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The oceanic Forno unit (Rhetic Alps): field relations, geochemistry and paleogeographic setting

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Keywords: Forno unit, ophiolite sequence, Austroalpine-Penninic boundary, continent-ocean transition

ABSTRACT

The Forno unit in the Eastern Central Alps (Oberengadin/Switzerland, Valtellina/Northern Italy) is an ophiolite sequence of the Alpine Tethys ocean. This unit is interpreted to connect the Margna domain, representing the distal part of the Adriatic continental margin, and the Malenco ultramafic rocks, representing pre-rift subcontinental mantle of the Adriatic plate.

Field relations in the study area show an uncommon lithostratigraphy for an oceanic sequence. A primary, oceanic association of Forno and Malenco domains is documented by metabasaltic dikes and bodies that intrude the Malenco peridotite, that preserves a complex pre-Alpine mantle history. The volcanic basement consists of porphyritic and Fe-Cu-Zn-bearing metabasalts and metapillows and metapillow breccias. A gabbroic layer has not been found. Locally, pre-Alpine contacts occur between metabasaltic rocks and Late Variscan intrusives of the Margna domain. These basalts are interpreted as dikes intruding the distal part of the continental margin. Main, trace and rare earth elements of Forno basalts and basalts in the Margna domain display a typical tholeiitic differentiation trend and a T-MORB character. It is suggested that both basalts come from the same source. The pelagic sedimentary sequence can be subdivided into a silicious-carbonatic and pelitic sequence (Rossi Series) and a flysch-type series (Muretto Series).

A continent-ocean transition can be reconstructed by retrodeformation of the Alpine structures. Denudated subcontinental mantle without a volcanic layer occurs continent-ward in the proximity of the Margna continental margin, whereas the mantle with a basaltic layer occurs ocean-ward. This geometry is very similar to the geometry of the western continental margin of Iberia (Galicia margin).

ZUSAMMENFASSUNG

Die Forno-Einheit in den Zentralalpen (Oberengadin/Schweiz, Veltlin/Norditalien) ist eine ophiolitische Abfolge des alpinen Tethysozeans. Diese Einheit wird als Bindeglied zwischen der Margna-Domäne, die den distalen Bereich des adriatischen Kontinentalrandes repräsentiert, und dem Malenco-Ultramafitit, der prä-rift subkontinentalen Mantel der Adriatischen Platte darstellt, betrachtet.

Die Feldbeziehungen im Untersuchungsgebiet zeigen eine für ozeanische Abfolgen ungewöhnliche Lithostratigraphie. Eine primäre, ozeanische Vergesellschaftung von Forno- und Malenco-Domäne ist dokumentiert durch metabasaltische Gänge und Körper, die den Malenco-Peridotiten intrudierten, der eine komplexe prä-alpine Mantelgeschichte aufweist. Die Forno-Vulkanite bestehen aus porphyrischen und Fe-Cu-Zn-führenden Metabasalten, sowie Metapillows und Pillowbrekzien. Eine Gabbro-Lage wurde nicht gefunden. An einigen Stellen gibt es prä-alpine Kontakte zwischen metabasaltischen Gesteinen und spätherzynischen Intrusiva der Margna-Domäne. Diese Basalte werden als Gänge, die in den distalen Bereich des Kontinentalrandes intrudierten, betrachtet. Haupt-, Spuren- und Seltene Erden Elemente von Forno-Basalten und Basalten der Margna-Domäne zeigen beide einen typischen tholeiitischen Differentiationstrend und einen T-MORB-Charakter. Es wird angenommen, dass beide Basalte von derselben Quelle stammen. Die pelagische Sedimentabfolge kann in eine kieselig-karbonatische und -pelitische Fazies (Rossi-Serie) und eine flyschartige Fazies (Muretto-Serie) unterteilt werden.

Durch Retrodeformation von alpinen Überprägungen kann ein Kontinent-Ozean-Übergang rekonstruiert werden. In der Nähe des Margna-Kontinentalrandes befindet sich denudierter Mantel, der keine vulkanische Lage aufweist. Von basaltischer Lage bedeckter Mantel befindet sich ozeanwärts. Diese Geometrie ist sehr ähnlich der des westlichen Kontinentalrandes von Iberien (Galicia Margin).

1. Introduction

Oceanic sequences play a fundamental role in the understanding of the break-up of continents and the formation of oceans. Such processes can be studied along continent-ocean transitions of modern passive continental margins (e.g. Iberian margin and the Red Sea), where the reconstruction of the early evolution relies mainly on the interpretation of seismic profiles, magnetic and gravity data, and samples from the ocean floor. In contrast, mountain belts provide easy accessible outcrops of oceanic and continental basement rocks and of the overlying pre-, syn- and post-rift sediments. However, studies

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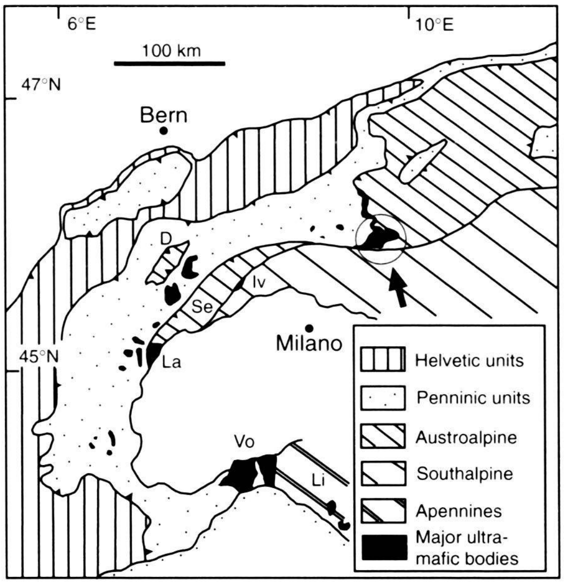

Fig. 1. Tectonic map of the Alps. The Helvetic units are part of the former European margin, whereas the Austroalpine, South Alpine and external Apennines were part of the Adriatic (African) margin. The Penninic and internal Apenninic (Ligurides) units include oceanic and distal continental margin associations. Li: Internal and external Ligurides, Vo: Voltri massif (Erro-Tobbio), La: Lanzo Massif, Se: Sesia-Lanzo zone, Iv: Ivrea zone, D: Dent Blanche klippe. The studied area is pointed out (Forno-Malenco unit).

in these units are often complicated by tectonic decoupling and metamorphic overprint, so that the history of the original continent-ocean transition can be tentatively reconstructed only under favourable conditions.

In some areas of the Alps, particularly in the South Penninic-Austroalpine boundary region in Southeastern Switzerland and Northern Italy (Fig. 1), detailed studies of the last few years allow for a reconstruction of the passive margin and the continent-ocean transition of the Alpine Tethys (see Froitzheim & Eberli 1990, Froitzheim & Manatschal 1996, Manatschal & Nievergelt 1997, Trommsdorff et al. 1993, Müntener & Hermann, 1996, Hermann & Müntener 1996). In the South Penninic realm the ultramafic body of the Valmalenco region (Fig. 2) does not only consist of ultramafic rocks, but also of lower crustal granulitic rocks that are both intruded by a Permian gabbro body. This demonstrates a welding of ultramafic and lower crustal rocks and a subcontinental origin of these peridotites (Trommsdorff et al. 1993, Müntener & Hermann 1996, Hermann & Müntener, 1996). In the Austroalpine realm the disintegration of the Triassic carbonate platform is well documented in sedimentary sequences and Jurassic structures (Eberli 1988, Froitzheim & Eberli 1990, Handy 1996, Manatschal & Nievergelt 1997). Two phases of rifting in Early to Middle Jurassic time with pronounced normal faulting are distinguished (Eberli 1988). Rifting ended in late Middle Jurassic time when an oceanic crust was formed and upper Middle Jurassic radiolarites were deposited on syn-rift sediments of the continental margin. During Jurassic rifting the subcontinental mantle of the Malenco area was denudated and exposed to the sea floor and the ultramafic rocks were serpentinized. Ophicarbonates were deposited in fractures on the top of these ultramafic rocks (Pozzorini & Früh-Green 1996).

