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The Val Malenco lower crust – upper mantle complex and its field relations (Italian Alps)

by *Othmar Müntener*[1] and *Jörg Hermann*[1]

Abstract

The western Val Malenco region (northern Italy) provides an opportunity to study directly the transition from subcontinental upper mantle into the lower continental crust in an Alpine nappe. Recent field work resulted in the discovery of fresh spinel peridotites, replacive dunites and garnet clinopyroxenites in the Malenco ultramafic body and of kyanite garnet gneisses with associated pegmatites in the overlying lower crust. Both upper mantle and lower crustal rocks were intruded by the Upper Permian Fedoz gabbro demonstrating that the subcontinental mantle was welded to the lower continental crust, at least since that time. The gabbroic rocks reveal a tholeiitic magmatic evolution from more primitive gabbronorites to highly differentiated quartz diorites and pyroxene hornblende gabbros. Crosscutting relationships between the different members of the intrusion demonstrate that the Fedoz gabbro cannot be regarded as a layered intrusion. Underplating of the Fedoz gabbro and concomitant heat supply has caused granulite facies metamorphism which is well developed in the lower crustal rocks but has left scarce imprints in the peridotites. In the granulitic pelites, anatectic melts have been generated which intruded the already solidified gabbroic rocks as dikes thus demonstrating the close relationships between deep gabbro intrusions and granulite facies metamorphism.

The well preserved field relations between lower crustal rocks, subcontinental mantle and gabbroic rocks allow to reconstruct a Permian lower crust-upper mantle interface and correlate the Late Permian – Early Mesozoic evolution of the subcontinental upper mantle to that of the lower crust.

Keywords: ultramafic rock, gabbro, crust-mantle transition, underplating, granulite facies, Permian, Val Malenco, Central Alps (N. Italy).

1. Introduction

There is a growing body of evidence that subcontinental upper mantle has been exposed at the bottom of the sea floor of the Tethyan ocean. Evidences include field observations, petrologic and isotope geochemical as well as structural and tectonic investigations (e.g. LEMOINE et al., 1987; PICCARDO et al., 1990; HOOGERDUIJN STRATING et al., 1993; RAMPONE et al., 1995). Many of these studies, however, focused on the mantle evolution alone and did not provide direct evidence for a subcontinental origin of the mantle rocks as no overlying crust was found attached to these peridotites. On the other hand, a lower crust-mantle association has been described from the Ivrea zone in the Southern Alps where isolated mantle rocks are associated with lower crustal mafic and pelitic rocks (e.g. MEHNERT, 1975; VOSHAGE et al., 1990). In contrast to the ultramafic rocks in the Western and Ligurian Alps, the Ivrea zone has never been exhumed at the Tethyan ocean floor.

Recently TROMMSDORFF et al. (1993) have shown that the Malenco ultramafic rocks formed the substratum of the former Adriatic lower continental crust. This crust-mantle transition has been welded together by a gabbroic intrusion. The age of the latter has been determined by HANSMANN et al. (1995) as Upper Permian. The whole crust-mantle section underwent exhumation in pre-Alpine time leading to retrograde metamorphism and final denudation on the Tethyan ocean floor. Therefore, the Val Malenco region in northern Italy is an excellent area to study a crust-mantle section and to investigate the common ex-

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humation history of both the lower continental crust and the lithospheric mantle.

In this work we will present new results of detailed mapping and a complete description of the rock types characterizing the lower crust-mantle complex in Val Malenco. Our data demonstrate that the Malenco peridotite has a complex, old history predating the intrusion of the Fedoz gabbro and predating the Upper Permian to Jurassic history of the lower crust-mantle complex. Contact relationships of the Fedoz gabbro allow to reconstruct the crust-mantle transition. The reconstruction provides evidence for a complicated situation at the transition from lower crustal to mantle rocks. We will follow the question under what conditions the lower crust and upper mantle were welded together and why the effects of heat supply provided by the intruding magma had contrasting effects in the lower crust compared to the mantle rocks. Finally, we will compare the Val Malenco geotectonic setting to similar rock sequences in the Ivrea zone and to the Ligurian Alps in order to emphasize similarities but also major differences.

2. General geological constraints

The lower crust-mantle complex is exposed at the Penninic to Austroalpine boundary zone in Val Malenco (northern Italy, Fig. 1) and has been in-

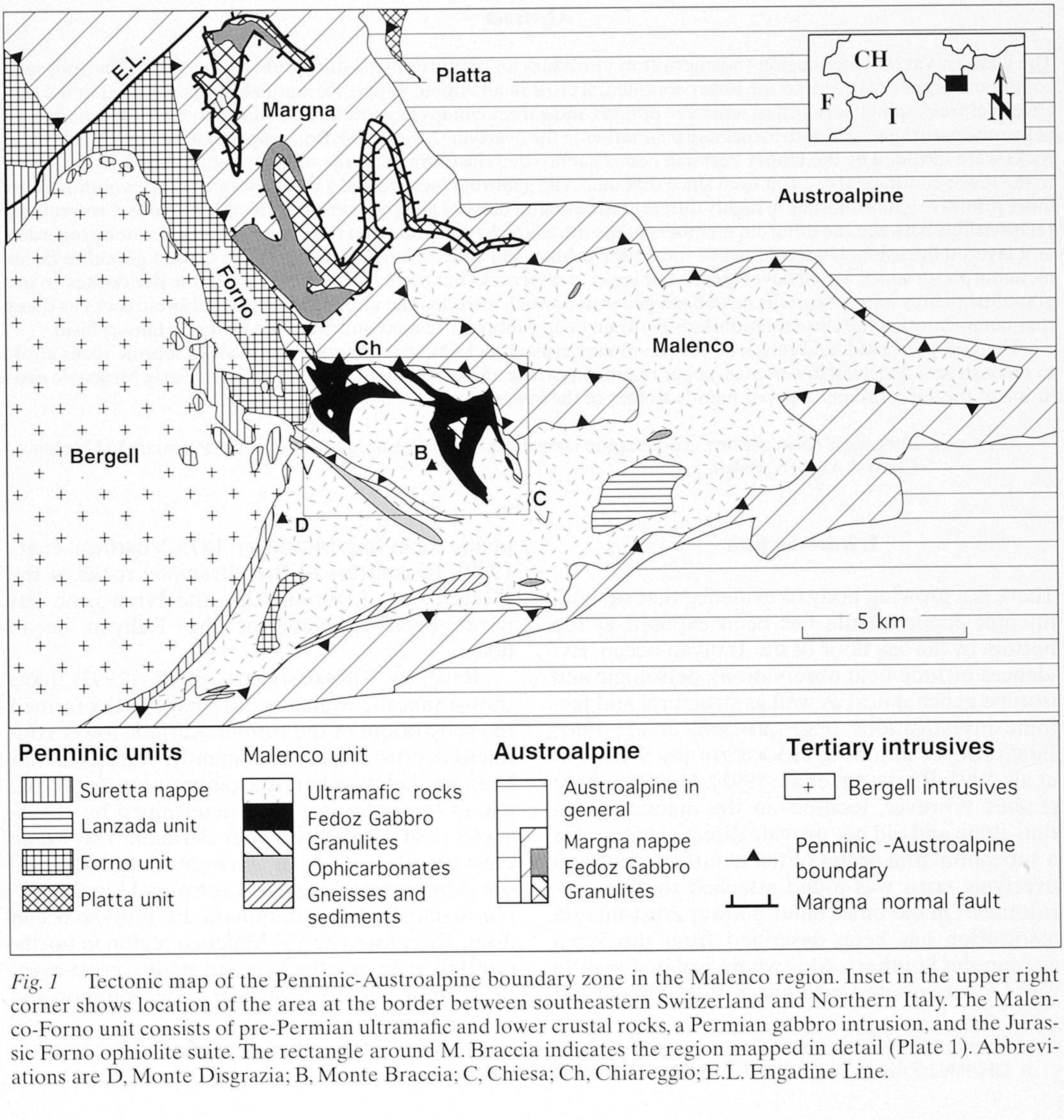


Fig. 1 Tectonic map of the Penninic-Austroalpine boundary zone in the Malenco region. Inset in the upper right corner shows location of the area at the border between southeastern Switzerland and Northern Italy. The Malenco-Forno unit consists of pre-Permian ultramafic and lower crustal rocks, a Permian gabbro intrusion, and the Jurassic Forno ophiolite suite. The rectangle around M. Braccia indicates the region mapped in detail (Plate 1). Abbreviations are D, Monte Disgrazia; B, Monte Braccia; C, Chiesa; Ch, Chiareggio; E.L. Engadine Line.

tegrated in the Alpine nappe pile during the Late Cretaceous. This Alpine nappe pile consists from top to bottom of (1) the lower Austroalpine Bernina, Sella and Margna nappes, (2) the south Penninic Malenco and Forno units, and (3) the middle Penninic Suretta nappe (SPILLMANN, 1993). Towards the west the nappe pile is crosscut by the Oligocene Bergell intrusives (TROMMSDORFF and EVANS, 1972).

The lower crustal basement and gabbroic rocks of the Monte Braccia – Lago Pirola area (Fig. 2) were mentioned by CORNELIUS as early as 1925 and have been considered as part of the Margna nappe (STAUB, 1946). In the late seventies this region has been mapped by several workers (SCHUMACHER 1975; HONEGGER, 1977; BANGERTER, 1978; GAUTSCHI, 1980). They recognized relics of a pre-Alpine upper amphibolite to granulite facies metamorphism and attributed these rocks to the Fedoz Series of the lower Austroalpine Margna nappe where similar rocks have been described (STAUB, 1917; 1946; GUNTLI and LINIGER,

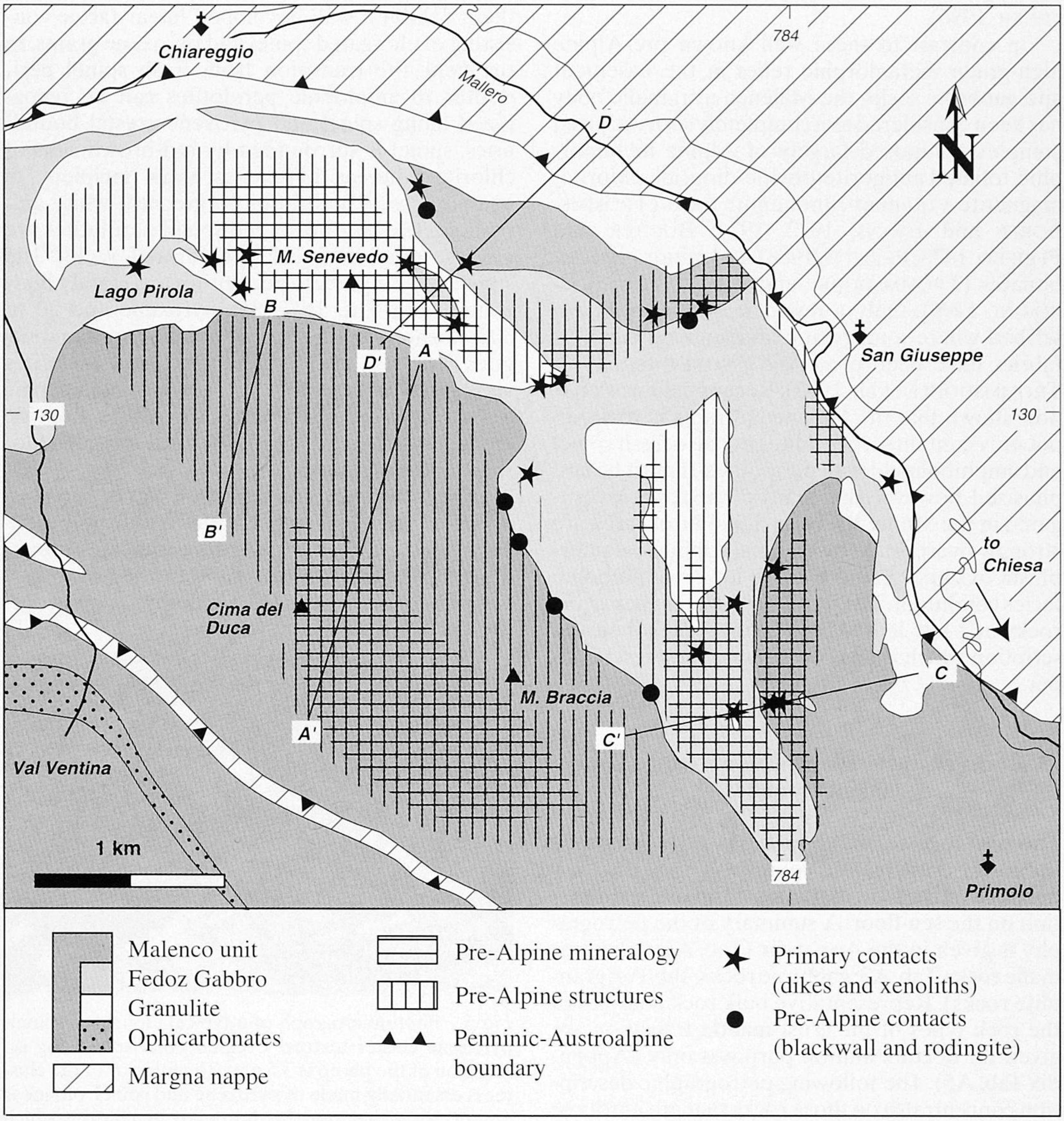


Fig. 2 Simplified geological map of western Val Malenco showing the distribution of primary contacts (gabbro dikes and xenoliths) between Fedoz gabbro, granulites and ultramafic rocks. A–A' and B-B' indicate traces of profiles displayed in figure 8, C–C' and D–D' indicate traces of profiles displayed in figure 9.

1989; SPILLMANN, 1993). Recently, intrusive contacts between Fedoz gabbro and both lower crustal and ultramafic rocks have been found (Fig. 2). In addition, structural investigations in the area of Monte Braccia – Lago Pirola indicate that the thrust contact between the Alpine Malenco- and Margna nappes does not follow the lithological contact of ultramafic to pelitic and mafic granulitic rocks (HERMANN and MÜNTENER, 1996). Therefore the pelitic granulites and the gabbros of the Monte Braccia – Lago Pirola area are part of the Alpine Malenco unit (HERMANN and MÜNTENER, 1996).

In contrast to these well known pre-Alpine high-grade metamorphic relics in the basement and gabbroic rocks, the Malenco ultramafic body has been considered as a completely serpentinized complex composed largely of Alpine metamorphic, foliated antigorite-olivine-diopside-chlorite-magnetite ± titanian-clinohumite rocks (TROMMSDORFF and EVANS, 1972, 1974; BUCHER and PFEIFER, 1973; PERETTI, 1988) and minor ophicarbonates (TROMMSDORFF and EVANS, 1977; POZZORINI, 1996). Only a few places have been described where a magmatic layering and cumulus fabrics have been preserved (HONEGGER, 1977; TROMMSDORFF et al., 1993). Recent field work has now shown that the Malenco ultramafic rocks do not only contain serpentinites but also fresh spinel and amphibole-chlorite peridotites. It must be emphasized, however, that many of the rocks investigated in the Monte Braccia – Lago Pirola area are strongly overprinted by regional Alpine metamorphism of upper greenschist to lower amphibolite facies conditions. The preservation of higher grade rocks in a few lenses (Fig. 2) motivates their description which is one objective of the present paper.

3. Rocks characterizing the lower crust – upper mantle complex

This part focuses on the rock types which formed the lower crust-mantle complex before they underwent retrograde metamorphism and exhumation on the sea-floor. A summary of the petrography is given in the Appendix (Tab. A1, A2: ultramafic rocks, Tab. A3: gabbroic rocks, Tab. A4: granulite rocks). Representative bulk rock analyses of the rock types of the crust-mantle transition are given for documentation purposes only (Appendix Tab. A5). The following petrographic description concentrates on those rocks that are hardly or not overprinted by Alpine metamorphic assemblages and is intended to emphasize important observations.

