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Ultramafic pseudotachylytes in the Mt. Moncuni peridotite (Lanzo Massif, western Alps): tectonic evolution and upper mantle seismicity

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Abstract. — The small ultramafic body at Mt. Moncuni consists of impregnated plagioclase peridotites, metre-scale masses of spinel dunites and harzburgites, and widespread gabbroic and porphyritic dykes. Metre- to decametre-scale shear zones cut the plagioclase peridotites and deform the pre-existing gabbroic dykes. Within the shear zones and in the host peridotite, millimetre- to decimetre-wide, decimetre- to metre-long, veins of pseudotachylytes are present, both concordant and discordant to the tectonite-mylonite foliation of shear zones. Late coarse-grained porphyritic dykes cut across both deformed plagioclase peridotites and shear zones.

The formation of decametre-scale shear zones and the sequence of metamorphic assemblages developed in the shear zones, under increasing fluid activity, from amphibole-bearing plagioclase-peridotite-facies to amphibolite-facies, show that these rocks underwent progressive exhumation to shallower lithospheric levels, under progressively decreasing pressure and temperature conditions.

Millimetre-wide pseudotachylyte veins are concordant with the fault planes of the shear zones (fault-vein type A) showing ultra-fine grained cryptocrystalline/microcrystalline and microlitic/spherulitic textures and rather large (up to 10-15% by volume) amounts of clastic olivine grains or aggregates and lithic mylonitic clasts. Decimetre-wide, metre-long, pseudotachylyte veins (injection-vein type B) cut discordantly the foliation of the host deformed peridotite and exhibit spinifex textures and limited presence (<1% by volume) or absence of exotic lithic aggregates. Pseudotachylytes type B show peridotitic major and trace element bulk rock compositions.

The occurrence of ultramafic pseudotachylytes is consistent with the occurrence of upper mantle earthquakes. The formation of millimetre-wide ultra-fine grained type A pseudotachylyte veins suggests that the fault planes acted as loci for the seismogenic release of the accumulated shear stress. The co-seismic shear heating and the associated temperature increase produced the strongly localized, almost complete melting of the host deformed peridotite, forming melts with peridotitic composition. Strong localized heating of the host rock (up to 1450°C) was associated with intrusion of parental melts of type B pseudotachylytes, where rapid crystallization produced spinifex textures, typical of komatiitic (peridotitic) magmas.

The mutual relations between the early (i.e., pre-shear zones) MORB-type gabbroic dyke intrusion, the formation of shear zones and pseudotachylytes, and the crosscutting of the late (i.e., post-shear zones)

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MORB-type porphyritic dyke intrusion give clear time constraints for the upper mantle seismicity.

The investigated pseudotachylytes are records of Jurassic earthquakes related to extensional faults in the upper mantle, during its exhumation from subcontinental lithospheric levels towards the sea-floor of the Jurassic Ligurian Tethys.

RIASSUNTO. — La piccola massa peridotitica di Monte Moncuni (Massiccio di Lanzo, Alpi Occidentali) è formata da peridotiti impregnate a plagioclasio, masse metriche di duniti ed harzburgiti a spinello, e diffusi filoni gabbrici e porfirici. Zone di *shear* di potenza da metrica a decametrica tagliano le peridotiti a plagioclasio e deformano i pre-esistenti filoni gabbrici. Entro le zone di *shear* e nella peridotite incassante sono presenti vene, di potenza da centimetrica a decimetrica, e di lunghezza da decimetrica a metrica, di pseudotachiliti, che sono sia concordanti che discordanti con la foliazione tettonitico-milonitica delle zone di *shear*. Successivi dicchi porfirici a grana grossa tagliano attraverso le peridotiti deformate e le zone di *shear*.

La formazione di zone di *shear* di potenza decametrica e la sequenza di associazioni metamorfiche sviluppata nelle zone di *shear*, sotto crescente attività dei fluidi, da facies delle peridotiti a plagioclasio e anfibolo a facies anfibolitica, indicano che queste rocce subirono una progressiva esumazione verso livelli litosferici superficiali, sotto condizioni di pressione e temperatura progressivamente decrescenti.

Pseudotachiliti in bande di spessore millimetrico sono concordanti con i piani di faglia delle zone di *shear* (*fault-vein* tipo A) e mostrano strutture ultrafini criptocristalline/microcristalline e microlitiche/sferulitiche e concentrazioni fino al 10-15% (in volume) di granuli clastici o aggregati di olivina e di clasti litici milonitici. Pseudotachiliti in vene di spessore decimetrico e lunghezza metrica tagliano la foliazione della peridotite incassante (injection-vein tipo B) e mostrano evidente cristallizzazione in strutture tipo spinifex e limitata presenza (<1% in volume) o assenza di materiale litico esotico. I dati composizionali di roccia totale (elementi maggiori ed in tracce) delle pseudotachiliti tipo B, prive di inclusi esotici, indicano che queste pseudotachiliti hanno una composizione peridotitica.

La presenza di pseudotachiliti ultrafemiche è indice dell'esistenza di terremoti nel mantello superiore. La formazione di pseudotachiliti millimetriche a struttura ultrafine di tipo A, concordanti con la foliazione delle zone di *shear*, indica che queste ultime agirono come i luoghi per il rilascio sismogenetico dello *shear stress* accumulato. Il riscaldamento di frizione co-sismico e l'associato incremento di temperatura produssero la completa fusione, fortemente localizzata, della peridotite deformata incassante, con la formazione di fusi a composizione peridotitica. Il forte riscaldamento localizzato della roccia incassante (fino e 1450° C) fu associato all'intrusione dei fusi parentali delle pseudotachiliti di tipo B, dove la rapida cristallizzazione produsse strutture di tipo *spinifex*, tipiche di rocce effusive a composizione komatiitica (peridotitica).

Le relazioni strutturali fra la precoce intrusione di dicchi gabbrici di tipo MORB, precedente la formazione delle zone di *shear*, le zone di *shear* e le pseudotachiliti, e la tardiva intrusione di dicchi femici porfirici di tipo MORB, posteriore alla formazione delle zone di *shear*, forniscono chiare indicazioni temporali relative per l'attività sismica connessa con le zone di *shear* e la formazione delle pseudotachiliti. Le pseudotachiliti studiate, quindi, sono la testimonianza di terremoti Giurassici collegati a faglie estensionali nel mantello superiore, che si svilupparono durante la sua esumazione da livelli litosferici sottocontinentali verso il fondo oceanico del bacino della Tetide Ligure Giurassica.

KEY WORDS: *Lanzo peridotite massif, western Alps ophiolites, Jurassic Ligurian Tethys, ultramafic pseudotachylytes, lithospheric mantle.*

INTRODUCTION

The small (a few km^2) ultramafic body at Mt. Moncuni (southern side of the Susa Valley, NW Italy), is a satellite of the South Lanzo ophiolitic peridotite body (Fig. 1). The Lanzo peridotite body (~150 km^2) is located ~30 km northwest of Turin in the western Alps and is bounded by Po plain sediments to the East, high-pressure ophiolites and schistes lustrés to the West, and continental units of the Sesia-Lanzo Zone to the North (Nicolas, 1974, 1984; Pognante, 1989; Spalla *et al.*, 1983). The Lanzo ultramafic massif has been subdivided into 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 massif is characterized by a large proportion of fresh peridotites that predominantly consists of plagioclase lherzolites,