In this context, the Forno oceanic sequence plays a key role, as it connects the continental Margna crust (Austroalpine realm) and the ex-subcontinental Malenco. In the context of the new paleogeographic reconstructions and evolutions in the studied area the Forno ocean floor sequence has been re-studied. The aim of this study is (i) to give a new and detailed petrographic and lithostratigraphic characterization of the Forno unit, (ii) to document the field relations between the Forno unit and the Malenco and Margna units, and (iii) to give a detailed geochemical characterization of the Forno and Margna metabasalts. Finally, a palinspastic reconstruction of the continent-ocean transition in the Valmalenco region will be made.

2. Regional setting

The Austroalpine-Penninic boundary in southeastern Switzerland and Northern Italy (Fig. 2) involves, from top to bottom and from east to west, the following units:

The Lower Austroalpine *Bernina* and *Margna nappe*. It is a system of west-facing recumbent folds of crystalline basement and Permo-Mesozoic cover (Fig. 3). These units represent the distal part of the Austroalpine plate (Adriatic continental margin s.l., Montrasio & Trommsdorff 1983, Weissert & Bernoulli 1985, Froitzheim & Manatschal 1996). The basement of the Lower Austroalpine Margna nappe consists of basement rocks (metapelites, carbonates and amphibolites) with locally preserved pre-Alpine amphibolite facies metamorphic assemblages (Guntli & Liniger 1989). This basement is intruded by a gabbro complex (Fedoz Gabbro), which preserves a pre-Alpine high-grade metamorphic overprint (Bissig 1997, Bissig & Hermann 1999). Lenses of amphibolites that have no traces of a pre-Alpine metamorphism occur within Late-Variscan granodioritic and granitic rocks. The Permo-Mesozoic cover of the Margna nappe consists of Permian phyllites, Triassic evaporites and carbonates, Liassic silicious marbles (Liniger & Guntli 1988) and Upper Jurassic to Lower Cretaceous radiolarites and Calpionella limestones (Liniger 1992).

The South-Penninic *Malenco* and *Forno units*. The Malenco ultramafic body (~130 km^2) is one of the largest ultramafic masses in the Alps dominated by variably serpentinized ultramafic rocks. In the area of Mt. Braccia (Fig. 2) gabbroic rocks and pelitic granulites are welded to the ultramafic rocks, as documented by intrusive contacts, and thus represent a preserved crust-mantle section (Trommsdorff et al. 1993, Müntener & Hermann 1996). In this reconstruction the Malenco ultramafic rocks may be interpreted as denudated, subcontinental portion of the Austroalpine (Adriatic) lithosphere. In Alpine less deformed and serpentinized areas (e.g. Mt. Braccia) spinel lherzolites of variable composition are predominant. Several

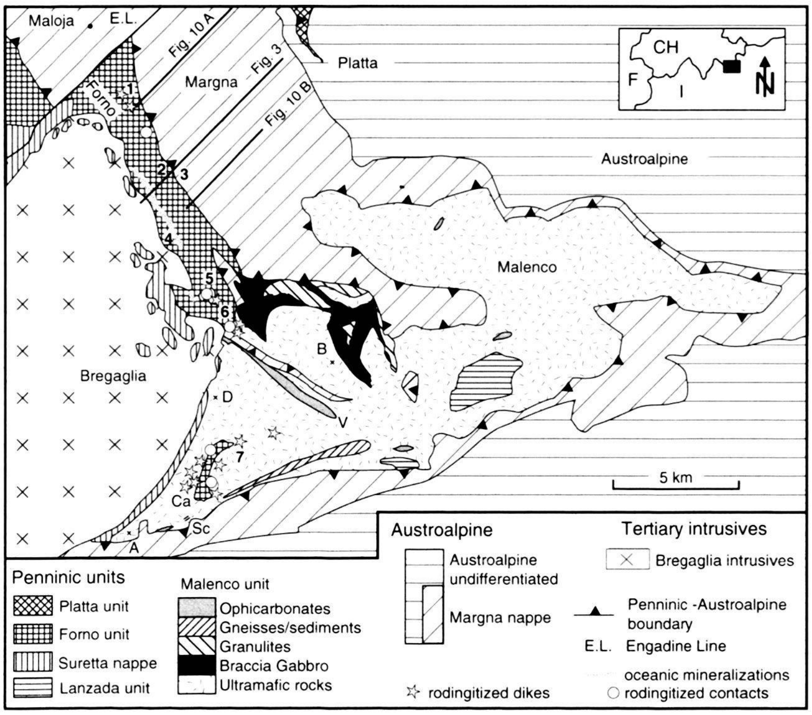

Fig. 2. Geological-tectonic map of the Austroalpine-Penninic boundary and the Bregaglia pluton. Primary and pre-Alpine contacts between metabasalts and ultramafic rocks of the Forno-Malenco unit are indicated. Abbreviations: A: Sasso Arso, B: Monte Braccia, Ca: Cassandra amphibolite body, D: Monte Disgrazia, Sc: Passo Scermendone, V: Passo Ventina, 1: Alp da Cavloc, 2: Passo del Muretto, 3: south of Passo del Muretto, 4: Val Bona, 5: Alpe Sissone, 6: Alpe Zocca, 7: Cassandra area.
The traces of the cross-sections of Figs. 3 and 10 are indicated.

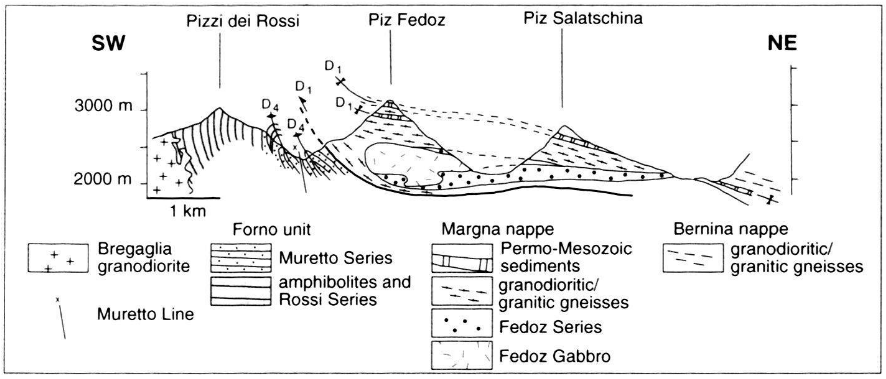

Fig. 3. Detailed SW-NE section through the eastern margin of the Bregaglia pluton (after Spillmann 1993).

generations of pyroxenites crosscut the peridotite and led to a pronounced layering. Dunites and harzburgites occur locally and are discordant to the layering. The gabbroic rocks of the Mt. Braccia area display a tholeiitic evolution from magnesian to ferroan gabbro-norite (Gautschi 1980, Hermann 1997). U-Pb dating on zircons yielded an age of 270+6/-4 Ma for the gabbro intrusion (Hansmann et al . 1996). The lower crust represents a metasedimentary sequence consisting of kyanite-bearing biotite-plagioclase-garnet gneisses with intercalations of calcsilicates and wollastonite- and olivine-bearing marbles. A detailed description of this crust-mantle section is given in Müntener & Hermann (1996) and Hermann et al. (1997).