3.1. PERIDOTITES AND RELATED ROCKS

Spinel peridotites and amphibole peridotites: The Monte Braccia – Lago Pirola area (Fig. 2) exposes a large number of relatively coherent bodies of spinel and amphibole peridotites with only minor or even absent Alpine metamorphic minerals. Spinel peridotites are preserved in about 100 m wide to 300 m long lenses. They form blocky red-brown outcrops with rough weathering surfaces. Some of the spinel peridotites are weakly deformed preserving massive textures, but most of them exhibit a well developed linear fabric consisting of elongated spinel and pyroxene grains. In the field, the transition from fresh spinel peridotites to amphibole peridotites can be recognized along spinel and pyroxene crystal boundaries: spinel is surrounded by red-brown rims of chlorite whereas pyroxenes show incipient to complete recrystallization to greenish-white amphibole. The best preserved spinel peridotites are always found in weakly deformed rocks. The spinel and amphibole peridotites are mainly lherzolites with 5 to 16% clinopyroxene and 20 to 30% orthopyroxene. A few samples are harzburgites with less than 5% clinopyroxene. Peridotites completely overprinted by Alpine metamorphic assemblages are characterized by white diopside embedded in a dark green antigorite-olivine-chlorite-magnetite matrix.

The most interesting microstructure is a clustering of holly leaf spinel, clino- and orthopyroxene (Fig. 3). This cluster texture indicates breakdown products of former garnet owing to the reaction olivine + garnet → clinopyroxene + or-

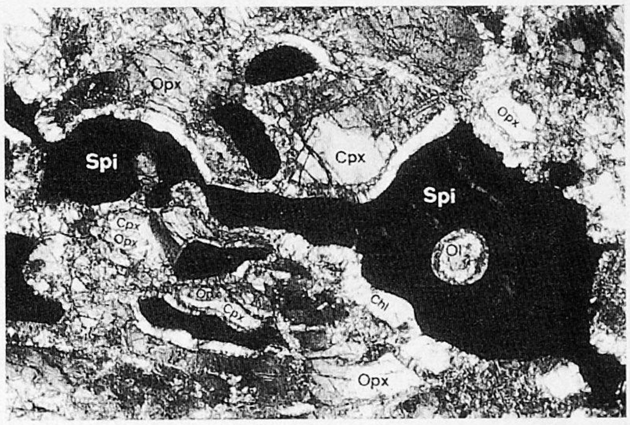


Fig. 3 Photomicrograph of a typical elongated spinel-pyroxene cluster texture. Crossed polarizers. Long dimension of the photo is 3.5 mm. The interior of the cluster is essentially made of pyroxene and spinel, olivine is absent. Note that spinel is bordered by chlorite which grew during retrograde amphibolite-facies metamorphism. Abbreviations are Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene; Spi, spinel; Chl, chlorite.

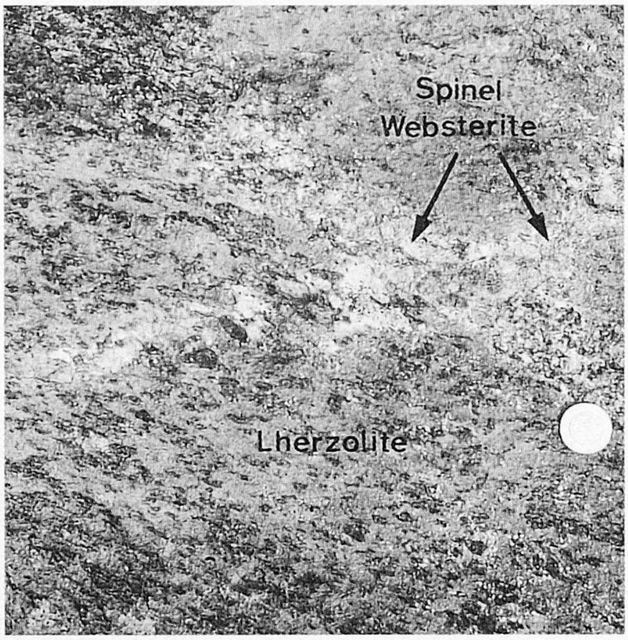


Fig. 4 Crosscutting relationships between spinel websterites in weakly deformed peridotite. Note the discordance of the weakly developed foliation to both spinel websterite dikes (Swiss coordinates 782'300 / 127'500).

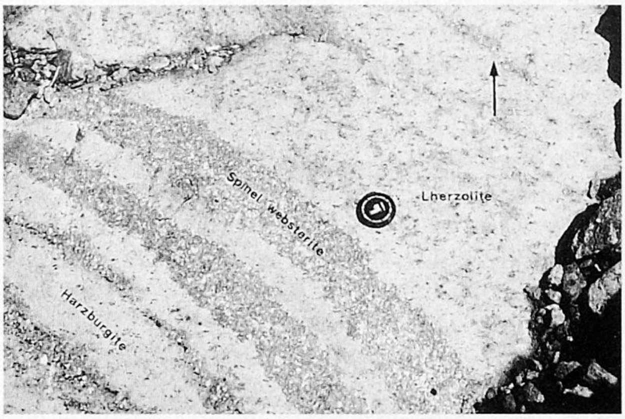


Fig. 5 Field aspect of several parallel spinel websterite layers within lherzolite and harzburgite. Diameter of lens cover 5 cm. The margins of thick dikes are essentially clinopyroxene free, giving rise to an apparent layered association of spinel websterites and harzburgites. In the upper right (indicated by arrow), thin spinel websterite layers are tectonically disrupted forming aligned boudins (Swiss coordinates 781'450 / 130'170).

thopyroxene + spinel. This mineral association is often interpreted to be the product of subsolidus reequilibration, based on mass balance of either major (SMITH, 1977) or trace element compositions (VANUCCI et al., 1993). In fact, mass balance calculations based on image analysis and electron microprobe data (major elements) lead to a calculated pyrope content for the inferred garnet of 60 to 65%, in agreement with pyrope contents from garnet peridotites in the Alps (e.g. EVANS and TROMMSDORFF, 1978). Thus, the clinopyroxene-orthopyroxene-spinel clusters probably record a decompression evolution from garnet lherzolite to spinel lherzolite conditions, similar to that shown by mantle peridotites in the Ulten zone of the Eastern Alps (GODARD et al., 1996).

Spinel websterites: The peridotites contain numerous spinel websterites which in most cases are parallel to each other. Only in a few weakly deformed peridotite bodies tensile bridges and/or crosscutting relationships among spinel websterites may be preserved (Fig. 4). In places, the spinel websterites volumetrically almost equal the lherzolites giving rise to the typical banded sequence which is widespread in the whole Malenco ultramafic body. The spinel websterites vary strongly in thickness from dikes of up to 50 cm to dikelets less than 5 cm across. In deformed parts of the peridotites, the spinel websterites are tectonically disrupted and reduced to aggregates of clinopyroxene and spinel aligned in the foliation. Spinel is always rimmed by chlorite, and orthopyroxene has been replaced pseudomorphically by greenish-white amphibole. Whether or not olivine was a primary phase is difficult to establish. In thick layers there is no olivine present, in thin and tectonically stretched layers olivine is always present but may be incorporated into the pyroxenites from the surrounding peridotite matrix. Websterites completely overprinted by Alpine metamorphic assemblages are characterized by abundant white diopside (pseudomorphic after primary clinopyroxene) in a chlorite ± serpentine matrix.

Towards the contact to the spinel websterites, the peridotites grade into an clinopyroxene-free spinel-poor harzburgite or even dunite (Fig. 5). Between narrowly spaced spinel websterites only harzburgites occur giving rise to an apparent "layered" sequence of spinel websterite and harzburgite/dunite. Between wider spaced spinel websterites lherzolites have been preserved. Therefore, the occurrence of lherzolites between spinel websterites is clearly a function of the spacing of the dikes indicating that the association harzburgite-websterite is not a layering in the sense of crystal settling in a magma chamber but rather a reaction process between spinel websterites and surrounding lherzolites.

Corundum-bearing garnet clinopyroxenites: These dark pyroxenites are widespread in the Monte Braccia – Lago Pirola region. They can be followed over several hundred meters in the field and occur as dikes ranging in thickness from 50 cm to more than 2 m. Usually, they are parallel to the spinel websterites indicating that they followed previous anisotropies given by the older spinel websterite dikes. However, in a few outcrops they branch and, locally, are discordant to the spinel websterite banding at very small angles. Even in regions where the surrounding peridotites are deformed and spinel websterites are boudinaged, the garnet pyroxenites are mostly continuous. They are distinct from spinel websterites by their much coarser grain size, the (macroscopic) lack of spinel and particularly their bulk rock chemistry. Strongly altered dikes are made up almost exclusively of amphibole exhibiting pseudomorphic textures after clinopyroxene (and are therefore mapped as amphibolites, see plate 1). Some of the dikes show late stage veins composed of rodingitic assemblages.

The microstructure of the garnet pyroxenites consists of porphyroclastic clinopyroxene and rare garnet. In one dike, corundum has been found surrounded by garnet. Cr–Al spinel smaller than 5 μm has been found as inclusions in corundum and its alteration products. The clinopyroxene porphyroclasts are deformed and exhibit small orthopyroxene exsolution lamellae and occasionally blebs of garnet. They are surrounded by neoblasts of exsolution-free clinopyroxene, Ti-rich pargasite, and rare garnet. Fine-grained pargasite ± chlorite ± zoisite forms the matrix. The association of corundum and garnet is partly altered to zoisite and rare preiswerkite.

Harzburgites and dunite (1): These rocks are easy to recognize in the field because of a distinct red-brown weathering color and much finer grain size on weathered surfaces than peridotites. Recent mapping revealed that these dunites can be followed over a distance of approximately 6 km (plate 1). Many of these harzburgites and dunites (1) are subparallel to the spinel websterite layers (REBER, 1995). On a large scale however (near Monte Braccia, plate 1), dunites form anastomozing zones enclosing 100 to 300 m long and up to 100 m wide bodies of peridotite and spinel websterite. South of Lago Pirola, the dunites show nearly vertical contacts to the subhorizontal spinel websterite dikes and are clearly discordant to the latter (see profile b in Fig. 9). In some outcrops field evidence for replacement of peridotite and spinel websterite by dunite can be found. These features include trains of Cr-spinel in dunite which are in continuation with spinel websterites in the surrounding peridotites (Fig. 6). As soon as the websterite grades into dunite, the amount and the grain size of spinel increases and clinopyroxene almost completely disappears. In some rare cases, the spinel websterite banding seems almost continuous on both sides of the dunite indicating no displacement during formation of the dunites.

It is striking that almost all of the freshest rocks preserved are spinel-bearing dunites, and despite careful searches no fresh harzburgite (with orthopyroxene preserved) was found. This might be due to the fact that harzburgites have a bulk composition much closer to serpentine minerals than dunites and consequently, have been more affected by serpentinization.

Dunite (2) and associated clinopyroxenites: These rocks are treated as a single group because this dunite (2) is markedly different from the dunite (1) and is always associated with clinopyroxenites. The dunites are massive red-brown-weathering rocks and occur only in the north-eastern part of the mapped area between Alpe Braccia and Alpe Girosso inferiore as well as north of Alpe Lagazzuolo (plate 1). The south-western contact is bordered by the Fedoz gabbro and contains several dikes of the latter (see also Fig. 4 of TROMMSDORFF et al., 1993). The north-eastern contact is difficult to locate because of poor and steep exposure and a gradual transition to clinopyroxene-bearing serpentinites. It could therefore not be evaluated whether the contact to the serpentinites was originally concordant or discordant. Aligned spinels in both dunite (2) and serpentinized lherzolites are

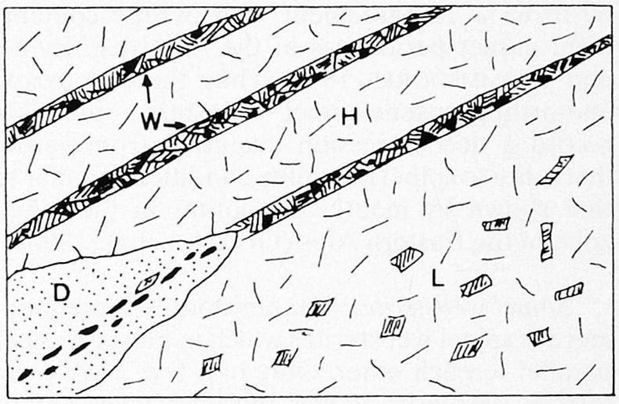


Fig. 6 Field sketch of spinel websterites and peridotites. Small dunite is replacing spinel websterites. Aligned spinel trains in dunite formed as a consequence of dissolution of Cr-clinopyroxene are in continuation with the surrounding spinel websterite indicating replacement of lherzolite/harzburgite by dunite. Note that the depleted zones between the spinel websterites are unrelated to the formation of dunite. Long dimension of the sketch is approximately 50 cm. Abbreviations are L, lherzolite; H, harzburgite; W, spinel websterite, D, dunite (Swiss coordinates: 781'650 / 130'160).

roughly parallel to each other indicating that they shared a common history.

Most of the dunites (2) are composed of more than 90% olivine and usually less than 5% Cr-rich spinel. Locally, spinel is more abundant (up to 10 vol.%) and forms elongated pods or nodules in an olivine matrix. The dunites always contain significant amounts of interstitial pentlandite and pyrrhotite. Even the freshest samples display small chlorite coronae around spinel. Near the contact to the Fedoz gabbro, the dunites form a banded sequence with clinopyroxenites which range considerably in thickness (< 5 cm to > 2 m). In general, the abundance of clinopyroxenite dikes decreases with increasing distance from the contact to the Fedoz gabbro. The clinopyroxenites are usually discordant to the banding in the dunites which is defined by aligned spinel trains. The clinopyroxenites are composed of more than 80% clinopyroxenes. They may contain significant amounts of spinel although the thickest dikes are almost devoid of any phase other than clinopyroxene. Olivine occurs only as a minor phase in small clinopyroxenites, but was not observed in the thick dikes. Pentlandite is always present.

Phlogopite hornblendite: Small dikes of phlogopite hornblendite are scattered throughout the ultramafic rocks of the mapped area. Their thickness ranges from a few mm to 20 cm. They crosscut folded associations of layered spinel peridotites and garnet pyroxenites. In many places the hornblendites branch and thus show both concordant and discordant contacts to the spinel websterite layering (Fig. 7). In other localities they follow older garnet clinopyroxenite dikes. The contact to the peridotites is always marked by a several cm thick rim of amphibole or chlorite blackwall. The phlogopite hornblendites are composed of various amounts of black Ti-rich pargasite, dark brown phlogopite and occasionally allanite. Many of the small dikelets are completely altered to chlorite and/or tremolitic amphibole which make reconnaissance of the small dikelets in the field somewhat difficult. In fact, many of the samples are retrogressed into an assemblage of pargasite, diopside, chlorite and ilmenite.

