MgO	16.08	15.99	16.31	32.66	32.75	32.88	48.77	15.17	15.74
CaO	21.88	22.40	22.15	1.29	1.25	1.31	0.06	22.81	22.90
Na_2O	0.34	0.37	0.31	0.02	0.01	0.02	0.01	0.68	0.59
K_2O	0.004	0.002	0.03	0.01	0.02	0.01		0.03	0.02
Total	100.51	100.85	100.10	101.36	100.68	100.79	100.77	100.56	101.06
Sample	LN 11 (continued)						LN 26a		
Rock Type	Impregnated Peridotite (Type 2)						Impregnated Pyroxenite (Type 2)		
Occurrence	Opx Porf Core	Opx Porf Rim	Opx Grain	Ol	Spl Core	Spl Rim	Cpx Grain	Opx Porf Core	Opx Porf Rim
SiO_2	56.16	56.09	56.48	40.52	0.21	0.11	52.06	54.77	54.97
TiO_2	0.20	0.19	0.19	0.02	0.24	0.47	0.99	0.25	0.26
Cr_2O_3	0.79	0.71	0.64	0.01	33.94	33.39	0.52	0.37	0.44
Al_2O_3	4.33	3.22	2.78	0.07	29.01	32.01	4.27	5.59	5.09
FeOTot	6.59	6.62	6.64	9.72	27.22	25.05	3.38	7.29	7.55
MnO	0.17	0.27	0.09	0.18	0.00	0.00	0.12	0.17	0.19
MgO	32.53	33.36	33.40	49.53	9.26	9.40	16.00	32.07	32.19
CaO	0.74	0.92	0.85	0.06	0.19	0.16	22.64	0.83	0.62
Na_2O	0.05		0.023				0.50		0.03
K_2O	0.01		0.001				0.00	0.02	0.04
Total	101.56	101.37	101.10	100.11	100.06	100.57	100.48	101.36	101.37

In LN11 sample, olivine has 0.32 wt% NiO, while spinel has 0.26-0.40 wt% NiO and 0.38-0.45 wt% ZnO.

TABLE 2
continued ...

Sample	LN 26a (continued)			LN 22					
Rock Type	Impregnated Pyroxenite (Type 2)			Replacive Peridotite					
Occurrence	Opx Grain	Plg	Ol	Cpx Porf Core	Cpx Porf Rim	Cpx Grain	Opx Porf Core	Opx Porf Rim	Ol
SiO_2	56.77	52.14	41.53	51.64	52.62	52.15	56.35	57.29	41.85
TiO_2	0.41	0.06	0.05	0.26	0.37	0.25	0.07	0.11	0.00
Cr_2O_3	0.52	0.01	0.03	1.80	1.59	1.47	0.91	0.65	0.01
Al_2O_3	2.30	30.03	0.00	5.54	3.98	4.55	3.62	2.82	0.00
FeOTot	7.23	0.11	10.72	3.05	2.80	2.64	5.95	6.02	9.01
MnO	0.20	0.00	0.15	0.12	0.09	0.11	0.13	0.10	0.11
MgO	33.07	0.01	48.39	15.38	15.81	15.39	32.90	33.47	49.08
CaO	0.82	13.55	0.01	22.12	22.95	23.00	0.77	0.78	0.02
Na_2O	0.02	3.81		0.64	0.63	0.77		0.01	0.01
K_2O	0.01	0.02		0.01	0.01	0.01	0.02	0.02	
Total	101.36	99.74	100.88	100.55	100.86	100.33	100.71	101.29	100.10
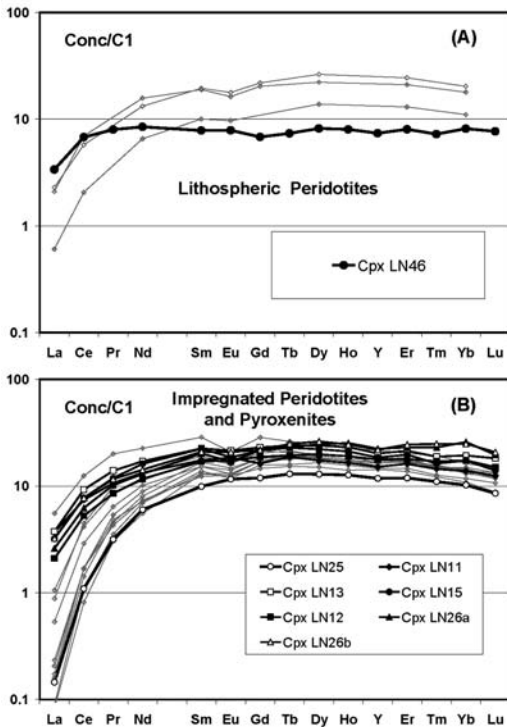
slightly LREE-depleted ($Sm_N/Ce_N = 1.12$), almost flat in the MREE-HREE, at 7-9 xC1 (Fig. 3a).