The post-intrusive retrograde evolution of the gabbroic rocks, of the felsic granulites and of the ultramafic rocks is similar (Trommsdorff et al. 1993, Hermann 1997). The p-T-t path of this crust-mantle section documents a near-isothermal decompression and exhumation starting in Late Triassic (Müntener 1997). The mantle denudation is documented by a penetrative serpentinization, supported by marine signatures of stable isotopes in serpentine minerals (Burkhard & O'Neil 1988), and by the occurrence of ophicarbonates (Trommsdorff & Evans 1977; Pozzorini & Früh-Green 1996). This reflects an extension and thermal relaxation after gabbro intrusion and subsequent exhumation of the whole section to the ocean floor (Hermann et al. 1997).

During serpentinization gabbroic dikes of the Mt. Braccia area have been rodingitizied (Hermann 1997).

The *Forno unit* is an oceanic sequence located NW of the Malenco unit (Fig. 2). It consists of Jurassic basaltic pillow lavas and volcanoclastic rocks as well as of Jurassic to Lower

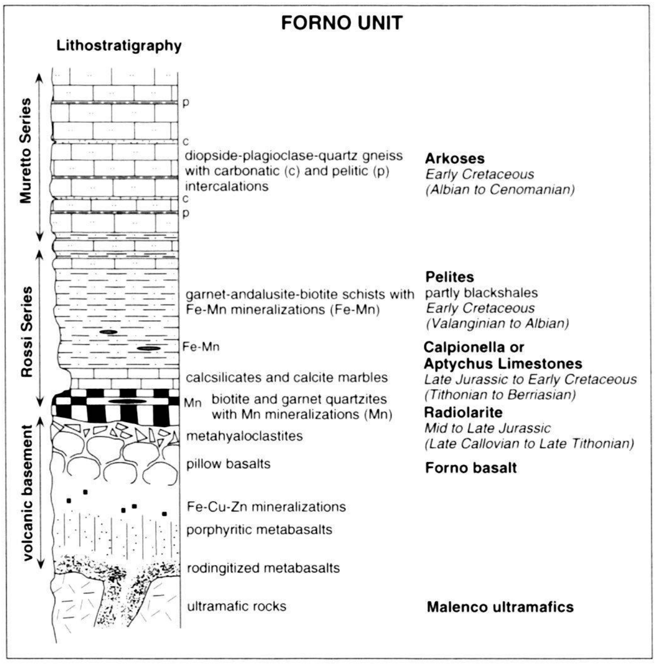

Fig. 4. Schematic lithostratigraphic sequence of the Forno unit. Age estimations based upon correlation with other ocean floor sequences in the Alpine Tethys (Baumgartner 1984, Weissert & Bernoulli 1985, Furrer et al. 1985, De Wever et al. 1987, De Wever & Baudin 1996).

Cretaceous sediments. This unit represents a part of the Piemontese-Ligurian ocean that formed adjacent to the Austroalpine margin in Middle to Late Jurassic.

The Middle Penninic *Suretta nappe* is composed of a crystalline basement and a Permo-Mesozoic cover. The pre-Mesozoic basement contains gneisses, amphibolites and metapelites with locally preserved pre-Alpine amphibolite facies metamorphic assemblages (Gieré 1985). The Mesozoic cover consists of Triassic quartzites, calcareous schists and marbles with concordant amphibolite layers. Middle Jurassic calcschists (Avers schists) with ophiolitic intercalations (Oberhänsli 1978) overlie the Suretta nappe with a tectonic contact (Milnes & Schmutz 1978). This sequence is distinct in lithostratigraphy from the sedimentary cover of the Forno unit and the Margna nappe.

The nappe pile of Penninic and Austroalpine units is partly intruded by the calc-alkaline Bregaglia (Bergell) intrusion, that has an Oligocene age (30 to 32 Ma, von Blanckenburg 1992).

The Alpine tectono-metamorphic evolution of the South Penninic-Austroalpine border region in the study area is characterized by 6 regional deformation phases (Puschnig 1996). The main deformation phase (D_1) of Late Cretaceous age (Jäger 1973, Frey et al. 1974) led to a westward thrusting and to the formation of large recumbent folds in the Margna nappe (Fig. 3, Liniger & Guntli 1988). The associated metamorphism is of upper greenschist to lower amphibolite facies conditions (Trommsdorff & Evans 1972, Guntli & Liniger 1989). Ductile shear zones leading to a thinning and collapse of the nappe pile are reported for the higher tectonic units (Liniger 1992, Spillmann 1993), but have not been observed in the study area. The south vergent first phase of backfolding (D_2) refolds the nappe contacts under retrograde conditions and is considered as deformation related to a north-south shortening in Paleogene and thrusting of the Austroalpine-South Penninic boundary region over the Middle and North Penninic units (Froitzheim et al. 1994). The subsequent deformation is characterized by shear zones with a top to the ESE sense of shear (D_3). North of the Engadine Line it is more prominent where a large detachment fault (Turba mylonite zone) cuts across the Tertiary nappe edifice (Liniger 1992, Nievergelt et al. 1996). The contact of the Forno-Malenco unit with the Suretta nappe represents the southern continuation of this fault (Puschnig 1996). All these structures are overprinted on a regional scale by the second phase of backfolding (D_4), characterized by large open anti- and synforms (Sidler & Benning 1992, Hermann & Müntener 1992, Spillmann 1993). Subordinate structures are the local verticalization of the tectonic units at the eastern border of the Bergell intrusives (D_5) due to the emplacement of the pluton and the regional transverse folding (D_6), perpendicular to the second phase of backfolding (D_4).

3. The Forno unit: lithostratigraphy and field relations

3.1 The volcanic basement

The Forno unit consists of a volcanic basement and an overlying sedimentary sequence (Fig. 4). The basement forms the major volume of the Forno unit. It consists of amphibolites and amphibolites with locally preserved magmatic structures. Minor masses of fine-grained chlorite-epidote-actinolite-plagioclase schists with large aggregates of plagioclase of variable composition (An: 0–50, Wenk & Keller 1969) are located at Alp da Cavloc (near Lägh da Cavloc, Kubli 1983) and 1 km southeast of Passo del Muretto (Gieré 1984). The plagioclase aggregates are sourrounded by dynamically recrystallized and elongated actinolite, chlorite and epidote. The aggregates are thought to replace formerly magmatic plagioclase (Gautschi 1980, Finger et al. 1982). The major part of the volcanic basement is formed by fine-grained chlorite-epidote-actinolite schists. Towards the Bregaglia intrusion the foliated texture of the amphibolites grades into a hornfels texture. Due to the high-temperature contact metamorphic overprint a plagioclase blastesis occurs and static hornblendes overgrow the elongated actinolites. In some areas amphibolites with schlieren of epidote occur. They can be interpreted as being part of pillow breccias and metahyaloclastites (Peretti 1985) or as metamorphosed interpillow sediments, when associated with calcite, or as former epidote veins formed during hydrothermal activity on the ocean floor. Locally pillow structures with variolitic borders (Montrasio 1973), ancient cavity fillings of carbonate (interpillow sediment matrix, Passo del Muretto, Val Bona)