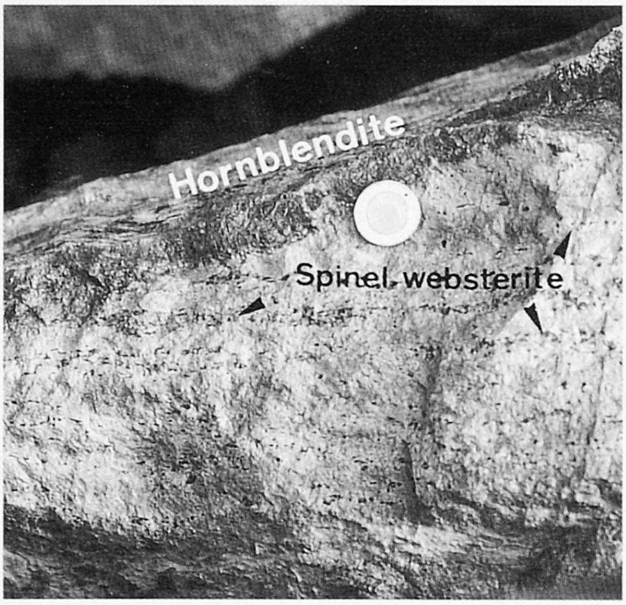


Fig. 7 Field aspect of phlogopite hornblendite showing a clear discordance to the highly elongated and boudinaged spinel websterites. Diameter of coin 2 cm (Swiss coordinates: 781'550 / 129'360).

An important feature has been preserved in small dikelets within fresh spinel peridotites. Ti-rich pargasite and phlogopite are clearly overgrowing and/or replacing granoblastic clinopyroxene and orthopyroxene thus indicating that the formation of these rocks post-dates granulite facies metamorphism in the peridotites.

3.2. GABBROS AND RELATED ROCKS

In the north-eastern part of the Monte Braccia area, the peridotites and the granulitic rocks are welded together by a gabbro intrusion[1]. Magmatic fabrics are only locally preserved, and most of the gabbroic rocks are characterized by granoblastic textures, resulting from post-intrusive deformation under granulite facies conditions GAUTSCHI, 1980). Because of the intense recrystallization, the gabbroic rocks in fact are mafic granulites. Nevertheless, in the following description we use igneous rock names to emphasize their plutonic origin.

Coarse-grained gabbronorite (Mg gabbro): This most widespread gabbro type appears as a dark grey granular rock consisting of black pyroxenes and dark grey plagioclase. Clusters of pyroxene form its characteristic flaser texture. Different types of flasers have been recognized:

[1] The gabbro of the Monte Braccia – Lago Pirola area was described as Fedoz gabbro by STAUB (1946) and GAUTSCHI (1980). Recent structural investigations, however, have shown that the gabbroic rocks described in this work belong tectonically to the Alpine Malenco nappe (HERMANN and MÜNTENER, 1996). Therefore it may be convenient to apply a new name (Braccia gabbro) to the gabbro mass which belongs to the Malenco unit. To prevent confusion among the different articles appearing in this volume of SMPM, the original name Fedoz gabbro is applied to the gabbros occurring in the Malenco nappe.

Plate 1 Parts of the map have been compiled from SCHUHMACHER (1975), HONEGGER (1977), BANGERTER (1979), RIKLIN (1978), MONTRASIO and TROMMSDORFF (1983), BORSIEN (1995), REBER (1995), ULRICH (1995), and POZZORINI (1996).

Peridotites

Serpentinites and contact metamorphic talc-olivine fels

Dunite/Harzburgite (partly serpentinized)

Amphibolites, partly with relics of garnet and clinopyroxene (Garnet clinopyroxenites)

Ophicarbonates

Mg-gabbro:
- Gabbronorite
- Albite-Amphibole schists and gneisses

Fe-gabbro:
- (Olivine)-ilmenite gabbronorite
- Amphibolites, partly garnet-bearing

Epidote-albite amphibolites (Forno metabasalts)

(Biotite-kyanite)-garnet gneiss

Micaschists

Olivine-clinopyroxene-phlogopite calcite marbles

Garnet-epidote-diopside fels (calcsilicates)

Quartz-feldspar pegmatites and aplites

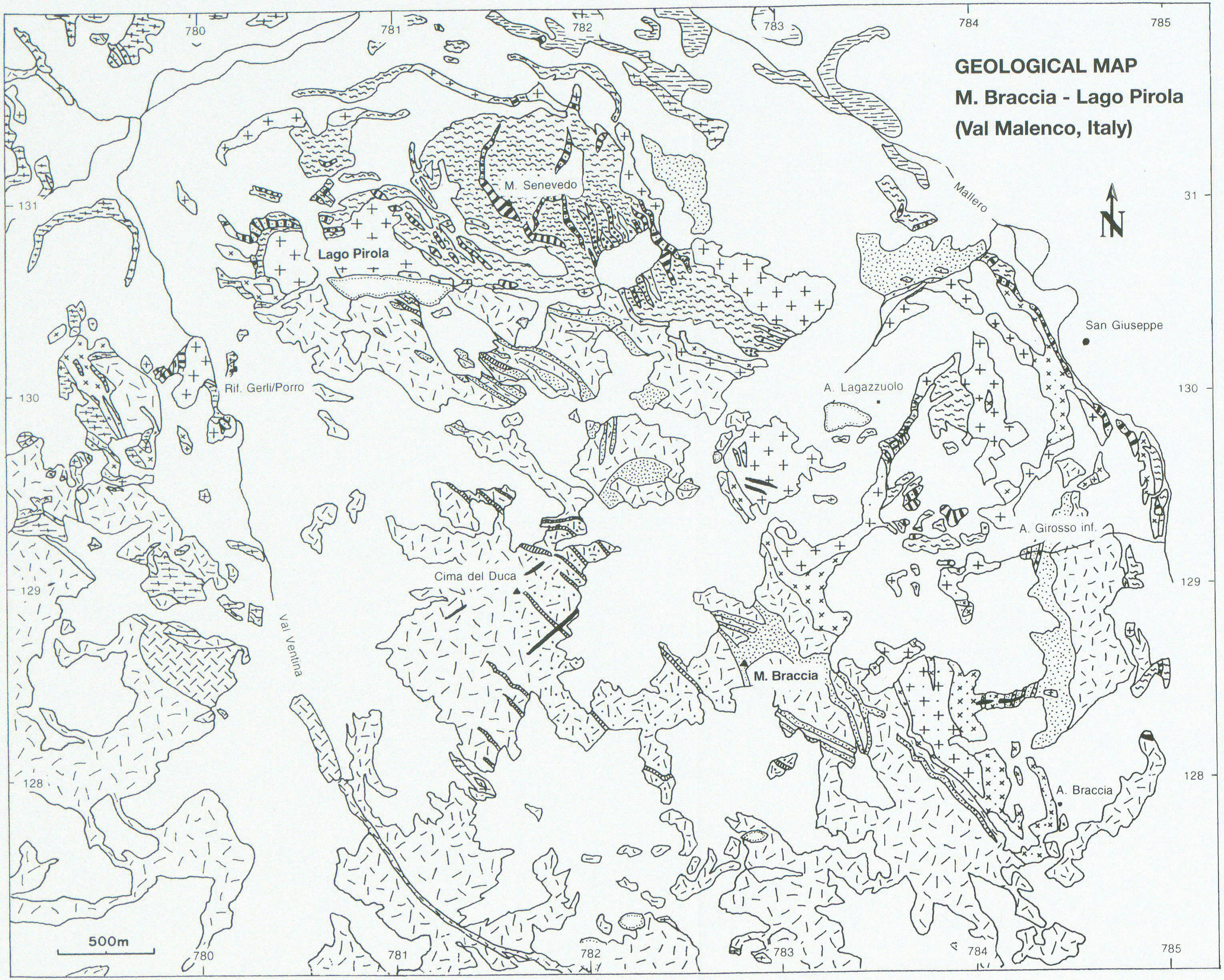
Chlorite-muscovite quartz feldspar gneiss (Orthogneiss)

(Garnet)-biotite-muscovite-quartz-feldspar schists (Paragneiss)

Andesitic-basaltic dykes

O. MÜNTENER and J. HERMANN

Plate 1 Geological map of the M. Braccia – Lago Pirola area (1:25 '000).



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(i) The most common and widespread flasers are of tectonic origin and are related to the subsolidus deformation under granulite facies conditions (HERMANN and MÜNTENER, 1996). Some of these stretched flasers can reach 1 m in length and may represent disrupted pyroxenitic cumulates. In most cases, the flaser-textured pyroxenes are evenly distributed throughout the Mg-gabbro, however, some parts of the Mg-gabbro are strongly enriched in plagioclase giving rise to anorthositic layers.

(ii) A few boudins have been recognized exhibiting weakly oriented large pyroxenes of irregular shape which are oblique to the granulitic foliation. The preferred orientation of these pyroxenes most probably represent magmatic flow textures. Rarely, almost undeformed Mg-gabbros preserved magmatic textures indicating that clinopyroxene was the liquidus phase. Rare (mantle?) xenoliths consisting of rounded brown-weathering olivine bordered by orthopyroxene have been found.

The transition from fresh gabbronorite to subsequent amphibolites may be seen on pyroxenes overgrown by black amphiboles. Alpine overprint of Mg-gabbros is documented by white-green rocks in which plagioclase and pyroxenes have been replaced by clinozoisite + albite and chlorite + hornblende, respectively. This type of metagabbro is common and occurs also in the Margna nappe where it has been described originally by STAUB (1917) as Fedoz gabbro. We apply this name also for the not overprinted gabbros in the Monte Braccia area.

Coarse- to fine-grained (olivine) amphibole ilmenite gabbronorite (Fe-gabbro): This type covers about 30% of the mapped area. In some places, the Fe-gabbro cuts across the Mg-gabbro indicating that it post-dates the emplacement of the latter (see also ULRICH and BORSIEN, 1996). It is usually darker and finer-grained than the Mg-gabbros and contains significant amounts of ilmenite and apatite. This type is therefore mineralogically more differentiated than the Mg-gabbro. Clusters of pyroxenes form the characteristic flaser texture. Although most of the Fe-gabbro is overprinted by granulite facies metamorphism, porphyroclasts of clinopyroxenes are widespread. Sometimes clinopyroxene-rich cumulates have been found. The textures reflect crystallization of clinopyroxene before plagioclase and orthopyroxene as phenocrysts followed by olivine, ilmenite, green spinel and Ti-rich pargasite as interstitial phases. Overprinted Fe-gabbros appear as black amphibolites containing albite, clinozoisite, chlorite, hornblende, rutile, titanite and garnet replacing the primary assemblage.

Fine-grained quartz diorite: The quartz diorites occur as rare dikes crosscutting the Fe-gabbro (see Fig. 6 in ULRICH and BORSIEN, 1996). They are characterized by elongated grey plagioclase, black orthopyroxene and blue quartz. The blue color most probably originates from fine inclusions of rutile needles. Compared to the previous lithotypes, the quartz diorite is extremely rare. Overprinted quartz diorites are characterized by chlorite pseudomorphs after orthopyroxene and clinozoisite-albite aggregates replacing primary plagioclase.

Medium-grained ilmenite pyroxene amphibole gabbro: This rock type is restricted to a few dikes preferentially occurring in the pelitic granulite rocks. It is made up of black poikilitic hornblende, grey plagioclase and variable amounts of dark

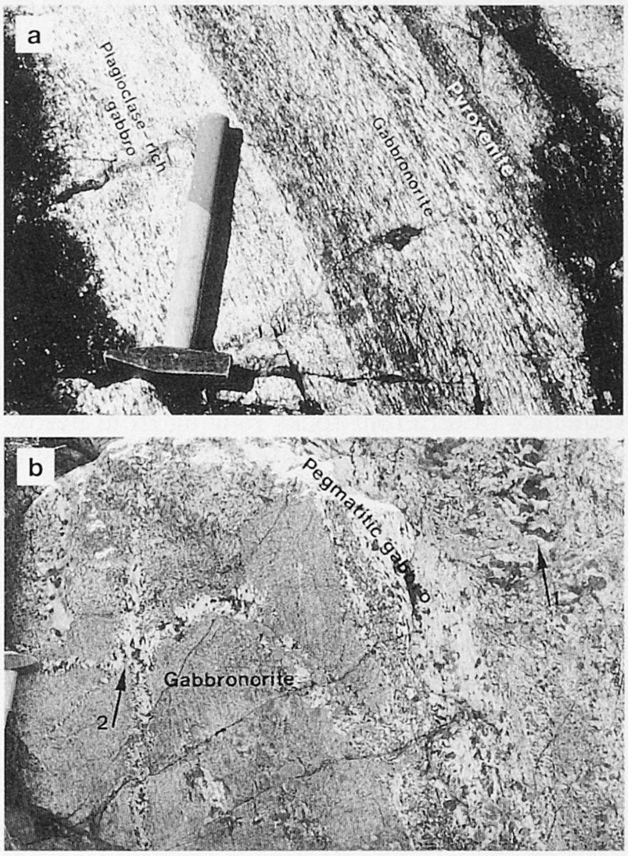

Fig. 8 Outcrop relationships of the Fedoz gabbro. (a) Small scale variation of different members of the gabbro ranging from pyroxenites to coarse- and fine-grained gabbronorite and to plagioclase-rich gabbros. Hammer is 20 cm long. (b) Intrusive relationships between different members of the gabbro. On the right side of the photograph (indicated by arrow 1), a coarse-grained magmatic foliation has been cut by branching, fine-grained gabbroic dikes. On the left, fine-grained gabbronorite has been cut irregularly by pegmatitic gabbroic segregations (arrow 2) (Swiss coordinates: 783'980 / 128'870).

green clinopyroxene. Ilmenite and apatite are distinctly more abundant than in the Fe-gabbro indicating an even higher grade of differentiation (ULRICH and BORSIEN, 1996). In one dike, significant amounts of zircon have been found. These zircons have been dated by HANSMANN et al. (1995). Overprinted pyroxene amphibole gabbros appear as black amphibolites and are difficult to distinguish from overprinted Fe-gabbros.

Mg-gabbro and Fe-gabbro form more than 99% of the gabbro complex. Detailed mapping (plate 1) does not reveal a systematic distribution of the two rock types over the entire area. Field relations demonstrate a magmatic evolution from Mg- to Fe-gabbro to highly differentiated quartz diorite and ilmenite pyroxene hornblende gabbro. Bulk chemical analyses point to a typical tholeiitic differentiation trend for the transition from Mg- to Fe-gabbro (GAUTSCHI, 1980). The highly differentiated rocks display a separation into an SiO_2-rich and an FeO-, TiO_2-, P_2O_5-rich part, and can be interpreted as immiscibility of the residual melt (e.g. ULRICH and BORSIEN, 1996). Due to macroscopic similarities of the different rocks and a granulitic overprint obliterating much (but not everything) of the magmatic history, the transition from one rock type to the other is not always easy to establish. However, there are a few outcrops still preserving primary magmatic relationships. This is particularly well documented by an outcrop south-east of Alpe Girosso inferiore (see plate 1 for locality): Here, field relations demonstrate that coarse- and fine-grained dikes form a sequence of different rocks ranging from pyroxenitic layers to almost pyroxene-free anorthositic gabbros (Fig. 8a). In the same outcrop, crosscutting relationships between layers indicate that they probably originated as dikes. Magmatic flow or synmagmatic deformation was important during intrusion of the Fedoz gabbro. This is demonstrated by Figure 8b, where a probably magmatic coarse-grained flow fabric has been cut by an undeformed pegmatitic gabbro segregation and later by a fine-grained massive variety. This fine-grained gabbro has been cut into schollen and lenses by a late pegmatitic gabbro. All these phenomena emphasize that the Fedoz gabbro represents a complex magmatic body with multiple intrusion of dikes rather than resulting from crystallization in a large magma chamber as a layered intrusion.

3.3. GRANULITIC ROCKS

The granulitic rocks are mainly exposed around Monte Senevedo, in two smaller lenses south of Alpe Girosso and along the Mallero river south of San Giuseppe (Fig. 2). These rocks consist in large parts of banded pelitic garnet gneisses/felses with intercalations of calcsilicate rocks and olivine- and spinel-bearing marbles. The widespread granoblastic fabric is the product of (almost complete) recrystallization under granulite facies conditions.

