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Extension-related structures in the Malenco-Margna-system: implications for paleogeography and consequences for rifting and Alpine tectonics

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

Abstract

In the Margna nappe and the Malenco unit (Val Malenco, northern Italy), a former continent-ocean transition of the Adriatic continental margin has been recognized. Extension-related structures in lower crustal and mantle rocks of these units reveal the following succession of events:

(1) A penetrative deformation overprints the lower crustal and mantle rocks leading to a foliation and lineation that are subsequently annealed under granulite facies conditions. This deformation post-dates the intrusion of the Fedoz gabbro and is attributed to Permian extension. (2) After a period of isobaric cooling, concentration of strain in shear zones and mylonites under retrograde conditions marks the initial stage of Jurassic rifting. (3) During uplift the lower crust was disrupted. (4) Major exhumation occurred along the Margna normal fault separating upper crustal rocks of the Margna block from lower crustal granulites and gabbros originating from approximately 35 km depth. (5) Denudation of the subcontinental mantle and the attached lower crust is documented by sedimentary ophicarbonates and basaltic dikes crosscutting the ultramafic rocks.

The Malenco unit represents a complex zone that in Jurassic time was situated between the ocean floor sequence of the Forno unit and the Margna continental margin. This zone contains denuded subcontinental mantle including attached lower crust, MORB-dikes, ophicarbonates and slivers of upper crust and Mesozoic sediments interpreted as extensional allochthons. As a consequence, a new Alpine tectonic boundary between Penninic and Austroalpine units is postulated that is not identical with the boundary between ultramafic rocks and rocks of the continental crust.

An evolution model for the formation of the Austroalpine passive continental margin is proposed in which the Permian extension is separated from Jurassic rifting. Two stages of simple-shear-dominated rifting with opposite sense of movement are inferred to have exhumed the lower crust-mantle complex.

Keywords: mantle, lower crust, exhumation, Jurassic rifting, continent-ocean transition, extensional tectonics, Central Alps, Val Malenco (N. Italy).

1. Introduction

Detailed studies of continental margins such as the ones of the Red Sea (Voggenreiter et al., 1988) and the Galicia margin (Boillot et al., 1995a) confirmed that the transition from the continent to the ocean bears the most important information about the break-up of continents and the formation of oceans. In the Alpine region, rifting and drifting was followed by subduction and collision, thereby destroying most of the information about ocean formation. The geometry of the margins, however, strongly influenced Alpine tectonics. Therefore, the reconstruction of the continent-ocean transition is fundamental for the understanding of both the break-up between Adria and Europe and their later collision.

The Penninic-Austroalpine boundary zone (Fig. 1) in south-eastern Grisons (Switzerland) and in Val Malenco (northern Italy, Fig. 2) is one of the best exposed fossil continent-ocean transitions in an orogen. The formation of the continental margin can be studied from sediments and structures developed in the uppermost crust (Eberli, 1988; Froitzheim and Eberli, 1990; Manatschal, 1995; Froitzheim and Manatschal, 1996) as well as from retrograde metamorphism and structures in an exhumed lower

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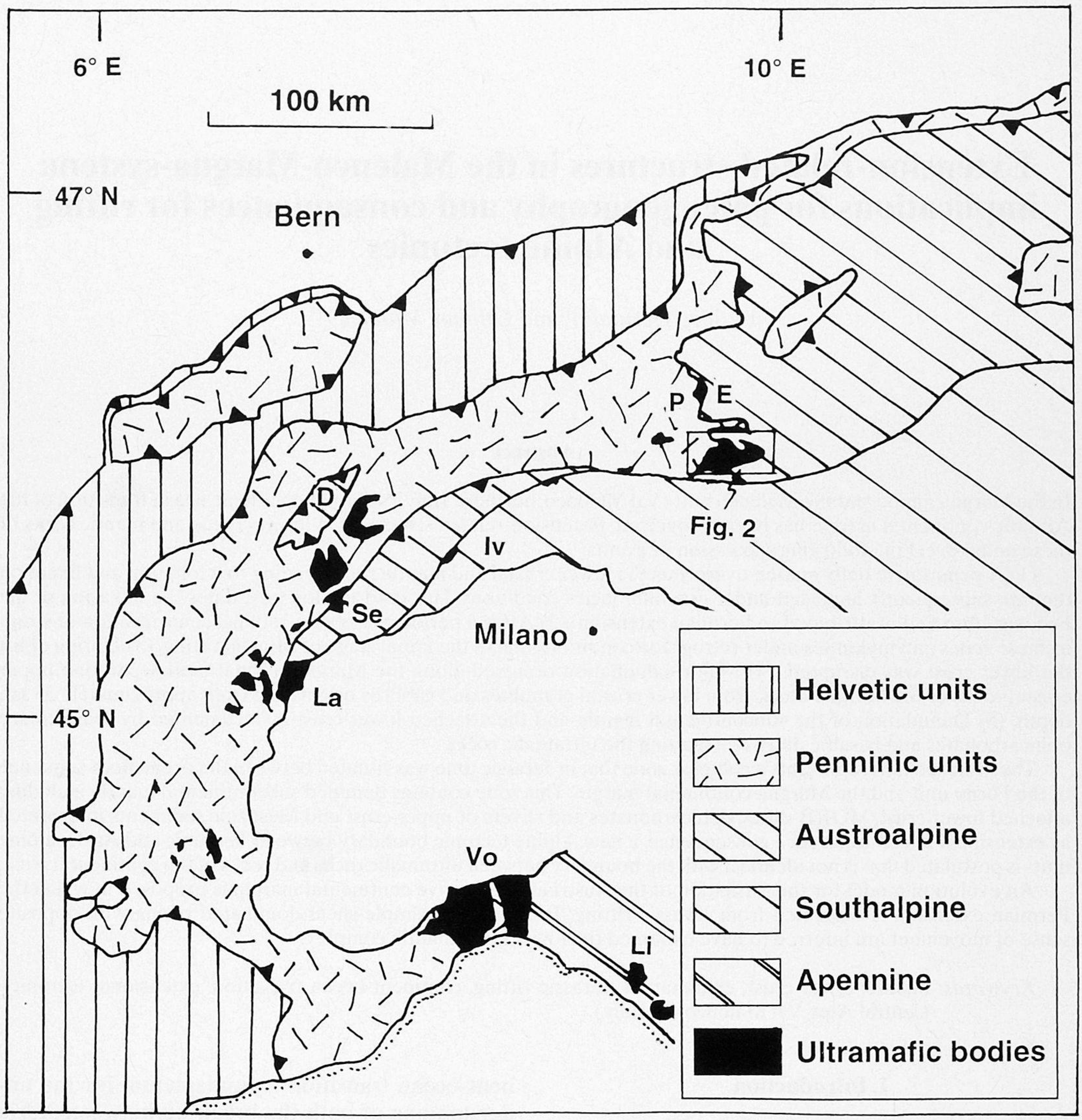

Fig. 1 Tectonic map of the Alps: The Helvetic units are part of the former European margin, whereas the Austroalpine, Southalpine and external Apennines were part of the Adriatic (African) margin. The Penninic units comprise oceanic and distal continental margin associations. Li = Internal and external Ligurides, Vo = Voltri (Erro-Tobbio), La = Lanzo, Se = Sesia zone, Iv = Ivrea zone, D = Dent Blanche klippe, P = Platta, E = Err.

crust-mantle complex (TROMMSDORFF et al., 1993; MÜNTENER and HERMANN, 1996; HERMANN et al., 1996). Thus, this area offers the possibility to link processes occurring contemporaneously at different levels in the lithosphere during rifting.

In this work, a palinspastic reconstruction of the Austroalpine margin in the Malenco region is presented. It is based upon (A) post-Permian, pre-collisional structural evolution in the Malenco lower crust-mantle complex and the Margna basement, and (B) retrodeformation of Alpine structures. It is the purpose of this paper to use field evidence in order to show that (1) Permian high-temperature penetrative deformation was followed by Jurassic localized deformation, (2) the Margna normal fault is an important rifting structure bringing lower crust and mantle rocks in contact with the uppermost crust, (3) the continent-ocean transition is a zone where rocks coming from all levels of the lithosphere occur together in a small area.

The pre-collisional structures will be compared to similar ones in the Ivrea zone and combined to the sedimentary record of the Austroalpine nappes in order to obtain an evolution model for the Margna-Malenco continent ocean transition.

2. Regional setting

In the Val Malenco region (northern Italy, Fig. 2) Alpine thrusting resulted in a nappe pile involving from top to bottom: (1) the Lower Austroalpine Bernina-, Sella- and Margna nappes representing the former Adria continental crust, (2) the South-Penninic Malenco and Forno units, (3) the Middle Penninic Suretta nappe which is interpreted as derived from the Briançonnais (SCHMID et al., 1990). New structural investigations by PUSCHNIG (1996) indicate that the contact between Suretta and the Malenco and Forno units probably does not represent an Alpine thrust but is a late Alpine low-angle detachment fault (Turba-Mylonite-Zone of LINIGER and NIEVERGELT, 1990; NIEVERGELT et al., 1996). In the western part of the studied area, the nappe pile is partly crosscut by the Oligocene Bergell intrusion.