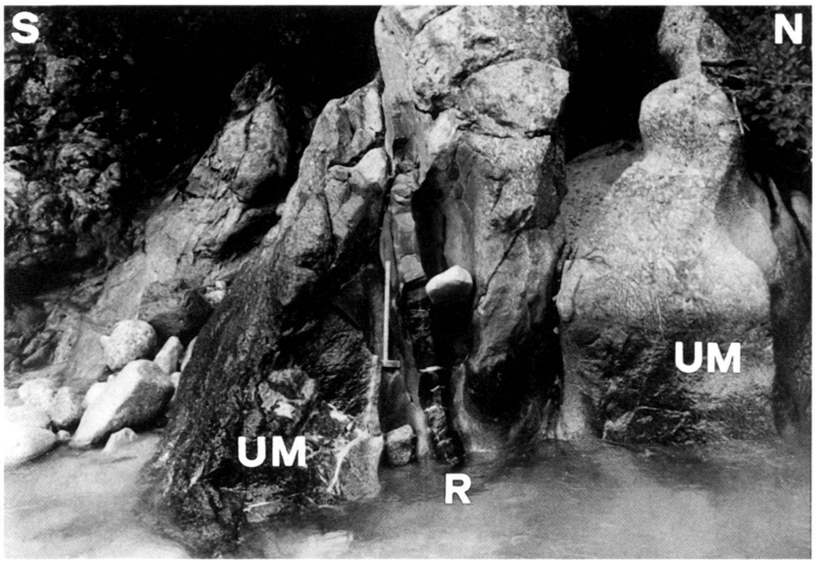

Fig. 5. Rodingitized metabasaltic dike (R) cutting across contact metamorphic ultramafic rocks (UM) in the Orlegna river (Swiss grid coordinates 774.879/138.610).

and metahyaloclastites indicate a submarine extrusion for these volcanic rocks. Major and trace element geochemical data (Gautschi 1980) as well as the Pb isotopic signature of the amphibolites (Peretti & Köppel 1986) reveal a MOR basalt character. A 50 m wide band of Fe-Cu-Zn mineralizations within the amphibolites can be followed over kilometers, being generally parallel to the sedimentary horizon of quartzites overlying the basalts (Ferrario & Montrasio 1976, De Capitani et al. 1981, Peretti 1985). Gabbroic rocks associated with the Forno metabasalts have not yet been observed and described.

3.1.1 Contacts to ultramafic rocks

Pre-Alpine structures and contacts of basaltic and ultramafic rocks are not easy to distinguish from Alpine structures and contacts. The best feature to identify pre-Alpine contacts are metarodingitized rocks. In Valmalenco, rodingitization can be considered as an ocean floor process. Hence, the observation of such rodingitized contacts, is a good indicator for the primary and pre-Alpine association of metabasaltic and peridotitic rocks on the ocean floor.

In minor amounts ultramafic rocks occur within porphyritic metabasalts near Lägh da Cavloc and at Alpe Sissone. Their position as xenoliths or tectonic slices is unclear. Towards the south, east of Chiareggio, the Forno metabasalts are in direct contact to the Malenco ultramafics. Primary intrusive contacts between ultramafic and mafic rocks are documented by basaltic dikes crosscutting the Malenco ultramafic rocks (Trommsdorff et al. 1993, Ulrich & Borsien 1996). These dikes have subsequently been rodingitized. An amphibolite body south of Pizzo Cassandra (Pika 1976) is chemically equivalent to the Forno metabasalts (Gautschi 1980) and displays intrusive contacts to the surrounding ultramafic rocks as well as rodingitized borders (Trommsdorff et al. 1993).

In the following, field relations from different localities (Alp da Cavloc, Alpe Sissone and Cassandra) are described, which give constraints for a primary association of mafic and ultramafic rocks in Valmalenco.

Alp da Cavloc

Around Alp da Cavloc (Fig. 2) several decameter long lenses of coarse-grained ultramafic rocks occur in a mass of porphyritic amphibolites. The ultramafics are olivine-talc felses metamorphosed during the intrusion of the Oligocene Bregaglia granodiorite. The contact metamorphic overprint within the amphibolites is documented by pargasitic rims around regional metamorphic actinolitic amphiboles (Gautschi 1980). Most of the ultramafic lenses do not exhibit their relationships with the surrounding metabasaltic rocks, because these lenses are exposed in isolated, glacially formed humps.

At Alp da Cavloc primary relationships between metabasaltic rocks and peridotites can be observed. Directly behind the Alp hut at Alp da Cavloc a 1 m wide, subvertical olive green dike crosscuts the ultramafic lens. This dike consists of a heteroblastic epidote-actinolite fels. This fels represents a rodingitized basaltic dike where primary plagioclase was replaced by epidote due to Ca-metasomatism. Along the northeastern rim of the dike, a beige coloured chlorite-clinopyroxene fels occurs in the ultramafic rock. This fels consists predominantly of coarse-grained green and brown clinopyroxenes (up to 2 mm) with exsolution lamellae, showing an equigranular texture. This texture is equivalent to clinopyroxenites of the Mt. Braccia area that are statically recrystallized under granulite facies conditions (Müntener & Hermann 1996). Therefore the fels at Alp da Cavloc is interpreted as a clinopyroxenite. At the contact to the ultramafic rocks, the pyroxenite grades into a heteroblastic chlorite-tremolite fels, representing the metasomatically altered rim of the clinopyroxenite. The

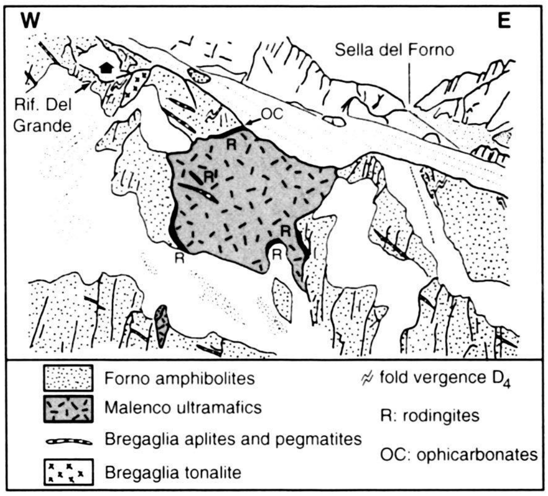

Fig. 6. View from Alpe Zocca to NW to an ultramafic mega-lens (200 m x 600 m) completely surrounded by amphibolites of the Forno unit, displaying the primary relations between ultramafic and mafic rocks. Vergencies of small-scale folds of D_4 (2nd phase of backfolding) do not change over the ultramafic lens.

oblique orientation of the main foliation S_1, surrounding the ultramafic lens, to the orientation of the dike indicates a pre-Alpine intrusive character of this dike.

An analogous relationship can be observed in the Orlegna river near Alp da Cavloc, where a 15 cm thick rodingitized dike cuts across an ultramafic lens (Fig. 5).

Alpe Sissone

At the northeastern side of Val Sissone, east of Rifugio Del Grande at Alpe Sissone (Fig. 2), a 200 m x 600 m long body of ultramafic rocks, is completely surrounded by amphibolites of the Forno unit. This body can be recognized from far away due to its brown-reddish weathering colour surrounded by black amphibolites. This association is cut by slightly NE-dipping aplitic dikes of the Bregaglia intrusives (Fig. 6).

The ultramafic rocks display a contact metamorphic overprint and generally are olivine-talc and olivine-anthophyllite-tremolite felses. Different rock types can be distinguished within this ultramafic lens, among these olivine-talc felses (meta-harzburgites) prevail, but minor amounts of olivine-diopside-tremolite felses (meta-lherzolites), olivine felses (meta-dunites) and dm-thick horizons of meta-clinopyroxenites are also present (Riklin 1977). The surrounding amphibolites show a contact metamorphic plagioclase blastesis induced by the intrusion of the Bregaglia tonalite and were strongly deformed during the Alpine orogeny.

Rodingites occur as two different types, as already described by Riklin (1977), (1) along the contact between the ultramafic lens and the surrounding amphibolites, and (2) as m-thick dikes within the ultramafic lens (Fig. 6). At places they are slightly discordant to the heterogeneous mantle rocks, which are characterized by alternating layers of lherzolitic, dunitic and pyroxenitic composition. Both rodingite types are fine-grained grossular-vesuvianite-chlorite felses with minor diopside, calcite and epidote. A blackwall of Alpine origin can be observed at the contact between rodingites and ultramafic rocks as dm-thick chlorite schists or amphibole felses.

