EXHUMATION OF MANTLE LITHOSPHERE:
FIELD RELATIONS, AND INTERACTION PROCESSES
BETWEEN MAGMATISM AND DEFORMATION
(FIELD TRIP TO THE NORTHERN LANZO PERIDOTITE)

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ABSTRACT

The Lanzo peridotite plays a key role in exploring the effects of deformation and magmatism in a system evolving from rifting to sea floor spreading. In this field guide we present new field observations, structural and petrological data that constrain the exhumation evolution of the northern Lanzo peridotites during the opening of the Piemonte Ligurian ocean. Gabbroic dikes ranging from troctolite to gabbro-norite to oxide gabbros and plagiogranites indicate fractionation of mafic magmas in a relatively thick thermal lithosphere. This lithosphere was thinned by a large shear zone separating different mantle domains. The thermal evolution of the shear zone is recorded by porphyroclastic to mylonitic plagioclase peridotites. Later, at least parts of the mantle rocks were exhumed to the ocean floor, as indicated by widespread serpentinization, rodingitization of mafic dikes, local occurrences of ophicarbonates and metabasalts. Possible origins of crustal remnants (pre-alpine granulite) within the serpentinites are discussed.

GEOLOGICAL OVERVIEW

The Lanzo peridotites are part of the high-pressure belt of the Western Alps (Fig. 1), which was formed during Upper Cretaceous - Early Tertiary subduction along the Eastern border of the Liguria-Piemonte Ocean and which includes other eclogite facies ophiolites such as Saas Zermatt and Mt. Viso (e.g. Lombardo and Pognante, 1982). To the northwest the peridotites are bounded by serpentinites and their oceanic cover (Fig. 2). To the north, the thinned continental crust of the Sesia zone is exposed, which consists of 3 units (Dal Piaz, 1999): the eclogitic micaschists, gneiss minuti and a monometamorphic sedimentary sequence, and the diorite-kinzigite units (lower crust). The paleogeographic position of the Sesia zone is subject of some debate. It either formed the most distal part of the Adriatic continental margin (Dal Piaz, 1999), or an extensional allochthon separated from the Adriatic margin by a window of exhumed continental man-
tle (Froitzheim and Manatschal, 1996), or is part of Europe (Fudral and Deville, 1986).

Peridotites and gabbroic dikes are partially transformed into eclogite facies rocks during Alpine metamorphism. The peridotite core is surrounded by serpentinized peridotites and strongly foliated serpentinites, mainly composed of antigorite and diopside, and minor olivine, chlorite, magnetite and titaniam-clinohumite. In places the top of the mantle rocks is covered by ophicarbonate breccias (Fig. 3). Depending on whole rock composition, gabbroic dikes developed different high-pressure mineral parageneses (chloritoid, talc, garnet, ± kyanite (Kienast and Pognante, 1988; Pelletier and Müntener, 2005), indicating peak metamorphic conditions of ~550-620°C and pressures in excess of 2.0 GPa (Pelletier and Müntener, 2005). Within the serpentinites, gabbro and basaltic dikes are partially transformed into metarodingites (Figs. 2, 3), consisting of Ca-rich garnet, diopside, chlorite, epidote, titanite, vesuvianite and Ca-amphibole. Rodingitization most probably occurred during exposure of the ultramafic rocks on the ocean floor by circulation of fluids associated with serpentinization of mantle rocks, increasing Ca and decreasing Na of the bulk rock (Evans et al., 1979; Pognante et al., 1985).

There are large areas with little high-pressure overprint, where mantle processes are well preserved. In the northern part of the Lanzo massif, the remnants of a high-temperature mantle shear zone are exposed, separating a fragment of a former subcontinental mantle lithosphere (spinel to plagioclase peridotites with abundant pyroxenites) from a mantle hybrid (mainly plagioclase peridotites, dunites in the western part, pyroxenites, abundant gabbroic dikes and a few basalts; e.g., Bodinier et al., 1991). The outcrop of the shear zone extends over an area of ~2 km long and several hundreds of meters large (Fig. 2).