Clinopyroxenes of Type 1 impregnated peridotites show a strongly LREE-depleted C1-normalized pattern ($Sm_N/Ce_N = 9.09$), which flattens, although resulting slightly convex-upward, in the M-HREE region (10-13.3 xC1) (Fig. 3b). Clinopyroxenes of Type 2 impregnated peridotites, as well as the enclosed pyroxenites, show closely similar REE contents. C1-normalized patterns are moderately LREE-depleted ($Sm_N/Ce_N = 2.35$ to 3.25), being flat to slightly convex-upward in the M-HREE region (10-30 xC1), with the random occurrence of negative Eu anomaly (Fig. 3b). They are strictly consistent with the trace element compositions

Fig. 3 – C1-normalized REE and Y content of the clinopyroxene from: (a) the lithospheric peridotite LN46. The composition of the clinopyroxenes from the Lanzo layered pyroxenites previously documented by Bodinier et al. (1991) are reported for comparison; (b) Type 1 (i.e. LN25) and Type 2 impregnated peridotites and pyroxenites from the North Lanzo body. The composition of clinopyroxenes from the plagioclase peridotites from the South and Central Lanzo bodies documented by Piccardo et al. (2007) is reported for comparison.

TABLE 3

Trace element composition (ppm) of the minerals from the North Lanzo ultramafics.

Sample	LN11		LN13		LN15		LN12		LN22	LN25	
Rock Type	1		1		1		1		2	1	
Mineral	Cpx	Opx	Cpx	Opx	Cpx	Opx	Cpx	Opx	Opx	Cpx	Opx
Sc	58	26	76	36	66	28	68	30	20	61	31
Ti	2710	1097	5004	1548	4569	1368	3761	1160	522	2789	1100
V	318	139	388	191	345	152	351	163	92	369	167
Cr	7555	3933	6869	4236	7877	4574	6838	4153	3795	9297	4907
Sr	6.5	0.33	5.5		6.5		4.1		0.2	0.9	
Y	24	2.18	32	3.9	29	3.3	28	2.84	0.9	18	2.86
Zr	37	2.99	55	7.3	53	5.6	33	3.5	2.2	11	2.0
Nb	0.20		0.03	0.024	0.14	0.16	0.07	0.063	0.008		
Ba									0.041		
La	0.86	0.010	0.88	0.032	0.75		0.49		0.023	0.03	0.006
Ce	4.5	0.053	5.6	0.120	4.7	0.116	3.2	0.043	0.051	0.66	
Pr	0.95		1.24		1.06	0.026	0.76	0.009	0.009	0.28	0.005
Nd	6.0	0.10	7.7		7.3	0.13	5.3	0.068	0.07	2.72	0.033
Sm	2.57	0.087	3.3		3.3		2.50	0.12		1.46	0.033
Eu	1.04	0.032	1.20	0.063	1.04		0.97	0.052	0.015	0.65	0.015
Gd	3.2	0.085	4.5	0.27	4.2	0.19	3.7	0.16	0.062	2.34	0.20
Tb	0.68	0.038	0.87	0.054	0.83	0.036	0.70	0.029	0.012	0.47	0.036
Dy	4.2	0.33	5.8	0.57	5.4	0.48	4.8	0.37	0.12	3.1	0.32
Ho	0.92	0.10	1.29	0.16	1.17	0.12	1.06	0.11	0.03	0.71	0.10
Er	2.57	0.30	3.4	0.54	3.1	0.46	2.84	0.39	0.13	1.89	0.30
Tm	0.35	0.064	0.46	0.105	0.39	0.075	0.41	0.076	0.024	0.27	0.052
Yb	2.24	0.41	3.1	0.84	2.82	0.60	2.82	0.82	0.17	1.66	0.49
Lu	0.30	0.069	0.44	0.13	0.34	0.091	0.37	0.12	0.028	0.21	0.079
Hf	0.81	0.14	1.63	0.20	1.64	0.28	1.01	0.15	0.14	0.57	0.11
Ta	0.027	0.007	0.015		0.021		0.015	0.008	0.007		
Pb											

1: impregnated plagioclase peridotites, 2: replacive spinel harzburgites

TABLE 3
continued ...

Sample	LN26a			LN26b			LN45		LN46	
Rock Type	3			3			2		4	
Mineral	Cpx	Opx	Pl	Cpx	Opx	Pl	Cpx	Opx	Cpx	Opx
Sc	84	38	2	75	38	2	50	20	64	29
Ti	5013	1780	352	5251	1772	328	1433	427	1223	380
V	485	219	2	444	213	2	270	110	320	127
Cr	2863	2607	2	2197	1635	25	9806	5151	9596	4955
Sr	3.8		82	5.1	2.9	141	9.5		14.8	
Y	35	4.9	0.28	34	4.4	0.27	10	1.1	12	1.3
Zr	49	6.1	0.036	47	4.7	0.25	23	2.0	10	1.2
Nb	0.06		0.014	0.10		0.014	0.45	0.042	0.07	0.032
Ba			0.12			0.47				
La	0.61	0.019	0.55	0.76	0.006	0.74	1.78		0.79	0.012
Ce	3.8	0.048	1.62	4.7	0.059	1.78	7.4	0.082	4.1	
Pr	0.91	0.021	0.19	1.04		0.18	1.21		0.71	
Nd	5.9	0.09	0.86	6.4	0.12	0.60	5.9	0.09	3.8	0.06
Sm	2.98		0.18	3.1	0.057	0.14	1.78	0.078	1.15	
Eu	0.95	0.025	0.40	1.17		0.46	0.61		0.44	
Gd	4.3	0.19	0.15	4.3	0.24	0.12	1.73		1.34	0.063
Tb	0.84	0.081	0.023	0.90	0.053	0.014	0.32	0.022	0.27	
Dy	6.0	0.51	0.097	6.4	0.52	0.064	1.89	0.12	1.99	0.22
Ho	1.41	0.16	0.013	1.36	0.16	0.012	0.43	0.04	0.45	0.06
Er	3.7	0.65	0.081	3.9	0.59	0.039	1.00	0.13	1.28	0.23
Tm	0.56	0.098	0.007	0.57	0.105	0.007	0.14	0.024	0.18	0.064
Yb	4.2	0.88	0.038	4.1	0.96	0.031	0.87	0.27	1.32	0.41
Lu	0.48	0.16	0.009	0.50	0.18	0.006	0.11	0.032	0.19	0.060
Hf	1.51	0.24	0.060	1.32	0.20		0.60	0.06	0.28	0.05
Ta				0.015			0.073		0.007	
Pb			0.34			0.52				