The Jurassic continent-ocean transition in the

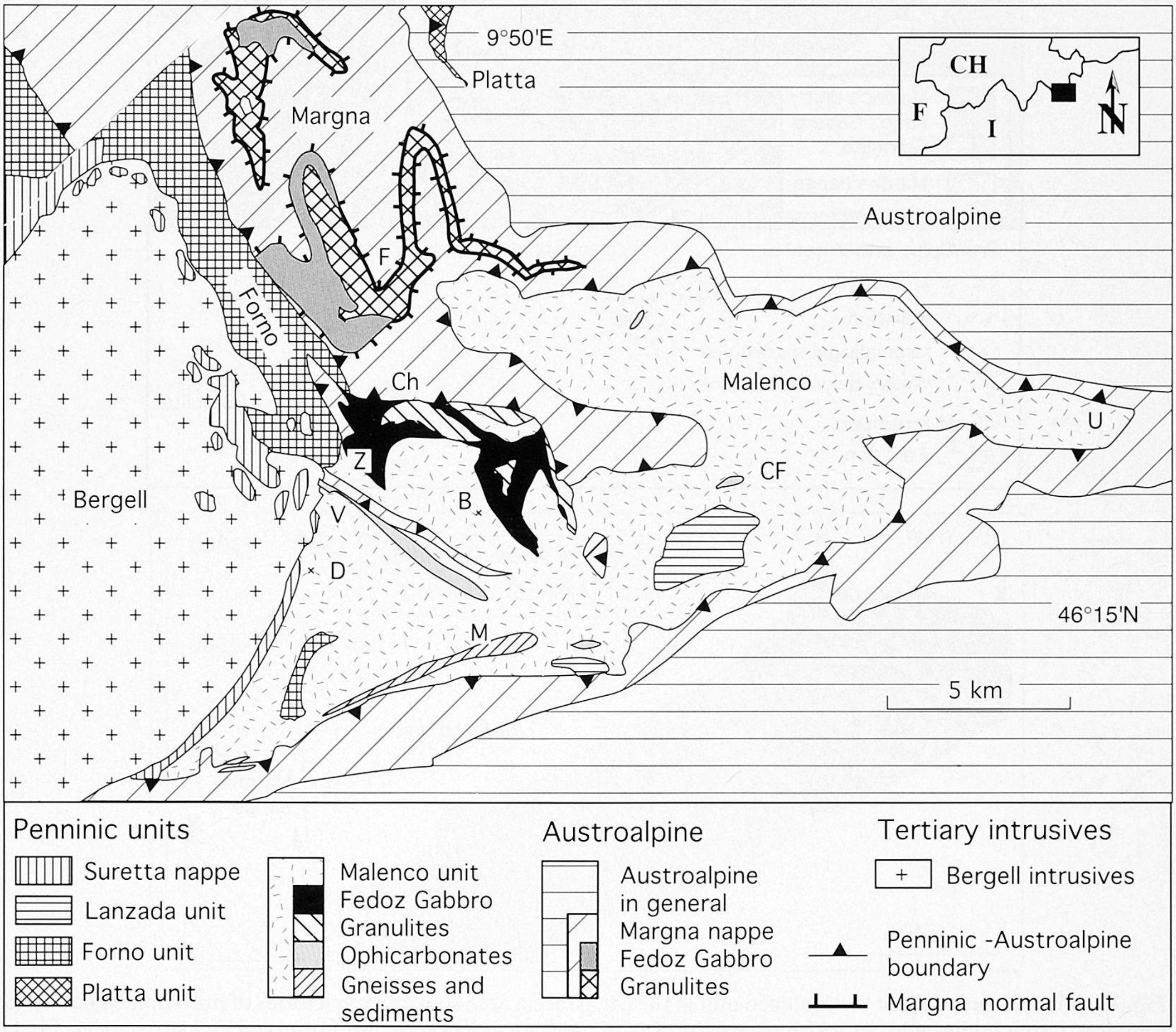

Fig. 2 Tectonic map of the Val Malenco region. The Margna normal fault separates lower from upper crustal rocks within the Margna nappe. The Fedoz gabbro and the granulites of the Mt. Braccia area are attached to the ultramafic rocks and belong to the Malenco unit. F = Piz Fora, Ch = Chiareggio, Z = Alpe Zocca, V = Val Ventina, D = Mt. Disgrazia, M = Mastabbia zone, B = Mt. Braccia, CF = Campo Franscia, U = Passo d'Ur.

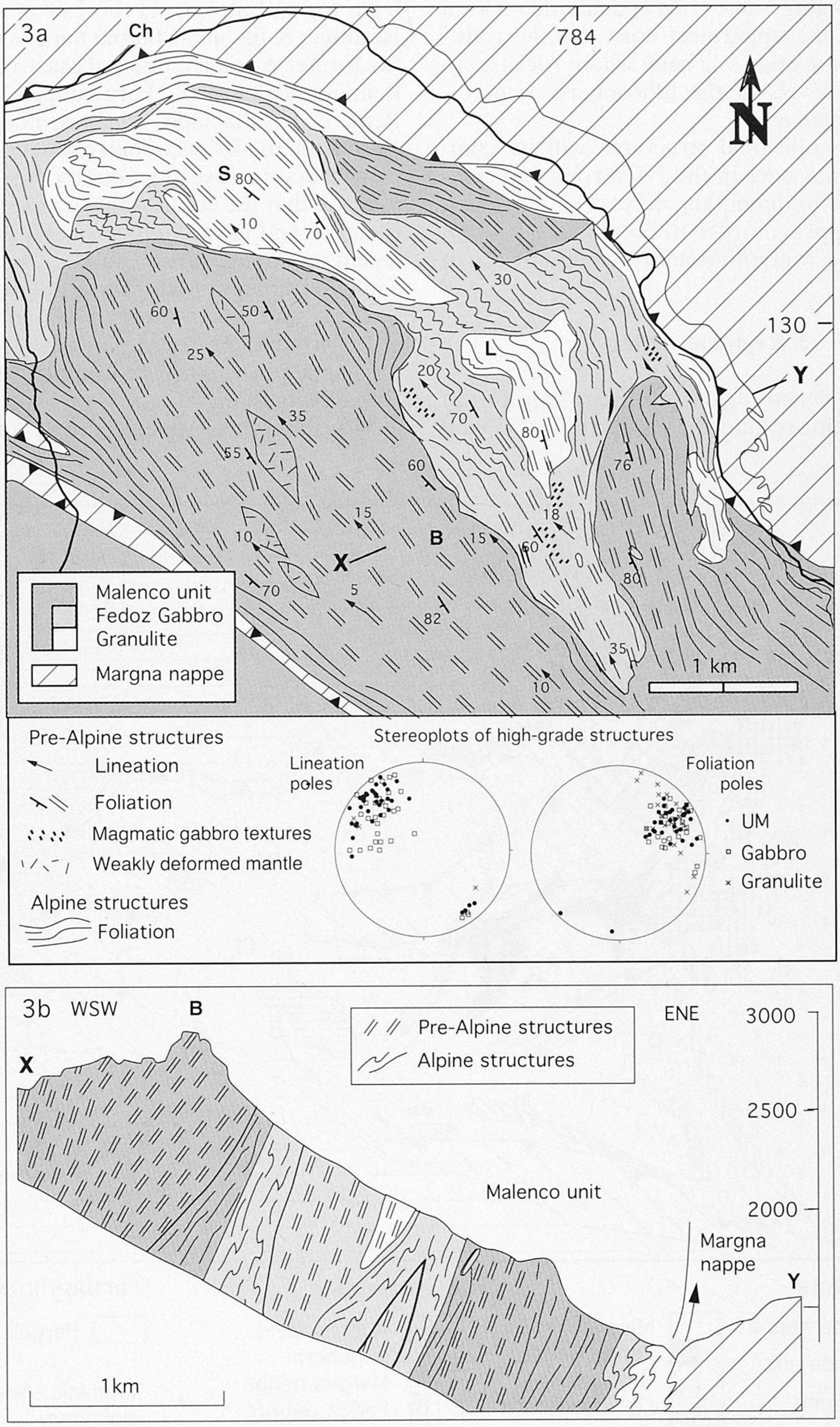

Fig. 3 (a) Structural map of the Malenco unit in the Mt. Braccia area showing trajectories of pre-Alpine and Alpine foliation. Large bodies with pre-Alpine structures with constant orientation are preserved and surrounded by the Alpine foliation. Points in the stereoplots lie in the lower hemisphere. UM = ultramafic rocks, B = Mt. Braccia, Ch = Chiareggio, S = Mt. Senevedo, L = Alpe Lagazzuolo.
(b) Section across the crust-mantle transition that lies within the Malenco unit. The rocks are slightly overturned due to the second backfolding event.

Val Malenco region is characterized by three units (Fig. 2): Forno, Malenco and Margna (e.g. TROMMSDORFF et al., 1993).

The *Forno unit* consists of metamorphosed volcanoclastic rocks and basalts that in some parts exhibit pillow structures. They are overlain by Mid-Jurassic to Lower Cretaceous sediments (PERETTI, 1985). Although affected by Alpine regional and contact metamorphism, the Forno unit still exhibits most features of a typical ocean floor sequence (MONTRASIO, 1973; FERRARIO and MONTRASIO, 1977; PERETTI, 1985). MORB-type Forno dikes cut across the Malenco ultramafic body.

The *Malenco unit* lies at the same tectonic level as the Forno unit and is dominated by ultramafic rocks that are serpentinized to variable extent. Ophicarbonates were found in several localities (POZZORINI, 1996). In the area of Mt. Braccia (Fig. 2, Fig. 3) gabbros and pelitic granulites are welded to the ultramafic rocks and thus represent a preserved crust-mantle section (HERMANN et al., 1996). As these rocks are similar to gabbros and high-grade metamorphic pelites of the Margna nappe, they were considered as part of the Margna nappe (CORNELIUS, 1925; STAUB, 1946). The new findings of intrusive contacts between the gabbro and both, lower crust and mantle rocks, demonstrate that the rock association of the Mt. Braccia area belongs to the Malenco unit. A detailed description of this lower crust-mantle complex is given in MÜNTENER and HERMANN (1996), and therefore only a short summary is given here: In the Malenco peridotite spinel-lherzolites of variable composition are predominant. Several generations of pyroxenites crosscut the peridotite and led to the pronounced layering in the mantle. Dunites and harzburgites occur in zones which are sometimes discordant to the layering. The tholeiitic Fedoz gabbro displays a magmatic evolution from magnesian to ferroan gabbro-norite (BANGERTER, 1978; GAUTSCHI, 1979, 1980; ULRICH and BORSIEN, 1996). Highly differentiated dikes of quartz-diorites and ilmenite-pyroxene-amphibole gabbros crosscut the main gabbro. U–Pb dating of zircons gives a maximum intrusion age of 280 Ma for the gabbro intrusion (HANSMANN et al., 1995). The lower crust represents a metasedimentary sequence which consists of kyanite-bearing biotite-plagioclase-garnet gneisses to felses, intercalations of calcsilicate rocks, and wollastonite- and olivine-bearing marbles. The granulites locally display migmatitic structures with granitoid partial melts crosscutting the lithological banding. Within the rocks of the crust-mantle section a retrograde evolution from granulite to low p-T conditions has been observed (HERMANN et al., 1996) indicating exhumation of these rocks. The evolution can be chronologically constrained by the Permian gabbro intrusion and the sediments of the Forno ocean floor sequence of presumably Jurassic age.