Kyanite garnet gneiss: This rock type is a coarse-grained massive to gneissic rock consisting of garnet porphyroblasts surrounded by a matrix of plagioclase, kyanite, biotite, ilmenite and blue quartz, but no kalifeldspar. The blue color most probably originates from fine inclusions of rutile needles. The modal compositions range from garnet-dominated gneisses to leucocratic quartz-plagioclase-rich rocks. In many places the gneisses occur as banded migmatites with alternating felsic and garnet-rich parts. The felsic parts are often pooled along small shearzones which are discordant to the foliation. There is a continuous transition from small leucocratic pods to thicker leucosomes or pegmatites (see below). Many of these kyanite garnet gneisses are strongly overprinted by pre-Alpine retrograde amphibolite facies parageneses. Staurolite and chloritoid developed at the expense of kyanite and garnet. Chloritoid, chlorite, clinozoisite and paragonite replaced garnet, kyanite and plagioclase. Kyanite garnet gneisses overprinted by the Alpine metamorphism are schists consisting of white mica, albite, garnet and quartz and form a major constituent of the Fedoz Series of the Margna nappe (SPILLMANN, 1993).

Pegmatites and aplites: Leucocratic pegmatites and aplites are common throughout the mapped area. They vary significantly in thickness from a few cm to more than 10 m, reaching mappable size in the vicinity of large gabbroic dikes (plate 1, Fig. 10b). There, they are more abundant and form a network of dikes. In places they intrude already solidified gabbroic dikes (see below). Pegmatites and aplites are made up of albite-rich plagioclase (up to 50%) and subordinate perthitic alkalifeldspar (0–40%) in a fine-grained quartz matrix. Occasionally, poikilitic garnet and small biotite flakes occur. These pegmatites and aplites most probably represent partial melting products of an initially homogeneous kyanite garnet gneiss (ULRICH, 1995).

Calcsilicates: Calcsilicate rocks are very coarse-grained greenish rocks occurring usually as boudins aligned in the banded gneisses. They consist mainly of diopside, clinozoisite, calcite and quartz with minor amounts of garnet, plagioclase and alkalifeldspar. In some calcsilicates wollastonite occurs together with garnet, quartz, calcite and diopside (Schumacher, 1975). Alteration of the primary assemblages produced green tremolite-albite rocks that are hardly distinguishable from fine-grained Mg-gabbros overprinted by Alpine metamorphism.

Olivine-clinopyroxene-phlogopite marbles: Several different varieties of calcite marbles have been summarized as olivine-clinopyroxene-phlogopite marbles. They are usually coarse-grained and mainly cropping out south-west of Alpe Girosso inferiore (plate 1). Some marbles are entirely made up of olivine, spinel, humite group minerals and calcite (Wenk, 1963), whereas others contain clinopyroxene, phlogopite and minor amounts of calcite. Olivine partly occurs as up to 2 cm thick knobs embedded in a brecciated phlogopite-calcite-clinopyroxene matrix. In places either Ti-rich clinopyroxene or phlogopite predominates and forms almost monomineralic layers and boudins with minor amounts of calcite.

4. Structural history of the Malenco lower crust-mantle complex

4.1. PRE-GABBROIC HISTORY OF THE PERIDOTITES AND THE LOWER CRUST

The intrusion of the Fedoz gabbro allows to distinguish the petrogenetic and structural events in the Malenco lower crust-mantle complex in terms of a pre-, syn- and post-gabbroic history (Tab. 1). The post-intrusive evolution is characterized by the development of several deformation stages which are parallel in all three rock types (Hermann and Müntener, 1996). With the exception of migmatitic phenomena and rare relics of isoclinal folds, the structural and metamorphic history of the pelitic rocks prior to the penetrative deformation under granulite facies conditions is largely unknown. Therefore, it was impossible to get any constraints about the lower crust-mantle interface prior to the intrusion of the Fedoz gabbro.

In contrast, the ultramafic rocks show several events predating the intrusion of the Fedoz gab-

	Ultramafic rocks	Fedoz gabbro	Lower crustal rocks
pre-intrusive	Layered mantle		
	Garnet-peridotite facies (clusters of cpx, opx, spinel)		
	Garnet clinopyroxenite		not preserved
	Spinel peridotite facies		
syn-intrusive	Dunite		
	Gabbro dikes	Intrusion (270 my)	Gabbro dikes Melting (formation of pegmatites/aplites)
post-intrusive	Deformation and recrystallization under granulite facies conditions		
	Phlogopite-hornblendite dikes		
	Deformation and retrograde metamorphism (Amphibolite-greenschist facies)		
	Exhumation of lower crust – upper mantle complex on the Tethyan ocean floor		

Tab. 1 Tentative scheme of successive stages in the Val Malenco lower crust – upper mantle complex. Further explanations of the relative sequence of events are given in the text.

bro. A tentative succession of these events is presented in Table 1 and field relations have been summarized in two profiles (Fig. 9). The main mass of the peridotite is made up of fertile (i.e. clinopyroxene-rich) and depleted (clinopyroxene-poor) lherzolite containing numerous spinel websterite layers giving rise to the widespread banded appearance of the Malenco ultramafic body. This layered mantle rocks have been overprinted by a penetrative deformation leading to boudinage of the spinel websterites and the formation of a tectonite fabric (Fig. 9b). A few lenses were less deformed and are completely embedded in the tectonites (Cima del Duca, Fig. 9a). The whole complex has possibly equilibrated under garnet peridotite facies conditions as indicated by cluster textures of orthopyroxene, clinopyroxene and spinel after garnet in the peridotite (Fig. 3). It must be emphasized that the relationships between the garnet clinopyroxenites and the equilibration in the garnet peridotite stability field is ambiguous: (i) Mafic melts intruded the peridotite before garnet peridotite facies conditions occurred and were then transformed to corundum bearing garnet clinopyroxenites. (ii) Mafic melts post-date garnet peridotite facies conditions and intruded as true garnet pyroxenites with garnet and clinopyroxene as primary phases. However, intrusion of these mafic melts seems to post-date the penetrative deformation as they are almost undeformed and not boudinaged in the vicinity of highly deformed spinel websterites. It is somewhat puzzling that the widespread spinel websterites did not preserve any relics of garnet. Field observations, however, have shown that the spinel websterite dikes are less wide than the corundum-bearing garnet clinopyroxenites and therefore most probably have been completely overprinted by the following equilibration under spinel peridotite facies.

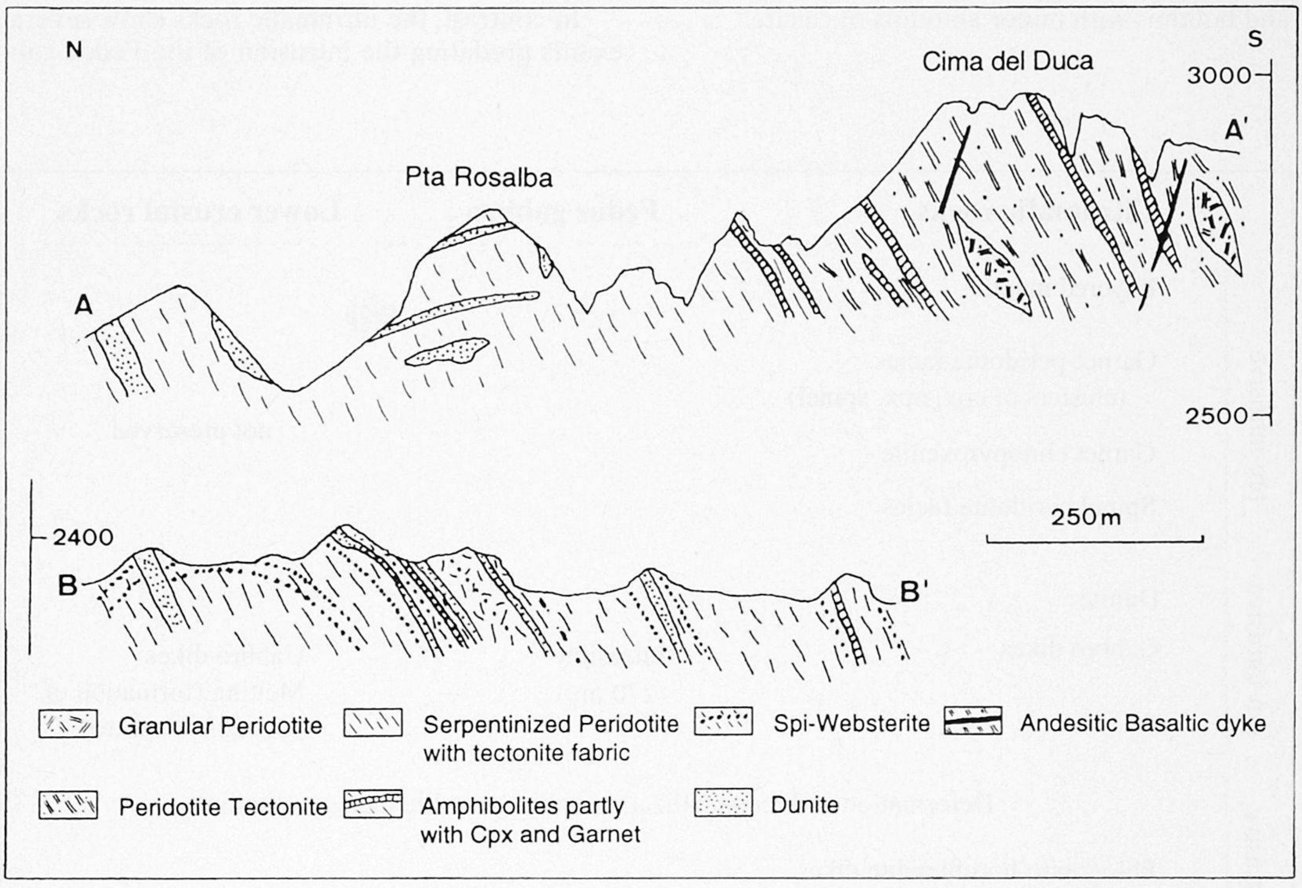

Fig. 9 Two cross sections through the Malenco ultramafic body (locations shown in Fig. 2). (a) Weakly deformed lenses of granular peridotite are embedded in a tectonite foliation. Spinel websterites and amphibolitized garnet clinopyroxenites are parallelized in this foliation. Towards the left of the profile the peridotite tectonites are strongly serpentinized. (b) Field relationships between the layered peridotites and dunites south of Lago Pirola. The layered peridotites exhibit weak open folding indicated by spinel websterites. On the south side of the antiform the dunites are subparallel to the banding defined by spinel websterites. On the north side, however, the dunites are clearly discordant to spinel websterites. These features demonstrate that the formation of replacive dunites postdates the weak open folding of the layered peridotites.

In the region between Mte Braccia and Lago Pirola, the peridotites have been partly replaced by km-scale dunite and harzburgite. South of Lago Pirola (Fig. 9b) the dunites show nearly vertical contacts to the folded spinel websterite banding and thus are clearly discordant to the latter. The formation of spinel trains in dunites has been explained by several workers as the product of dissolution of pyroxenes and concomitant precipitation of olivine and spinel in a magma moving through peridotites (e.g. BOUDIER and NICOLAS, 1977; QUICK, 1981; REMAÏDI, 1993; KELEMEN and DICK, 1995). This interpretation is entirely consistent with the observations in Malenco dunites. The conditions of dunite formation are not well constrained, but the abundant evidence of spinel trains in dunite points to a formation in the spinel lherzolite stability field. The intrusion of the Fe-

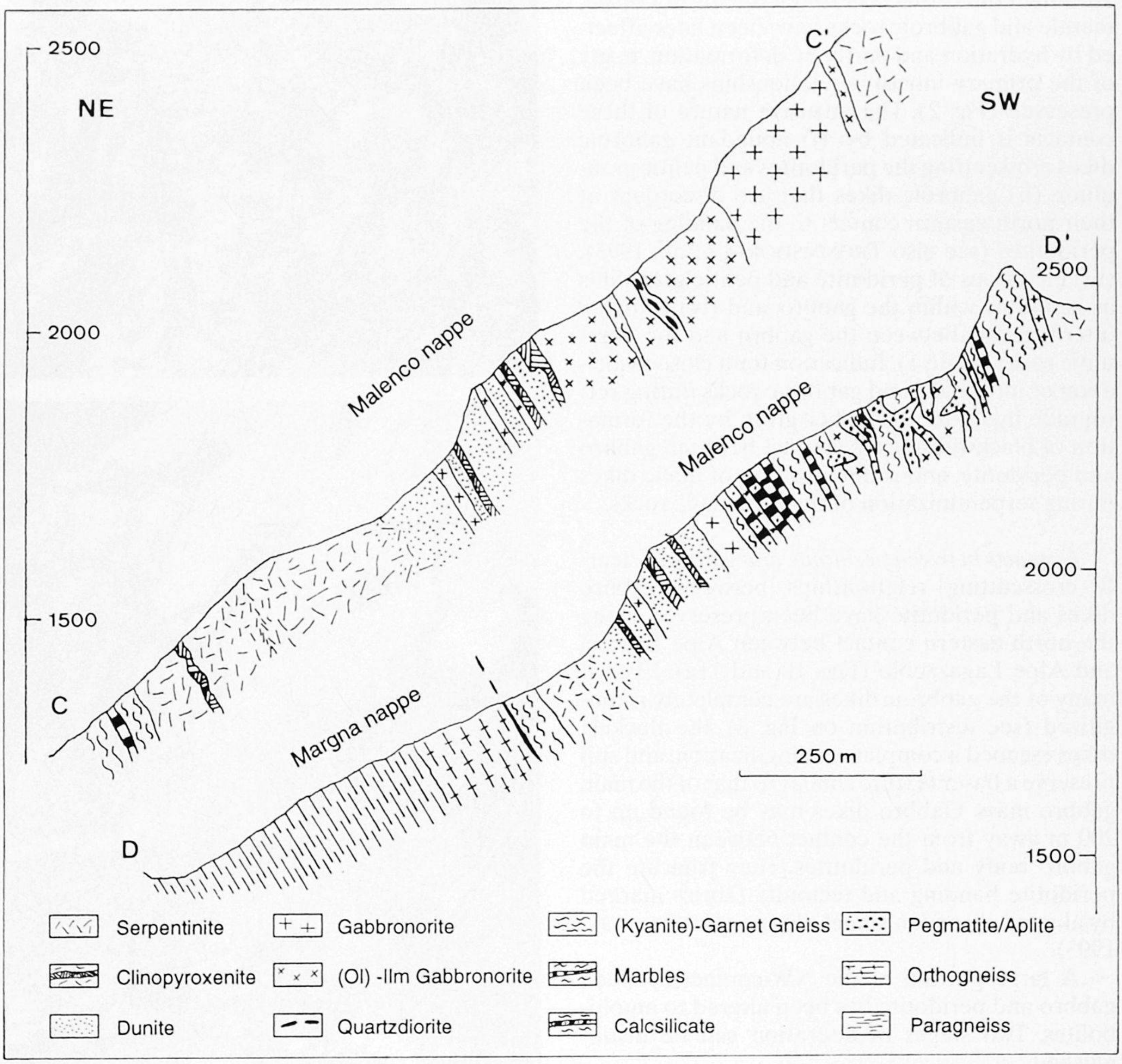

Fig. 10 Two cross sections demonstrating the various intrusive relationships between gabbroic rocks, peridotites and granulites. (a) Cross section east of M. Braccia (locations shown on Fig. 2): The completely serpentinized peridotites show a continuous transition to massive dunites which are crosscut by numerous pyroxenitic and gabbroic dikes. The gabbroic rocks along this profile contain only small inclusions of granulites. (b) Cross section through the northeastern part of Mte Senevedo (locations shown on Fig. 2): A complex interfingering between pelitic granulites, anatectic melts and Fedoz gabbro can be recognized at the SW end of the profile. The transition to the ultramafic rocks is again characterized by dunites which are cut by several gabbroic dikes. The presence of gabbroic dikes in both mantle rocks and granulitic basement as well as the numerous anatectic melts strongly indicates that the gabbroic rocks intruded at the crust-mantle transition.

doz gabbro marks the onset of a common structural and metamorphic history of the lower crustal and upper mantle rocks (HERMANN and MÜNTENER, 1996).