2: replacive spinel harzburgites, 3: impregnated pyroxenites, 4: lithospheric spinel lherzolite
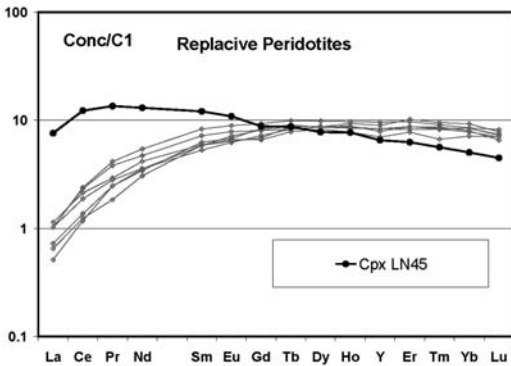
Fig. 4 – C1-normalized REE and Y content of the clinopyroxene from the replacive spinel harzburgite (LN45) cutting plagioclase peridotites in the North Lanzo body. The composition of clinopyroxenes from replacive harzburgites and dunites from the South Lanzo body documented by Piccardo *et al*. (2007) are reported for comparison.

found by Bodinier *et al.* (1991) for clinopyroxenes from plagioclase peridotites of North Lanzo.

Clinopyroxenes of the replacive spinel harzburgites show a C1-normalized patterns characterized by enrichments in L-MREE (maximum at Pr = 13.6 xC1; Sm_N/Yb_N = 2.40), and significantly low absolute HREE content (Lu = 4.5 xC1) (Fig. 4). The Nb and Ta content is significantly larger than in the other clinopyroxenes from Lanzo North ultramafics, being up to 2.8 and 7 xC1, respectively. Sr determines marked negative spikes.

Orthopyroxenes from the different lithotypes show the typical strongly-fractionated HREE-enriched patterns (Fig. 5a). Their trace element compositions appear in chemical equilibrium with the associated clinopyroxenes. Importantly, orthopyroxenes from lithospheric and replacive peridotites are HREE-depleted with respect to those from impregnated rocks, confirming the geochemical differences unravelled by the clinopyroxenes.

The trace element composition of plagioclases in impregnated pyroxenites is characterized by LREE, Eu and Sr enrichments, and very low Ba contents (0.12-0.47 ppm; Table 3), being in chemical equilibrium with that of the associated clinopyroxenes (Fig. 5b).

Discussion

Geochemical Constraints

A) The composition of the pristine lithospheric mantle

On the basis of Sr-Nd isotope data on two spinel-plagioclase lherzolites (samples L213 and L215), Bodinier *et al.* (1991) inferred that the North Lanzo body was accreted to the thermal lithosphere after isolation from the convective mantle at 400-700 Ma.

Previous documentation of the trace element composition of bulk rock and clinopyroxene composition of North Lanzo lithospheric spinel lherzolites is lacking. Bodinier *et al.* (1991) analyzed the trace element composition of clinopyroxenes of the L213 and L215 lherzolites from the North Lanzo body: they show moderately LREE-depleted normalized REE patterns, being slightly convex-upward in the M-HREE region (at about 20 xC1) (Fig. 2, in Bodinier *et al.*, 1991). As previously evidenced, they are strictly consistent with the trace element compositions of clinopyroxenes of Type 2 impregnated plagioclase peridotites from the North Lanzo body.

Accordingly, the geochemical signature argued on the basis of the trace element composition of the pyroxenes from the spinel lherzolite LN46 is significantly different with respect to the North Lanzo spinel-plagioclase lherzolites documented by Bodinier *et al.* (1991). The peculiar REE pattern of LN46 clinopyroxene shares strict similarity with those of some Cr-diopside pyroxenites in the mantle bodies outcropping on the westernmost boundary of the Adria plate in the Ivrea-Verbano Zone (e.g. the Balmuccia massif; Rivalenti *et al.*, 1995). They could be interpreted as transient geochemical features which, according to Rivalenti *et al.* (2007), may have been acquired by clinopyroxene during the reactive migration of alkaline melts through the lithospheric mantle.