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**EXCURSION ROUTE**

The aim of the excursion to the Lanzo north peridotite is to visit structures and rock types that are related to the spatial and temporal evolution of deformation and magmatism in a system undergoing exhumation to the seafloor, during the incipient opening of the Liguria-Piemonte Ocean. We start with a group of small outcrops near Maddelene (Fig. 2) where the field relations between pyroxenite layering, peridotite foliation and intrusion of gabbroic dikes can be studied (Stop 2) before inspecting a traverse of a high-temperature mantle shear zone (Gran Costa, Stop 1), visiting mainly the footwall and its increasing deformation gradient towards the mylonite zone. We will continue with a cross section from peridotites to serpentinized peridotites and shall discuss the importance of granulites enclosed within the Lanzo peridotites (Combasistel, Stop 3). Finally, time permitting, we will visit some rocks of the oceanic cover of...
the Lanzo peridotites (ophicarbonates, mafic rocks, Lassieri, Stop 4), or gneiss and calcschists in the area of Richiaglio (see Fig. 17).

**Gabbroic rocks in the Lanzo peridotite: fractional crystallization in a thick thermal lithosphere (Stop 1)**

Within the unmetamorphosed parts of the Lanzo peridotite, mafic rocks can be separated into 3 groups (Boudier, 1978; Boudier and Nicolas, 1972):

(1) an oldest ‘indigenous’ group of troctolites to olivine gabbronorites and olivine gabbros, a few centimeters to several decameters long and frequently occurring ‘en echelon’ with diffuse contacts to the surrounding lherzolites. This type is frequently found in the southwestern part of the Lanzo massif (see Field Trip part I), but can also be recognized in the lower parts of Rio Ordagna (Fig. 2).

(2) An intrusive group of troctolites, olivine gabbros, gabbrororites to oxide gabbros and rare plagiogranites, with sharp contacts and chilled margins towards the peridotite. These gabbroic dikes can be followed over tens of meters in the field and may be found all over the Lanzo peridotite. Locally, the gabbros are cut by or grade into high temperature shear zones (Fig. 4a). Within these shear zones cm-sized amphibole phenocrysts are common and are associated with ilmenite, apatite and rare zircon. Ilmenite is often xenomorphic between plagioclase, pyroxenes and amphibole, indicating late stage magmatic crystallization (Desmurs et al., 2001; Tribuzio et al., 2000). Previously, the hornblende-bearing gabbros were interpreted to be of metamorphic origin (Compagnoni et al., 1984; Pognante et al., 1985). Rarely, zircon-rich plagiogranites cut deformed peridotites. They either represent late stage differentiates from the main gabbros (Desmurs et al., 2002; Tribuzio et al., 2000), or, alternatively, they represent the products of hydrous partial melting of gabbro cumulates (Koepke et al., 2005).

(3) Porphyritic basaltic dikes of MORB affinity crosscutting peridotites, gabbros and shear zones (Pognante et al., 1985).

![Fig. 3 - Simplified geological map of the northwestern part of the Lanzo massif, illustrating serpentinite-sedimentary cover contacts and the occurrence of a metapiperidotites, prasinites, chlorite-phenritic gneisses, phengite-quartz calcschists successions along the contact (Pelletier and Müntener, 2005).](image)
Age determinations of gabbroic rocks

Zircons were studied by cathodoluminescence (CL) and analysed with SHRIMP II for U-Pb dating and LA-ICP-MS for trace element determination. CL imaging of zircon reveals magmatic zoning cut by an unzoned recrystallized domain (Fig. 5). U-Pb dating of 3 samples indicates an age of magmatism of about 160 Ma (Kaczmarek et al., 2005), similar to other Western Alps ophiolitic gabbros. Trace element chemistry of zircon by LA-ICP-MS indicates a positive Ce anomaly and a variable Eu negative anomaly (Fig. 6). The Eu anomaly suggests plagioclase fractionation in the magma and is consistent with the magmatic origin of the zircon.

Geochemistry

The Lanzo gabbros show highly variable bulk rock compositions (Pognante et al., 1985; Bodinier et al., 1986). In terms of mineralogy and major elements, the gabbros from the northeastern part of Lanzo are generally more evolved than those from the southwestern part. Chondrite normalized REE data, compiled in Fig. 7, illustrate that most of the gabbroic dikes represent cumulates with little or no trapped liquid indicating efficient extraction of interstitial liquids (Bodinier et al., 1986). Fig. 7 also illustrates calculated liquid compositions derived from cpx from dunites, harzburgites and primitive troctolite to olivine gabbros (Piccardo et al., 2005). These data are similar to basaltic dikes (Pognante et al., 1985) supporting the idea that ‘indigenous’ group 1 gabbros are cumulates that formed in equilibrium with liquids, that were extracted to form basalts.

High-temperature shear zones in the mantle (Stop 2)

One of the major discoveries along mid-ocean ridges and along ocean-continent transitions in the past decades was the observation that mantle rocks can be exposed over several kilometers. There is a general consensus that the final deformation occurred along low-temperature detachment faults, but there is little observational data about the deep, high-temperature deformation that presumably preceded detachment faulting, or alternatively, represents the deep roots of detachment faults.