4.2. CONTACT RELATIONSHIPS BETWEEN PERIDOTITE, GRANULITIC ROCKS AND GABBROS

Although the contacts between the lower crustal, mantle and gabbroic rocks have been later affected by hydration and partly by deformation, many of the primary intrusive relationships have been preserved (Fig. 2). The intrusive nature of these contacts is indicated by: (i) abundant gabbroic dikes crosscutting the peridotites and pelitic granulites, (ii) gabbroic dikes that are discordant at their north-eastern contact to the banding of the peridotites (see also TROMMSDORFF et al., 1993), (iii) inclusions of peridotite and pelitic granulites as xenoliths within the gabbro, and (iv) complex interfingering between the gabbro and the granulitic rocks (plate 1). Indication for a close association of ultramafic and gabbroic rocks during retrograde hydration is further given by the formation of blackwalls at the contact between gabbro and peridotite, and rodingitization of mafic dikes during serpentinization of the ultramafic rocks.

Contacts between peridotite and gabbro: Clearly crosscutting relationships between gabbro dikes and peridotite have been preserved along the north-eastern contact between Alpe Braccia and Alpe Lagazzuolo (Figs 10 and 11a). Even if many of the gabbroic dikes are completely rodingitized (see distribution on Fig. 2), the thickest dikes escaped a complete rodingitization, and still preserve a flaser texture similar to that of the main gabbro mass. Gabbro dikes may be found up to 200 m away from the contact between the main gabbro body and peridotites. They truncate the peridotite banding and tectonite fabrics marked by aligned chromian spinel (TROMMSDORFF et al., 1993).

A large portion of the NW-contact between gabbro and peridotite has been altered to amphibolites. Two stages of alteration can be distinguished.

The early high temperature alteration transformed the gabbros to pargasite-clinozoisite blackwalls. The ultramafic part of the contact consists of monomineralic chlorite rocks. A few blackwalls contain Na-rich diopside and clinozoisite. The second episode of alteration led to the formation of rodingites frequently occurring between older blackwalls and ultramafic rocks or

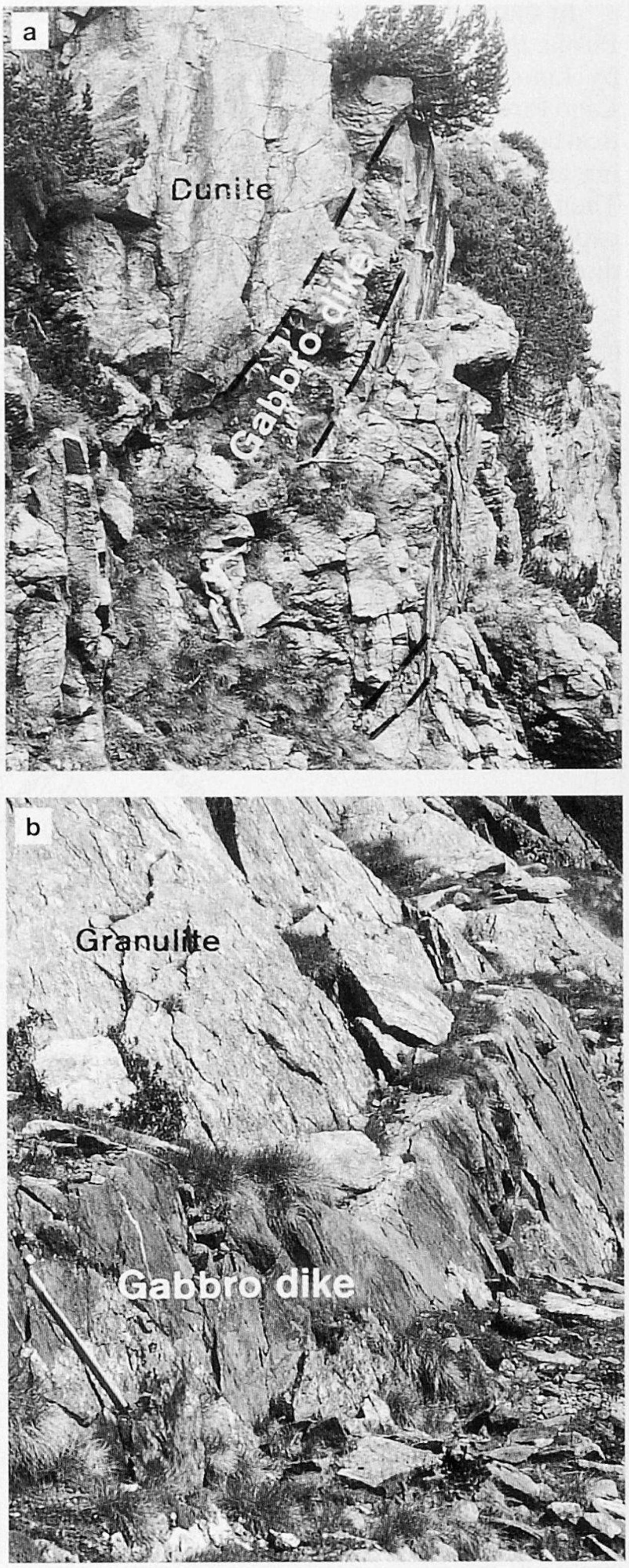

Fig. 11 Field aspects of gabbroic dikes intruding their country rocks. (a) a 2 meter thick gabbroic dike intruding massive dunites (Val Furaz, Swiss coordinates: 784'300 / 128'430). (b) Dark, amphibolitized gabbroic dike intruding garnet gneisses (Mte Senevedo, Swiss coordinates: 781'350 / 130'600).

crosscutting foliated blackwalls. Their mineral assemblage consists of Ca-rich garnet, Na-free diopside, epidote and chlorite and minor amounts of vesuvianite, titanite and calcite. Field relationships demonstrate that the rodingite (II) assemblage replaces the older chlorite-amphibole blackwall. The neighbouring ultramafic rocks are completely serpentinized.

Contacts between gabbro and granulitic rocks: Intrusive relationships between granulitic rocks and gabbros are particularly evident south and south-east of Monte Senevedo. Numerous dikes reaching 10 m in thickness crosscut the banded kyanite garnet gneiss (Fig. 10b). The gabbros often contain pelitic xenoliths which may have been molten. The resulting leucosomes crosscut flaser textures of the gabbroic dikes. In the vicinity of larger dikes, the contact between granulitic rocks and gabbros is often made of decimetre to meter thick leucosomes. Such leucosomes, generated in the pelites close to the gabbro contacts, intruded the gabbro as small dikes (Fig. 12). These dikes thus must have been formed while the gabbro was already solidified. Bulk rock analyses of leucosomes indicate compositions ranging from close to the granite minimum melt to more albite enriched compositions in a quartz-alkalifeldspar-plagioclase ternary diagram (ULRICH, 1995). Correspondingly, the inferred melting temperature varies from about 650 to 850 °C. The dikes in the gabbro and the formation of pegmatitic and aplitic leucosomes clearly indicate that the incipient melting of metapelite is closely associated to the gabbroic intrusion. Preliminary U/Pb dating of zircons of a small pegmatite leucosome (HANSMANN, pers. comm.) points to a similar age as obtained for the main gabbro mass (HANSMANN et al., 1995).

4.3. COMMON HISTORY AFTER THE INTRUSION OF THE GABBRO

Subsequent to the gabbroic intrusion at the crust-mantle boundary, all participating rock types underwent high-temperature deformation forming a pronounced mineral lineation. Detailed structural analysis of the lower crust-mantle complex has revealed that mineral stretching lineations and foliations are roughly parallel (HERMANN and MÜNTENER, 1996). Granulite facies conditions outlasting the deformation led to annealing and polygonization of stretched minerals. This annealing affected most of the metapelitic and mafic rocks and formed granoblastic textures in the underlying ultramafic rocks. Temperatures provided by two-pyroxene thermometry in mafic and ultramafic rocks range from 800 to 850 °C for the granulitic equilibration. Minimum temperatures in the basement rocks may be obtained by the paragenesis olivine + spinel + calcite + clinopyroxene in silica-undersaturated marbles and coexisting garnet + ilmenite + kyanite + biotite + plagioclase in kyanite garnet gneisses (T > 760 °C, HERMANN, in prep.). Pressure estimates on kyanite garnet gneisses resulted in about 10 kbar at 800 °C and are in agreement with spinel as the stable Al-phase in peridotites (JENKYNS, 1983). In a first phase, the subsequent retrograde evolution was largely isobaric within the kyanite stability field (MÜNTENER et al., 1995) and therefore, the Malenco lower crust-mantle complex represents isobarically cooled (IBC) granulitic rocks in the sense of HARLEY (1989). Phlogopite hornblendite dikelets intruded the peridotites, crosscut the high-temperature structures and partly replaced the granoblastic granulite facies mineral assemblage. The later retrograde evolution is characterized by considerable hydration leading to amphibolite and greenschist facies assemblages in ultramafic, mafic and lower crustal rocks. The exhumation of the lower crust-mantle complex on the Tethyan sea floor occurred during the Jurassic (TROMMSDORFF et al., 1993).

Fig. 12 Synmagmatically foliated gabbroic dike intruding the granulitic basement. The gabbroic dike has been crosscut marginally by dikes generated by partial melting of the surrounding kyanite garnet gneisses. Diameter of lens cover is 5 cm (Swiss coordinates: 782'130 / 130'750).

5. The crust-mantle transition

5.1. TENTATIVE RECONSTRUCTION

Many gabbroic dikes in both the ultramafic and the lower crustal rocks demonstrate the welding of the lower crust to the lithospheric mantle. Further indications for a close association of lower crust and mantle are given by the common retrograde structural and metamorphic history after the gabbroic intrusion. Therefore the Malenco lower crust-mantle complex is believed to represent a Permian crust-mantle transition that survived pre-Alpine extensional and Alpine compressional tectonics without significant disintegration. Alpine deformation caused the present steepened exposure of the crust-mantle transition, but left the pre-Alpine structures largely coherent (see Fig. 3 in HERMANN and MÜNTENER, 1996). Retrodeformation of Alpine structures allows to reconstruct a scheme of the crust-mantle transition in Permian times (Fig. 13).

The crust-mantle transition is underlain by a large, heterogeneous lithospheric mantle with a preserved thickness of about 2 km, which in many places is represented by layered peridotites with intercalations of spinel websterites, garnet clinopyroxenites, harzburgites and dunites. Feeder dikes of the Fedoz gabbro have not been found, but towards the east, the lithospheric mantle is continuous and completely encloses the sill-like gabbroic rocks (Fig. 13).

The actual crust-mantle transition is a complex zone of gabbroic, ultramafic and lower crustal rocks of about 1 km thickness. The ultramafic lenticular bodies in the upper part of the gabbroic rocks most probably were separated from the main ultramafic mass during the intrusion of the gabbro. Towards the contact to the gabbro, these rocks consist of spinel-rich dunites with spinel pods and clinopyroxenites. Large masses of the granulitic rocks are interleaved with gabbroic rocks and partly isolated from the continuous lower crust. As outlined by HERMANN (in prep.) the melting of lower crustal rocks significantly increased the density of the kyanite garnet gneisses to values similar to or even higher than densities of upper mantle rocks. This gives a feasible explanation why crustal rocks were able to sink into the gabbro and explains the heterogeneous distribution of gabbroic and lower crustal rocks. A similar explanation for crustal slivers interlayered with mafic rocks has recently been proposed for the Ivrea zone by SINIGOI et al. (1995).

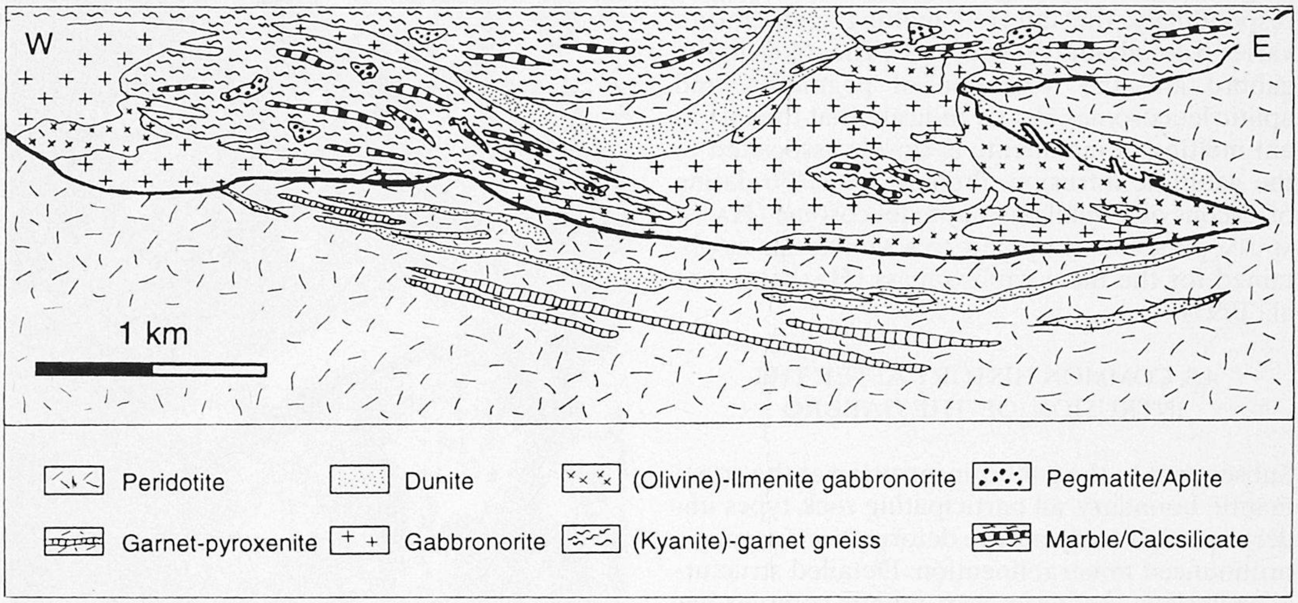

Fig. 13 Schematic reconstruction of the Permian crust-mantle transition summarizing the complex geometry between lower crustal carbonaceous and pelitic, ultramafic and intruding gabbroic rocks. The crust-mantle transition in Val Malenco has been transposed and steepened during Alpine orogeny, therefore the reconstruction represents roughly a profile through the mapped area (compare Plate 1). The geometry of the gabbroic rocks indicates that the Fedoz gabbro does not represent a large layered intrusion, but is made of differentiated mafic rocks exhibiting mutual intrusive relationships. Large bodies of ultramafic rocks have been isolated from the continuous lithospheric mantle. On the other hand several lenses of lower crustal rocks have been separated from the continuous lower crust and stuck now as xenoliths in the gabbroic rocks. The presence of such features suggests that the crust-mantle transition in Val Malenco may not appear as a sharp boundary, but as a large transition zone of approximately 1 km thickness.

5.2. AMBIENT CONDITIONS DURING INTRUSION OF THE FEDOZ GABBRO

The metamorphic conditions during welding of the subcontinental mantle to the lower crust, i.e. the ambient temperatures of crust and mantle during intrusion as well as the temperature of the intruding tholeiitic liquid, are not well established. In contrast, temperature and pressure conditions of the subsequent granulite facies metamorphism are known (T > 760 °C, 10 kbar, see above). Minimum pressure estimates of 10 kbar are probably also appropriate for the intrusion of the Fedoz gabbro, as clinopyroxene rather than olivine seems to form as liquidus phase. Experimental work on olivine tholeiite and MOR basalts (THOMPSON, 1975; FUJII and KUSHIRO, 1977) indicate that clinopyroxene becomes a liquidus phase at pressures higher than about 8 to 10 kbar. These conditions are in agreement with the pressure estimates of 9 to 10 kbar for the immiscibility of highly differentiated liquids in the Fedoz gabbro given by ULRICH and BORSIEN (1996). The pressure estimates correspond to 30 to 35 km depth for the Permian crust-mantle transition.