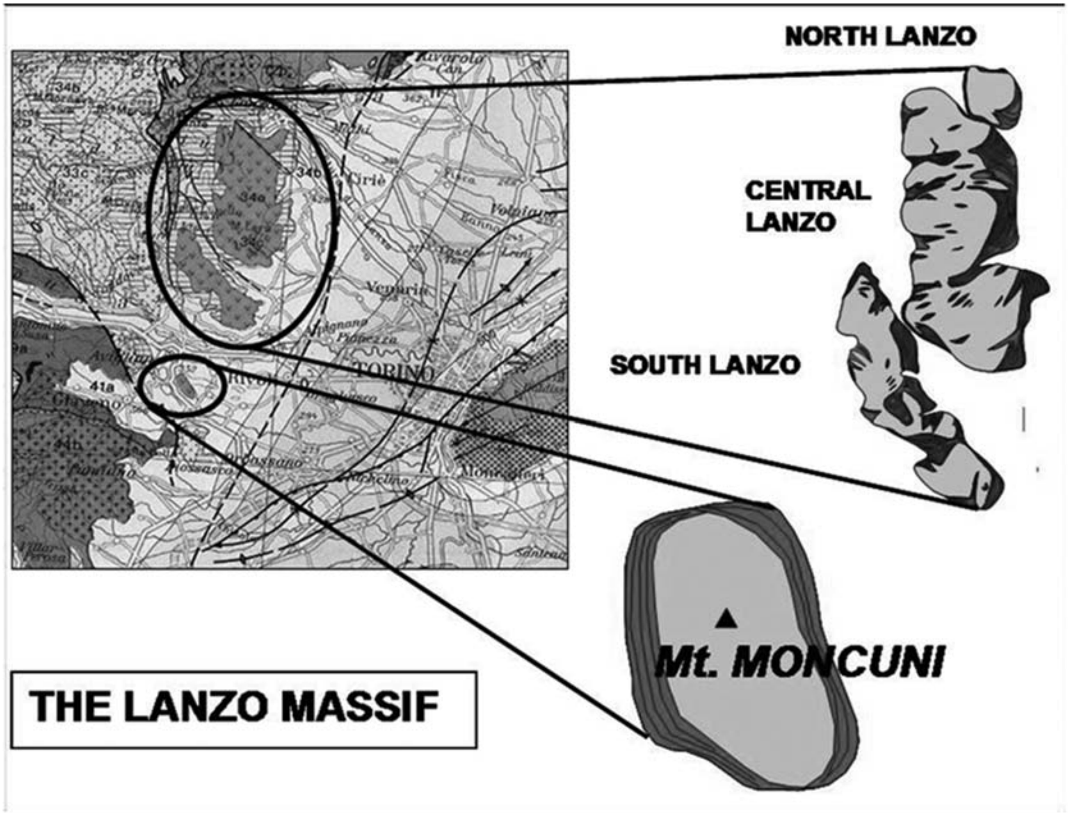

Fig. 1 – Sketch map of the Mt. Moncuni peridotite and the Lanzo peridotite massif.

with minor spinel lherzolites, pyroxenites and dunites, surrounded and partially overprinted by serpentinites (Boudier, 1978). Lithostratigraphic studies indicate that the Lanzo peridotites are overlain by a reduced oceanic crust (i.e. metabasites, Mn-rich metaquartzites and calcschists; Lagabrielle *et al.*, 1989; Pelletier and Müntener, 2006), similarly to other Jurassic ophiolite sequences of the western Alps and the Northern Apennines. This suggests that the Lanzo peridotite massif was exhumed to the seafloor of the Ligurian Tethys ocean.

The small ultramafic body at Mt. Moncuni consists of plagioclase peridotites, metre-scale masses of spinel dunites and harzburgites, and widespread gabbroic and porphyritic dykes. Metre- to decametre-scale shear zones cut the plagioclase peridotites and deform the pre-existing gabbroic dykes. Within the shear zones, cm- to dm-wide, dm- to m-long, veins of extremely fine-grained pseudotachylytes are present, both concordant and discordant to the tectonite-mylonite foliation of shear zones, and showing sharp contacts with the host rock. Late coarse-grained porphyritic dykes cut across both deformed plagioclase peridotites and shear zones.

The aims of the present work are:

1) to investigate the main petrological features of the Mt. Moncuni peridotite and associated rocks, with particular attention to the structural and paragenetic features of the tectonite-mylonite shear zones and of the pseudotachylyte veins;

2) to reconstruct the evolution stages recorded in the Mt. Moncuni peridotite preceding the sea-floor exposure in the Jurassic Ligurian Tethys, and to discuss qualitatively the processes

responsible for pseudotachylyte formation in the upper mantle.

GEOLOGICAL BACKGROUND

The Lanzo plagioclase peridotites have been interpreted by Nicolas (1984, 1986) as formed by “in situ” low-pressure (plagioclase-facies) partial melting during the adiabatic upwelling of an asthenospheric diapir and by consequent redistribution and entrapment of part of the produced melt within the peridotite. On the basis of isotope studies, Bodinier *et al*. (1991) interpreted the North Lanzo body as a fragment of the sub-continental mantle lithosphere which became isolated from the convective mantle and accreted to the thermal lithosphere about 400-700 Ma.

Recent investigations on the Lanzo peridotite (Müntener and Piccardo, 2003; Piccardo, 2003; Piccardo *et al*., 2004; Müntener *et al*., 2005; Piccardo *et al*., 2007a, and references therein; Piccardo *et al*., 2007b) document the complexity of rock-types and mantle processes recorded by the Lanzo peridotites and describe the composite tectonic and magmatic evolutions of the different sectors of the massif.

In synthesis, present knowledge on North and South Lanzo peridotite bodies indicates 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 being remarkably different (see Piccardo *et al*., 2007b, for a more detailed discussion).

It has been speculated (Piccardo *et al*., 2007b) 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, relatively to the extension of the lithosphere, the decompression partial melting of the asthenosphere and the melt migration in the lithosphere.

Ongoing lithosphere extension and stretching caused progressive upwelling of the more axial, deeper sectors (i.e. South Lanzo), which were located at More Internal Oceanic (MIO) settings of the basin, whereas the more shallow sectors (i.e. North Lanzo) were confined to more External Ocean-Continent Transition (OCT) zones of the basin (see Piccardo, 2008, for a more detailed geodynamic discussion). At a later stage the Lanzo peridotite bodies have been cut by gabbroic dykes who have been dated at 160 Ma by Kaczmarek *et al*. (2005). This age is consistent with the inferred age of opening of the oceanic basin.

ROCK TYPES, FIELD RELATIONSHIPS, PETROGRAPHIC AND MICRO-STRUCTURAL FEATURES

Field investigations show that the Mt. Moncuni body consists mainly of impregnated plagioclase peridotites, m-scale masses of spinel dunites and harzburgites, and widespread dm-wide intrusive gabbroic dykes and subvolcanic porphyritic dykes. Metre- to decametre-wide ductile shear zones with cataclastic bands cut the plagioclase peridotites and deform the pre-existing gabbroic dykes, whereas coarse-grained porphyritic dykes cut across both deformed plagioclase peridotites and shear zones. Within the shear zones mm-wide bands of pseudotachylytes are present, mostly concordant to the tectonite-mylonite foliation and the cataclastic bands of the shear zones and the foliated host rock, whereas dm-wide metre-long sinusoidal veins of pseudotachylytes propagate from the shear zones into the ambient peridotite, showing sharp contacts with the host rock.

Plagioclase peridotites and gabbro dykes

Plagioclase peridotites outcrop as isolated decametric bodies having plagioclase content up to 20% by volume. They show porphyroclastic texture consisting of a deformed and corroded spinel-facies assemblage surrounded by a microgranular aggregate with plagioclase-rich gabbroic composition.

These peridotites are characterized by the presence of peculiar micro-structural features, both indicating: (1) olivine formation at the expense of mantle pyroxenes and (2) orthopyroxene formation at the expenses of mantle olivine. As previously described for the plagioclase peridotites of the South Lanzo massif (Piccardo *et al*., 2007a, and references therein), micro-structures (1) reflect the reactive interaction of the pristine mantle peridotites with silica-undersaturated melts, whereas micro-structures (2) reflect the reactive interaction and interstitial crystallization of orthopyroxene(-silica)-saturated melts. Mutual relationships between the two groups of micro-structures suggest that pristine mantle protoliths suffered early reactive percolation of silica-undersaturated melts and late percolation and impregnation of silica-saturated melts.

Plagioclase peridotites are, accordingly, pristine spinel-facies peridotites which underwent melt-peridotite interaction and melt refertilization by the interstitial crystallization of percolating basaltic melts.