The *Margna unit* consists of a composite basement including upper crustal granitoids and paragneisses as well as lower crustal pelitic granulites and the Fedoz gabbro (SPILLMANN, 1993). The upper crustal rocks are covered by a sequence of Mesozoic sediments. Pelitic granulites and gabbros are similar to the ones of the Mt. Braccia area but in terms of Alpine tectonics they belong to different thrust sheets (Margna nappe and Malenco unit, respectively). The Margna nappe is strongly overprinted by Alpine deformation and metamorphism (LINIGER and GUNTLI, 1988; SPILLMANN, 1993), and therefore only relics of pre-collisional features are preserved.

3. High-temperature structures in the Malenco unit

Pre-Alpine high-temperature structures are preserved in all three main rock types of the Malenco unit in the Mt. Braccia area. The distribution of Alpine and pre-Alpine structures is shown in figure 3. As the Alpine and the pre-Alpine foliation is often parallel they cannot be distinguished by different orientations. The pre-Alpine structures are best recognizable in rocks where the pre-Alpine granulite facies paragenesis is preserved. Most of the rocks have suffered Alpine metamorphism, but the older high-grade structures are still observable because of only weak Alpine deformation and static Alpine metamorphic overprint in these rocks. The pre-Alpine metamorphic conditions, however, can only be determined from a few outcrops where the pre-Alpine mineralogy is preserved too (see MÜNTENER and HERMANN, 1996).

3.1. FEDOZ GABBRO[1]

The oldest structure found in the Fedoz gabbro is a texture indicative of magmatic flow as pyroxene crystals of variable size (0.5–10 cm) and irregular shape are aligned in parallel bands. Concentration of pyroxene and plagioclase crystals at different levels lead to a pronounced layering. The magmatic flow texture has an orientation that is completely different from the later foliations and is preserved in lenses surrounded by a tectonic flaser structure (Fig. 4). This flaser structure, marked by stretched pyroxenes in a plagioclase matrix, is the main structure within the gabbro (Gautschi, 1980). Linear fabrics are dominant and only minor flattening occurred. Depending on the original size, the length of the tectonic flasers varies from 1 to 5 cm. In thin section, all minerals show a polygonal texture indicating annealing and reequilibration by subsequent granulite facies metamorphism (Fig. 5). In a few samples, dynamic recrystallization is preserved in plagioclase which exhibits lobate grain boundaries. The strong reequilibration makes it impossible to deduce the sense of shear from micro structures. Rotation of the magmatic flow textures into the tectonic foliation, however, can be used as a shear sense indicator and points to a predominant movement of the northern block towards the east (Fig. 4).

The tectonic flasers are crosscut by shear zones and mylonites (Fig. 4, Fig. 6). In contrast to the widespread flaser texture, the mylonites are localized and exhibit grain size reduction and dynamic recrystallization without annealing. Rotation of the flasers into the mylonites also indicates a movement of the northern block towards the east.

3.2. MALENCO ULTRAMAFIC ROCKS

The field relationships found in the ultramafic rocks are shown schematically in figure 7. The oldest elements are weakly deformed peridotitic lenses that are crosscut by spinel-websterites

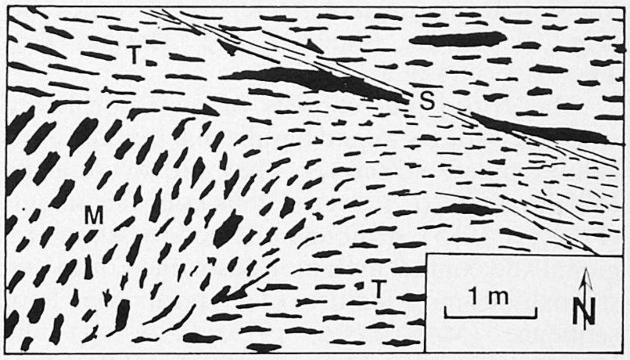

Fig. 4 Outcrop sketch of near-vertical gabbro structures above Alpe Lagazzuolo (Swiss grid coordinates: 782.900/129.500). Magmatic flow textures (M) occur in boudins surrounded by tectonic flaser structures (T) which are cut by later shear zones (S).

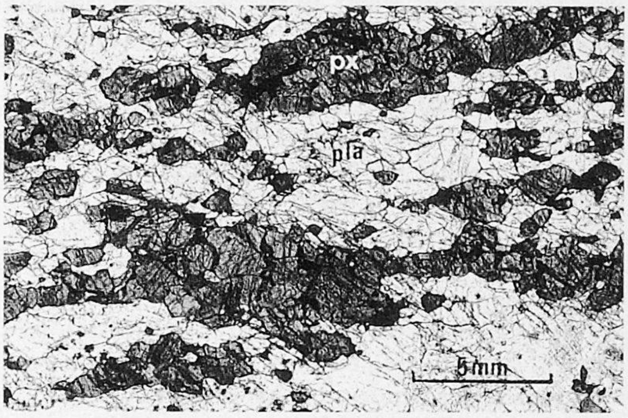

Fig. 5 Photo of thin section of a flasered gabbro. The tectonic flaser structure, marked by elongated pyroxenes (px) and plagioclase (pla), is completely reequilibrated under subsequent granulite facies metamorphism. Swiss grid coordinates: (783.970/128.860).

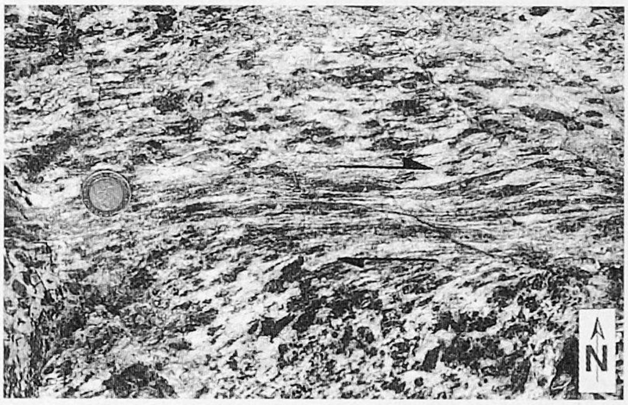

Fig. 6 Ductile shearing of flaser gabbro. The rotation of the flaser structure into the shear zone indicates a movement of the northern block towards the east. Coin diameter: 2.5 cm. Swiss grid coordinates: (783.650/128.600).

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[1] The gabbro of the Monte Braccia – Lago Piorola area was described as Fedoz gabbro by Staub (1946) and Gautschi (1980). This work has shown that the gabbroic rocks described here belong tectonically to the Alpine Malenco nappe. Therefore it may be convenient to apply a new name (Braccio 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.

forming a pronounced layering. The spinel-websterites are boudinaged within a first generation of tectonized peridotite (tectonite 1) which surrounds the undeformed peridotites. Elongated crystals of spinel and pyroxene are responsible for the linear fabric of the tectonite 1. Pyroxenite dikes within the tectonite 1 are not boudinaged and only weakly undeformed indicating that they intruded after the deformation leading to the tectonite 1. Harzburgitic to dunitic zones partly replace the peridotites and spinel-websterites.

In a second generation of tectonized peridotite (tectonite 2) all rock types and structures mentioned above are overprinted. The two generations of tectonites are only distinguishable in places where pyroxenites crop out. The pyroxenites intruded the peridotite after the formation of the tectonite1, but are deformed by the tectonite 2. Depending on their prior orientation they are folded or boudinaged.

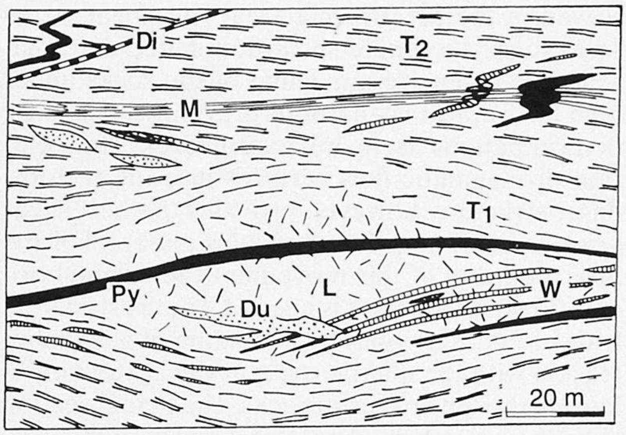

Fig. 7 Schematic sketch of field relations in the Malenco mantle sequence. L = weakly deformed lherzolite, W = spinel websterites, T_1 = first generation of tectonized peridotite, Py = pyroxenite dikes, Du = dunites, T_2 = second generation of tectonized peridotite, Di = dikelets with titanian pargasite and phlogopite, M = mylonites.