5.3. CONTRASTING BEHAVIOUR OF CRUST AND MANTLE DURING GABBRO UNDERPLATING

Assuming an undisturbed crust-mantle transition at an average depth of 35 km and using different temperature-depth profiles of FOUNTAIN (1989), the ambient temperature at the intrusion level prior to the gabbroic intrusion would range between 650 to 750 °C. This is in any case considerably lower than the temperature of the intruding magma and indicates a significant temperature contrast between the intruding magma and the surrounding rocks, probably around 400 to 500 °C. It is therefore likely that the surrounding rocks have been heated during the gabbro intrusion and that the high temperature metamorphism of the surrounding rocks is a contact metamorphism caused by underplating of the Fedoz gabbro. The peak conditions are hitherto not known, but they are most probably higher than the recorded temperatures of the final granulitic equilibration at 800 to 850 °C. In fact, the latter equilibration overprints and polygonizes the flaser structure in the gabbros which in turn is post-dating the intrusion.

The metapelites show abundant evidence of contact metamorphism induced by gabbro underplating. All phenomena from incipient melting of the garnet gneisses to the formation of discordant aplitic and pegmatitic dikes crosscutting the banding and the formation of dikes intruding the gabbro have been found. Furthermore the garnets display no inherited zonation (ULRICH, 1995) and thus probably equilibrated completely during granulite facies metamorphism. The U/Pb ages obtained from separated zircons of one of the leucocratic dikes cutting the gabbro are broadly similar to the ages of the main gabbro mass (HANSMANN, pers. comm.) and therefore give additional evidence for granulite facies metamorphism driven by gabbroic intrusions.

Although we infer contact metamorphism to have affected the whole lower crust-mantle transition, the question still arises why contact metamorphism induced by gabbroic underplating is not visible in the mantle rocks, but is well recorded by the lower crustal rocks. In our opinion, the following arguments may clarify this apparent discrepancy:

(i) Under subsolidus conditions as inferred for the Malenco peridotite, four-phase spinel lherzolites are relatively insensitive to an increase in temperature in terms of mineralogical reactions unless major fluid and/or melt introduction occurred. This is the case in the Ronda peridotite, where four-phase spinel lherzolite has been affected by pervasive porous melt flow inducing essentially grain growth but not causing an apparent variation in the mineralogy (VAN DER WAL and VISSERS, 1996).

(ii) Conversely, carbonates and especially pelites are sensitive to changes in temperature. Metapelites contain much more hydrated phases which easily dehydrate during heat supply, hence the liberating fluid is likely to enhance melting of the surrounding rocks.

(iii) The frequent association of quartz-feldspar assemblages allows (minimum) melting of the "leucocratic" part of pelitic gneisses leaving behind a restitic assemblage of kyanite, garnet and plagioclase.

Although the mantle rocks show no obvious signs of a Permian contact metamorphism, the peridotites lying above the gabbroic rocks (Fig. 13) exhibit several features probably linked to the gabbro intrusion. The crystallization of sulfides in the dunite-clinopyroxenite rock association as well as the formation of chromite pods and clinopyroxenites may be related to fluid/melt infiltration into the surrounding ultramafic rocks. Recently, several workers described similar associations of chromite pods and sulfides in dunites (GERVILLA and REMAÏDI, 1993; GERVILLA et al., 1995; ZHOU et al., 1996). These workers interpreted the genesis of this association as a result of interaction between mantle lithosphere and intruding melts. However, a cogenetic origin of sulfides in both gabbroic and dunitic/clinopyroxenitc rocks remains to be verified by a more detailed study of the sulfides.

6. Discussion

Taking into account the evidence for underplating of the Fedoz gabbro in Permian times, we propose that a fossil crust-mantle transition has been preserved in the Val Malenco region. This situation allows a comparison to other regions in the Alps where either subcontinental mantle without remnants of continental lower crust has been preserved (Erro Tobbio, Voltri massif; External Ligurides, Northern Apennines) or where the continental lower crust is predominant (Ivrea zone). It must be emphasized, however, that neither the Ligurian and Northern Apennine peridotites nor the Ivrea zone have preserved a complete crust-mantle transition (e.g. QUICK et al., 1995).

6.1. COMPARISON TO THE IVREA ZONE

The close association of mantle rocks with lower crustal mafic and pelitic rocks in the Malenco area bears many similarities, but also major differences to the Permian situation in the Ivrea zone (Southern Alps). Both areas show evidence of granulite facies metamorphism driven by gabbroic underplating although it must be emphasized that some associations of mafic and pelitic rocks in the Ivrea zone probably belong to an independent (Variscan or older?) event (for overview, see SCHMID, 1993).

Underplating of mafic rocks has been claimed to be an important process in the formation of stronalites in the Ivrea zone (SCHMID and WOOD, 1976; FOUNTAIN, 1989; DAL PIAZ, 1993). QUICK et al. (1994) have shown that partial melting and migmatite formation in the Kinzingite formation of the Ivrea zone increases towards the contact with the mafic complex. These observations demonstrate that the underplating of mafic rocks may trigger granulite facies metamorphism and partial melting in the overlying lower crust as suggested by FOUNTAIN (1989) and RUDNICK and FOUNTAIN (1995). VOSHAGE et al. (1990) suggested that the intrusion of the mafic complex most probably occurred between 290 and 250 Ma based on monazite and lower intercept zircon age data from the Kinzingite formation (KÖPPEL, 1974; KÖPPEL and GRÜNENFELDER, 1979; VOSHAGE et al., 1987) and zircon ages from diorites of the mafic complex (PIN, 1986). Recent SHRIMP dating of zircons confirmed a major episode of granulite facies metamorphism between approximately 296 and 260 Ma (VAVRA et al., 1996). These data broadly overlap with the intrusion age obtained for the Fedoz gabbro (270 + 6/–4 Ma, HANSMANN et al., 1995).

Apart from these remarkable similarities, there exist also important differences:

(i) The mafic complex exposed in the Ivrea zone has a minimum thickness of 7 km (QUICK et al., 1994) whereas in the Malenco lower crust-mantle complex approximately 500 m of mafic rocks have been preserved.

(ii) The metamorphic conditions of the Ivrea lower crust point to an equilibration within the sillimanite stability field (SCHMID and WOOD, 1976; SILLS, 1984) whereas the granulitic rocks from Val Malenco equilibrated in the kyanite stability field. Therefore the pressures obtained from lower crustal granulitic rocks are somewhat lower in the Ivrea zone (max. 8 kbar, SILLS, 1984) than in Val Malenco (10 kbar). Overall lower pressure in the Ivrea zone might be explained by a greater amount of Permian extension and associated exhumation. Such a hypothesis is also in agreement with the much larger amount of underplated gabbros in the Ivrea zone compared to the Val Malenco.

(iii) The ultramafic bodies in the Ivrea zone are partly enclosed in the mafic rocks and occasionally interfingered with paragneisses (QUICK et al., 1995). Therefore, QUICK and co-workers stated that the distance to the underlying continuous mantle is unknown. This contrasts with the findings in Val Malenco where approximately 2 km of ultramafic rocks are attached to the lower crust. The crust-mantle transition is approximately 1 km thick and does not represent a sharp boundary from mantle to lower crustal rocks. Indeed, the fossil crust-mantle transition in Val Malenco is represented by a rather complicated geometry of lower crustal, gabbroic and upper mantle rocks (Fig. 13).

Finally we note that the Late Permian to Early Mesozoic evolution of the two areas also shows some similarities and differences. Both terrains have been affected by south-east-dipping km-scale extensional shear zones: the Pogallo fault in the Ivrea zone (HODGES and FOUNTAIN, 1984; HANDY, 1987) and the Margna normal fault in Val Malenco (HERMANN and MÜNTENER, 1996) which are most probably associated with extensional tectonics in the Mesozoic. The uplift of lower crustal rocks to shallower levels is documented by retrograde amphibolite to greenschist facies parageneses in both regions. However, the final stage of the Late Permian – Early Mesozoic evolution of the two regions is different in that the Malenco rocks have been exhumed on the sea floor of the Tethyan ocean (as evidenced by abundant serpentinization) and partly covered by MOR basalts (Forno unit), as pointed out by TROMMSDORFF et al. (1993), whereas the Ivrea zone was exposed owing to a regional tilting of the Southalpine basement during Alpine collision (SCHMID et al., 1987).

6.2. COMPARISON WITH THE LIGURIAN AND NORTHERN APENNINE PERIDOTITES

Many of the Ligurian and Northern Apennine peridotites presently associated with ophiolite sequences have been regarded as slices of subcontinental lithospheric mantle because of their chemical and isotopic signature (e.g. BODINIER et al., 1991; RAMPONE et al., 1995) and/or their non-adiabatic subsolidus evolution during rifting (HOOGERDUIJN STRATING et al., 1993; RAMPONE et al., 1993). However, none of the mentioned peridotite bodies contain slices of continental lower crust as a direct evidence for their subcontinental origin. In contrast, the Malenco peridotite bears the advantage that its subcontinental origin can still be observed in the field.

The presence of spinel websterites, dunites and the (few) relics of garnet clinopyroxenite demonstrate that the Malenco peridotites had a long and complex history prior to their attachment to the lower crust. Such a complex history has not been reported from the Ligurian and Northern Apennine peridotites. Anyhow, the exhumation-related structural evolution of the Ligurian and Northern Apennine peridotites, with formation of tectonites and mylonites and the final emplacement at the Ligurian-Piemontese ocean floor (DECANDIA and ELTER, 1969; PICCARDO, 1977; VISSERS et al., 1991; HOOGERDUIJN STRATING et al., 1993) is broadly similar to the retrograde structural evolution recognized in the Malenco peridotites (MÜNTENER et al., 1995). All these ultramafic bodies are characterized by extensive serpentinization at the sea floor and only a limited number of fresh peridotites have been preserved. Thus we believe that the rifting-related exhumation history of the Malenco lower crust-mantle complex bears many similarities to the Western and Ligurian Alps peridotites, but that the situation during intrusion of the Permian Fedoz gabbro corresponds much more to the situation of the Ivrea zone.

7. Conclusions

Detailed mapping in the western Val Malenco confirmed that the Malenco ultramafic rocks represent a piece of subcontinental mantle. The internal structure of the peridotites is much more heterogeneous and mineralogically more diverse than previously realized. The preservation of spinel peridotites and garnet pyroxenite dikes indicates that the Malenco ultramafic rocks had a complex history recording an evolution that is older and unrelated to the Permian Fedoz gabbro. Numerous intrusive contacts of this gabbro with the mantle and lower crustal rocks as well as the occurrence of lower crustal and mantle xenoliths demonstrate that the Fedoz gabbro intruded at the crust-mantle boundary. Magmatic crosscutting relationships indicate that the Fedoz gabbro cannot be regarded as a layered intrusion. Granulite facies metamorphism in the lower crustal rocks, induced by gabbroic underplating, is characterized by (i) formation of kyanite garnet gneiss (restites), and (ii) partial melting and formation of pegmatites and aplites crosscutting the banding of the lower crustal rocks and partly intruding the already solidified gabbroic rocks. The description of these characteristics in the Ivrea zone and other lower crustal environments underline the significance of gabbro underplating as an important process for the formation of granulitic rocks.

In analogy to the situation in Val Malenco, many of the peridotites along the Alpine arc may represent former lithospheric, subcontinental mantle. The exhumation history of the Malenco region is comparable to the one of Ligurian and Northern Apennine peridotites all reaching the Tethyan sea floor during the Late Jurassic, with the important difference that in Val Malenco lower crustal rocks have been integrated. Therefore, the Val Malenco can be considered as a key area in the Alps where a Permian lower crust – subcontinental mantle transition has been preserved, which was already exhumed during the Jurassic.

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References

BANGERTER, G. (1978): Strukturen und Metamorphose im Grenzbereich des Malencoserpentins und der Margna-Decke im Gebiet um den Monte Braccia. Diploma thesis University of Zürich (unpubl.).

BODINIER, J.L., MENZIES, M.A. and THIRLWALL, M.F. (1991): Continental to oceanic mantle transition – REE and Sr–Nd isotopic geochemistry of the Lanzo lherzolite massif. J. Petrol., Special issue orogenic lherzolites and mantle processes, 191–210.

BORSIEN, G.R. (1995): Strukturelle und petrographische Untersuchungen im oberen Val Malenco. Teil 1. Diploma thesis ETH Zürich (unpubl.).

BOUDIER, F. and NICOLAS, A. (1977): Structural controls on partial melting in the Lanzo peridotites. In: DICK, H.J.B. (ed.): Magma genesis. Bull. Oreg. Dep. Geol. Miner. Ind. 96, 63–78.

BUCHER, K. and PFEIFER, H.R. (1973): Über Metamorphose und Deformation der östlichen Malenco-Ultamafitite und deren Rahmengesteine. Schweiz. Mineral. Petrogr. Mitt. 53, 231–241.

CORNELIUS, H.P. (1925): Über einige Gesteine der "Fedozserie" aus dem Disgraziagebiet (Rhätische Alpen). Neues Jb. f. Min., Geol. u. Paläont., Beilage Band LII, Abteil A., 1–50.

DECANDIA, F.A. and ELTER, P. (1969): Riflessioni sul problema delle ofioliti nell'Appennino settentrionale: Att. Soc. Tosc. Sci. Nat. Mem. 76, 1–19.

DAL PIAZ, G.V. (1993): Evolution of Austro-Alpine and upper Penninic basement in the northwestern Alps from Variscan convergence to post-Variscan extension. In: VON RAUMER, J.F and NEUBAUER, F. (eds): The pre-mesozoic geology in the Alps, Springer Verlag Berlin, 327–344.

EVANS, B.W. and TROMMSDORFF, V. (1978): Petrogenesis of garnet lherzolite, Cima di Gagnone, Lepontine Alps. Earth Plan. Sci. Lett. 40, 333–348.

FOUNTAIN, D.M. (1989): Growth and modification of lower continental crust in extended terrains: the role of extension and magmatic underplating. In: MEREU, R.F. et al. (eds): Properties and processes of Earth's lower crust. Geophys. Monogr. Series 51, 287–299.

FUJII, T. and KUSHIRO, I. (1977): Melting relations and viscosity of an abyssal tholeiite. Carnegie Inst. Wash. Yearbook 76, 461–465.

GARDIEN, V., REUSSER, E. and MARQUER, D. (1994): Pre-Alpine metamorphic evolution of the gneisses from the Valpelline series (Western Alps, Italy). Schweiz. Mineral. Petrogr. Mitt. 74, 489–502.

GAUTSCHI, A. (1980): Metamorphose und Geochemie der basischen Gesteine des Bergeller Ostrandes. Ph. D. Thesis ETH Zürich, Nr. 6672.

GERVILLA, F. and REMAÏDI, M. (1993): Field trip to the Ronda ultramafic massif: an example of asthenosphere-lithosphere interaction? Ophioliti 18, 21–35.

GERVILLA, F., GARUTI, G. and LEBLANC, M. (1995): Chromitites from the Ojen lherzolite massif (Serrania de Ronda, Spain): Late stage melt-rock reaction products in porous flow channels. Proc. 2nd workshop on orogenic lherzolites and mantle processes, 21.