Widespread gabbro dykes cut plagioclase peridotites, showing coarse grained to pegmatoid texture and plagioclase + clinopyroxene assemblage, with subordinated olivine.

Peridotite shear zones

Plagioclase peridotites and gabbro dykes are strongly deformed along metre- to decametre-wide bands where tectonite-mylonite and cataclastic structures are developed (Plate 1).

Plagioclase peridotites are deformed to strongly foliated tectonite-mylonite fabrics consisting of a granoblastic fine-grained matrix, mostly composed by olivine and plagioclase grains, and strongly elongated deformed-recrystallized porphyroclasts of pyroxenes. The plagioclase-peridotite-facies mineral assemblage (Ol + Cpx + Opx + Pl ± Spl, abbreviation after Bucher and Frey, 2002) of the tectonite-mylonite rocks suggests that early stages of deformation and recrystallisation occurred at plagioclase-facies conditions ($P < 1$ GPa). Amphiboles developed in the shear zones, both Mg-hornblende (Am1) in equilibrium with the plagioclase-facies assemblages (Ol + Cpx + Opx + Pl + Am), and tremolitic amphibole (Am2) stable with plagioclase, but replacing pyroxenes and olivine. Amphibole development in the shear zones suggests that they became preferential ways for fluid migration. Mutual relationships between anhydrous plagioclase-bearing assemblage, amphibole-bearing plagioclase-facies assemblage (amphibole-peridotite-facies conditions) and amphibole + plagioclase-bearing assemblage (amphibolite-facies conditions) suggest that the metamorphic conditions were gradually changing (from plagioclase-peridotite-facies to amphibolite-facies) towards lower pressure and temperature conditions.

Following the tectonite-mylonite foliation, thin mm-size near-parallel bands are present, showing evident cataclastic textures. Geometric relations evidence that they formed later than the ductile tectonite-mylonite deformation.

Mm-wide fault-vein type (sensu Sibson, 1975) pseudotachylyte bands (type A) are associated with the cataclastic bands, often running inside the bands. Relatively larger (a few mm-wide) veins frequently connect neighbouring parallel bands forming bridges between them which cut at high angles the tectonite-mylonite and cataclastic bands. These fault veins (type A) consist of an ultra-fine grained to cripto- or microcrystalline matrix showing microlitic/spherulitic structures and significant amounts (< 10-15% by volume) of clastic olivine grains or aggregates and lithic mylonitic/cataclastic clasts (Plate 2).

Larger (dm-wide and m-long) injection-vein (sensu Sibson, 1975) sinusoidal pseudotachylyte veins (type B) crosscut the shear zones and extend to the host plagioclase peridotite (Plate 3). These injection veins consist of a fine-grained mineral aggregates showing an Ol + Opx + Cpx ± Spl mineral association, where euhedral olivine grains (> 50% by volume) and elongated orthopyroxene laths (> 30% by volume) are dominant, with a few percents of interstitial cryptocrystalline material, and an evident spinifex structure (sensu Donaldson, 1982). This structure consists of radial aggregates of elongated orthopyroxene crystals, showing clinopyroxene rims, which enclose and are surrounded by euhedral to rounded olivine grains, with interstitial cryptocrystalline material (Plate 4). The spinifex structures, the modal composition and the peculiar compositions of the component minerals indicate that type B pseudotachylytes formed by very rapid crystallization of an ultramafic melt at very high temperature conditions (see below).

Porphyritic mafic dykes

Dark green colored mafic dykes cut across plagioclase peridotites, deformed gabbroic dykes and shear zones (Plate 5). They have a porphyritic structure with cm-size clinopyroxene phenocrysts, showing widespread magmatic twinnings, and subordinate plagioclase and olivine phenocrysts,

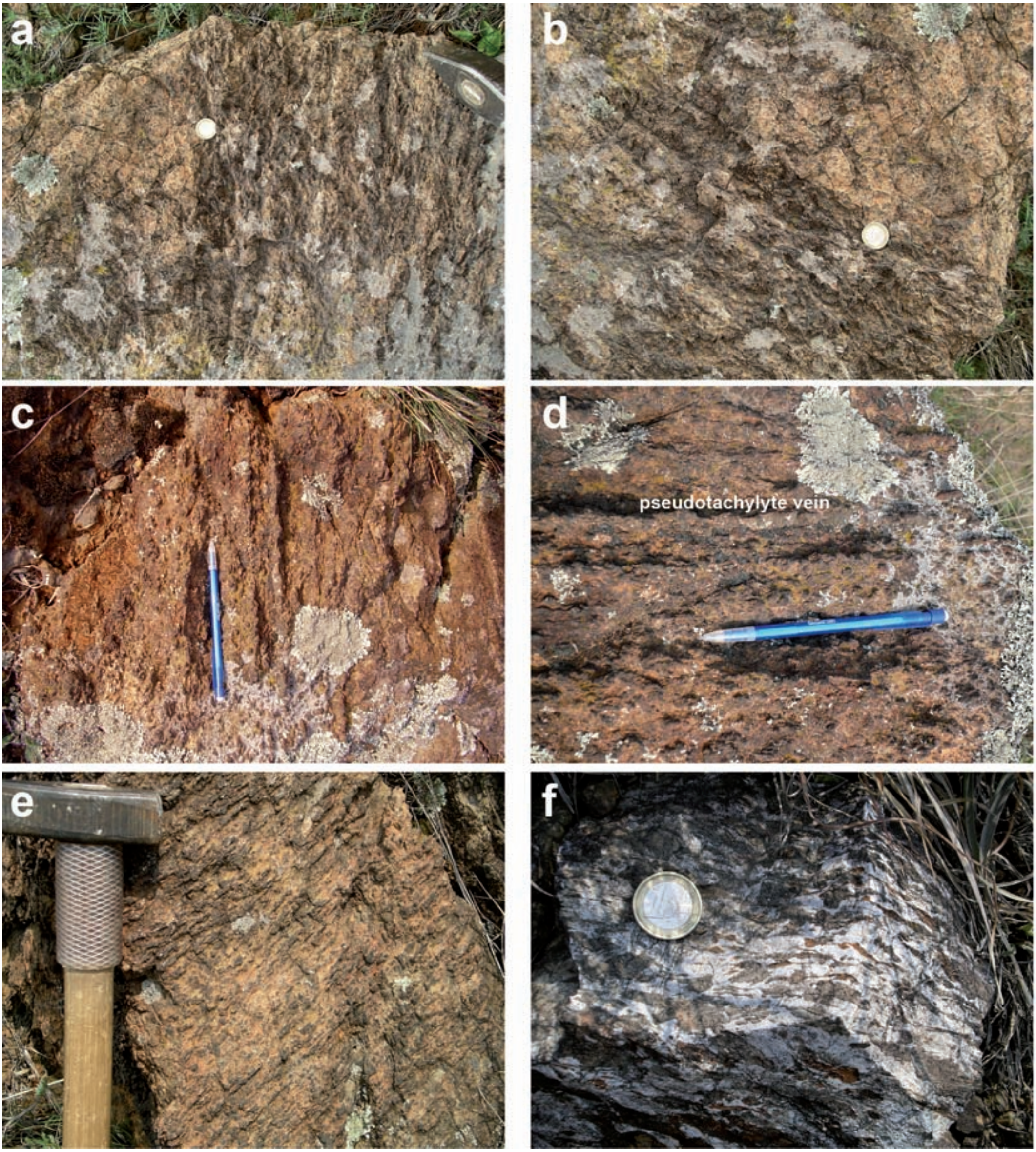

Plate 1 – (a) Contact between foliated plagioclase peridotite (on the left) and tectonite-mylonite shear zone (on the right), which show parallel cataclastic bands and fault-vein (type A) mm-size pseudotachylytes; (b) Close up of the contact between plagioclase peridotite and shear zone; (c) Peridotite tectonite-mylonite shear zone, which show almost parallel cataclastic bands and fault-vein (type A) pseudotachylytes; (d) Close up of the shear zone showing a few mm-wide fault-vein (type A) pseudotachylyte; (e) Strongly foliated mylonitic and cataclastic peridotite in a shear zone; (f) Strongly foliated tectonite-mylonite gabbro dyke in a shear zone.