The position of this ultramafic body within amphibolites cannot be explained by Alpine deformation, e.g. imbrication or a folding structure. In the amphibolites fold vergences of parasitic folds of one of the strongest Alpine deformation phases in this area, the second phase of backfolding (D_4), point to an antiform towards NE and do not change over the lens in a SW-NE cross section (Fig. 6). The rodingites at the rims of the ultramafic body are not disrupted, and folded rodingites and rodingitized dikes have not been observed. The calcsilicatic paragenesis of the rodingites suggest a more rigid behaviour than the surrounding ultramafic (serpentinized) and amphibolitic rocks. Therefore the rodingites have not been deformed in Alpine times which implies a primary association of mafic and ultramafic rocks.

Cassandra area

The Cassandra area is situated southeast of M. Disgrazia (Fig. 2). The studied outcrop consists of a large amphibolite body completely surrounded by ultramafic rocks (Fig. 7). Further to the south occurs the verticalized Margna nappe (Fig. 8). At some places small tectonic windows occur within the Malenco ultramafic rocks. These sediments represent the cover of the underlying Suretta nappe. The complex nappe refolding is explained by D_4 anti- and synforms (Puschnig 1998).

The ultramafic rocks to the southeast of this amphibolite body are composed of serpentinites, predominantly antigorite schists, minor olivine-antigorite schists, clinopyroxene-antigorite schists and minor occurrences of pyroxenites deformed during Alpine orogeny (see also Honegger 1977). Northwest of the amphibolite body, the ultramafic rocks are overprinted by the high temperature contact metamorphism induced by the Bregaglia intrusion in the olivine plus tremolite stability field, and along the northwestern contact in the talc plus olivine stability. Locally spinel lherzolites occur in this area, which exhibit mantle layering and subordinate dunitic layers. The decameter-thick dunitic layers that can be followed over hundreds of meters are sometimes slightly discordant to the layered mantle fabric and contain oriented fragments of country rocks. Folding of the layered peridotite and dunite layers can be observed east of Rifugio Desio (Fig. 7). Refolding of spinel layering and dunite layers and ductile deformation and recrystallization of olivine imply high temperature deformation. This deformation occurred at distinctly higher temperature than that reached during eo-Alpine regional and Oligocene contact metamorphism, respectively, and suggests a pre-Alpine deformation.

The amphibolite body, also called 'Cassandra body', extends 400 m × 2 km with a NE-SW trend. The amphibolite is a

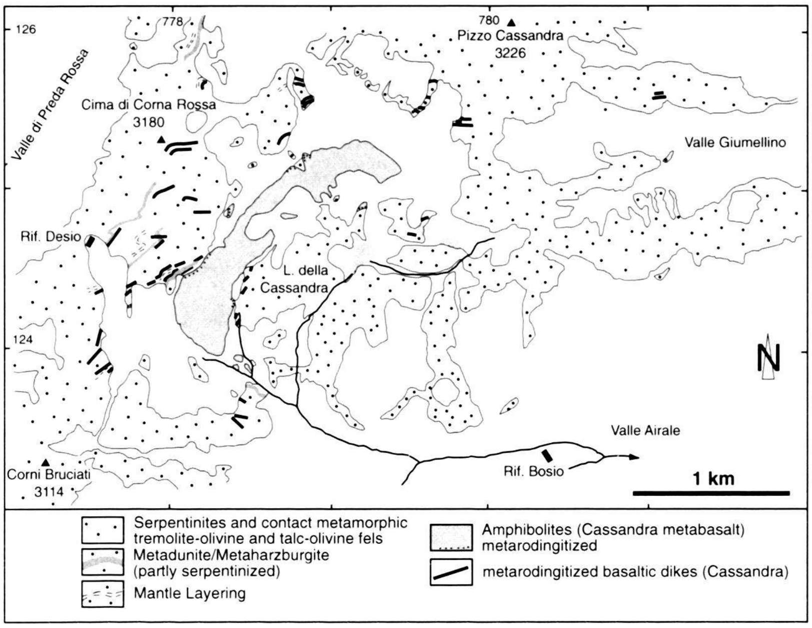

Fig. 7. Geological map of the Corni Bruciati – Pizzo Cassandra area. Partly compiled from Pika (1976), Honegger (1977), Fornera (1996) and Paglia (1996).

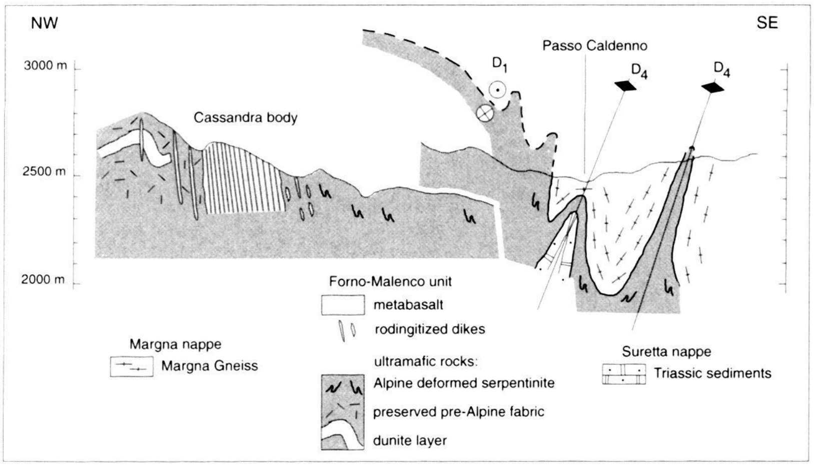

Fig. 8. Section across the Malenco unit and the Margna unit at Passo Caldenno showing the position of the Cassandra amphibolite body. Small-scale folds of D_4 (2nd phase of backfolding) disappear in the vicinity of the Cassandra body and the pre-Alpine fabric is preserved.

fine-grained epidote-actinolite-plagioclase fels. The lack of a coarse-grained primary texture or flaser texture suggests rather a basaltic than a doleritic or gabbroic origin. Primary features like pillow structures and hyaloclastite fabric or oceanic mineralization have not been observed. In addition, no sedimentary cover overlying the basalts is preserved. The body is generally characterized by a parallel arrangement of dm-thick layers (see Fig. 9), that are parallel to the rodingitized dikes (fine-grained chlorite-vesuvianite-grossular fels) outside the body. The contacts preserved between the Cassandra body and the surrounding ultramafics are all rodingitized.

The Cassandra body is accompanied by a set of subvertical metabasaltic dikes within the ultramafic rocks that are all rodingitized and striking parallel to the body and the internal layering. These dikes can be followed from southeast of Corni Bruciati, to Cima di Corna Rossa, from south of Pizzo Cassandra to Valle Giumellino over a distance of about 5 km. At the southeastern part of the Cassandra body, these dikes are very often boudinaged by the eo-Alpine deformation phase D_1, with boudin elongations parallel to the E-W trending D_1 stretching lineation of magnetite within the serpentinites. At the northwestern part of the Cassandra body the dikes are undeformed and can be followed over hundreds of meters. At several localities these chlorite-vesuvianite-grossular felses discordantly cut across the layered peridotites, at one locality even across the folded mantle tectonites and their mantle fabric.