The shear zone in the northern Lanzo peridotite is ~2 km wide, and oriented NW-SE with a sub-vertical foliation (Fig. 2). Pyroxenitic layering and high temperature foliations are parallel in the ultra-mylonite zone (Fig. 2). In contrast, they are discordant in less deformed rocks, with re-orientation of the pyroxene in the pyroxenitic layering parallel to the high-temperature foliation. Several cross sections indicate that the deformation is not symmetrically distributed along the shear zone. There is a relatively sharp transition (about 400 to 500 m) from weakly deformed porphyroclastic peridotites (grain size up to 1.5 cm) to ultramylonites (grain size ~50 µm or less) on the northern side of the mylonite. The southern part of the shear zone, however, shows a much smoother transition. Reconstructing the main deformational features in 3D indicates that this shear zone is...
anastomozing (Fig. 8), with progressive localization of de-
formation with increasing strain. Mylonites thus include ar-
eas of less deformed regions (Fig. 8).

Preliminary grain size analyses indicate 4 types of mi-
crostructures from “porphyroclastic” with magmatic and im-
pregnation textures (olivine grain size: 0.2 to 1.05 mm, as-
pect ratios: 1.6 to 2) to ultra-mylonitic (grain size: < 0.05 to
0.15 mm, aspect ratios ~ 1.6) with extremely stretched (as-
pect ratio up to 10:1) porphyroclastic opx (Fig. 9). There is
a clear difference in the recrystallized grain size between
‘monomineralic’ bands of olivine and ‘polycrystalline
bands’ (Fig. 9). Typical peridotite mylonite bands consist of
olivine (ol) + clinopyroxene (cpx) + opx + plagioclase (plg)
+ Cr-Al spinel ± Ti hornblende and enclose coarse porphy-
roclasts of pyroxene or polycrystalline bands of olivine.
Some cpx porphyroclasts show signs of previous reaction
textures with a melt (cpx + liq → opx + plg ± ol; Fig. 10).
This indicates that the mylonite formation postdates cpx-
corroding melt/rock reactions.

Detailed mineral chemical investigations by SEM and by
electron microprobe (EMS) revealed that porphyroclastic
pyroxenes and spinel are strongly zoned in some elements,
suggesting disequilibrium mineral compositions. Cores of
pyroxenes are rich in Al and poor in Ti and probably indi-
cate equilibration in the spinel peridotite facies (Fig. 10).
Large pyroxene porphyroclasts record processes of melt in-
filtration and melt/rock reaction, which is reflected by com-
plex zonation patterns of Ti. Rim compositions of pyroxenes

Fig. 6 - REE spectra of zircons from hbl-oxide gabbro 165b. The chondrite
normalized REE spectra are smooth with a regular increase in HREE. Note
the weak negative Eu anomaly, indicating that zircons crystallized from
differentiated liquids (Kaczmarek et al., in preparation).

Fig. 7 - Geochemical variation of gabbroic rocks from the Lanzo peri-
dotite. (a) Chondrite normalized REE spectra of different gabbroic dikes
ranging from troctolite, olivine gabbro, and gabbronite. Positive Eu
anomalies in troctolite and olivine gabbronite are indicative of a cumu-
late origin. (gabbro data from Bodinier et al., 1986; Piccardo et al., 2005;
basalt data from Pognante et al., 1985). Gray shaded area is the range of
calculated liquids from cpx in dunite, harzburgite and olivine gabbros (Pic-
cardo et al., 2005), which is similar to the measured basalt data from Pog-
nante et al. (1985). Note that Gd values for the data of Bodinier et al.
(1986) are interpolated between Tb and Sm.

Fig. 8 - (a) Schematic cross section of the peridotite mylonite zone, illustrating the relationships between high temperature foliations and pyroxenite layers.
For profile location, see Fig. 2. (b) Schematic model of an anastomozing shear zone, which could explain the irregular distribution of peridotite mylonites in
the field.
as well as small, recrystallized grains within the mylonite indicate equilibration under plagioclase facies conditions (Fig. 11) and relatively low temperatures (800 to 900°C, based on single opx and two pyroxene thermometry, e.g., Brey and Köhler, 1990). Spinel porphyroclasts show strongly variable Mg# and Cr#. Zoning of spinel seems to be unrelated to its microstructural setting and indicates disequilibrium conditions (Fig. 12), probably related to rapid cooling and incomplete re-equilibration during fast exhumation.