GODARD, G., MARTIN, S., PROSSER, G., KIENAST, J.R. and MORTEN, L. (1996): Variscan migmatites, eclogites and garnet-peridotites of the Ulten zone, Eastern Austroalpine system. Tectonophysics, in press.

GUNTLI, P. and LINIGER, M. (1989): Metamorphose in der Margna-Decke im Bereich Piz da la Margna und Piz Fedoz (Oberengadin). Schweiz. Mineral. Petrogr. Mitt. 69, 289–301.

HANDY, M. (1987): The structure, age and kinematics of the Pogallo fault zone, southern Alps, northwestern Italy. Eclogae geol. Helv. 80, 593–632.

HANDY, M. and ZINGG, A. (1991): The tectonic and rheological evolution of an attenuated cross section of the continental crust: Ivrea crustal section, southern Alps, northwestern Italy and southern Switzerland. Geol. Soc. Am. Bull. 103, 236–253.

HANSMANN, W., HERMANN, J. and MÜNTENER, O. (1995, 1996): U-Pb-Datierung des Fedozer Gabbros, einer Intrusion an der Krusten-Mantel-Grenze. Abstract SANW, St. Gallen. Schweiz. Mineral. Petrogr. Mitt. 76, 116–117.

HARLEY, S.L. (1989): The origins of granulites: a metamorphic perspective. Geol. Mag. 126, 215–247.

HERMANN, J. and MÜNTENER, O. (1996): Extension-related structures in the Malenco-Margna system: implications for paleogeography and its consequence for rifting and Alpine tectonics. Schweiz. Mineral. Petrogr. Mitt. 76, 501–519.

HODGES, A.K. and FOUNTAIN, D.M. (1984): Pogallo Line, South Alps, northern Italy, an intermediate crustal level, low angle normal fault? Geology 12, 151–155.

HOOGERDUIJN STRATING, E.H., RAMPONE, E., PICCARDO, G.B., DRURY, M.R. and VISSERS, R.L.M. (1993): Subsolidus emplacement of mantle peridotites during incipient oceanic rifting and opening of the Mesozoic Tethys (Voltri massif, NW Italy). J. Petrol. 34, 901–927.

HONEGGER, K. (1977): Der Malencoserpentinit und seine Nachbargesteine östlich der Kette Pizzo Cassandra – Pizzo Rachele. Diploma thesis, ETH Zürich (unpubl.).

JENKYNS, D.M. (1983): Stability and composition relations of calcic amphiboles in ultramafic rocks. Contrib. Mineral. Petrol. 83, 375–384.

KELEMEN, P.B. and DICK, H.J.B. (1995): Focused melt flow and localized deformation in the upper mantle: juxtaposition of replacive dunite and ductile shear zones in the Josephine peridotite, SW Oregon. J. Geophys. Res. 100, 423–438.

KÖPPEL, V. (1974): Isotopic U–Pb ages of monazites and zircons from the crust-mantle transition and adjacent units of the Ivrea and Ceneri zones (Southern Alps, Italy), Contrib. Mineral. Petrol. 43, 55–70.

KÖPPEL, V. and GRÜNENFELDER, M. (1979): Monazite and zircon U–Pb ages from the Ivrea and Ceneri zones. Mem. Ist. Geol. Mineral. Univ. Padova 33, 257.

LEMOINE, M., TRICART, P. and BOILLOT, G. (1987): Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Apennines): In search of a genetic model. Geology 15, 622–625.

MEHNERT, K.R. (1975): The Ivrea zone: A model of the deep crust. Neues Jahrb. Mineral. Abh. 125, 156–199.

MONTRASIO, A. and TROMMSDORFF, V. (1983): Guida all'escursione del massicio di Val Masino-Bregaglia, Val Malenco occidentale, Sondrio. Mem. Soc. Geol. It. 26, 421–434.

MÜNTENER, O., HERMANN, J. and TROMMSDORFF, V. (1995): Extensional metamorphism and exhumation of granulites, mantle-crust section (Malenco, Central Alps). Terra abstracts 1, 315.

PERETTI, A. (1988): Occurrence and stabilities of opaque minerals in the Malenco serpentinite (Sondrio, Northern Italy). Ph. D. Thesis, ETH Zürich.

PICCARDO, G.B. (1977): Le ophioliti dell areale ligure: petrologia ed ambiente geodinamico di formazione. Rend. Soc. It. Min. Petr. 33, 221–252.

PICCARDO, G.B., RAMPONE, E. and VANNUCCI, R. (1990): Upper mantle evolution during continental rifting and ocean formation: evidences from peridotite bodies of the western Alpine-northern Apennine system. Mém. Soc. géol. France 156, 323–333.

PIN, C. (1986): Datation U–Pb sur zircons a 285 Ma du complexe gabbro-dioritique du Val Sesia-Val Mastallone et âge tardi-hercynien du métamorphisme granulitique de la zone Ivrea-Verbano (Italie). C.R. Acad. Sci. Paris 303, 827–830.

POZZORINI, D. (1996): Stabile isotope investigations of ophicarbonate rocks, Bergell aureole, Valmalenco: Constraints on fluid rock interaction. Ph. D. Thesis ETH-Zürich. Nr. 11436.

QUICK, J.E. (1981): The origin and significance of large tabular dunite bodies in the Trinity peridotite, northern California. Contrib. Mineral. Petrol. 78, 413–422.

QUICK, J.E., SINIGOI, S. and MAYER, A. (1994): Emplacement dynamics of a large mafic intrusion in the lower crust, Ivrea-Verbano zone, northern Italy. J. Geophys. Res. 99, 21559–21573.

QUICK, J.E., SINIGOI, S. and MAYER, A. (1995): Emplacement of mantle peridotites in the lower continental crust, Ivrea-Verbano zone, northwest Italy. Geology 23, 739–742.

RAMPONE, E., PICCARDO, G.B., VANUCCI, R., BOTTAZZI, P. and OTTOLINI, L. (1993): Subsolidus reactions monitored by trace element partitioning: the spinel-to plagioclase-facies transition in mantle peridotites. Contrib. Mineral. Petrol. 115, 1–17.

RAMPONE, E., HOFMANN, A.W., PICCARDO, G.B., VANUCCI, R., BOTTAZZI, P. and OTTOLINI, L. (1995): Petrology, mineral and isotope geochemistry of the External Liguride peridotites (Northern Apennines, Italy). J. Petrol. 36, 81–105.

REBER, D. (1995): Strukturelle und petrographische Untersuchungen im oberen Val Malenco. Teil 3. Diploma thesis University of Zürich (unpubl.).

REMAÏDI, M. (1993): Etude géochimique d'une association péridotites réfractaires-pyroxenites dans le massif de Ronda (Espagne). Implications pour les méchanismes de circulation des magmas dans le manteau supérieur. Unpubl. Ph. D. Thesis, Montpellier France.

RUDNICK, R.L. and FOUNTAIN, D.M. (1995): Nature and composition of the continental crust: A lower crustal perspective. Rev. Geophysics 33, 267–309.

SCHMID, R. and WOOD, B.J. (1976): Phase relationships in granulitic metapelites from the Ivrea-Verbano zone (Northern Italy). Contrib. Mineral. Petrol. 54, 255–279.

SCHMID, S.M. (1993): Ivrea zone and adjacent southern Alpine basement. In: VON RAUMER, J.F and NEUBAUER, F. (eds), The pre-mesozoic geology in the Alps, Springer Verlag Berlin, 327–344.

SCHMID, S.M., ZINGG, A. and HANDY, M. (1987): The kinematics of movements along the Insubric line and the emplacement of the Ivrea zone. Tectonophysics 135, 47–66.

SCHUMACHER, T. (1975): Geologisch-petrographische Untersuchungen des Malenco-Serpentinits und der Margna-Gesteine bei Chiareggio. Diploma thesis University of Zürich (unpubl.).

SILLS, J.D. (1984): Granulite facies metamorphism in the Ivrea zone. Schweiz. Mineral. Petrogr. Mitt. 64, 169–191.

SINIGOI, S., QUICK, J.E., MAYER, A. and DEMARCHI, G. (1995): Density controlled assimilation of underplated crust, Ivrea-Verbano zone, Italy. Earth Plan. Sci. Lett. 129, 183–191.

SMITH, D. (1977): The origin and interpretation of spinel-pyroxene clusters in peridotite. J. Geol. 85, 476–482.

SPILLMANN, P. (1993): Die Geologie des penninisch-ostalpinen Grenzbereichs im südlichen Berninagebirge. Ph. D. Thesis ETH-Zürich. Nr. 10175.

STAUB, R. (1917): Das Äquivalent der Dentblanchedecke in Bünden. Vjschr. natf. Ges. Zürich 62, 349–370.

STAUB, R. (1946): Geologische Karte der Berninagruppe 1:50'000. Spez.-Karte Nr. 118, Schweiz. Geol. Kommission.

THOMPSON, R.N. (1975): Primary basalts and magma genesis II, Snake river plain, Idaho, U.S.A. Contrib. Mineral. Petrol. 52, 213–232.

TROMMSDORFF, V. and EVANS, B.W. (1972): Progressive metamorphism of antigorite schist in the Bergell tonalite aureole. Am. J. Sci. 272, 423–437.

TROMMSDORFF, V. and EVANS, B.W. (1974): Alpine metamorphism of peridotitic rocks. Schweiz. Mineral. Petrogr. Mitt. 54, 333–352.

TROMMSDORFF, V. and EVANS, B.W. (1977): Antigorite ophicarbonates: Contact metamorphism in Val Malenco. Contrib. Mineral. Petrol. 62, 301–312.

TROMMSDORFF, V., PICCARDO, G.B. and MONTRASIO, A. (1993): From magmatism through metamorphism to sea floor emplacement of subcontinental Adria lithosphere during pre-Alpine rifting (Malenco, Italy). Schweiz. Mineral. Petrogr. Mitt. 73, 191–203.

ULRICH, T. (1995): Strukturelle und petrographische Untersuchungen im oberen Val Malenco. Teil 2. Diploma thesis ETH Zürich (unpubl.).

ULRICH, T. and BORSIEN, G.R. (1996): Fedozer Metagabbro und Forno Metabasalt (Val Malenco, Norditalien): Vergleichende petrographische und geochemische Untersuchungen. Schweiz. Mineral. Petrogr. Mitt. 76, 521–535.

VAN DER WAL, D. and VISSERS, R.L.M (1996): Structural petrology of the Ronda peridotite, SW Spain: deformation history. J. Petrol. 37, 23–43.

VANNUCCI, R., SHIMIZU, N., PICCARDO, G.B., OTTOLINI, L. and BOTTAZZI, P. (1993): Distribution of trace elements during breakdown of mantle garnet: an example from Zabargad. Contrib. Mineral. Petrol. 113, 437–449.

VAVRA, G., GEBAUER, D., SCHMID, R. and COMPSTON, W. (1996): Multiple zircon growth and recrystallization during polyphase Late Carboniferous to Triassic metamorphism in granulites of the Ivrea Zone (Southern Alps): an ion microprobe (SHRIMP) study. Contrib. Mineral. Petrol. 122, 337–358.

VISSERS, R.L.M., DRURY, M.R., HOOGERDUIJN STRATING, E.H. and VAN DER WAL, D. (1991): Shear zones in the upper mantle: a case study in an Alpine lherzolite massif. Geology 19, 990–993.

VOSHAGE, H., HUNZIKER, J.H., HOFMANN, A.W. and ZINGG, A. (1987): A Nd and Sr isotopic study of the Ivrea zone, Southern Alps, N. Italy. Contrib. Mineral. Petrol. 97, 31–42.

VOSHAGE, H., SINIGOI, S., MAZZUCCHELLI, M., DEMARCHI, G., RIVALENTI, G. and HOFMANN, A.W. (1990): Isotopic constraints on the origin of ultramafic and mafic dykes in the Balmuccia perido-tite (Ivrea zone). Contrib. Mineral. Petrol. 100, 261–267.

WENK, E. (1963): Klinohumit und Chondrodit in Marmoren der Tessineralpen und der Disgrazia-Gruppe. Schweiz. Mineral. Petrogr. Mitt. 43, 269–293.

ZHOU, M., ROBINSON, P.T., MALPAS, J. and LI, Z. (1996): Podiform chromitites in the Luobusa ophiolite (Southern Tibet): Implications for melt-rock interaction and chromite segregation in the upper mantle. J. Petrol. 37, 3–21.

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Appendix

Tab. A1 Petrography, mineralogy and modes of peridotites and dunites in the Malenco ultramafic body.

Rock type	Microstructure	Minerals	Grain size (mm)	Mode (Vol.%)
Spinel peridotite (L-UM 216)	Spinel peridotites are dominated by coarse-grained olivine surrounded by smaller olivine neoblasts. Deformation induced undulatory extinction and deformation bands subparallel or parallel to (100) are common. Coarse-grained opx contains cpx exsolution lamellae which are not present at the outermost 100 μm towards the rim. Opx is partly recrystallized to neoblasts. Clinopyroxene crystals are smaller (2–3 mm) and often occur as clusters of 2 or 3 grains, often exhibiting exsolution lamellae of ilmenite and rarely opx. Cpx neoblasts are smaller and occur between larger porphyroclasts. Porphyro-clastic brown spinel is holly-leaf textured and occasionally forms clusters with opx and cpx. Spinel neoblasts are subidiomorphic or rounded and often located between triple junctions of olivine neoblasts. Ti-amphibole occurs as interstitial grains and sometimes as embayment filling of opx together with olivine. Retrograde recrystallization of chlorite-chromite symplectites, amphibole and olivine can be virtually absent or complete, leading to progressive formation of amphibole-chlorite peridotite.	Porphyroclasts		
		Olivine	3–17	58–72
		Orthopyroxene	2–10	19–30
		Clinopyroxene	1–3	4–16
		Spinel	1–5	1–4
		Neoblasts		
		Olivine	0.2–0.5	
		Orthopyroxene	0.1–0.3	
		Clinopyroxene	0.05–0.2	
		Spinel	0.1–0.5	
		Ti-Pargasite	0.1–0.3	
Dunite 1 and harzburgite (P-UM 103)	Olivine forms a granoblastic to mylonitic fabric. Large grains are elongated and often oblique to the main foliation. Aspect ratios can reach up to 5:1. Kinking or deformation lamellae are rare. They often show complex interlocking textures. Mylonitic recrystallized olivine is much smaller and equigranular and mostly forms a continuous network surrounding olivine porphyroclasts. Porphyroclastic spinels exclusively occurs in domains with coarse-grained olivine and often shows discontinuous zoning towards the rim. Small grains of Cr-magnetite is associated within mylonitic olivine.	Porphyroclasts		
		Olivine	2–15	80–96
		Cr-Spinel	2–10	1–4
		Orthopyroxene[1]		3–20
		Clinopyroxene[1]		0–1
		Neoblasts		
		Olivine	0.05–0.2	
		Cr-Magnetite	0.05–0.1	
Dunite 2 (L-UM 106)	Porphyroclastic olivine may be isometric but is more often elongated with aspect ratios up to 3:1. Olivine exhibits undulatory extinction and deformation bands subparallel to (100). Olivine neoblasts form triple junctions and do not exhibit any deformation bands. Many olivine neoblasts show equilibrium textures with Fe-rich pentlandite and pyrrhotite. Spinel forms equant grains interstitial to olivine and is always bordered by Cr-rich chlorite. In places, spinel forms clumps of grains aligned parallel to the elongated porphyroclastic olivine.	Porphyroclasts		
		Olivine	2–3	80–97
		Cr-Spinel	0.2–0.5	1–9
		Orthopyroxene[1]		0–15
		Clinopyroxene[1]		0–2
		Neoblasts		
		Olivine	0.1–0.2	
		Pyrrhotite	0.1–0.5	
		Pentlandite		

[1] Orthopyroxene and Clinopyroxene are completely altered in these rocks. Their modal amount has been calculated from bulk rock analyses.