In the Cassandra area there is a gradient of Alpine deformation from SE to NW (Fig. 8): the serpentinites southeast of the Cassandra body are strongly deformed and become blocky

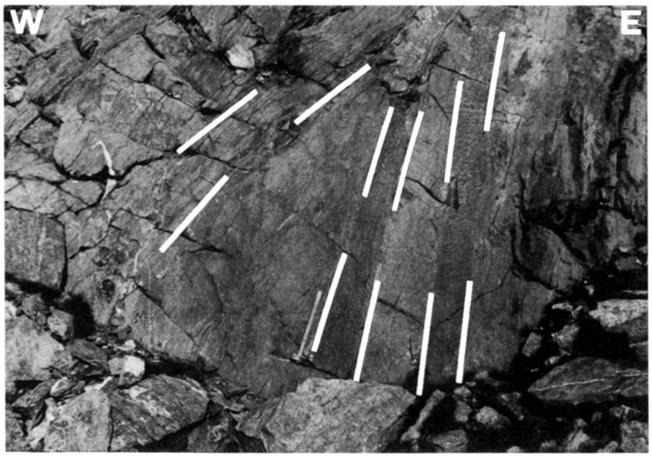

Fig. 9. Parallel arrangement of dm thick layers within the Cassandra amphibolite body (Swiss grid coordinates 778.290/124.210).

in the vicinity of the body, showing only minor serpentinization and preserving their original lherzolitic character. The Alpine most intense deformation phase in this area, the second phase of backfolding (D_4), has a variable orientation of the fold axes and cannot be observed in the vicinity of the Cassandra body. In the NW, the Alpine deformation is only weak and D_1 and D_4 folds have not been observed. A complex pre-Alpine mantle history is well preserved by large-scale folding of dunites and the mantle layering (see Figs. 7 and 8). The Cassandra body itself is only slightly affected by eo-Alpine deformation. The strike of the metabasaltic dikes northwest of the Cassandra body shows only a minor reorientation. At the southern rim of the Cassandra body the metabasaltic dikes are reoriented and strongly boudinaged due to Alpine deformation. A synformal structure of the amphibolite within ultramafic rocks can be excluded, because Alpine meso-scale and small-scale folds at the rim of the basaltic body have not been observed and the rodingites are not folded. These observations suggest at least for the NW part the preservation of a primary ultramafic-mafic association.

3.1.2 Contacts to the basement of the Margna domain

The basement of the lowermost Austroalpine Margna unit comprises pelitic, carbonatic and mafic rocks that underwent a high-grade pre-Alpine amphibolite facies metamorphism (Guntli & Liniger 1989, Bissig 1997, Fig. 10). These rocks are crosscut by granitoid rocks (Margna Gneiss). Geochemically, these granitoid gneisses show close affinities to the Late-Variscan intrusives rocks of the nearby Bernina nappe (Guntli 1987, Spillmann 1993). The intrusives of the Bernina nappe represent an intrusive suite consisting of (i) a calc-alkaline gabbro-diorite-granodiorite-granite suite with an intrusion age of approximately 333 Ma (U-Pb on zircons, von Quadt et al. 1994), (ii) an alkaline syenite-alkaligranite-leucogranite suite with an intrusion age of 295 ± 12 Ma (U-Pb on zircons, von Quadt et al. 1994), and (iii) alkaline subvolcanic to volcanic rhyolitic bodies with an intrusion age of 288 ± 7 Ma (U-Pb on zircons, von Quadt et al. 1994). These rock suites are crosscut by alkaline dikes and lamprophyres (Spillmann, 1993). These dikes did not preserve their magmatic mineralogy, but show, in undeformed areas of the Bernina nappe, still their chilled margins. Most of the dikes however were rotated parallel to the (mylonitic) Alpine main foliation. A Permo-Triassic age for these dikes is assumed by Spillmann (1993).

For the Margna unit Liniger & Guntli (1988) mapped several occurrences of amphibolites or greenschists within the Margna Gneiss. Bulk rock analyses of these amphibolites/greenschists (Guntli 1987) showed a tholeiitic character. Therefore a genetic relation to the alkaline dikes/lampro-

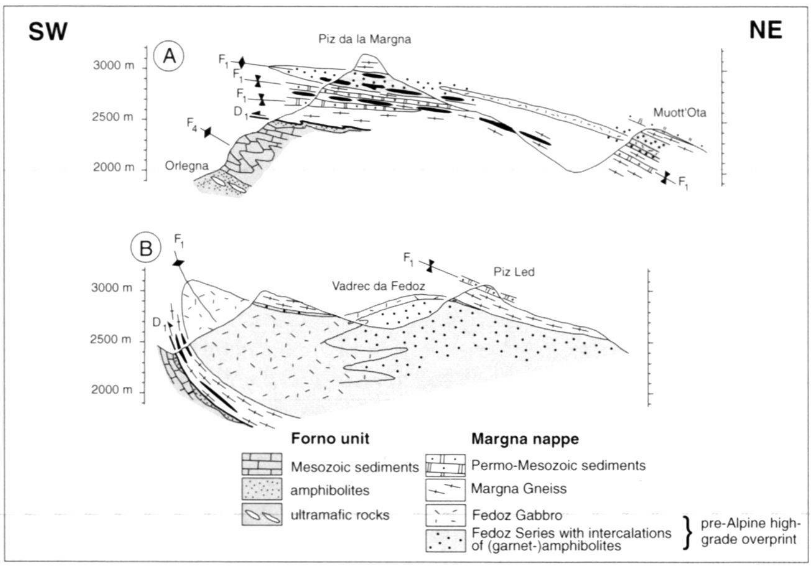

Fig. 10. Two cross-sections across the South Penninic Forno-Malenco unit and the Lower Austroalpine Margna unit show the occurrences of basic rocks (amphibolites and metagabbros) in these tectonic units.
Intercalations of amphibolites in the Margna Gneiss and the Fedoz Series are indicated in black.

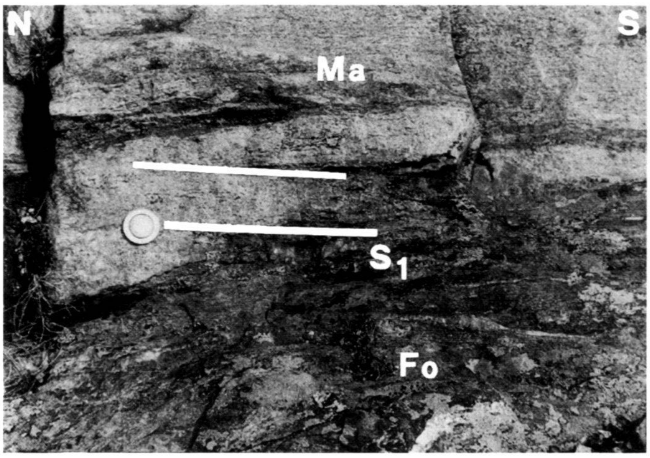

Fig. 11. D_1-folded contacts of Margna Gneiss (Ma) and Forno amphibolites (Fo, with penetrative axial plane foliation S_1 (main foliation), Passo del Muretto; Swiss grid coordinates 776.830/135.470).

phyres of the Bernina nappe can be excluded. In this context, a re-examination of the amphibolites within the Late-Variscan gneisses of the Margna domain was done. The field relations will be explained from two localities.

Passo del Muretto

Amphibole-plagioclase-epidote-chlorite schists occur as 20 to 50 m thick, 100 m to 1 km long layers or horizons in muscovite-albite-biotite-clinozoisite gneisses (Margna Gneiss, Fig. 10 cross-section A). These amphibolites form horizons which can be followed over kilometers parallel to the Alpine main foliation and approximately at the same tectonic level (Liniger & Guntli 1988). At Passo del Muretto, D_1-folded contacts of Margna Gneiss and amphibolites can be observed (Fig. 11). This suggests a pre-Alpine association of amphibolites and metagranitoid gneisses. A D_1-folding of Margna Gneiss and underlying amphibolites of the Forno unit can be excluded, because the thrust contact of the Margna unit on to the Forno unit lies tectonically approximately 50 m deeper than this outcrop (see Fig. 10, cross-section B). Macro- and microscopically these amphibolites are very similar to the Forno amphibolites. Relics of a pre-Alpine high-grade metamorphic overprint and/or a pre-Alpine foliation and therefore a relationship to the pre-Alpine high-grade metamorphic basement has not been found. Features of an intrusive character of these amphibolites like chilled margins have not been observed. These amphibolites have a tholeiitic character and the chemistry is very similar to the Forno amphibolites, as can be demonstrated by main, trace and rare earth elements (see chapter 3.3).