B) Pervasive melt migration

Piccardo *et al*. (2007) evidenced that the plagioclase-bearing assemblages of South Lanzo peridotites formed by interstitial crystallization of melts that percolated pervasively the mantle section. As a whole, the impregnation process
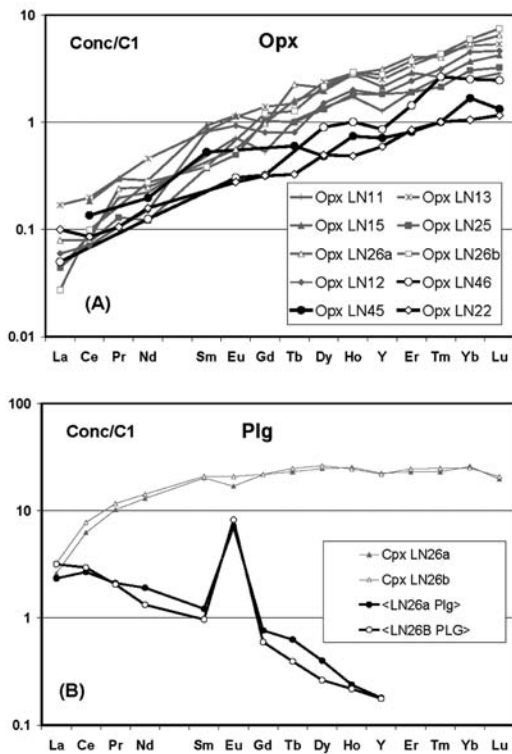
Fig. 5 – C1-normalized REE and Y content of the orthopyroxenes (a) and plagioclases (b) from the North Lanzo peridotite. According to clinopyroxene composition, the orthopyroxenes from lithospheric peridotite LN46 and replacive peridotites LN22 and LN45 are M-HREE depleted with respect to those from impregnated peridotites. In (b), plagioclases are from the impregnated pyroxenites LN26a and LN26b. The composition of the associated clinopyroxenes is reported for comparison.

produced a strong refertilization of the bulk rock composition of the peridotites, which reached major and trace element contents closely similar to that modelled for the DM reservoir. Piccardo *et al.* (2007) also documented that the clinopyroxenes from the South Lanzo impregnated plagioclase peridotites show trace element contents significantly larger than those observed in clinopyroxenes from MORB cumulates and/or modelled for residual clinopyroxenes after partial melting. This trace element enrichment in clinopyroxenes can be the result of the increase of the trace elements in the evolving melts owing to the fractional

crystallization likely associated to an increase of the $^{Solid/Liquid}D$.

The strong fractionation and depletion of LREE in the Type 1 clinopyroxenes from LN25 plagioclase peridotite is consistent with their segregation from a liquid produced by 5% fractional melting of a spinel-facies DM source (Fig. 6). This evidence suggests that the Lanzo North peridotite body locally records the pervasive melt migration of melt increments produced by fractional melting, as extensively documented in the South Lanzo peridotite.

Likewise, the REE fractionation of the Type 2 clinopyroxenes from plagioclase peridotites would mainly correspond to that expected for clinopyroxenes in equilibrium with liquids produced by low degrees (lower than 2%) of fractional melting of a spinel-facies DM source (Fig. 6). On the other hand, the similarity between the REE and HFSE fractionations of Type 2 clinopyroxenes and those shown by clinopyroxenes in equilibrium with aggregate N-MORB (e.g. Cortesogno *et al.*, 2000) is striking. The very homogeneous composition deduced for the melts in equilibrium with Type 2 clinopyroxenes leads us to consider more plausible that Type 2 clinopyroxenes segregated from aggregate N-MORB rather than single melt increments of a fractional melting process. Given that Type 2 clinopyroxenes are by far more abundant in the North Lanzo body, it can be speculated that the pervasive stage of melt impregnation in the North Lanzo peridotite was characterized by a marked geochemical discontinuity with the same process recorded by the South Lanzo body, where the impregnating melts were derived by single melt fractions after fractional melting processes. Piccardo *et al.* (2007) evidenced that in the South Lanzo massif similar aggregate MORB melts characterized the channeled migration stage, following diffuse impregnation by fractional MORB-type melts.

C) Channeled melt migration

The bulk rock and mineral geochemical features of the replacive peridotites LN22, LN41 and LN45 (Fig. 2a) document the dramatic compositional changes experienced by the formerly impregnated, plagioclase peridotites as a consequence of the channeled migration of
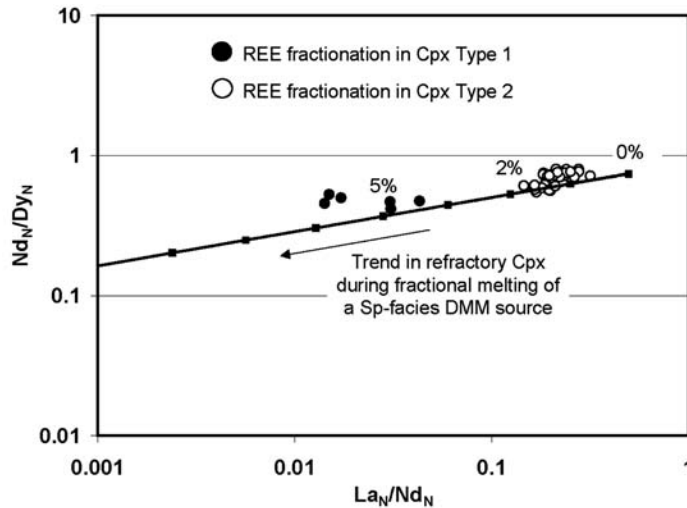
Fig. 6 – Comparison of the L-MREE fractionation shown by the clinopyroxenes from impregnated ultramafics of the North Lanzo impregnated plagioclase peridotites and that modelled for refractory clinopyroxenes after different degrees of fractional melting of spinel facies DM. The composition of Cpx Type 1 is consistent with segregation from a melt increment produced by around 5% partial melting. In this frame, the REE fractionation of the dominant Type 2 composition would be consistent with chemical equilibrium with a melt increment produced by 1-2% partial melting. On the other hand, Cpx Type 2 fractionation is very similar to that characterizing clinopyroxene in equilibrium with aggregate N-MORB. See text for further explanations.