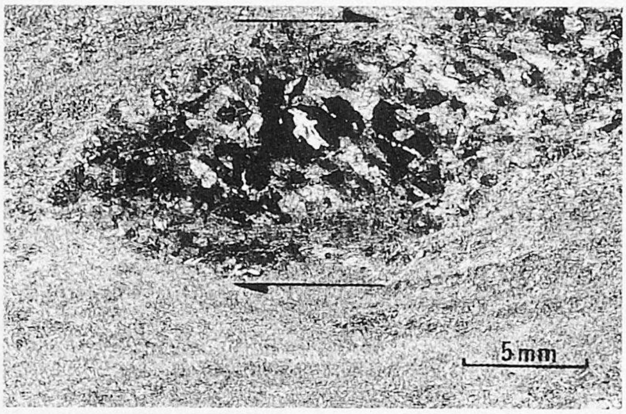

Fig. 8 Photomicrograph of a mylonite within the dunites. Large tabular olivines coexisting with spinel are surrounded by a very fine-grained olivine mylonite. The asymmetric clast indicates a dextral shear sense within the mylonite that can be translated into a movement of the northern block towards the west. Swiss grid coordinates: (781.510/130.060).

The tectonite 2 is crosscut by dikelets containing Ti-rich pargasite, phlogopite and apatite (Fig. 7). In dunitic parts, olivines display a tabular shape and deformation lamellae. Further deformation is localized in mylonites leading to a drastic grain size reduction (Fig. 8). In peridotites with lherzolitic composition, amphibole grew synkinematically in the pressure shadow of porphyroblastic clinopyroxene indicating retrograde conditions during mylonitization. No systematic shear sense could be deduced from mylonites. The relationship of these mylonites to titanian mineral dikelets remains unclear. Subsequent boudinage of mylonitic dunites gives evidence for a competence inversion under ongoing retrogression.

3.3. PELITIC GRANULITES

A first deformation led to tight folding of the bedding in the metapelites. As these folds are crosscut by Fedoz gabbro dikes, this deformation must have occurred prior to the gabbro intrusion.

The main feature is a weak foliation with a rare kyanite lineation that formed under granulite facies conditions. This foliation is parallel to the high-temperature foliation in the Fedoz gabbro (Fig. 3a). A clinozoisite-paragonite foliation which is parallel to the granulitic foliation indicates retrograde hydration. Asymmetric pressure shadows around garnets have been observed occasionally.

3.4. METAMORPHIC CONDITIONS

All three rock types display a granulite facies metamorphism. In the Fedoz gabbro and in the pelitic granulites no older metamorphism has been observed. In the ultramafic rocks the granulitic metamorphism is documented in neoblasts and overprints an older metamorphism. Metamorphic conditions can be deduced from two-pyroxene thermometry in the Fedoz gabbro yielding temperatures around 800 °C (Gautschi, 1980). Identical temperatures are obtained from thermometry of granulitic recrystallized pyroxenes in the ultramafic rocks. In the metapelites the paragenesis kyanite-plagioclase-quartz-garnet-biotite-ilmenite is indicative for pressures of about 10 kbar when assuming 800 °C.

Parageneses that developed in shear zones and mylonites are retrograde in respect to the granulite facies metamorphism. The amphibole peridotite mylonites indicate a formation temperature between 750 °C and 550 °C (e.g. Jenkyns, 1983). The replacement of aluminum by ferric iron in chromium-rich spinels in dunitic mylonites indicates retrograde conditions during deformation. In the metapelites the formation of clinozoisite and paragonite is characteristic for amphibolite facies conditions with elevated pressure (600 °C, 8.5 kbar).

The rocks of the Mt. Braccia area therefore followed an isobaric cooling path after the intrusion of the Fedoz gabbro (e.g. Hermann et al., 1996). It is important to note that staurolite and chloritoide have been observed in the metapelites but neither sillimanite nor cordierite formed. In the peridotites no evidence for retrograde formation of plagioclase could be found.

3.5. COMPILATION OF HIGH-TEMPERATURE STRUCTURES

Pre gabbro structures: The evolution of high-grade structures is separated by the gabbro intrusion. As the gabbro is of Permian age (Hansmann et al., 1995) all structures found in this rock have to be younger. A sequence of structures occurring exclusively in the ultramafic rocks and predating the granulitic overprint is considered as mantle deformation which developed prior to the Fedoz gabbro intrusion (Tab. 1). The oldest folds in the pelitic granulites are crosscut by gabbroic dikes and therefore represent pre-gabbro structures too.

Granulite facies conditions: Subsequent to the Fedoz gabbro intrusion, all three rock types display the same deformational events and shared a common metamorphic evolution (Tab. 1). The linear and planar fabric that formed under granulite facies conditions maintained the same orientation in the gabbro, the pelitic granulites and in the ultramafic rocks (Figs 3a, 3b) indicating a high-temperature deformation affecting the whole crust-mantle transition. It is suggested that this deformation led to a parallelisation of older structures in the ultramafic rocks and produced the second generation of tectonites. Alpine shear zones within this section did not rotate the foliation formed under granulite facies condition which indicates that the original relative geometry is still preserved in the Mt. Braccia area. The linear structures suggest a simple-shear-dominated deformation. The extensive annealing of the rocks under high temperature conditions prevents shear sense determinations from microstructures. The rotation of magmatic flow textures into the tectonic flaser structure, however, provides the best shear sense indicators within the Fedoz gabbro. For the interpretation of this movement the original orientation of the section is needed. The crust-mantle transition has a polarity at the time of gabbro intrusion with the mantle rocks at the bottom overlain by the lower crustal rocks. The actual section (Fig. 3b) is overturned by later Alpine folding (second backfolding event of Hermann and Müntener, 1992; Spillmann, 1993). Thus the movement of the northern block towards the east within the gabbro (Fig. 4) can be translated into an originally top-to-the-east sense of shear. The second generation of tectonite in the peridotite is crosscut by later phlogopite-Ti-rich pargasite dikelets.

Tab. 1 Correlation of high-temperature, pre-Alpine structures of the Malenco lower crust-mantle complex.

Rock type **Event**	**Fedoz gabbro**	**Ultramafic rocks**	**Pelitic granulites**
Pre-gabbro structures		– layered mantle – boudinage of layers – tectonite 1 – pyroxenite intrusion	– folding
Gabbro intrusion	– magmatic flow texture	– gabbro dikes	– gabbro dikes
Granulite facies	– tectonic flaser structure – foliation+lineation – reequilibration	– foliation+lineation – (tectonite 2) – reequilibration	– foliation+lineation – reequilibration
Retrograde conditions	– shearzones+mylonites	– shearzones+mylonites – boudinage of dunites	– paragonite foliation

Retrograde conditions: The linear fabric formed under granulite facies conditions is crosscut by later mylonites and shear zones indicating strain localization with decreasing temperatures. The mylonites developed after a period of isobaric cooling. The rotation of pre-existing lineation into mylonites and shear zones can be used for shear sense determination. Although the sense of shear is not uniform, most of the observed mylonites indicate an original movement of the upper block towards the east. During the mylonite formation the rocks became partly hydrated. Strain localization, retrograde metamorphism and hydration are interpreted to be related to considerable exhumation.

To summarize the high-temperature structures we point out that the common evolution of the crust-mantle transition in the Malenco unit is characterized by two main features: (1) A penetrative deformation producing a dominantly linear fabric and a weak foliation that is almost completely annealed under high temperature conditions. (2) Increasingly localized retrograde deformation formed mylonites and shear zones leading to grain size reduction and dynamic recrystallization without later annealing.

4. Extensional shear zone within the Margna nappe

4.1. ROCK TYPES OF THE MARGNA NAPPE

Already at the beginning of this century, STAUB (1917) defined two different series of rocks within the Margna nappe: (i) The Maloja series containing highly deformed paragneisses and orthogneisses, and (ii) the Fedoz series consisting of rocks with relics of a high-grade pre-Alpine metamorphism. The most complete description of the complex relationship within the Margna basement rocks is given by SPILLMANN (1993) who defined the Fedoz and Maloja series in a slightly different way. To prevent confusion we use in the following the names in the sense of SPILLMANN (1993).

Lower crust (Fedoz series and Fedoz gabbro): In the Fedoz series paragneisses, marbles and calcsilicate rocks with relics of high-grade metamorphism are found. The Fedoz gabbro crosscuts the metasedimentary banding documenting intrusive contacts to the Fedoz series (SPILLMANN, 1989). The Fedoz gabbro shows exactly the same features as in the Malenco unit around Mt. Braccia. A differentiation trend from magnesian gabbro to ferroan gabbronorite has also been found in the Margna nappe. In addition, pre-Alpine structures formed under high-grade conditions are preserved in some places. Therefore, we suggest that the Fedoz gabbro and the Fedoz series of the Margna nappe are similar to the gabbro and the pelitic granulites of the Malenco unit. As a consequence the Fedoz gabbro and the Fedoz series in the Margna nappe represent lower crustal rocks too and were located at 35 km depth in Permian time.

Upper crust (Maloja series and orthogneisses): The Maloja series consists of paragneisses which have suffered a regional metamorphism at middle amphibolite facies conditions in pre-Alpine time and represent the old Variscan basement (SPILLMANN, 1993). In regions with strong Alpine overprint, the Maloja- and Fedoz series are hardly distinguishable. The orthogneisses are deformed Late Variscan calcalkaline granitoids similar to the Bernina intrusives (SPILLMANN and BÜCHI, 1993) which have a crystallization age of about 330 Ma (VON QUADT et al., 1994). These rocks are overlain by Permo-Mesozoic sediments and were thus the highest crustal basement rocks in Permian and Mesozoic time.

The Margna basement is therefore an association of upper and lower crustal rocks both consisting of metasediments (Maloja- and Fedoz series, respectively) and intrusives (orthogneisses and Fedoz gabbro, respectively). Through detailed mapping, LINIGER and GUNTLI (1988) and SPILLMANN (1993) investigated the geometric relationship between the two series. The Margna nappe forms a recumbent fold with two parts (Fora and Maloja segments) both having the lower crustal rocks in the core and the upper crustal rocks in the outer part. Figure 9 shows a reconstruction of the nappe pile with the two typical rock associations in the Margna basement.