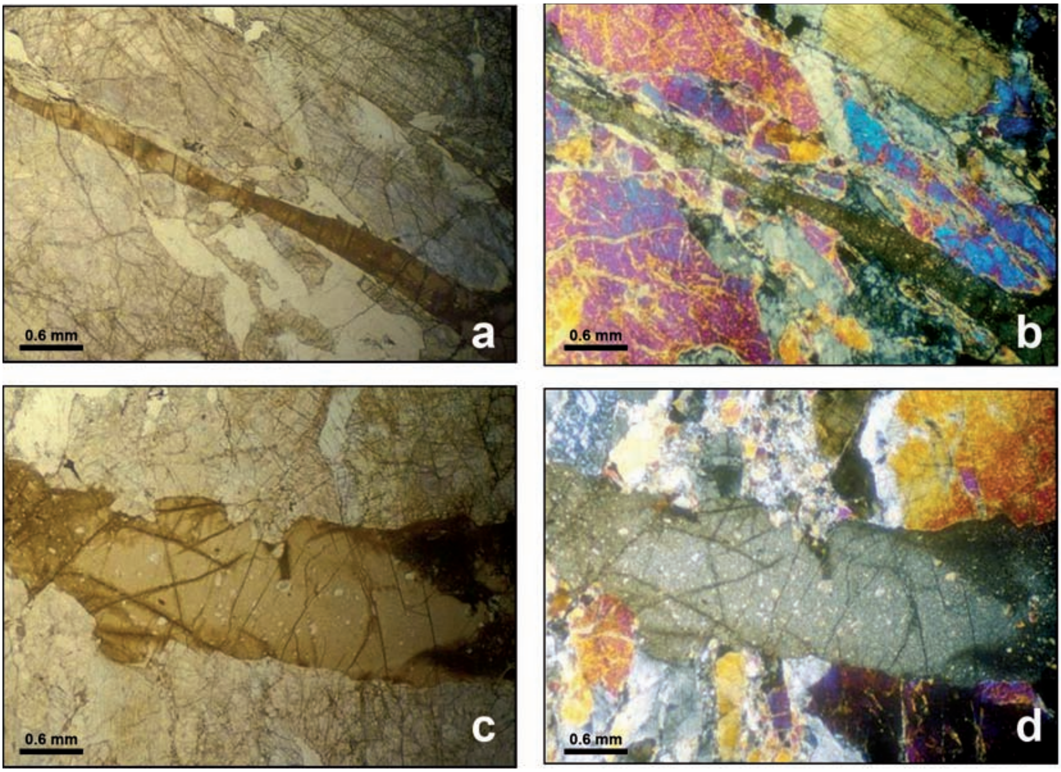

Plate 2 – (a) Millimetre-wide fault vein (type A) pseudotachylyte within a tectonite-milonite plagioclase-bearing peridotite (parallel nicols); (b) Same as (a) (crossed nicols); (c) Millimetre-wide fault vein (type A) pseudotachylyte bridge cutting at high angle the tectonite-mylonite foliation of the host plagioclase-bearing peridotite and the cataclastic bands (parallel nicols); (d) Same as (c) (crossed nicols).

surrounded by a finer grained granular matrix mostly composed by clinopyroxene and plagioclase.

Compositional features

Analytical methods

Bulk rock major and trace element compositions were analyzed at the ACTLAB (Toronto, Canada). Major element compositions of minerals were determined by EMPA at the Istituto di Geoscienze e Georisorse – Consiglio Nazionale delle Ricerche (IGG-CNR) of Padova.

Bulk rock major and trace element composition

Plagioclase peridotites (Table 1) have relatively high Al and Ca and low Si contents (Al_2O_3 = 2.87-3.20 wt%, CaO = 2.83-2.99 wt%, SiO_2 = 43.6-45.0 wt%) and high Mg content (MgO = 39.6-40.5 wt%) (Fig. 2). Bulk rock C1-normalized REE patterns are almost flat in the MREE-HREE region (Er up to 3xC1) and variably LREE-fractionated (Ce_N/Sm_N =0.17-0.21) (Fig. 3), very similar to the impregnated plagioclase peridotites of South Lanzo (Piccardo *et al.*, 2007a).

The gabbro dykes (Table 1) shows high Al and Na contents (Al_2O_3 = 19.81 wt%, NaO = 2.91 wt%) and high Mgvalue (Mg# 80) (Fig. 2). Bulk rock

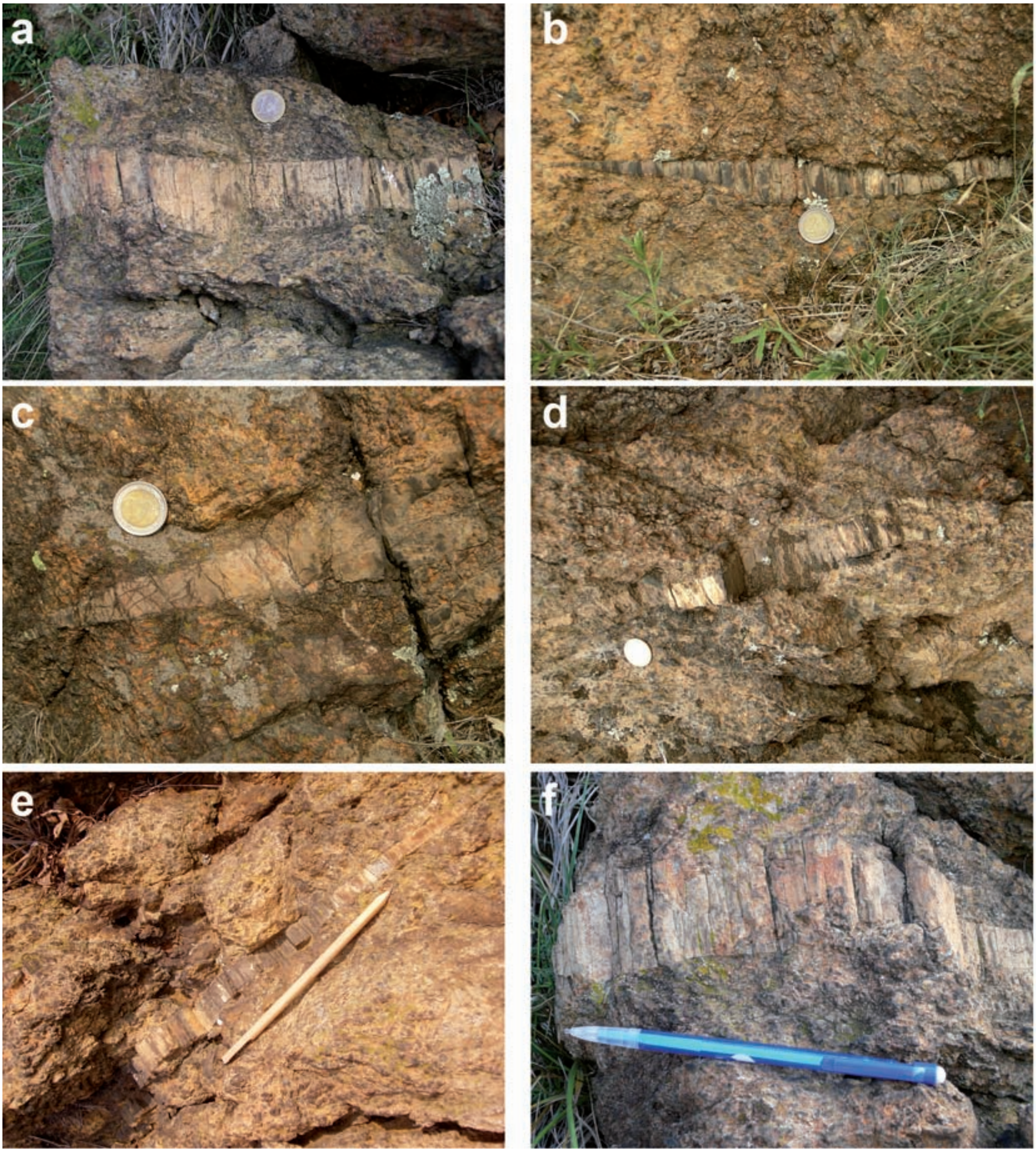

Plate 3 – Decimetre-wide injection-vein (type B) pseudotachylytes. Note the very sharp contact with the host peridotite. Frequently, these type B pseudotachylytes show very fine-grained phaneritic textures and aphanitic chilled margins towards the host rock.