late melts. The late melts migrating within these refractory channels crystallized small amounts of interstitial clinopyroxenes, as represented by LN45 clinopyroxene, which shows strongly LREE-enriched and HREE-depleted REE patterns (Fig. 4). The geochemical affinity of the migrating melts can be unraveled by the clinopyroxene composition. Accordingly, the REE composition estimated for the liquid in equilibrium with LN45 clinopyroxene (using the $^{Cpx/Liquid}D$ of Hart and Dunn (1993) shows a strong LREE-HREE fractionation ($La_N/Yb_N > 11$), very high $LREE_N$ ($La_N > 140$) and significantly low $HREE_N$, pointing to an overall alkaline affinity.

This evidences that at North Lanzo a strong variation of the geochemical affinity of the migrating melts existed between the early pervasive percolation and impregnation and the late channeled migration stages, pointing to significant changes in terms of composition and physico-chemical characteristics of the mantle sources. In particular, if the partial melting of a spinel facies DM source can reconcile the geochemical features deduced for the parental melts of the plagioclase-bearing impregnation, a more fertile garnet-bearing mantle

source must be considered for the melts migrating through the replacive conduits.

This observation evidences an important difference with respect to the melt migration processes recorded by the South Lanzo body, in which the focused melt percolation through the plagioclase peridotites was mostly operated by aggregate MORB-type melts, showing both Normal and slightly Enriched affinities, and solely sporadically by melts showing alkaline affinity (see: Piccardo, 2008, and discussion therein).

The presence of alkaline melts

The presence of alkaline melts in the Ocean-Continent Transition (OCT) peridotites from the Jurassic Ligurian Tethys has been recently discussed (Piccardo *et al.*, 2007; Piccardo, 2008).

Alkaline magmas can be generated by partial melting of garnet pyroxenite (Hirshmann *et al.*, 2003, and references therein). Accordingly, the alkaline trace element signature of the magmatic clinopyroxenes in replacive harzburgites of North Lanzo suggest that the mantle sources were characterized by the presence of garnet pyroxenites.

The dramatic change of the geochemical affinity of the percolating melts from MORB to alkaline could be interpreted as the evidence of the renewal of the mantle source, involving uprising asthenospheric levels characterized by the occurrence of garnet pyroxenites. Experimental data indicate that, at a given pressure, pyroxenites melting produces basaltic melts at significantly lower temperature than that of peridotites; accordingly, if present in the upwelling mantle asthenosphere, pyroxenites melt at a greater depth than the surrounding peridotite (Petermann and Hirschmann, 2003). It implies that, if a garnet-pyroxenite-bearing asthenospheric mantle source is upwelling and melting under decompression, alkaline liquids deriving from melting of garnet pyroxenites should form at greater depth and rise preceding MORB melts deriving from melting of DM peridotites.

Field evidence from North Lanzo indicates that the alkaline melts did not ascend *preceding* MOR melts diffuse percolation, but migrated upwards during the focused melt migration stage *following* the MOR melts percolation. Accordingly, it is highly improbable that the North Lanzo alkaline melts were formed by deep asthenospheric levels mostly characterized by garnet pyroxenite composition.

The appearance of alkaline melts indicates a drastic compositional change in the melting mantle source after inception of partial melting of the DMM astenosphere at spinel-facies conditions and implies the entrainment of garnet pyroxenites into the melting regime.

Garnet/spinel pyroxenites are present in the lithospheric mantle peridotites from the OCT settings of the Jurassic Ligurian Tethys (e.g. Montanini *et al.*, 2006). It may be inferred that the deep levels of the sub-continental lithospheric mantle (at P > 1.5 GPa), pre-existing inception of lithosphere extension, were characterized by presence of widespread garnet pyroxenite banding and it may be speculated that they were the source rocks of the alkaline melts.

It may be speculated that the MORB-type melts uprising during the early stages of lithosphere percolation and the thermomechanical erosion of the extending lithosphere (Piccardo, 2003) induced partial melting of the garnet pyroxenite layers in the mantle lithosphere, at T about 1200°C and P > 1.5GPa. Inferences on the depth of partial melting

inception of the upwelling mantle asthenosphere along the whole Ligurian Tethys rifting system can be deduced by the characteristics of the upwelling percolating melts. Almost all were formed by fractional melting of spinel-facies peridotite sources, i.e. by partial melting at P < 2.5 GPa (Piccardo *et al.*, 2007; Piccardo and Vissers, 2007). Field and petrographic evidence suggests that the earliest melt fractions related to decompression melting of the uprising asthenosphere entered the extending lithosphere when lithospheric peridotites and pyroxenites were already recrystallized to spinel-facies assemblages (Piccardo and Vissers, 2007), i.e. they were already exhumed to P < 1.5 GPa. Accordingly, it is highly improbable that the garnet or alkaline geochemical signature of these melts may be derived by relict lithospheric mantle which entrained into the asthenospheric material during the thermomechanical erosion events of the subcontinental lithosphere [according to the mechanism suggested by Bodinier and Godard (2003), and Montanini and Tribuzio (2007a, 2007b) for the garnet signature in Ligurian MORB (see below)].