4.2. CONTACTS

The interface between the upper- and lower crustal rocks is overprinted by the first Alpine deformation forming the nappe pile (Fig. 9). This interface is a prominent structure and is mappable over the whole western part of the Margna nappe (Margna normal fault, Fig. 2). Although the contact is usually overprinted by the Alpine deformation, some extensional features are preserved north-west of Chiareggio (Fig. 2): (i) The gabbro displays a mylonitic foliation in the first 10–20 m above the contact and then passes into well preserved high temperature flaser texture. (ii) In the contact zone, imbricated gabbro blocks of 1–10 m dimension lie within the orthogneisses. (iii) Along the interface, boudins of ultramafic rocks occur. One lens, about 30 m long, lies directly to the east of Piz Fora (Fig. 2) and is overprinted by Alpine metasomatism (Spillmann, 1988). Another lens, south of Piz Fora, displays a static serpentinization, with preservation of the old layered structure. This demonstrates that imbrication occurred when the ultramafic bodies were still competent peridotite, i.e. before serpentinization.

Between the Malenco ultramafic rocks and the Margna nappe, a tectonic breccia (Ur breccia) of variable thickness (2–30 m) occurs in some places. Cm- to m-sized knobs and components of both, upper crustal Margna rocks and ultramafic rocks were found in a micaschist-rich matrix (Gerber, 1966; Pfeifer, 1972; Sidler and Benning, 1992). Although the Margna nappe is thrusted at least 25 km over the Malenco-Forno unit, there are some arguments that the Ur-breccia formed earlier at the top of the Malenco unit: (i) In general, the Alpine deformation within the serpentinites and the Margna basement has led to the formation of mylonites and not to brecciation. Because serpentinites are less competent than basement rocks, the formation of ultramafic components in the breccia has to be older than the serpentinization in an overall low temperature brittle regime (Trommsdorff et al., 1993). (ii) Sidler and Benning (1992) reported a foliation older than the Alpine main schistosity in many breccia components. This pre-Alpine foliation is often preserved in albite and marked by rutile. Rutile is common in the Fedoz gabbro and the Fedoz series but is not reported from the Maloja series and the orthogneisses. Therefore it is suggested that the Ur breccia involved components of the mantle, the lower and the upper crust.

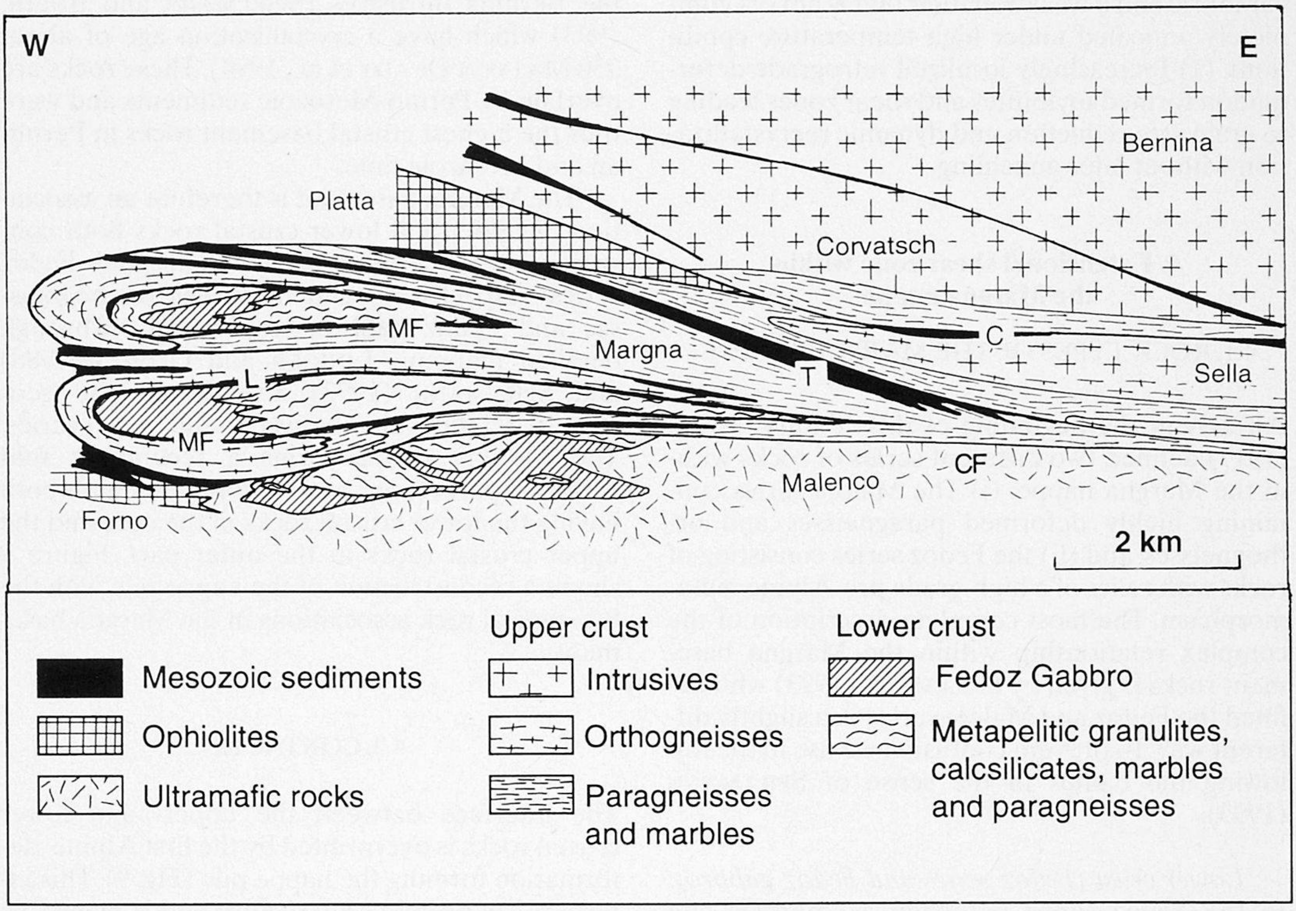

Fig. 9 Profile through the upper Penninic-lower Austroalpine nappe pile (modified after Spillmann, 1993) after retrodeformation of late Alpine structures. The Margna normal fault (MF) separates the lower crust from the upper crust and was folded during nappe formation. Lenses of ultramafic rocks (L) occur along the Margna normal fault. The Alpine nappe contacts are marked by the occurrence of Mesozoic sediments. The Tremoggia syncline (T) with its Mesozoic sediments connects the Margna with the Sella nappe (Hermann and Müntener, 1992). In the northwest, Margna and Sella nappes are separated from the Corvatsch/Bernina nappe by the Platta ophiolithes. To the south-east the Coaz sediments (C) occur between the Sella and Corvatsch nappe. CF mark the approximately position of the ophicarbonates of Campo Franscia.

4.3. THE MARGNA NORMAL FAULT

There are three arguments that the interface between the upper crustal- and lower crustal rocks is older than the Alpine compressional tectonics. (i) The interface is folded by the first Alpine deformation that forms the huge recumbent folds (Fig. 9). (ii) Retrodeformation of the nappe fold results in a geometry with the upper crustal rocks lying above the lower crustal rocks. Such a situation is more typical for normal faulting than for thrusting. (iii) The ultramafic boudins lying at the interface were integrated as competent peridotite. This indicates that this shear zone was active before the ultramafic rocks became serpentinized at the Tethyan ocean floor.

The upper crustal rocks lay near the surface in Mesozoic time because they are covered with sediments. The lower crustal rocks resided in about 35 km depth (10 kbar) in the Permian and in about 30 km depth (8.5 kbar) after the period of near isobaric cooling. The contrasting metamorphic conditions between upper crustal and lower crustal rocks at the interface indicate that about 25 km of rocks are missing between these two associations. This gives evidence for a huge extensional shear zone, the Margna normal fault, along which the lower crustal granulites were brought near the surface. It is difficult to determine the metamorphic conditions of this shear zone because of later Alpine metamorphic overprint. The mylonitic fabric of the Fedoz gabbro at the contact and the imbricated blocks of gabbros within the orthogneiss indicate that the Margna normal fault was a narrow shear zone with ductile to brittle behaviour along which mantle and crustal rocks have been integrated.

It is a matter of debate, whether the Ur breccia formed during Alpine thrusting or even earlier, by extensional faulting as proposed by TROMMSDORFF et al. (1993). The formation of a breccia instead of a mylonite is a good argument for a pre-collisional origin of this breccia. The breccia components with mantle, lower and upper crust further support an extensional formation along a fault zone. It is suggested that the Ur-breccia represents another part of the Margna normal fault where mantle rocks were in contact to the uppermost crust.

5. The continent-ocean transition

The exhumation of the Malenco mantle rocks at the Tethyan sea floor has been described by TROMMSDORFF et al. (1993) and can be summarized as follows:

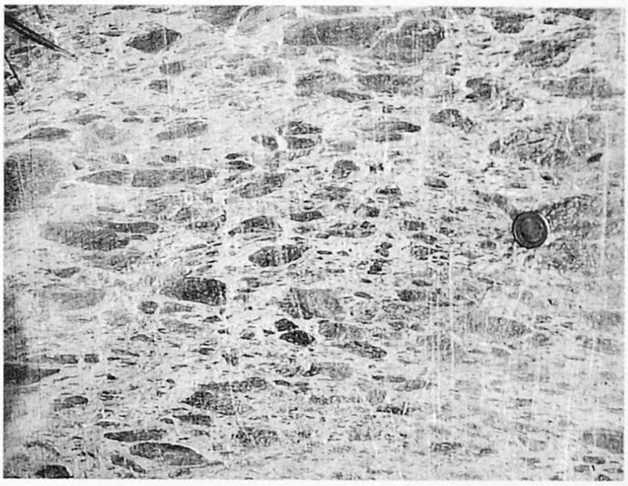

Fig. 10 Sedimentary ophicarbonates from Campo Franscia. Ultramafic pebbles lie in a calcite dominated matrix. Coin diameter: 2.5 cm. Swiss grid coordinates: (790.000/129.150).