C1-normalized REE patterns are almost flat in the MREE-HREE region (Er at 2.5xC1), slightly LREE-fractionated ($Ce_N/Sm_N = 0.71$) and show clear positive Eu anomaly (Fig. 4). Compositional characteristics are consistent with petrography, indicating high modal plagioclase contents and crystallization from a rather primitive magma with MORB affinity.

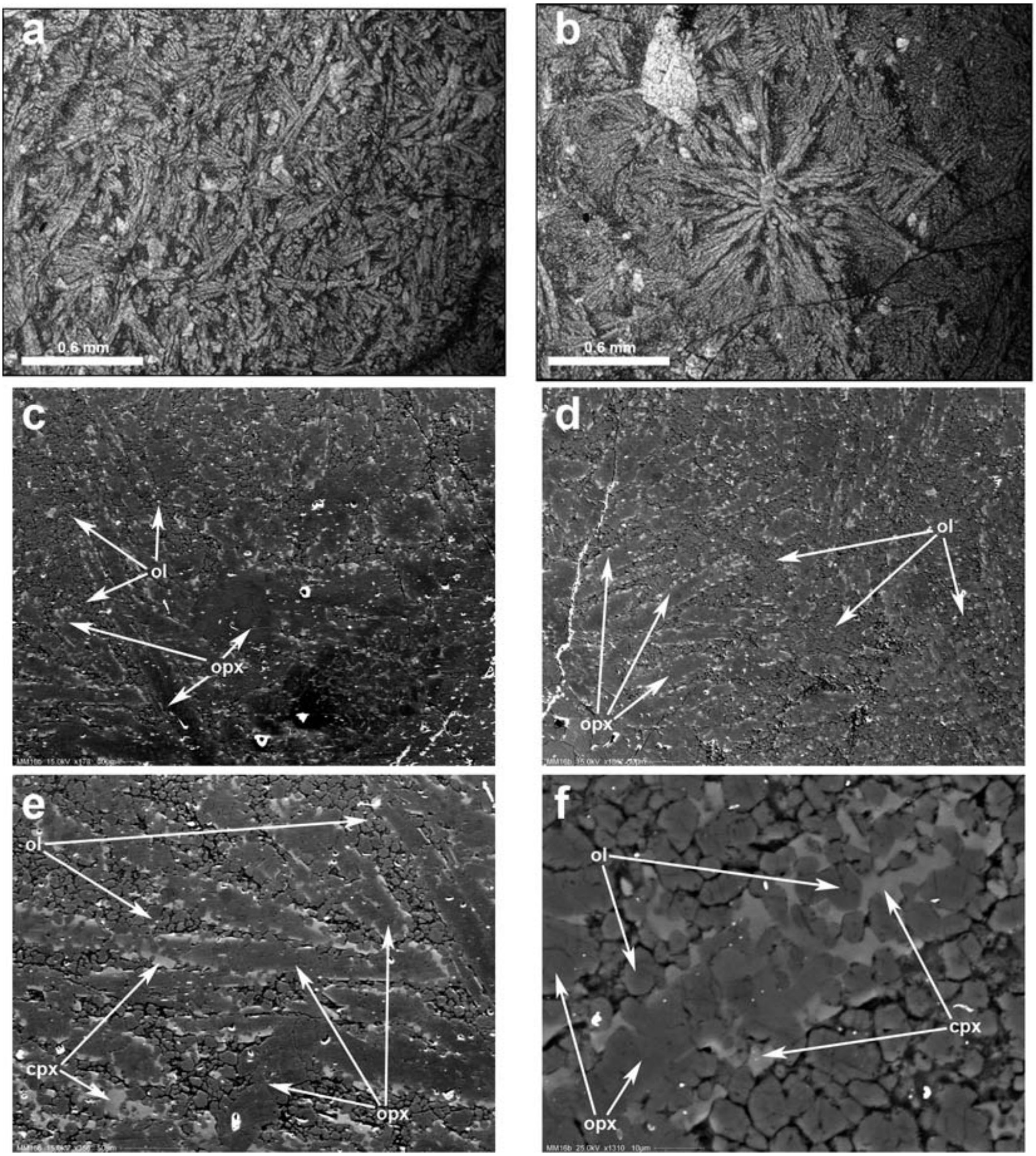

Plate 4 – (a) (b) Spinifex-type texture in a decimetre-wide injection vein (type B) pseudotachylyte; (c) (d) (e) SEM images of the spinifex texture, showing orthopyroxene (Opx) laths and euhedral olivine (Ol) grains; (f) Close up of the spinifex texture showing the crystallization order which consists of euhedral olivine grains, both enclosed within the Opx laths and surrounding the Opx laths, within dusty ultra-fine grained interstitial matrix. Note that the Opx laths are surrounded and replaced by Cpx rims.

Some samples of the wider injection veins (type B) have been analyzed: particularly attention has been dedicated to sample selection to avoid the presence of exotic lithic clasts. Type B pseudotachylyte injection veins (Table 1) show a peridotitic composition (SiO_2 = 42.9-44.3 wt%,

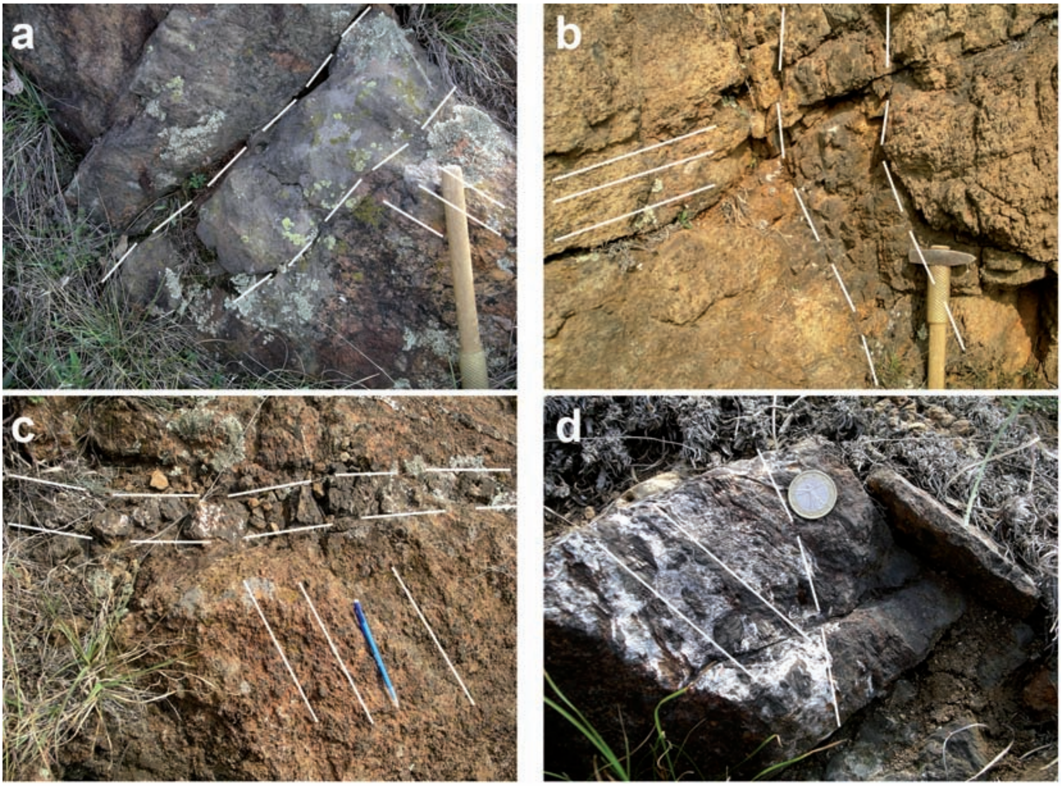

Plate 5 – (a) (b) Decimetre-wide mafic porphyritic dyke cutting at high angle the folation of a tectonite-mylonite shear zone, bearing thin cataclastic bands and mm-size fault-vein (type A) pseudotachylytes; (c) Centimetre-wide mafic porphyritic dyke cutting at high angle the folation of a tectonite-mylonite shear zone, bearing thin cataclastic bands and mm-size fault-vein (type A) pseudotachylytes; (d) Metre-wide mafic porphyritic dyke cutting at high angle the folation of a strongly deformed gabbro in a tectonite-mylonite shear zone