This implies that garnet pyroxenites should have been introduced into the melting asthenosphere at pressure conditions higher than 1.5 GPa, to escape recrystallization from garnet- to spinel-facies assemblages. A suitable mechanism for introducing garnet pyroxenite-bearing mantle sections into the melting asthenosphere is the early delamination of the deep, garnet pyroxenite-bearing sectors of the mantle lithosphere during inception of lithosphere extension and preceding the decompressional subsolidus transition of garnet-pyroxenites to spinel-facies assemblages. It can be speculated that segments of the lower lithospheric mantle were tectonically detached and sank into the upwelling hot mantle asthenosphere, where they were heated and underwent partial melting under the proper pressure conditions. The produced alkaline melts should have migrated upwards and have percolated the extending lithospheric mantle *subsequently* to the MORB percolation and impregnation.

Focused percolation within replacive harzburgite channels, *following* diffuse percolation and impregnation by aggregate MORB melts, is well represented also in the OCT peridotites from the Ligurian sector of the Tethys basin (i.e. the External Liguride ophiolitic peridotites, see Piccardo,

2007, 2008, and references therein). Both MORB impregnation and alkaline focused percolation preceded MORB gabbroic intrusion and basaltic extrusion, i.e. the formation of the oceanic crustal rocks of the Ligurian ophiolites.

It has been recently stressed out by Montanini and Tribuzio (2007a, 2007b) and Montanini *et al.*, (2007) that the oceanic magmatism, which gave rise to the crustal rocks (gabbroic intrusives and basaltic volcanites) of the Ligurian ophiolites, although showing MORB affinity, is characterized by peculiar trace element fingerprints. According to these Authors, the Zr enrichment, the relatively high Sm/Yb ratios and the anomalous composition of the less radiogenic Nd isotope of the Ligurian ophiolitic crustal rocks cannot be compatible with low degrees of fractional melting of a depleted spinel peridotite but, on the contrary, they can be explained by low degree melting of a mixed source of spinel peridotite with small amounts of garnet pyroxenite.

In our opinion it is highly unlikely that interaction between uprising MORB melts and lithospheric pyroxenites, most probably recrystallized to spinel-facies assemblages during lithosphere extension and mantle exhumation, may have played a role in generating the peculiar garnet signatures of the MORB-type melts formed during the early phases of ocean opening (as speculated by Montanini and Tribuzio, 2007a, 2007b; Montanini *et al.*, 2007). It is more plausible that these signatures were produced by garnet pyroxenite relics left in the DM melting sources after delamination and siking of the deep garnet pyroxenite-bearing mantle lithosphere and the formation of alkaline melts, as previously suggested.

According to the above scenario: i) MORB melts were formed and migrated earlier through the extending lithosphere; ii) alkaline melts were formed subsequently by melting of the sinking garnet-pyroxenites; iii) garnet-pyroxenite relics were left in the melting mantle source to generate the enriched signature of the subsequent magmatism, which formed the crustal rocks (gabbros and basalts) of the Ligurian ophiolites.

Thus, the early detachment and sinking of garnet pyroxenite-bearing lithospheric mantle sections in the upwelling melting asthenosphere can be responsible of both: i) the formation of alkaline liquids (Piccardo *et al.*, 2006, Piccardo, 2007,

2008), and ii) the presence of a relict enriched component in the source of the subsequent MORB magmatism, responsible of the garnet signature of the gabbroic intrusions and basaltic extrusions (Montanini and Tribuzio, 2007a, 2007b; Montanini *et al.*, 2007).

Geodynamic implications

The North Lanzo peridotite body is mostly composed of rather fertile spinel lherzolites, characterized by an older spinel-facies assemblage and abundant spinel pyroxenite banding. The abundance of preserved clinopyroxene porphyroclasts and pyroxenite bands indicate that this mantle section escaped important effects of reactive interaction (i.e. pyroxene dissolution and olivine precipitation) by silica(-pyroxenes)-undersaturated melts at spinel-facies conditions, as widespread in the South Lanzo peridotite body (see: Piccardo *et al.*, 2007, and references therein). The diffuse partial recrystallization at plagioclase-facies conditions suggests that these lithospheric peridotites were involved in the processes of lithospheric mantle exhumation related to the lithosphere extension. The subsequent localized impregnation by aggregate MORB melts indicates that asthenospheric melts percolated through the North Lanzo peridotites when they had been already exhumed to plagioclase-facies conditions, i.e. at relatively shallow levels in the mantle lithosphere. The late formation of replacive spinel harzburgite channels, which have interstitial magmatic pyroxenes showing clear alkaline affinity, indicates that after pervasive percolation and impregnation by MORB-type melts these peridotites underwent focused percolation along strongly pyroxene-depleted channels of alkaline melts, deriving from garnet-bearing mantle sources.

Thus, our present data evidence that the North Lanzo lherzolites, after their complete subsolidus equilibration at spinel-facies conditions (accretion to the sub-continental lithosphere?), underwent a composite evolution consisting of: 1) subsolidus tectonic-metamorphic events, 2) percolation and impregnation events by aggregate MORB melts at relatively shallow, plagioclase-facies conditions, and 3) focused percolation of alkaline melts.

Accordingly, it can be inferred that the North Lanzo spinel-facies lherzolite protoliths are

the remnant of the sub-continental lithospheric mantle of the Europe-Adria system involved in the tectonic and magmatic evolution linked to the opening of the Ligurian Tethys. The lithospheric mantle underwent subsolidus exhumation from spinel-facies to plagioclase-facies conditions (P < 1.0 GPa), whereas the underlying asthenosphere underwent partial melting under decompression in response to adiabatic upwelling related to extension and thinning of the lithosphere. Field relations and textural evidences suggest that asthenospheric melts entered the North Lanzo peridotites when they had been already exhumed to shallow, plagioclase-facies conditions.