(1) Matrix-supported ophicarbonates form in part the sedimentary cover on the top of exhumed mantle rocks (Fig. 10). This type of ophicarbonate is best preserved near Campo Franscia (Fig. 2) and indicates the minimum area of denuded mantle. The Ventina ophicarbonates in which ultramafic fragments predominate over carbonates, are interpreted as the filling of a fracture zone (POZZORINI, 1996). The δ^{13}C isotopic values (0.5 to 2‰) of the carbonates suggest a marine origin (POZZORINI, 1996). (2) The Malenco ultramafic rocks are crosscut by basaltic dikes belonging to the Forno unit. The Forno unit consists of metabasalts with typical MORB chemistry (GAUTSCHI, 1980; PERETTI and KÖPPEL, 1986) overlain by presumably Mid-Jurassic to Lower Cretaceous sediments. It shows most features of an ocean floor sequence (MONTRASIO, 1973; FERRARIO and MONTRASIO, 1977; PERETTI, 1985). (3) Rodingitization of mafic bodies within the ultramafic rocks indicates serpentinization of the mantle rocks in an oceanic environment.

Structural and petrographic investigations in the area of Alpe Mastabia and of Alpe Zocca (Fig. 2) provide new evidence about the geometry of the continent-ocean transition.

5.1. ALPE MASTABIA

In the southwestern part of the Malenco ultramafic body a zone of about 4 km length and 400 m width crops out above Alpe Mastabia consisting mainly of Mesozoic sediments and minor slivers of basement rocks (Fig. 2). The sedimentary sequence has an affinity to the Mesozoic sediments of the Margna nappe. For this reason, STAUB (1946) mapped the area as part of the Margna nappe. In the basement slivers, calcsilicate rocks with a high-grade pre-Alpine metamorphism similar to the one of the Fedoz series have been found (HONEGGER, 1977). In the vicinity of this zone, matrix-supported ophicarbonates occur (HONEGGER, 1977).

Detailed structural analysis by FORNERA (1996) revealed that the Mastabia zone lies in a synform of the second backfolding event and therefore, had been situated above the main ultramafic body. A general sequence of rocks can be defined from bottom to the top: The serpentinized ultramafic rocks are partly overlain by ophicarbonates. They are separated by a tectonic contact from the basement slivers forming the substratum of the Permo-Triassic meta-sandstones (e.g. HERMANN and MÜNTENER, 1992). The predominant rock type is a meta-dolomite of presumably Triassic age which is overlain by Jurassic marbles. The sequence is not complete everywhere. In some places the dolomite is in direct contact with the ultramafic rocks. The Permo-Mesozoic sequence, however, indicates a normal polarity with upward younging. Therefore the sediments cannot be the cover of the overturned limb of the Margna nappe fold (Fig. 9). The absence of an inverted polarity further indicates that no megascopic folds associated with nappe folding occur within the Mastabia zone (FORNERA, 1996). As a consequence of these observations the rocks of the Mastabia zone most likely belong to the Malenco unit.

The tectonic position of the Mastabia zone, the predominance of sediments and the similarity of the rocks to those of the Margna unit can best be explained by an extensional allochthon derived from the Austroalpine continental margin. Paleogeographically the margin was located further to the east. Therefore a fault with a top to the west movement was responsible for the formation of the allochthon. The mantle was denuded at this time, as demonstrated by the occurrence of sedimentary ophicarbonates.

5.2. ALPE ZOCCA

At Alpe Zocca (Fig. 2), all rock types that characterize the continent-ocean transition occur in a small area (BORSIEN, 1995).

(i) Dikes of Forno basalts with rodingitized borders have been found in the Malenco ultramafic rocks (ULRICH and BORSIEN, 1996).

(ii) The ophicarbonates of the Val Ventina lie in the vicinity of Alpe Zocca. Both observations suggest that the mantle was exhumed in the region of Alpe Zocca.

(iii) The Fedoz gabbro partly occurs as dikes within the mantle rocks. The border between gabbro and ultramafic rocks is often rodingitized, indicating that dike intrusion preceded serpentinization of the mantle rocks.

(iv) Granulitic metapelites and calcsilicates are overprinted by Alpine metamorphism but still contain relics of pre-Alpine high-grade metamorphic assemblages. They are associated with the Fedoz gabbro and are overlain by a thin ultramafic sheet. This indicates that both gabbro and lower crust are part of the Malenco unit.

(v) Orthogneisses that are in contact with ultramafic rocks occur in two different tectonic positions (e.g. ULRICH and BORSIEN, 1996). The Ventina gneiss wedge and an orthogneiss of Alpe Zocca lie above the ultramafic rocks and form a synform related to the second backfolding event. There are two possibilities to explain their position. (a) They are part of the overturned limb of the Margna nappe and form a klippe. (b) They are part of the Malenco unit and represent an extensional allochthon. However, a very similar orthogneiss occurs at Alpe Zocca also within the ultramafic rocks (BORSIEN, 1995) and has no structural relation to the one lying above.

The occurrence of orthogneisses at different tectonic levels at Alpe Zocca suggest, that the gneisses have been disrupted during rifting. As a consequence we interpret the orthogneisses within the Malenco unit as extensional allochthons.

6. Reconstruction of the continental margin in the Malenco-Margna region

6.1. OCEAN DOMAIN

From the data and observations presented above, and additional information obtained from the sedimentary cover of the Austroalpine nappes (EBERLI, 1988; FROITZHEIM and EBERLI, 1990; SPILLMANN, 1993), the passive continental margin of the Adriatic plate can be reconstructed in this area (Fig. 11). Between the ocean floor sequence of the Forno unit and the Margna continental margin a region with denuded subcontinental mantle existed. The minimum lateral extent (10 km) of denuded mantle is given by the eastern-most occurrence of sedimentary ophicarbonates in Campo Franscia. The Ventina ophicarbonate zone is interpreted as a fracture zone within the denuded mantle (POZZORINI, 1996).

The fossil crust-mantle section of Mt. Braccia was completely exhumed. The intrusive contacts of the Fedoz gabbro and the Forno basalt dikes with the Malenco mantle were found in close proximity at Alpe Zocca. Both mafic rocks show a tholeiitic differentiation trend (Ulrich and Borsien, 1996). Although this feature is common in an oceanic lithosphere, the Forno basalts have no genetic relationships to the gabbros because they are separated in time (Jurassic vs Permian) as well as in intrusion depth (surface vs 35 km).

Some parts of the mantle rocks were covered with slivers of continental crust which are interpreted as extensional allochthons formed during rifting. They have a great affinity to the rocks of the Austroalpine continental margin. Best evidence for such extensional allochthons was found in the Mastabia Zone where large masses of Mesozoic sediments with minor basement slivers overlay the mantle rocks.

6.2. CONTINENTAL BLOCKS

The Austroalpine margin can be subdivided into three main continental blocks which are the precursors of the later Alpine nappes: Margna, Sella and Bernina block (Fig. 9, Fig. 11). A detailed description of their geometry is given in Spillmann (1993). The eastern border of the Bernina block is marked by an E-dipping normal fault, forming the Alv basin partly filled with syntectonic breccias of Toarcian age (Eberli, 1988). In the southern part, the Coaz trough lies between the Bernina and the Sella blocks (Spillmann, 1993). More to the north, the Bernina and Err blocks are separated from the Sella and Margna blocks by the ophiolithic Platta wedge. In the Tremoggia trough sedimentary breccias provide evidence for a Jurassic fragmentation of the Sella and Margna block (Hermann, 1991).

6.3. MARGNA NORMAL FAULT

Below the upper crustal rocks of the Austroalpine continental margin, lower crustal rocks are attached. The interface corresponds to a major extensional low angle normal fault (Margna normal fault). Retrodeformation of the Alpine nappe structure allows reconstruction of the approximate position of the Margna normal fault. Westward overthrusting led to the formation of the Lower Austroalpine nappe pile (Liniger and Guntli, 1988; Hermann and Müntener, 1992). As the cores of the two Margna nappe segments comprise lower crustal rocks, their original position was below the upper crustal rocks (Fig. 11). The gabbros and lower crust of the Malenco unit are completely surrounded by ultramafic rocks and isolated from the ones of the Margna nappe. This indicates that the lower crustal rocks were disrupted prior to the Alpine compression. Therefore the Fedoz gabbro and the pelitic granulites cannot be regarded as the undisturbed passively uplifted lower crust of a lower plate margin. In fact, the occurrence of lower crust is restricted to the Malenco-Margna region. Along the Austroalpine margin to the north (Err and Platta nappes, Fig. 1) relics of lower crust have not been found (Manatschal, 1995).