Our results indicate that melt migration and high-temperature deformation are juxtaposed both in time and space. Melt-rock reaction may cause grain size reduction, which in turn led to localization of deformation. Observations indicate that actively deforming peridotite mylonite might suppress brittle failure and that ascending gabbros might terminate and partially crystallize along actively deforming shear zones. Field observations also indicate that gabbros are asymmetrically distributed with respect to the shear zone. A schematic model to illustrate these speculations is shown in Fig. 13, where melt-assisted extension in the deep parts of the lithosphere might be important. Similar models are currently debated for the origin of oceanic core complexes (e.g., Escartin et al., 2003; Tucholke et al., 2001; Tucholke et al., 1998).

Granulite facies remnants in the Lanzo mantle (Stop 3)

Phengite-bearing mafic gneisses with intercalated quartz-feldspar-rich bands interpreted as leucosomes were found within the serpentinites along the Ordagna river (B11, for location see Figs. 2, 3) and are separated from the serpentinites by an intensely foliated metaophicarbonate zone about 10 m wide. The leucosomes form a discontinuous and thin network between more mafic parts. Locally, a faint banding between mafic layers and quartz-feldspar-rich leucosomes are reminiscent of migmatites. The mafic gneiss is dominated by greenschist facies assemblages, consisting of chlorite, actinolite, epidote, titanite, and albite porphyrob-
lasts. High-pressure relics are phengite (Si ~3.6), glaucophane (only present in actinolite core), garnet rims around pre-Alpine garnet-porphyroclasts, quartz, rutile and zoisite. Accessory zircon crystals are abundant in this rock. The intercalation of mafic gneisses and quartz-rich leucosomes is similar to ‘polymetamorphic paraschists’ of Pognante (1989). Fe-Mg thermometry applied to phengite-garnet rim pairs indicates peak metamorphic conditions of ~ 500°C, at pressures exceeding 1 GPa (Pelletier and Müntener, 2005). The only relics documenting a pre-Alpine history are zoned garnets (Fig. 14d) and zircon crystals. Garnets show little zoning and have small rims with decreasing Mg# and increasing grossular and spessartine contents. The cores show a large plateau of nearly constant composition (Fig. 14b), high pyrope and low grossular contents, similar to some garnets from the high-temperature granulite-facies basement rocks in the Sesia zone (II DK or polymetamorphic paraschists: Pognante, 1989). The association is equivalent to rocks known in the II DK in the Sesia Zone, interpreted as pre-Alpine lower continental crust.

CL images of the numerous zircon crystals reveal metamorphic rims surrounding detrital cores (Fig. 15). The cores yield ages from Devonian to Proterozoic, as expected for a detrital population. CL imaging indicates two different domains in the metamorphic rims. A dark inner rim surrounding the detrital core, which was dated at ~ 304 Ma, and an outer rim dated at ~ 293 Ma (Kaczmarek et al., 2005, and in preparation). Zircon REE patterns from the granulitic sample show a positive slope from Gd to Lu for the core and a near flat pattern for the external rim, suggesting equilibration with garnet (Fig. 16). Composition of garnets, trace element equilibrium between garnet and zircon (Rubatto, 2002), and the U-Pb ages strongly suggest that the protolith of the phengite gneisses were equilibrated under granulite facies conditions in post-Variscan pre-Alpine times (Kaczmarek et al., 2005).

The oceanic cover of the Lanzo peridotite (Stop 4)

Detailed mapping along the Western border of the Lanzo massif revealed a series of metamorphosed oceanic rocks covering the serpentinitized peridotites between Pugnetto and Richiaglio (Figs. 1, 3, 17). This succession includes from bottom to top (Lagabrielle et al., 1989; Pelletier and Müntener, 2005): serpentinitized peridotites, local opicarbonates, metabasites, metaquartzites, phengite-quartz-calcshists and marbles, locally containing eclogite facies basaltic pebbles,
Fig. 13 - A simplified model illustrating the potential tectonic significance of the Lanzo shear zone in the framework of the formation of ocean-continent transition zones and mantle exhumation. Migrating mafic melts might terminate along large shear zones, crystallize and get exhumed to shallower crustal levels. This could explain the observation of abundant gabbroic dikes in the ‘footwall’ of the shear zone.