Al_2O_3 = 2.4-3.8 wt%, CaO = 2.3-3.1 wt%) and MgO = 39.4-41.9 wt%) (Fig. 2). Bulk rock C1-normalized REE patterns are almost flat in the MREE-HREE region (Er up to 2xC1) and variably LREE-fractionated (Ce_N/Sm_N = 0.22-0.68) (Fig. 3), plotting within the field of the impregnated plagioclase peridotites of South Lanzo (Piccardo *et al*., 2007a).

Porphyritic mafic dykes (Table 1) shows low Al and Na contents (Al_2O_3 = 1.04-1.49 wt%, NaO = 0.60-0.72 wt%), high Fe and Si contents (Fe_2O_3 = 14.22-21.39 wt%, SiO_2 = 47.06-51.10 wt%) and rather low Mgvalues (Mg# 44-53) (Fig. 2). Bulk rock C1-normalized REE patterns are almost flat in the MREE-HREE region (Dy up to 152xC1) and significant LREE-fractionated (Ce_N/Sm_N = 0.33), and show a well evident negative Eu anomaly (Fig. 4). Compositional characters evidence extremely high REE contents: according to petrography, they have very high modal clinopyroxene contents (>90% by volume). All the data converge to indicate crystallization from a Fe-rich highly evolved magma with MORB affinity.

Major element mineral chemistry

Plagioclase peridotites (Table 2) are composed of magnesian olivine (Fo_{89}) and pyroxenes (orthopyroxene Mg# 90, clinopyroxene Mg# 92) and anorthite-rich plagioclase (An_{81-88}). Spinels are significantly enriched in Ti (TiO_2 = 0.47-1.29 wt%) with respect to mean mantle peridotites, as usual in

TABLE 1
Representative bulk rock major and trace element compositions of the Mt. Moncuni ultramafic-mafic rocks

Rock Type	1	2	3	4
SiO_2	44.30	50.30	43.78	49.08
Al_2O_3	3.03	19.81	3.04	1.27
Fe_2O_3tot	9.26	2.87	9.10	17.80
MnO	0.13	0.05	0.13	0.51
MgO	40.02	11.79	40.87	16.12
CaO	2.91	12.09	2.68	14.19
Na_2O	0.22	2.91	0.28	0.66
K_2O	0.01	0.05	0.08	0.03
TiO_2	0.11	0.11	0.09	0.32
P_2O_5	0.01	0.01		0.01
Total	100.00	100.00	100.00	100.00
La	< 0.05	0.35	0.13	4.12
Ce	0.22	1.08	0.36	23.75
Pr	0.07	0.19	0.06	6.13
Nd	0.55	1.06	0.44	42.15
Sm	0.28	0.37	0.19	17.50
Eu	0.12	0.256	0.07	4.38
Gd	0.42	0.46	0.28	23.60
Tb	0.09	0.09	0.06	5.04
Dy	0.65	0.6	0.41	32.15
Ho	0.14	0.13	0.09	6.56
Er	0.44	0.4	0.29	19.60
Tm	0.07	0.059	0.04	2.88
Yb	0.43	0.37	0.30	17.95
Lu	0.06	0.053	0.05	2.73

1: impregnated plagioclase peridotite, 2: gabbro dyke, 3: dm-wide injection-vein pseudotachylyte (type B), 4: porphyritic mafic dyke.

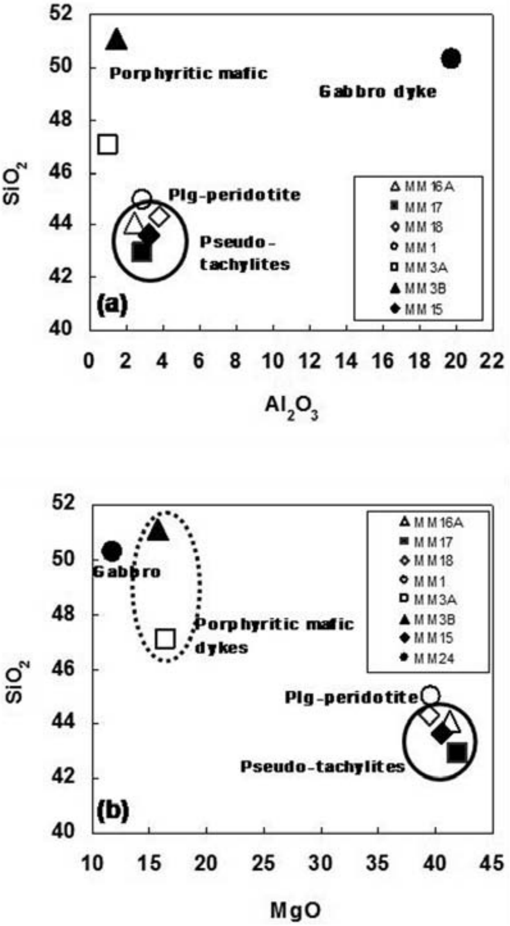

Fig. 2 - Bulk rock SiO_2 versus Al_2O_3 (a) and SiO_2 versus MgO (b) diagrams of the different rock types at Mt. Moncuni. Note that pseudotachylytes compositions are almost coincident with plagioclase peridotites compositions.

spinels from impregnated plagioclase peridotites (Piccardo *et al.*, 2007a, and references therein).

Mylonitic peridotites in the shear zones (Table 3) are composed by magnesian olivine (Fo_{89-90}) and pyroxenes (orthopyroxene Mg# 90, clinopyroxene Mg# 88-92) and anorthite-rich plagioclase (An_{75-82}). Spinels are significantly enriched in Ti (TiO_2 = 0.27-0.99% wt%) with respect to mean mantle peridotites, stressing out the impregnated character of the plagioclase peridotite protolith. Amphiboles developed within the shear zones: Mg-hornblendes in equilibrium with the plagioclase-facies assemblages and hornblendes-tremolites replacing clinopyroxenes and olivine, in equilibrium with rather sodic plagioclase.

TABLE 2

Major element composition of minerals from a representative Mt. Moncuni plagioclase peridotite (sample MM1)

mineral/ occurrence	Cpx PC	Cpx PR	Cpx GR	Opx PC	Opx PR	Opx GR	Pl	Spl
SiO_2	51.52	51.73	52.03	56.59	56.86	56.29	48.27	0.12
TiO_2	0.57	0.74	0.68	0.21	0.23	0.26	0.01	0.47
Cr_2O_3	1.36	1.12	1.27	0.68	0.64	0.69	0	39.32
Al_2O_3	4.81	4.63	3.99	2.74	2.56	2.76	32.97	25.69
Fe_2O_3								2.7
FeO	2.46	2.16	2.36	6.73	6.58	6.64	0.05	19.91
Mno	0.09	0.09	0.05	0.15	0.11	0.13	0.04	0.26
MgO	15.61	16.30	15.93	32.84	32.97	32.51	0	10.54
CaO	23.31	23.20	23.43	0.87	0.64	1.39	16.46	0.01
Na_2O	0.44	0.47	0.46	0.00	0.00	0.03	2.17	0.01
K_2O	0.01	0.00	0.00	0.03	0.04	0.01	0.02	0.00

PC: porphyroclast core, PR: porphyroclast rim, GR: interstitial grain.