Previous works suggested the provenance of the North Lanzo peridotites from the sub-continental mantle lithosphere of the Adria block (Bodinier *et al.*, 1991; Müntener *et al.*, 2005). Our structural and petrologic-geochemical data evidence important similarities with other peridotite bodies from the OCT zones of the Adria block in the Jurassic Ligurian Tethys and, particularly, with the External Ligurides peridotites of the Northern Apennine (see: Piccardo, 2008, and references therein). In fact, they are commonly characterized by: i) pre-Jurassic ages of isolation from the convective mantle and accretion to the sub-continental thermal lithosphere; ii) early spinel-facies assemblage and abundance of spinel- (and garnet-) pyroxenite bands; iii) subsequent subsolidus evolution towards shallower, plagioclase-facies conditions; iv) km-scale areas showing effects of percolation and impregnation by aggregate MORB-type melts; v) late focused percolation of alkaline melts along replacive spinel harzburgite channels.

The evolution of the Lanzo peridotite bodies in the frame of rifting of the Ligurian Tethys

It has been recently discussed (Piccardo, 2008) that Western Alpine – Northern Apennine ophiolitic peridotites document the different stages of lithosphere-asthenosphere evolution during the pre-oceanic rifting stages of the Late Jurassic Ligurian Tethys basin:

1) lithosphere extension caused the tectonic-metamorphic evolution of the sub-continental mantle lithosphere, starting from spinel-facies conditions, with formation of km-scale tectonite-

mylonite shear zones (e.g. Montanini *et al.*, 2006; Piccardo and Vissers, 2007);

2) lithosphere extension and thinning caused adiabatic upwelling and decompressional melting of the underlying asthenosphere; the asthenospheric melts migrated via diffuse porous flow through the extending mantle lithosphere (Piccardo *et al.*, 2007);

3) deformation and melt-related processes in the mantle lithosphere were inter-dependent and mutually enhancing during lithosphere exhumation (Piccardo and Vissers, 2007);

4) heating by asthenosphere upwelling and reactive percolation of asthenospheric melts through the mantle lithosphere caused diffuse structural, compositional and rheological modification of the mantle lithosphere, leading to its thermo-chemical erosion (Piccardo, 2003; Corti *et al.*, 2007; Ranalli *et al.*, 2007).

Moreover, it has been recognized (Piccardo, 2008) that the petrologic characteristics of mantle peridotites are significantly different in the various ophiolitic peridotite bodies and are strictly correlated to the inferred paleogeographic settings in the ancient Ligurian Tethys. In fact, peridotites deriving from the OCT zones of the basin are represented by exhumed sub-continental mantle which mostly escaped melt percolation, whereas mantle peridotites from the More Internal Oceanic (MIO) settings of the basin (i.e. the more axial zones) are represented by depleted and enriched peridotites, strongly modified by melt-rock interaction and melt impregnation.

As previously evidenced, the North Lanzo body exposes large areas preserving lithospheric characteristics, which escaped spinel-facies reactive melt percolation. The mantle section was significantly recrystallized at plagioclase-facies conditions (i.e. underwent significant exhumation under subsolidus conditions) and was, later on, impregnated at plagioclase-facies conditions by aggregate N-MORB. Finally, it experienced focused percolation of alkaline melts.

On the contrary, the South and Central Lanzo bodies are mostly composed of peridotites profoundly modified by interaction with MORB-type fractional melts (Piccardo *et al.*, 2007, and references therein). In fact, only sporadic, decameter-hectometer-scale remnants of the sub-continental spinel-facies lherzolite precursors

are preserved and peridotites showing significant effects of melt-peridotite interactions are dominant. They reveal a composite sequence of melt-peridotite interaction processes characterized by: i) the early diffuse and reactive percolation of silica-undersaturated MORB-type single melt increments at plagioclase-facies conditions; ii) the subsequent diffuse percolation and interstitial crystallization of silica-saturated MORB-type single melt increments at plagioclase-facies conditions; iii) the late focused migration along olivine-rich channels of aggregate MORBs, showing both Normal and slightly Enriched compositions. Sporadically, replacive spinel harzburgite channels in Central Lanzo have been exploited for uprising of alkaline liquids (see: Piccardo, 2008, and discussion therein). Subsequently the South-Central Lanzo peridotite bodies are cut by gabbroic dikes recording differentiation processes, going from olivine gabbros (Mg-Al-gabbros) to oxide gabbros (Fe-Ti-gabbros) (Bodinier *et al.*, 1986), which have been dated to 160 Ma by Kaczmarek *et al.* (2005). This age is well consistent with the inferred age of opening of the oceanic basin (see Piccardo, 2008, for a more detailed discussion).

As previously mentioned, lithostratigraphic studies indicate that the South-Central Lanzo serpentinized peridotites are overlain by metabasites (partially with breccia textures), Mn-rich metaquartzites and calc-schists (Lagabrielle *et al.*, 1989; Pelletier and Müntener, 2006), similar to other less metamorphic ophiolite sequences in the Alps and Apennines. This strongly suggests that the South-Central Lanzo massifs were exhumed to the seafloor of the Jurassic Ligurian Tethys ocean and was covered by volcanics and oceanic sediments, similarly to the ophiolite sequences deriving from MIO setting of the Ligurian Tethys oceanic basin (e.g. the Internal Ligurides ophiolite sequences of the Northern Apennine).