Tab. A2 Petrography, mineralogy and modes of pyroxenite dikes and hornblendite in the Malenco ultramafic body.

Rock type	Microstructure	Minerals	Grain size (mm)	Mode (Vol.%)
Spinel websterite (Or-UM 222)	Large elongate pale-green porphyroclastic clinopyroxene forms a network with mostly interlocking contacts. They are often deformed and/or kinked and contain numerous exsolution lamellae of orthopyroxene (now altered to chlorite), ilmenite and/or blebs of Cr-spinel. Fine-grained, oriented kelyphite in clinopyroxene has been altered to tremolite and chlorite and may interpreted as replacement products of former garnet. Orthopyroxene has been completely transformed to tremolitic amphibole and chlorite. Spinel forms rounded grains interstitial to pyroxenes. Interstices between clinopyroxene porphyroclasts are filled with exsolution-free clinopyroxene granoblasts and rare Ti-pargasite and olivine.	Porphyroclasts Clinopyroxene Orthopyroxene Cr-Spinel Olivine Neoblasts Clinopyroxene Olivine Ti-Pargasite Cr-Spinel	 5–30 2–10 2–5 1–2 0.3–0.6 0.1–0.2 0.2–0.5	 60–75 15–22 [1] 3–10 2–10 [1]
Corundum bearing garnet clinopyroxenite (L-UM 218)	Large porphyroclastic Al-rich clinopyroxene and Mg-rich garnet is partly surrounded by granoblastic clinopyroxene and rare garnet. Porphyroclastic clinopyroxene is deformed and exhibits small opx exsolution lamellae and occasionally blebs of garnet. Towards the rims to the surrounding peridotites secondary Ti-amphibole and rare phlogopite may form as major constituent. Very fine grained Fe-rich pargasite forms the matrix. Contacts between corundum and garnet are surrounded by zoisite and rare preiswerkite.	Porphyroclasts Clinopyroxene Garnet ± Corundum ± Cr-Spinel Granoblasts Clinopyroxene Ti-Pargasite ± garnet ± Phlogopite	 10–50 2–8 0.1–0.3 < 0.05 0.3–1.0 0.1–1 < 0.05	 80–95 5–20 < 0.5 < 0.1
Clinopyroxenite (B-UM 204)	This type of pyroxenite is associated with dunite (2). Equigranular elongated aggregates of green or brown clinopyroxene encloses rare porphyroclastic clinopyroxene. Small rounded spinel and anhedral olivine fill interstices between granoblastic clinopyroxene. Sulfides can be present in significant amounts. A few samples are very coarse-grained clinopyroxenites without any spinel and olivine. Many of the granoblastic and porphyroclastic clinopyroxenes contain ilmenite exsolutions.	Porphyroclasts Clinopyroxene Spinel Olivine Neoblasts Clinopyroxene Olivine Spinel ± Pentlandite	10–40 0.5–3 1–3 0.2–1.0 0.1–0.2 0.1–0.2 0.1–0.5	80–95 0–9 5–20
Phlogopite hornblendite (Or-UM 227)	Large and intensely deformed kaersutite and phlogopite form a network with straight or curved grain boundaries. Rare apatite and sulfides are interstitial to amphibole. Both kaersutite and phlogopite contain abundant exsolutions of rutile and ilmenite, in most cases aligned parallel to (110) and (010) in amphibole and in typical sagenite fabrics in phlogopite. Many samples are intensely retrogressed. Fe-pargasite, diopside, ilmenite, and chlorite grew along cleavages and grain boundaries substituting the primary magmatic assemblage.	Porphyroclasts Phlogopite Kaersutite ± Apatite ± Pyrite ± Pyrrhotite ± Allanite	0.5–2 3–30 0.1–0.3 0.2–1.0	5–70 30–95 < 0.1 < 0.1

[1] Calculated from bulk rock analyses.

Tab. A3 Petrography, mineralogy and modes of the Fedoz gabbro.

Rock type	Microstructure	Minerals	Grain size (mm)	Mode (Vol.%)
Gabbronorite (B-F 217)	Rare clinopyroxene and orthopyroxene porphyroclasts with abundant exsolution lamellae are embedded in a polygonal granoblastic matrix of clinopyroxene, orthopyroxene and plagioclase. All granoblasts occur as sligthly to highly elongated clusters of several recrystallized grains. These clusters are responsible for the flaser texture. Ilmenite and Ti-pargasite is rare and interstitial to pyroxenes and plagioclase. Plagioclase shows sometimes dynamic recrystallization with the formation of lobate grain boundaries.	Primary phases		
		Clinopyroxene	3–15	15–30
		Plagioclase	5–20	55–75
		Orthopyroxene	3–15	15–30
		± Ilmenite	0.3–0.5	0–1
		± Ti-Pargasite	0.5–1	0–1
		Neoblasts		
		Clinopyroxene	0.5–2	
		Orthopyroxene	0.5–2	
		Plagioclase	0.5–2	
		Ti-Pargasite	0.2–0.5	
(Olivine) ilmenite amphibole gabbronorite (B-F 11)	Rare clinopyroxene and orthopyroxene porphyroclasts with abundant exsolution lamellae are embedded in a granoblastic matrix of clinopyroxene, orthopyroxene and plagioclase. These granoblasts show a polygonal texture and 120° angles between them. Interstices are filled with ilmenite, magnetite, green Al-spinel, apatite, frequently Ti-rich pargasite and occasionally olivine. At the interface between olivine and plagioclase a complex three shell corona developed, locally leading to two pyroxene-spinel assemblages, which are successively overgrown by a two pyroxene-garnet assemblage. Hydration of these water-free coronas lead to garnet-amphibole intergrowth.	Primary phases		
		Clinopyroxene	2–10	15–20
		Plagioclase	2–5	50–55
		Orthopyroxene	2–10	10–20
		Ilmenite	0.5–2	1–5
		Ti-Pargasite	0.5–2	0–2
		± Apatite	0.5–1.5	0–1
		± Al-Spinel	0.2–1	0–0.5
		± Olivine	0.5–1.5	0–5
		Neoblasts		
		Clinopyroxene	0.3–2	
		Orthopyroxene	0.3–2	
		Plagioclase	0.5–2	
		Ti-Pargasite	0.2–0.5	
		± Al-Spinel		
		± Garnet		
		± Corundum		
Pyroxene hornblende gabbro (T 24)	Equigranular texture of brown Ti-rich pargasite, clinopyroxene and plagioclase. Amphiboles are often irregularly zoned with a dark brown core. Smaller amphibole may be included in clinopyroxene and plagioclase. Apatite is abundant in these rocks either occurring as euhedral inclusions in amphibole, clinopyroxene and plagioclase or filling interstices between them. Ilmenite is always present as interstitial grains. Clinopyroxene is mostly altered to amphibole.	Primary phases		
		Hornblende	0.5–4	30–50
		Clinopyroxene	0.5–1.5	15–20
		Plagioclase	1–1.5	30–50
		Ilmenite	0.1–1	3–7
		± Biotite	0.5–2	0–1
		± Apatite	0.1–0.5	0–1
		± Zircon		
		Neoblasts		
		Hornblende	< 0.1	
		Plagioclase	0.2–1	
Quartz diorite (Fed 34)	Large and highly stretched (length/width ratio up to 8:1) plagioclase, quarz and orthopyroxene porphyroclasts are surrounded by granoblastic plagioclase, orthopyroxene, quartz and rare clinopyroxene. Orthopyroxene is exsolution free with the exception of large porphyroclasts. Ilmenite fills interstices between orthopyroxene and plagioclase. Most of the grain boundaries among granoblastic plagioclase are curved indicating dynamic recrystallization. In most samples quartz is intensely recrystallized.	Primary phases		
		Orthopyroxene		
		Plagioclase	1–2	5–10
		Quartz	2–5	65–70
		Ilmenite	2–10	20–25
		Neoblasts	0.2–0.5	0–1
		Orthopyroxene		
		Clinopyroxene	0.2–1	
		Plagioclase	0.2–0.5	
		Quartz	0.5–2	
			0.1–1	

Tab. A4 Petrography, mineralogy and modes of the granulitic rocks.

Rock type	Microstructure	Minerals (granulitic parageneses)	Grain size (mm)	Mode (Vol.%)
Kyanite garnet gneiss (T 64)	Idiomorphic garnets have inclusion-rich cores and inclusion-poor rims. The inclusions consist of rounded quartz, plagioclase and biotite. The garnets are embedded in a granoblastic matrix of kyanite, plagioclase, quartz and rare biotite. Plagioclase often displays a polygonal equilibration texture. Quartz forms elongated grains with abundant deformation lamellae and contains tiny inclusions of rutile. Biotite with exsolution of rutile occur as big flakes or as inclusion in garnet. Xenomorphic ilmenite is often rimmed by rutile.	Garnet Plagioclase Quartz Biotite Kyanite Ilmenite ± Zircon ± Rutile	10–20 1–4 1–15 0.5–4 1–15 0.5–1	10–40 10–70 5–50 0–10 0–10 0–1
Pegmatites and aplites (Ch-FS 205)	Weakly deformed phenocrysts of perthitic or antiperthitic kalifeldspar and albitic plagioclase are embedded in a matrix of fine grained polygonal quartz. Rarely, idiomorphic garnet occurs. Towards the contact to their country rocks, the pegmatites and aplites contain sometimes xenolithic garnet and biotite fragments.	Perthite Albit Quartz ± Garnet ± Zircon	2–20 1–10 0.1–0.2	0–40 20–50 30–55
Calcsilicates	Calcsilicates exhibit a granoblastic texture containing various amounts of garnet, epidote, clinopyroxene, quartz, plagioclase, kalifeldspar and calcite. Rare nematoblastic wollastonite is embedded in a fine-grained quartz-calcite-grossularite matrix. Granoblastic diopside is partly rimmed by a light-green Na-rich diopside.	Calcite Quartz Clinopyroxene Clinozoisite / Epidote Grossularite Kalifeldspar Plagioclase Wollastonite Titanite Pyrite	0.1–3 0.05–3 0.05–4 0.1–2 0.1–2 0.2–1.5 0.1–0.5 0.5–7 0.1–2	5–80 5–20 0–50 0–70 0–30 0–10 0–10 0–15 0–5
Marbles	Ilmenite-phlogopite-clinopyroxene and olivine-phlogopite knobs are embedded in a calcitic matrix. Clinopyroxenes occur as large porphyroblasts as well as inclusions in phlogopite. In monomineralic layers they display an equigranular, polygonal texture. The olivine-phlogopite knobs can reach up to 10 cm in length. Porphyroblasts of olivine and phlogopite are surrounded by small neoblasts. Phlogopite often displays oriented rutile exsolutions.	Calcite Dolomite Clinopyroxene Phlogopite Olivine Pyrite Pyrrhotite ± Spinel ± Titanite	0.1–0.5 0.1–1 0.5–20 0.2–20 0.2–20 0.1–1 0.1–0.3 0.1–1	10–100 0–20 0–90 0–30 0–20 0–2

Tab. A5 Representative bulk rock analyses of lithologic units of the crust-mantle transition in Val Malenco. Detailed petrographic description of the analyzed samples are given in tables 1–4, respectively. Samples T 24 and T 64 are taken from ULRICH (1995).

Sample	L-UM 216	P-UM 103	L-UM 106	Or-UM 222	L-UM 218	B-UM 204	Or-UM 227	B-F 217	B-F 11	T 24	Fed 34	T 64	Ch-FS 205	
Major elements (wt%)														2σ (rel.)
SiO_2	42.8	37.0	35.8	44.2	45.3	46.7	36.5	52.9	47.7	46.5	61.0	43.6	70.4	0.71
TiO_2	0.14	< 0.01	0.06	0.19	0.13	0.42	4.34	0.46	2.49	3.39	0.28	0.89	0.36	0.01
Al_2O_3	3.04	0.25	2.54	8.4	13.2	4.92	13.4	16.2	16.0	17.0	19.5	26.8	15.0	0.27
Fe_2O_3[1]	8.7	7.7	11.5	3.05	7.26	5.09	11.7	7.99	12.8	13.0	4.14	15.6	1.80	0.06
MnO	0.12	0.06	0.14	0.04	0.14	0.12	0.16	0.16	0.19	0.19	0.10	0.30	< 0.01	0.02
MgO	39.7	44.5	42.1	24.3	14.4	20.3	17.9	10.2	7.56	5.13	2.43	6.16	0.75	0.14
CaO	2.42	0.05	0.03	11.6	14.7	16.9	8.83	9.01	9.84	9.77	6.16	1.65	0.64	0.16
Na_2O	< 0.21	< 0.21	< 0.21	0.66	2.83	0.44	1.96	2.53	2.32	3.47	4.75	0.78	2.32	0.2
K_2O	< 0.02	< 0.02	< 0.02	0.02	0.11	< 0.02	0.58	0.18	0.37	0.78	0.41	0.77	7.42	0.1
P_2O_5	0.02	0.01	< 0.01	0.02	< 0.01	0.01	0.05	0.02	0.20	0.45	0.02	< 0.01	0.09	0.02
Cr_2O_3	0.34	0.44	1.11	0.74	0.10	0.85	0.06	0.05	0.02	0.01	0.01	< 0.01	< 0.01	0.01
NiO	0.31	0.45	0.33	0.12	0.04	0.13	0.11	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01
LOI[2]	1.74	8.33	5.60	5.53	0.44	3.29	2.75	0.18	0.0	0.34	0.62	1.85	0.37	
Σ	99.3	98.8	99.2	98.9	98.7	99.3	98.3	99.9	99.5	100.0	99.4	98.4	99.2	
Trace elements (ppm)														Detection limit
F	< 50	< 50	< 50	< 50	< 50	< 50	< 50	117	164	902	< 50	337	1551	50
Ba	< 10	< 10	< 10	< 10	< 10	< 10	35	47	120	210	302	792	1389	10
Rb	< 3	< 3	< 3	< 3	< 3	< 3	<3	3	< 3	< 3	< 3	73	154	3
Sr	< 10	< 10	< 10	23	17	21	155	273	280	530	455	70	237	10
Pb	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	< 5	61	5
Nb	< 5	< 5	< 5	< 5	< 5	< 5	25	< 5	< 5	20	< 5	< 5	< 5	5
La	< 17	< 17	< 17	< 17	< 17	< 17	28	< 17	< 17	65	< 17	23	62	17
Ce	< 17	< 17	< 17	< 17	< 17	< 17	22	< 17	< 17	64	< 17	51	46	17
Nd	< 11	< 11	< 11	< 11	< 11	< 11	< 11	< 11	< 11	39	< 11	< 11	< 11	11
Y	< 3	< 3	< 3	< 3	< 3	< 3	8	< 3	23	26	< 3	32	< 3	3
Zr	< 4	< 4	< 4	< 4	< 4	< 4	62	< 4	56	226	< 4	171	15	4
V	64	< 16	58	146	345	185	487	152	325	397	64	261	40	16
Cr	2712	2709	8163	6955	760	8358	412	360	144	36	12	242	< 18	18
Ni	2008	2764	1937	887	316	968	915	68	81	31	14	120	< 11	11
Co	98	88	80	8	47	51	107	21	54	77	13	33	< 11	11
Cu	< 8	< 8	375	< 8	< 8	150	57	< 8	27	< 8	< 8	75	< 8	8
Zn	43	31	62	28	39	18	38	48	85	130	33	278	34	6
Ga	< 4	< 4	< 4	< 4	5	< 4	11	10	16	22	15	35	9	4
Sc	12	< 2	8	33	65	31	20	31	36	33	7	41	5	2
S	< 50	< 50	1278	< 50	< 50	< 50	< 50	< 50	1318	< 50	< 50	2964	< 50	50

[1] Fe_2O_3 is total iron
[2] LOI: Loss on ignition