Type B (dm-wide) pseudotachylyte injection veins (Table 4) consist of olivine grains enclosed and surrounding the orthopyroxene laths which show clinopyroxene rims. Olivine grains in orthopyroxene are highly magnesian (Fo_{91-92}) and shows unusually high contents of Al (Al_2O_3 up to 0.17 wt%), Cr (Cr_2O_3 in the range 0.09-0.4 wt%) and Ca (CaO in the range 0.21-0.39 wt%). Olivine grains in the cryptocrystalline matrix are highly magnesian (Fo_{88-90}) and show unusually high contents of Al (Al_2O_3 up to 0.11 wt%), Cr (Cr_2O_3 in the range 0.21-0.29 wt%) and Ca (CaO in the range 0.25-0.34 wt%). Orthopyroxenes are magnesian (Mg# 89-93) and show very high Ca (CaO up to 2.03 wt%) contents. Clinopyroxenes are also magnesian (Mg# 88-90) and show unusually high Al (Al_2O_3 sporadically up to 14.5 wt%) and Ti (TiO_2 up to 1.86 wt%) contents.

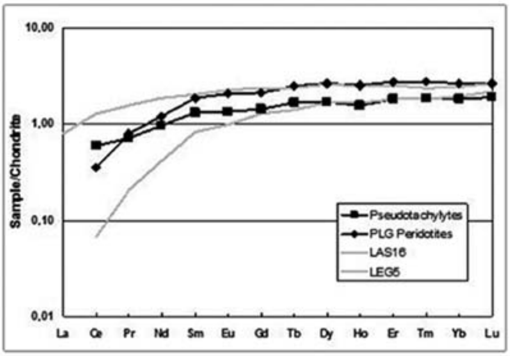

Fig. 3 – Bulk rock chondrite-normalised REE patterns of representative average compositions of Mt. Moncuni plagioclase peridotites and type B injection-vein pseudotachylytes. The range of plagioclase peridotites from South Lanzo (LAS16-LEG5) is also reported for comparison (from Piccardo *et al.*, 2007a). Note that ultramafic pseudotachylyte has REE pattern closely similar to that onr of the plagioclase peridotite and fall in the range of plagioclase peridotites from the North Lanzo body.

Orthopyroxene grains in the host deformed peridotite very close to the pseudotachylyte vein have sometimes very high Ca contents (CaO = 2.79-3.34 wt%).

Porphyritic mafic dykes (Table 5) have abundant phenocrystic clinopyroxenes, showing evident magmatic twinnings, which have relatively low in Al, Ti and Cr contents (Al_2O_3 = 2.32-4.20 wt%, Cr_2O_3 0.06-0.21 wt%, TiO_2 0.39-0.87 wt%), and show Mg# in the range 83-87. Clinopyroxenes in the granular matrix have low Al, Ti and Cr contents (Al_2O_3 = 0.76-2.32 wt%, Cr_2O_3 = 0.05-0.09 wt%, TiO_2 = 0.24-0.43 wt%) and Mg# in

TABLE 3

Major elements composition of minerals from a Mt. Moncuni tectonitic-mylonitic plagioclase peridotite (sample MM16B)

mineral/	Cpx	Opx	Opx	Ol	Pl	Spl
occurrence	GR	GR	GR1			
SiO_2	51.42	56.83	55.77	41.41	47.26	0.19
TiO_2	0.60	0.18	0.26	0.01	0.11	0.60
Cr_2O_3	1.34	0.62	0.72	0.01	0.01	30.23
Al_2O_3	4.78	2.18	2.74	0.02	33.28	31.27
Fe_2O_3					0.37	5.15
FeO_T/FeO	3.38	6.54	6.44	10.10	0.05	21.57
MnO	0.11	0.16	0.17	0.11	0.01	0.00
MgO	16.35	32.78	30.92	47.98	0.01	0.00
NiO						10.20
CaO	21.81	0.91	3.34	0.02	16.37	0.15
Na_2O	0.40	0.01	0.09	0.01	2.27	0.00
K_2O	0.03	0.01	0.00	0.02	0.02	0.00

GR: granoblastic grain, GR1: granoblastic grain very close to the contact to a type B pseudotachylyte vein.

the range = 68-82. Plagioclase phenocrysts have mean An_{54} contents in the cores, An_{53} in the rims, whereas plagioclase in the granular matrix varies from An_{52} to An_{14}. Modal composition (very high clinopyroxene contents) and mineral chemistry suggest that these porphyritic dykes represent mineral cumulates formed during crystallization in dykes of strongly evolved magmas with Fe-rich basaltic composition.

Accordingly, the porphyritic mafic dykes are characterized by progressively more evolved mineral chemistries going from porphyroclast cores to groundmass grains: e.g. clinopyroxenes from about Mg# 90 to Mg# 68; plagioclase from An_{54} to An_{14}. These mineral chemistry variations (i.e. decreasing Mg and Ca, increasing Fe) are quite consistent with fractional crystallisation during magmatic evolution.

THERMOMETRIC ESTIMATES

Thermometric estimates have been obtained by applying the method of Brey and Köhler (1990), based on the Ca content in orthopyroxene.

Impregnated plagioclase peridotites record relatively high equilibration temperature (as high as 1150°C) which can be related to the percolation and impregnation event by melts migrating via diffuse porous flow, consistently with what described for the same rock types in the South Lanzo massif (Piccardo *et al.*, 2007a).

TABLE 4

Major element composition of minerals from a Mt. Moncuni type B pseudotachylyte (sample MM16B)

mineral	Opx lath	Opx lath	Cpx rim	Cpx rim	Ol grain in Opx	Ol grain
SiO_2	55.73	55.13	50.27	44.10	40.54	40.38
TiO_2	0.17	0.19	0.62	1.86	0.00	0.00
Al_2O_3	1.93	2.79	7.55	14.51	0.11	0.04
Cr_2O_3	1.07	1.74	0.44	0.23	0.25	0.25
FeO_T	6.48	6.54	6.19	7.22	8.73	10.47
MnO	0.23	0.20	0.25	0.24	0.20	0.19
NiO	0.00	0.00	0.00	0.00	0.38	0.39
MgO	33.09	32.25	17.97	13.04	49.90	48.60
CaO	1.12	2.03	16.55	17.86	0.30	0.31
Na_2O	0.00	0.00	0.59	0.74	0.00	0.00
K_2O	0.00	0.00	0.05	0.07	0.00	0.00

Table 5

Major elements composition of minerals of a Mt. Moncuni porphyritic mafic dyke (sample MM3B)

mineral/ occurrence	Cpx PC	Cpx PR	Cpx GR	Pl GR
SiO_2	53.21	52.73	53.25	65.95
TiO_2	0.50	0.48	0.43	0.04
Cr_2O_3	0.16	0.15	0.05	0.02
Al_2O_3	3.16	2.49	0.76	21.50
Fe_2O_3				0.07
FeO_T/FeO	5.99	9.40	11.57	0.00
Mno	0.23	0.36	0.48	0.00
MgO	17.85	15.51	13.68	0.00
NiO	0.00	0.00	0.00	0.00
CaO	18.97	18.30	19.56	2.93
Na_2O	0.82	0.91	0.70	9.77
K_2O	0.01	0.03	0.00	0.14

PC: porphyroclast core, PR: porphyroclast rim, GR: groundmass grain.

The strongly deformed mylonitic assemblage of the shear zones records a temperature of about 900°C, which is consistent with the amphibole-bearing plagioclase-facies conditions and suggests significant temperature decrease associated to the development of hydrated, amphibole-bearing assemblages. Since the plastic deformation events forming tectonite-mylonite rocks clearly precede formation of the thin cataclastic bands to which mm-size pseudotachylyte fault veins are related, this temperature estimate cannot be interpreted as the ambient temperature during pseudotachylyte formation.