South of Passo del Muretto

Approximately 500 m south of Passo del Muretto and 1.3 km east of Monte dell'Oro two lenses of epidote-biotite amphibolites occur in the Margna Gneiss parallel to the main foliation. These amphibolites have schlieren of epidote and a slight contact metamorphic plagioclase blastesis like the Forno amphibolites. The contact between the amphibolites and the gneisses is isoclinally folded (D_1), where a penetrative axial plane foliation S_1 developed. This contact suggests a pre-Alpine association. These amphibolites have no relics of a pre-Alpine metamorphism or foliation. The chemistry of these rocks shows a tholeiitic character (Bissig 1997, Bissig & Hermann 1999).

3.1.3 Oceanic mineralizations

Different types of oceanic hydrothermal mineralizations occur in the study area. (1) Fe-Ni-Cu mineralizations occur in the Malenco ultramafics (De Capitani et al. 1981). (2) Fe-Cu-Zn mineralizations were found in the Forno metabasalts (Ferrario & Montrasio 1976, De Capitani et al. 1981, Peretti 1985) and (3) Mn-Fe mineralizations are described for the Forno metasediments by Ferrario & Montrasio (1976) and Peretti (1985). With the exception of the Fe-Cu-Zn mineralizations, all mineralizations are localized and isolated. The Fe-Cu-Zn mineralization occur as a NW-SE trending zone within the Forno metabasalts (Fig. 2). It is located in the proximity of the sediments of the Rossi Series (Fig. 12). This zone is situated on the normal and overturned limb of a D_4 fold, that trends NW-SE with a subvertical NE-dipping axial plane.

3.2 Ophicarbonates

Ophicarbonates in Val Scermendone form an east-west trending zone which can be followed over 1.5 km from Passo di Scermendone to Sasso Arso (Fig. 2). The ophicarbonates are characterized by mm- to dm-sized fragments of serpentinites within a matrix of predominantly calcite (ophicalcites). In clast-supported breccias of Val Scermendone yellow dolomite

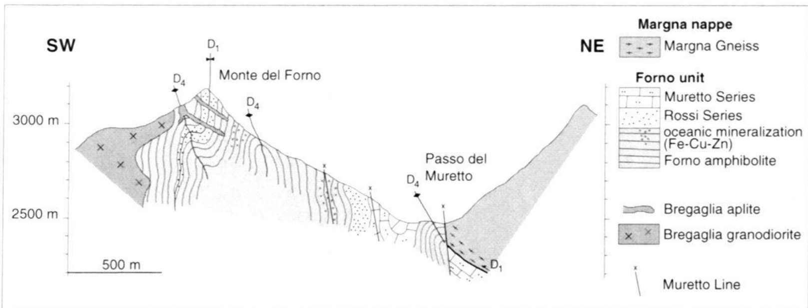

Fig. 12. Section across the Forno and the Margna units at Passo del Muretto showing the occurrences of Fe-Cu-Zn mineralizations.

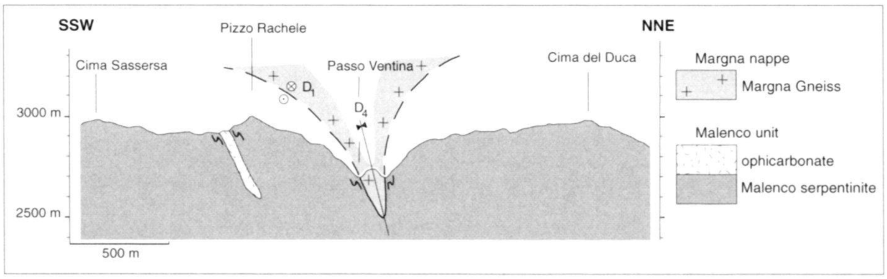

Fig. 13. Section across the Malenco unit and the Margna unit at Passo Ventina. Vergencies of small-scale folds of D_4 (2nd phase of backfolding) do not change over the Ventina ophicarbonate zone.

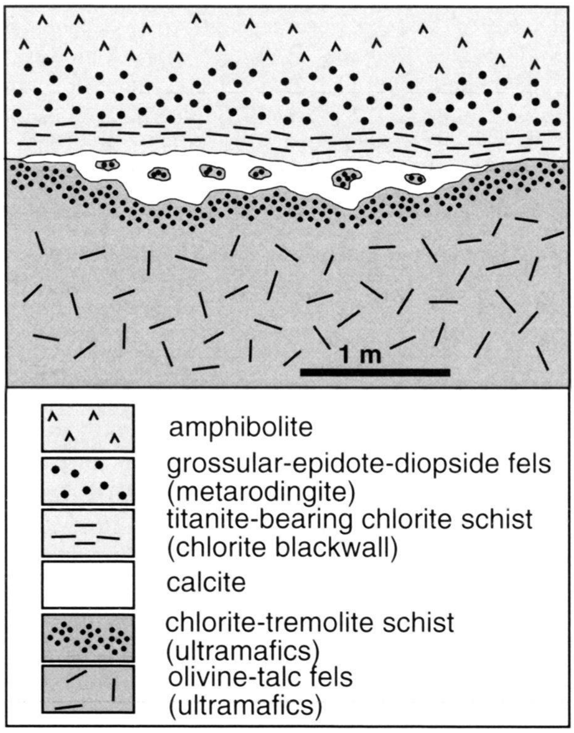

Fig. 14. Schematic sketch illustrating the field relations of the ophicarbonates at Alpe Sissone (see Fig. 6).

fragments of 2 to 10 cm size occur (Puschnig 1998). These dolomite fragments may represent embedded relics of Triassic platform carbonates. Fragments of a crystalline basement have not been found.

In the present-day situation the Ventina ophicarbonate zone is a 10 to 400 m wide steep NE-dipping and NW-SE striking 6 km long zone within the Malenco ultramafic body. Towards the northwest, this zone is intruded by the Bregaglia pluton. The Ventina ophicarbonate zone has minor occurrences of a dolomitic matrix (ophidolomites; Pozzorini & Früh-Green 1996). The fabric is variable, ranging from veined and fractured clast-supported to matrix-dominated breccias. Its orientation is parallel to the fold axis of the Ventina synform, a synform of crystalline basement rocks of the Margna domain (Fig. 13). This synform is a structure of the second phase of backfolding D_4 (Spillmann 1993, Puschnig 1998), where the fold axis of the synform trends E-W, and the axial plane is subvertically SSW dipping. The ophicarbonates are situated on the western, normal limb of the D_4 fold, not being in direct contact to the Margna rocks.

At the northeastern side of Val Sissone, along the western boundary of the ultramafic body within the Forno metabasalts (see chapter 3.1.1) a restricted outcrop of ophicarbonates has been found (see Fig. 6). Along a subvertical contact ultramafic rocks, ophicarbonates, metarodingites and amphibolites crop out from east to west. The ultramafic rocks grade into ophicarbonates across a 20 cm thick zone of chlorite-tremolite schists (Fig. 14). The ophicarbonates occur as a 20 cm × 2 m thick zone, which cannot be followed further along the contact between the basaltic and ultramafic rocks; they have a fine-grained pure calcite matrix with some mm- to cm-sized fragments of chlorite-tremolite schists and fragments of chlorite schists. The contact to the ultramafic rocks is irregular and probably represents ancient fracture fillings and pockets. Towards the metarodingites the ophicarbonates display a sharp contact to chlorite-titanite schists, representing metasomatized mafic rocks. Metarodingites are present in a 50 cm thick zone of grossular-epidote-diopside felses with several generations of epidote and diopside veins, followed by amphibolites.