The assumed dip direction of the Margna normal fault results from the following observations. In the Mt. Braccia area the lower crustal rocks were exhumed and represent the footwall of the Margna normal fault. More to the east, the Margna normal fault lies below the upper crust of the Margna block. In the Sella block no relics of mantle or lower crustal rocks could be found. Therefore we suggest an eastward dip for the Margna normal fault (Fig. 11). Prior to the westward thrusting, the lower crustal rocks of the tec-

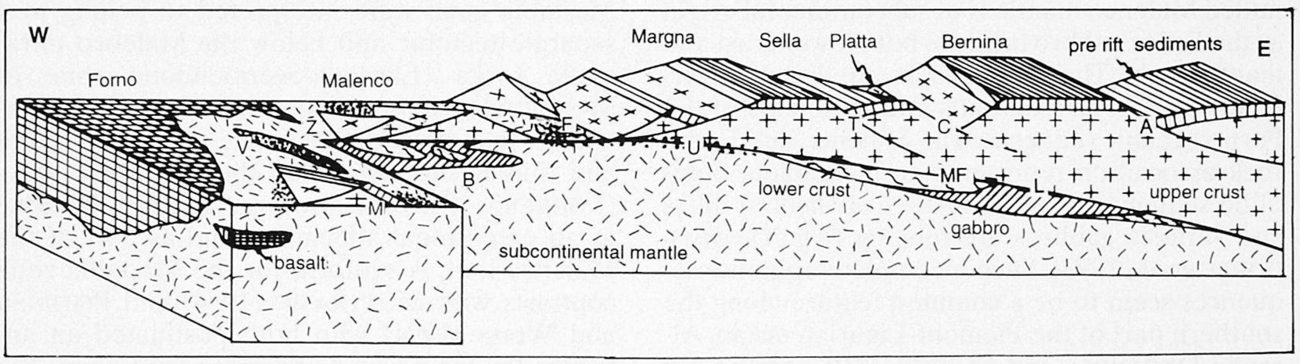

Fig. 11 Reconstruction of the continent-ocean transition in the Val Malenco region. Syn- and post-rift sediments are not shown. Abbreviations: A = Alv trough, C = Coaz trough, T = Tremoggia trough, U = Ur-breccia, F = Sedimentary ophicarbonates of Campo Franscia, B = Fossil crust-mantle transition of the Mt. Braccia area, Z = Alpe Zocca region, V = Ophicarbonates of a fracture zone in the Val Ventina, M = Extensional allochthon of the Mastabia zone, MF = Margna normal fault, L = Lenses of ultramafic rocks.

tonically higher Margna nappe were located more to the east than the ones of the Malenco unit. Hence, the disruption of the lower crustal rocks most probably reflects a top-to-E sense of shear along the Margna normal fault.

The Ur breccia is interpreted as the continuation of the low angle normal fault between upper and lower crust bringing the ultramafic rocks in direct contact with the upper crustal basement rocks. It is not clear, whether the Ur breccia was still covered by the continent or if it was also denuded at the sea floor.

The reconstruction presented here is very similar to the geometry reported from the Galicia margin (BOILLOT et al., 1995a): In Galicia, blocks of upper continental crust are separated from the mantle rocks by a low angle normal fault. In the zone between the large basaltic lava flows and the continental margin, denuded subcontinental mantle lies at the ocean floor. In contrast to the Austroalpine continental margin, large boudins of lower crust were not found until now on the Galicia margin. It must be checked carefully if the Ur-breccia could correspond to a tectonic breccia found at the interface of mantle rocks to upper crustal rocks in the Galicia margin (BOILLOT et al., 1995b).

7. Discussion

The following discussion is focused on two different subjects, both related to the reconstructed continental margin in the Margna-Malenco region: (1) The implication of the margin geometry for Alpine tectonics. (2) A model for the development of this continental margin.

7.1. IMPLICATIONS FOR ALPINE TECTONICS

Field data unequivocally demonstrate that the denuded Malenco mantle is of subcontinental origin as the Fedoz gabbro intrudes both lower crust and mantle rocks. The mantle rocks are directly overlain by pillow lavas, basalts and sediments of the Forno oceanic sequence. The Malenco and Forno rock association represents an incomplete ophiolitic sequence as great masses of sheeted dikes and Jurassic gabbros are missing (e.g. TROMMSDORFF et al., 1993). Such incomplete ophiolite sequences seem to be a common feature along the southern part of the Piemont-Ligurian ocean. Already DECANDIA and ELTER (1969) pointed out that this might be due to denudation of subcontinental mantle. In recent time, many authors postulated a subcontinental origin for several ultramafic masses in the Alps (see Fig. 1 for location) based on petrographic, structural and chemical arguments: Lanzo (POGNANTE et al., 1985), N-Lanzo (BODINIER et al., 1991), Western Alps (LEMOINE et al., 1987), Erro-Tobbio (PICCARDO et al., 1990; VISSERS et al., 1991), External Ligurides (PICCARDO et al., 1990; RAMPONE et al., 1993). All of these ultramafic bodies seem to have occupied a similar paleogeographic position at the continent-ocean transition.

The good preservation of the continent-ocean transition in the Malenco-Margna area and in the Err and Platta nappes indicate that these units were lying above the Alpine subduction zone. This agrees with the observation that no Alpine metamorphic discontinuity occurs at the Penninic-Austroalpine boundary in Val Malenco. Therefore it is suggested that subduction started within the oceanic domain in this region.

Traditionally, the Penninic-Austroalpine boundary was defined in the Malenco region by the lithological change from ultramafic to continental basement rocks (MONTRASIO and TROMMSDORFF, 1983; LINIGER, 1992). All basement rocks found in this region were considered as part of the Margna nappe (CORNELIUS, 1925; STAUB, 1946). However, the pelitic granulites of the Mt. Braccia area are welded to the mantle rocks by a gabbroic intrusion and clearly belong to the Penninic Malenco unit (Figs 2, 3). The Alpine nappe contact in this region thus is defined by the contact between the strongly deformed Malenco granulites and the upper crustal rocks of the overturned limb of the Margna nappe (see Fig. 9). A lot of complications in such boundary zones are not necessarily due to compressional imbrication but might be due to a complex geometry of the continent-ocean transition created during rifting. With the newly defined Penninic-Austroalpine boundary large-scale structures that overprint the nappe pile are more easily explained.

The sediments and basement slivers of the Mastabia zone were interpreted to belong to a separate tectonic unit below the Malenco ultramafic rocks (Lanzada-Scermendone zone of MONTRASIO, 1984). Structural analysis demonstrated that the Mastabia zone forms a synform and thus is situated above the ultramafic rocks (FORNERA, 1996). We interpret the Mastabia zone as an extensional allochthon and as part of the Malenco unit. A synform for the Mastabia zone contrasts with MONTRASIO (1984) and PFIFFNER and WEISS (1994) who both postulated an antiform for the Lanzada-Scermendone zone. The correlation of rock types between the Scermendone zone and the Mastabia zone is weak. In the Mastabia zone Mesozoic sediments predominate over basement rocks whereas in the Scermendone zone only relics of Mesozoic sediments occur (PFIFFNER and WEISS, 1994). Thus, it remains unclear if both zones belong to the same tectonic unit. To clarify this, more structural data from the zone between Alpe Mastabia and Val Scermendone is needed.

The extensional allochthons and the denuded pelitic granulites integrated in the Malenco unit demonstrate that this unit, characterizing the former continent-ocean transition, is very heterogeneous but has nothing in common with an ophiolitic mélange of an accretionary wedge.

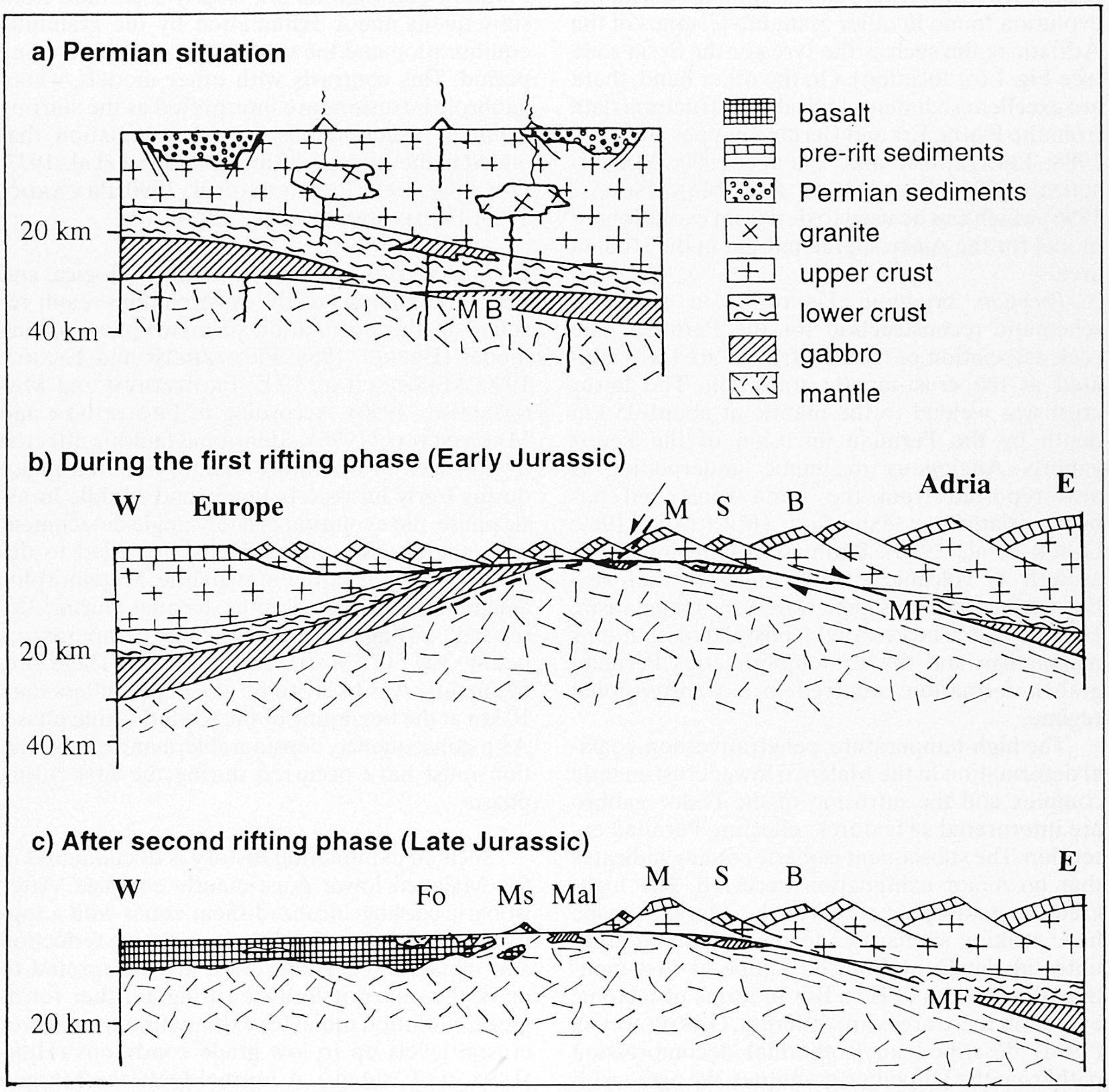

Fig. 12 Evolutionary model for the Austroalpine margin in the Val Malenco area. Abbreviations: MB = Crust-mantle transition of the Mt. Braccia region, M = Margna, S = Sella, B = Bernina, MF = Margna normal fault, Mal = Malenco, Ms = Mastabia, Fo = Forno.
(a) Permian extension led to magmatism penetrating the entire continental crust, in particular to magmatic underplating of gabbroic rocks.
b) In a first rifting phase, the mantle and lower crustal rocks were uplifted along the E-dipping Margna normal fault. The area where the later W-dipping detachment started is indicated by a dashed arrow and a dashed line. Syn-rift sediments are not shown.
c) Situation after the final break-up of Europe and Adria. Syn- and post-rift sediments are not shown.