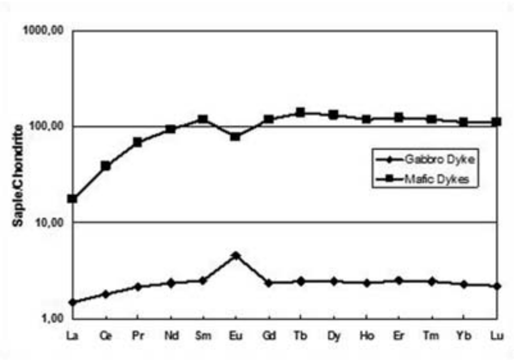

Fig. 4 - Bulk rock chondrite-normalised REE patterns of a representative MORB-type gabbro and a representative average composition of MORB-type porphyritic mafic dykes. The positive Eu anomaly in gabbro suggests, in agreement with modal composition, cumulus of plagioclase, whereas the negative Eu anomaly in mafic dykes suggests, in agreement with modal composition, cumulus of clinopyroxene formed in equilibrium with plagioclase.

Interestingly, some orthopyroxene crystals in the host peridotite, very close (a few mm) to the contact with a dm-wide injection-type (type B) pseudotachylyte vein have very high Ca contents, which give very high temperature estimates (1315-1430°C). They most probably reflect the thermal regime locally induced in the host rock at the time of intrusion of the parental melt of the pseudotachylyte vein.

Orthopyroxene in the spinifex textures of pseudotachylytes has very high Ca contents (CaO up to 2.03 wt%), which give very high temperature estimates (up to 1236°C), most probably related to the crystallisation of the ultramafic melt.

Discussion and conclusion

The main rock type at Mt. Moncuni is represented by mantle peridotite which has been enriched in plagioclase and micro-gabbroic material (i.e. refertilized) during percolation of a MORB-type basaltic melt. Equilibration temperature of the plagioclase-bearing assemblage (1150°C) indicates that this process occurred at high temperature, compatible with melt percolation in a peridotite matrix, as evidenced for the South Lanzo peridotite body (Piccardo *et al.*, 2007a).

Pristine plagioclase peridotites underwent strong localized deformation along shear zones, where they acquired tectonite-mylonite textures and they recrystallized progressively to plagioclase-peridotite-facies, amphibole-bearing plagioclase-peridotite-facies and finally amphibolite-facies conditions. The paragenetic evolution and the thermal conditions evaluated for the amphibole-bearing assemblages (about 900°C) suggest progressive decompression and cooling accompanied by hydration. It may be inferred that the shear zones accomodated the progressive ascent of these peridotites from plagioclase-facies conditions in the mantle lithosphere to cooler shallow conditions close to, and eventually above, the brittle/ductile transition, when cataclastic structures were developed.

Tectonitic-mylonitic bands in shear zones are deformed by millimetre- to centimetre-wide cataclastic bands, clearly postdating the plastic deformation events responsible of the tectonite-mylonite formation.

Fault vein pseudotachylytes are mostly localized parallel to the cataclastic bands, but sporadically they cut across both tectonite-milonite foliation and the cataclastic bands.

The occurrence of pseudotachylytes is consistent with the occurrence of upper mantle earthquakes.

On the basis of the present evidence, it is possible to speculate that pseudotachylyte formation occurred in the later (brittle) stages of deformation. Moreover, the formation of mm-size ultra-fine grained pseudotachylyte veins which are concordant with the brittle fractures of the shear zones suggest that the latter acted as loci for the seismogenic release of the accumulated shear stress.

The co-seismic shear heating and the associated temperature increase produced the strongly localized, almost complete melting of the host deformed peridotite, forming melts with peridotitic compositions. Some of the produced peridotitic melt remained confined very close to the fault planes, forming fault-vein type pseudotachylytes, and some was intruded along discordant fractures, forming injection-vein type pseudotachylytes. Strong localized heating of the host rock (up to 1450°C) was associated with vein intrusion of the pseudotachylyte type B parental ultramafic melts. The rapid quenching of the melt formed mostly crypto/microcrystalline material, but within the thicker (decimetre-wide) discordant veins, crystallization produced spinifex textures, which are typical of rapid crystallisation of ultramafic magmas with komatiitic (peridotitic) composition (Donaldson, 1982).

Although pseudotachylytes are often reported in crustal rocks (see e. g. Sibson 1975; Wenk *et al*., 2000; Caggianelli *et al*., 2005; Di Toro *et al*., 2005; among others), to our knowledge their occurrence in ultramafic mantle rocks has been reported only twice before [in a spinel lherzolite from the Ivrea-Verbano zone (Obata and Karato, 1995), and in a gabbro-peridotite subduction complex in Corsica (Austrheim and Andersen, 2004)]. The Mt. Moncuni pseudotachylytes, therefore, provide an important confirmation of the seismogenic nature of the shallow lithospheric mantle, most probably at conditions near the brittle/ductile transition. Although a quantitative analysis of the seismic process at Mt. Moncuni is not yet possible (it requires estimation of temperature increase, melt volume, and amount of slip), the following qualitative inferences can be made:

(i) the shear heating was significant, with consequent large temperature increase (most probably from T significantly lower than 900°C at the time of pseudotachylyte formation to T > 1400°C, the liquidus of the peridotite system at the relevant pressure conditions;

(ii) given the low viscosity of ultrabasic melts (1-10 Pas), the stress drop and seismic moment release were probably at the high end of the spectrum commensurate with the size of the seismic shocks (as also concluded by Obata and Karato, 1995);

(iii) the thermal pulse associated with pseudotachylyte formation was both very localized (as shown by the limited spatial extent of heating of the host rock) and of short duration (as shown by the spinifex textures). This last point is in qualitative agreement with the small earthquake pseudotachylyte model of Caggianelli *et al*. (2005). Based on a three-stage rupture model including nucleation, propagation and stopping, this model predicts localised temperature increases of several hundreds degrees even for relatively small (a few cm) amounts of slip.

A later event recorded in the Mt. Moncuni peridotite is the shallow intrusion of mafic dykes, showing porphyritic textures and clinopyroxene-rich compositions. Both bulk rock and mineral compositions suggest that they derive from intrusion and crystallization of an evolved MORB-type magma, most probably having a Fe-rich composition. Paucity of plagioclase and abundance of clinopyroxene (and accordingly the bulk rock compositions) suggest that significant clinopyroxene accumulation occurred during melt flow in the dykes and the plagioclase-rich fraction of melt was expelled from the dykes. Accordingly, these dykes represent clinopyroxene cumulates formed during flow fractional crystallization.

The presence of hydrous minerals and amphibolite-facies assemblages and, moreover, the sub-volcanic, porphyritic textures of the late mafic dykes suggest that the last stages of evolution occurred at rather shallow levels, close to the sea-floor of the Jurassic basin. Mutual relationships between intrusive MORB gabbroic dykes, shear zones, pseudotachylyte veins and late porphyritic MORB-type dykes indicate that shear zones and associated earthquakes occurred after the intrusive emplacement of MORB-type dykes and preceding the sub-volcanic emplacement of porphyritic MORB-type dykes, i.e. during the MORB oceanic magmatism of the Jurassic Ligurian Tethys.

Field evidence and petrographic-structural and compositional data allow to infer the relative timing of the seismic events testified by the presence of the ultramafic pseudotachylytes. Shear zones and related pseudotachylytes are more recent that the gabbroic dyke intrusion, which has been dated at about 160 Ma in the Lanzo Massif by Kaczmarek *et al.* (2005). In their turn, shear zones and pseudotachylytes are relatively older than the stage of subvolcanic emplacement of MORB-type fractionated magmas at very shallow crustal levels as testified by the crosscutting porphyritic mafic dyke intrusion.

Accordingly, present knowledge indicates that shear zones and pseudotachylytes (i.e. seismic activity in the upper mantle) were related to the shallow evolution of this peridotite massif during exhumation and near sea-floor emplacement in a geodynamic setting were oceanic MORB magmatism was active, i.e. during rifting and formation of the Jurassic Ligurian Tethys.

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