Fig. 14 - (a) compositional variation of garnet from granulites and from Mesozoic metasediments from the cover of the Lanzo peridotite. Mn-rich garnets show a prograde metamorphic evolution with Mn-rich cores and progressive decrease towards the rim (Lagabrielle et al., 1989; Pelletier and Müntener, 2005). (b) Granulite garnet cores are almandine-pyrope solid solutions, with very low Mn and Ca content. The garnets from the Lanzo granulite are similar to garnet from lower crustal rocks from the Sesia zone (Pognante, 1989). (c) compositional profile of garnet from the granulites show high Mg# in the core and low Ca and Mn contents, suggesting previous high temperature equilibration. (d) BSE image showing the incomplete reequilibration of garnet during Alpine metamorphism. GM- gneiss minutii; EM- eclogitic micaschists; pA-2DK- pre-Alpine garnets from the “seconda zona dioritica-kinzigitica”; A-2DK- Alpine garnets from the “seconda zona dioritica-kinzigitica”. Modified from Pelletier and Müntener (2005).

Fig. 15 - Cathodo-luminescence (CL) images of zircons from granulite B11. Circles represent approximate diameter of SHRIMP spot analyses, stippled lines is the approximate diameter of Laser Ablation ICP-MS analysis of zircons. Most analyses provide an age between 300 and 290 Ma. Note the inherited cores in some zircons, indicating a sedimentary protolith of the granulites.
and fine-grained leucocratic-gneisses. Metaquarzites were also found in the northern area near Pugnetto and are associated with calcschists (Fig. 3). Although most of the lithological contacts are strongly overprinted by Alpine deformation and metamorphism, two important field observations strongly suggest that at least parts of the Lanzo peridotites once formed the ocean-floor of the Jurassic Liguria-Piemont Ocean: (1) Serpentinite schists (detritus?) and blocs of eclogitized mafic rocks within marbles (Fig. 17) indicate that erosion of ultramafic and mafic rocks occurred contemporaneously with pelagic sedimentation of carbonate rocks (Lagabrielle et al., 1989). (2) The local occurrence of ophicarbonate rocks, covered by metabasites, suggests that the serpentinized peridotites were (at least partially) exposed on the ocean floor.

The occurrence of gneisses and lower crust rocks within the oceanic cover of the Lanzo peridotite is more difficult to explain. Either (1) they represent stratigraphic or tectonic intercalations of acidic material within the oceanic sediments, similar to occurrences in the Western Alps (Lago Nero unit, Chenaillot ophiolite: Polino and Lemoine, 1984) the eastern Central Alps (Err-Platta nappe: Manatschal and Nievergelt, 1997), the northern Apennine (Marroni et al., 1998) and the Iberia ocean-continent transition (Manatschal et al., 2001), or (2) alternatively, these rocks are tectonically imbricated during (early) collision between the Lanzo peridotites and the Sesia zone, a contact that shows a polyphase deformation history (Spalla et al., 1983). The former hypothesis suggests a close paleogeographic connection between the continental crust and the Lanzo peridotites in the Late Jurassic, where continental sources are not too far away from the oceanic crust. This would imply that lower crustal continental and oceanic units were already juxtaposed in Mesozoic times, a typical feature of ocean-continent transition zones (Manatschal et al., 2001; Müntener and Hermann, 2001). Associations of oceanic sediments with exhumed lower crustal and mantle rocks have been described in the eastern Central Alps (Müntener et al., 2000) and the present-day Iberia margin (Manatschal et al., 2001). If this interpretation holds for the Sesia-Lanzo connection, it would have several important consequences for the origin and paleogeographic setting of the Lanzo peridotites, fostering the model of a continental to oceanic mantle transition in the Lanzo peridotite (Bodinier et al., 1991).

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Fig. 16 - REE spectra of zircons from granulites. Note that the cores show typical igneous pattern, with large positive Ce and negative Eu anomalies, and smooth increase in HREE. In contrast the inner and outer rim both show reduced or absent Eu anomalies and a less fractionated HREE pattern, indicating equilibration with garnet (e.g., Rubatto, 2002).

Fig. 17 - The Lanzo massif and its sedimentary cover along the western contact near Richiaglio, taken from Lagabrielle et al. (1989). (a) Overview map, (b) Simplified geological map of the Lanzo peridotite body, surrounding rocks and location of cross section. (c) Detailed cross sections showing the relationships between the serpentinite basement and associated metasediments and metavolcanics. (1) serpentinitized peridotites, (2) foliated serpentinites, (3) metabasites, (4) calcschists, (5) Mn-rich garnet metaquartzites, (6) phyllitic marbles, (7) marbles with blocs of eclogites, (8) finegrained leucogneiss, (9) quaternary, (10) pegmatitic gabbro dikes with the serpentinites.
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