7.2. EVOLUTIONARY MODEL FOR THE MALENCO-MARGNA CONTINENTAL MARGIN

One of the outstanding characteristics of the Malenco-Margna system is that the evolution of lower crust and mantle rocks can be linked to the sedimentological record of the same continental margin. On one hand, the high-grade metamorphic features presented here can be compared with the evolution found in other granulite terranes of the Adriatic realm such as the Ivrea or the Sesia zone (see Fig. 1 for location). On the other hand, there are excellent sedimentological and structural data from the Platta, Err and Bernina nappes (EBERLI, 1988; FROITZHEIM and EBERLI, 1990; MANATSCHAL, 1995; FROITZHEIM and MANATSCHAL, 1996) which can be used to derive an evolutionary model for the Austroalpine margin in the studied area.

Permian situation: Figure 12 a shows a schematic reconstruction for the Permian. The rock association of the Mt Braccia area was situated at the crust-mantle transition. The lower crust was welded to the mantle at about 35 km depth by the Permian intrusion of the Fedoz gabbro. Analogous magmatic underplating is also reported from the Ivrea zone, and has been related to extension (FOUNTAIN, 1989; QUICK et al., 1992). Permian granite intrusions as well as volcanic activity indicates that also the upper crust was penetrated by magmatism. HANDY and ZINGG (1991) postulated that this magmatism and the contemporaneous Permian graben formation occurred in a transtensional regime.

The high-temperature, penetrative, non-coaxial deformation in the Malenco lower crust-mantle complex and the intrusion of the Fedoz gabbro are interpreted as features reflecting Permian extension. The subsequent isobaric cooling indicates that no major exhumation occurred. The high-grade metamorphic rocks of the Margna nappe have striking similarities to the Valpelline granulites in the Dent Blanche klippe as first mentioned by STAUB (1917). But in terms of tectonic evolution these areas are different. GARDIEN et al. (1994) described an isothermal decompression path from the Valpelline granulites. We agree with the interpretations of GARDIEN et al. (1994) who point out that this isothermal decompression indicates post-Variscan extension of thickened crust that had no relation to the later opening of the Tethyian ocean.

In the Ivrea zone, Permian extension with gabbroic underplating and ductile high-temperature shearing (BRODIE and RUTTER, 1987) is followed by deformation along the Pogallo line that is related to Jurassic rifting (SCHMID et al., 1987; HANDY and ZINGG, 1991). The division in a Permian and a Jurassic extensional event is further supported by sedimentological evidence from the Southern Alps (BERTOTTI et al., 1993). Based upon the extensional metamorphic evolution, a similar scenario is proposed for the Val Malenco region. The intrusion of the Fedoz gabbro and the Permian deformation are clearly separated from subsequent major exhumation by the granulitic equilibration and the subsequent isobaric cooling period. This contrasts with other models, where gabbroic intrusions are interpreted as the starting event of a continuous crustal attenuation that ended in the Jurassic rifting (DAL PIAZ et al., 1977; DAL PIAZ, 1993; PICCARDO et al., 1990; PICCARDO, 1995; TROMMSDORFF et al., 1993).

Jurassic rifting: Detailed sedimentological and structural analysis of the Austroalpine realm resulted in the postulation of a two-phase rifting model (EBERLI, 1988; FROITZHEIM and EBERLI, 1990; MANATSCHAL, 1995; FROITZHEIM and MANATSCHAL, 1996). According to FROITZHEIM and MANATSCHAL (1996) extensional faulting affected a wide area of the future margin in a first phase during Early Jurassic. In the second, Middle Jurassic phase, the evolution of a low-angle detachment with a top-to-W sense of movement led to denudation of subcontinental mantle. Metamorphic assemblages in cataclasites formed during the second rifting phase indicate temperatures below 300 °C (MANATSCHAL, 1995). Therefore, the mantle was likely to be at a depth of less than 10 km at the beginning of the second rifting phase. As a consequence, considerable mantle exhumation must have occurred during the first rifting phase.

Such an exhumation history is documented in the Malenco lower crust-mantle complex. After isobaric cooling, localized shear zones with a top-to-E sense of shear leading to grainsize reduction and dynamic recrystallization are interpreted to mark the onset of Jurassic rifting. Further retrograde evolution indicates exhumation from lower crustal levels up to low grade conditions (HERMANN et al., subm.). A normal fault, the Margna normal fault, along which the lower crustal and mantle rocks have been brought in contact with the upper crust, has been found inside the Margna nappe. The lack of about 25 km of continental lithosphere between upper and lower crustal rocks implies a displacement of about 50 km along the Margna normal fault assuming a dip of the fault surface of 30°. The geometric reconstruction suggests a top-to-E sense of movement. Therefore this first rifting phase which led to uplift of the mantle and of the lower crustal rocks along an E-dipping low angle normal fault, is postulated to have been dominated by simple shear.

Such an evolution would be in agreement with the evolution reported from the Ivrea zone where a top-to-E movement along the Pogallo line led to Jurassic exhumation of the Ivrea high-grade metamorphic rocks (HANDY, 1987; SCHMID et al., 1987; HANDY and ZINGG, 1991). A simple shear-dominated first rifting phase contrasts with the interpretation of FROITZHEIM and MANATSCHAL (1996) who postulated a pure shear regime for this phase. The estimated stretching factor of 1.2 (BERTOTTI et al., 1993) for the Jurassic extension recorded in the south-Alpine sediments of the Lombardian segment, however, clearly indicates that no major mantle uplift can be explained by pure-shear rifting mechanisms alone.

Figure 12b shows a reconstruction of the first rifting phase. Along the E-dipping Margna low angle normal fault (MF) the lower crustal and mantle rocks were affected first by ductile shearing. With ongoing uplift the deformation became more and more localized and brittle, leading to disruption of the lower crust. The area of the initiation of the second rifting phase is indicated with a dashed arrow and line. The combination of two low-angle faults with opposite sense of movement offers a simple possibility to eliminate the lower crust. In fact, the absence of large bodies of lower crust has always been a major problem of one-phase rifting models. During the second rifting phase in the Err-Platta area, the mantle was denuded by a low angle detachment with top-to-W sense of movement (MANATSCHAL, 1995). In the Malenco region such a detachment probably led to the formation of extensional allochthons. The transition from rifting to the opening of the ocean is marked by the formation of pillow lavas and sediments of the Forno ocean floor sequence (Fig. 12c).

The Austroalpine margin has been considered a lower-plate margin (FROITZHEIM and MANATSCHAL, 1996) as well as an upper-plate margin (FAVRE and STAMPFLI, 1992). Detailed investigations of sediments and upper crustal structures (EBERLI, 1988; FROITZHEIM and EBERLI, 1990; MANATSCHAL, 1995; FROITZHEIM and MANATSCHAL, 1996) as well as of exhumation metamorphism and structures in lower crustal and mantle rocks (MÜNTENER and HERMANN, 1996) demonstrate that a simple one-phase rifting model cannot explain the studied margin. Therefore, one has to be careful in applying concepts such as isostatic response (i.e. uplift and subsidence) coming from one-phase models. We propose that the terms upper/lower plate margin should no longer be used for the Austroalpine margin.

8. Conclusions

From the study of exhumation-related structures in the Malenco lower crust-mantle complex the following conclusions can be drawn:

(i) Subcontinental mantle and attached lower crust were denuded along the Austroalpine margin in the Malenco region.

(ii) Exhumation started with ductile shear zones followed by more and more localized deformation under retrograde conditions.

(iii) Associated with the exhumation, the lower crust was disrupted and the mechanical behaviour of the rocks changed from ductile to brittle.

(iv) The Margna normal fault is one of the most important rifting structures in the Austroalpine as lower crustal and mantle rocks coming from about 35 km depth are juxtaposed to upper crustal rocks covered by Mesozoic sediments. This implies that the Margna normal fault accommodated at least 50 km of displacement.

(v) All observations are consistent with simple-shear-dominated Jurassic rifting.

The complex geometry of the reconstructed continent-ocean transition has important consequences for Alpine tectonics. (a) Ultramafic thrust sheets paleogeographically situated at continental margins may be very heterogeneous comprising ophicarbonates, basalts, remnants of lower crust as well as slivers of upper crustal rocks representing extensional allochthons. Such rock associations formed during extensional tectonics and are not necessarily a product of compressional imbrication. (b) The Penninic-Austroalpine boundary can no longer be regarded as the transition from ultramafic to crustal rocks and should be structurally defined. (c) Extensional structures are often reactivated during the compressional tectonics. The Margna normal fault, however, was integrated in the Margna nappe indicating that extensional and compressional faults do not always coincide.

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