As a result, present knowledge on the different bodies of the Lanzo massif allows the tentative conclusion that both OCT-type peridotites (i.e. North Lanzo body) and MIO-type peridotites (i.e. South-Central Lanzo body) deriving from different palaeogeographic settings of the Western Alpine sector of the Jurassic Ligurian Tethys are preserved in the Lanzo Massif.

In fact, present knowledge on the South and North Lanzo bodies indicate that, notwithstanding

the evidences that: 1) they derive from the subcontinental lithospheric mantle, 2) they underwent subsolidus exhumation towards shallow levels, 3) they were differently percolated by melts formed in the upwelling asthenosphere, the tectonic-magmatic evolution of the South and North Lanzo mantle sections was remarkably different. The North Lanzo peridotite: i) was significantly recrystallized at plagioclase-facies conditions (i.e. underwent significant exhumation under subsolidus conditions), ii) escaped large reactive percolation at spinel-facies conditions, iii) was, later on, impregnated at plagioclase-facies conditions by aggregate MORB melts, and iv) it underwent focused percolation of alkaline melts. The South Lanzo peridotite: i) underwent significant melt reactive percolation at spinel-facies conditions, ii) was deeply melt impregnated at plagioclase-facies conditions, and iii) underwent focused percolation of aggregate MORB melts and, sporadically, of alkaline melts.

It must be speculated that the lithospheric protoliths of the North and South Lanzo peridotites were originally located at different depths in the sub-continental lithosphere and evolved at different times, in relation to the decompressional partial melting of the asthenosphere and the melt migration in the lithosphere. In fact, undersaturated aggregate MORBs impregnated the North Lanzo peridotite section when it was already exhumed to plagioclase-facies conditions whereas the South Lanzo peridotite section was diffusely and reactively percolated by undersaturated MORB-type fractional melts were still resident at deeper levels, under spinel-facies conditions, and was later impregnated by saturated MORB-type fractional melts at plagioclase-facies conditions, prior to focused percolation of aggregate MORB and, sporadically, alkaline liquids.

In this scenario, it may be inferred that early fractional melts, formed in the upwelling asthenosphere at the inception of decompressional melting, percolated and modified the deeper spinel-facies lithospheric mantle levels (the South Lanzo peridotite), forming the South Lanzo reactive spinel peridotites; whereas the shallower lithospheric mantle levels (the North Lanzo peridotite) mostly escaped this event, thus preserving their pristine fertile lherzolite compositions. Subsequently, saturated MORB-type fractional melt increments

invaded the reacted and depleted levels (the South Lanzo peridotite) when they have been exhumed to plagioclase-facies conditions, forming the South Lanzo impregnated plagioclase peridotites, whereas shallower levels (i.e. the North Lanzo peridotite) escaped this stage.

The focused migration of aggregate MORB in harzburgite-dunite channels through the South Lanzo peridotite allowed these melts to pass through the deeper plagioclase-impregnated levels (the South Lanzo plagioclase peridotites) and to percolate diffusely the shallower, more fertile levels (the North Lanzo peridotite), producing significant interstitial crystallization and impregnation by aggregate MORB in the North Lanzo pyroxenite-bearing fertile peridotites. Later on, the high permeability olivine-rich channels allowed the upward migration of enriched and alkaline liquids (in Central and North Lanzo peridotites).

Ongoing lithosphere extension and stretching caused progressive upwelling of the more axial, deeper sectors (i.e. South Lanzo), which were located at more Internal MIO settings of the basin, whereas the more shallow sectors (i.e. North Lanzo) were confined to more External OCT zones of the basin.

Conclusion

Available field and petrographic data on the North Lanzo peridotite body indicate that large remnants of spinel-facies fertile lherzolite, with diffuse spinel-pyroxenite banding, are preserved, most probably representing the ancient sub-continental lithospheric mantle, that was accreted to the thermal lithosphere after isolation from the convective mantle: on the basis of isotopic data, Bodinier *et al.* (1991) inferred that isolation occurred presumably at 400-700 Ma.

Wide areas of the spinel-facies lherzolites and the enclosed spinel pyroxenites show significant records of partial subsolidus recrystallization at plagioclase-facies conditions, whereas hectometer-scale bodies display strong plagioclase enrichment, subsequently to the plagioclase-facies subsolidus recrystallization. Both lithospheric spinel-plagioclase lherzolites and impregnated plagioclase peridotites are cut by meter- to decameter-wide channels of strongly pyroxene-depleted, coarse

granular harzburgites, which contain interstitial magmatic clinopyroxenes showing enriched trace element composition indicating that these replacive high permeability channels were exploited for the upward migration of alkaline liquids.

This composite tectonic-metamorphic and melt-related evolution indicates that the North Lanzo peridotite body represents a piece of sub-continental, spinel-facies lithospheric mantle that: i) was exhumed to shallow levels, ii) was pervasively percolated and impregnated by MORB melts, and iii) was focused percolated along refractory harzburgite channels by alkaline melts.

Field and structural features indicate that MORB melts entered the North Lanzo peridotite when they had been already exhumed to shallow lithospheric levels, thus suggesting close relationships between lithosphere extension, asthenosphere decompression partial melting and lithosphere melt percolation, during the rifting stages of the Ligurian Tethys basin.

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