3.3. The chemistry of the amphibolites

The chemistry of the Forno and Cassandra amphibolites has been described by Riklin (1977), Gautschi (1980), Kubli (1983) and Peretti & Köppel (1986). These authors demonstrated a tholeiitic differentiation and a MORB character for these rocks on the base of major and trace element bulk rock analysis. The mafic index of the Forno amphibolites (FeO_{tot}/MgO ratio) shows a range from 0.43 to 0.69 (table 1). Whereas the SiO_2 content remains constant during differentiation, FeO_{tot}, TiO_2, P_2O_5 and MnO increase. The contents of Al_2O_3, MgO, CaO decrease (Puschnig 1998). The trace elements Zr, Y and V show a linear increase with increasing differentiation, whereas the compatible elements Ni and Cr display the inverse behaviour.

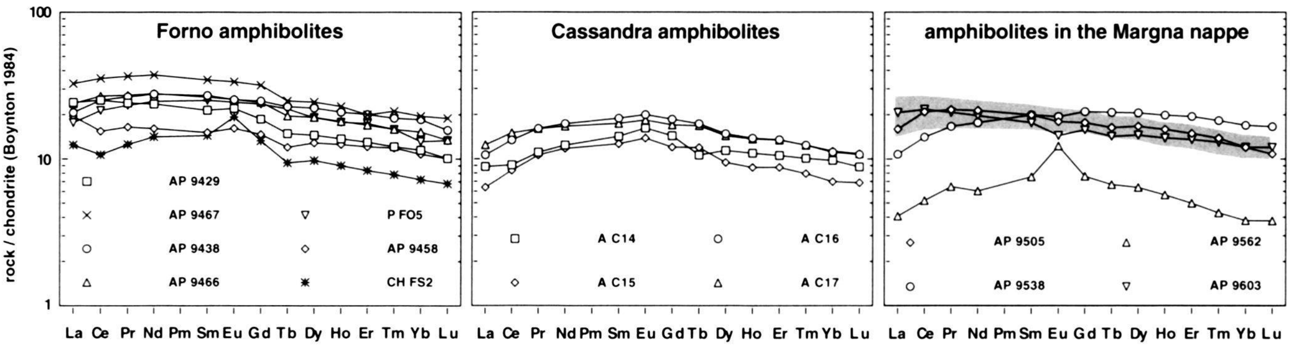

Fig. 15. REE patterns of Forno amphibolites, Cassandra amphibolites and Margna amphibolites. REE pattern of Margna amphibolites from Bissig (1997) is given for comparison (shaded area). Normalization on an average CI chondrite (Boynton 1984).

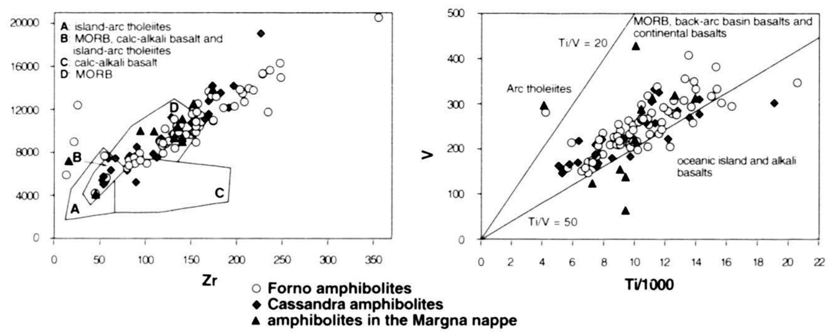

Fig. 16. Forno, Cassandra and Margna amphibolites in the Ti-Zr discrimination diagram of basalts (Pearce & Cann 1973) and in the Ti-V discrimination diagram of basalts (Shervais 1982). Own data and data from Gautschi (1980), Kubli (1983), Diethelm (1984), Gieré (1985), Guntli (1987), Borsien (1995), Paglia (1996) and Bissig (1997).

The rocks of the Cassandra body show a mafic index ranging from 0.39 to 0.69 and the range of oxides and trace elements fully coincides with the trend of the Forno rocks (Puschnig 1998, including data of Gautschi 1980 and Paglia 1996, table 1). All trends overlay with the range of basalts from the Mid-Atlantic Ridge (Schilling et al. 1983).

The rare earth elements (REE) of the Forno amphibolites (Fig. 15, table 2) show an almost flat pattern and a higher normalized content of the light REE with respect to the heavy REE with a range of $(La/Yb)_N$ ratios from 1.12 to 2.11 and a range of $(La/Sm)_N$ ratios from 0.70 to 1.13. In comparsion with the Forno amphibolites the Cassandra amphibolites display no higher normalized content of the light REE with respect to the heavy and display lower total REE contents. The range of the $(La/Yb)_N$ ratio is 0.90 to 1.10 and the range of the $(La/Sm)_N$ ratio is 0.51 to 0.72. In both diagrams the amount of REE increases with increasing differentiation as indicated by the increase of the mafic index from 0.51 for the sample CH FS2 to 0.56 for the sample AP 9467 in the Forno amphibolites and an increase from 0.43 for A C14 to 0.50 for A C17 in the Cassandra amphibolites.

The measured REE contents with 10 to 30 times chondrite are characteristic for a tholeiitic magma and are comparable to MOR basalt values. This suggests that these patterns did not change significantly during oceanic and Alpine metamorphism. In particular, they follow the trend of transitional MOR basalts (T-MORB, Walker 1991) with a slight decrease of the heavy REE from Tb to Lu.

In the Ti-Zr diagram of Pearce & Cann (1973, Fig. 16) Forno and Cassandra metabasalts expand from the field of island-arc tholeiites, MORB and calc-alkali basalts to the field of MOR basalts. In the Ti-V diagram of Shervais (1982) Forno and Cassandra metabasalts lie in the range of Ti/V ratios of 33 to 50 within the field of MOR basalts.

The amphibolites of the Margna Gneiss in the Margna domain scatter over a range of 0.49 to 0.68 for the mafic index. The trends for the oxides and the trace elements are comparable with the differentiation trend from the Forno and Cassandra amphibolites (Puschnig 1998, including data of Guntli 1987 and Bissig 1997). This demonstrates a tholeiitic differentiation and MORB character for these rocks.

These Margna amphibolites show a flat REE pattern with variable $(La/Yb)_N$ ratios ranging from 0.64 to 1.72 and $(La/Sm)_N$ ratios ranging from 0.54 to 1.17 (Fig. 15). The variability of the REE reflects the increasing differentiation as indicated by an increase of the mafic index from 0.52 for sample AP 9505 to 0.61 for AP 9538. The sample AP 9562 shows a distinctly different REE pattern and lower chondrite values

Table 1. Major and trace element variation of Forno, Cassandra and Margna amphibolites (XRF). F.A.: Forno amphibolites, C.A.: Cassandra amphibolites, M.A.: Margna amphibolites, Fe_2O_3: total iron, L.O.I.: loss on ignition, M.I.: mafic index.

	AP 9303 F.A.	AP 9307 F.A.	AP 9309 F.A.	AP 9429 F.A.	AP 9438 F.A.	AP 9458 F.A.	AP 9466 F.A.	AP 9467 F.A.	AP 9476 F.A.	AP 9482 F.A.	AP 9529 F.A.	AP 9530 F.A.	AP 9534 F.A.	AP 9535 F.A.	AP 9554 F.A.	AP 9561 F.A.	AP 9688 F.A.	AP 9696 F.A.
major elements (wt%)																		
SiO_2	51.42	45.66	43.96	48.2	50.12	47.05	46.93	42.41	48.01	50.16	45.56	48.61	48.38	49.41	40.26	46.52	41.38	49.21
TiO_2	1.28	1.81	1.21	1.48	1.96	1.09	1.76	2.31	1.13	2.20	1.74	2.12	1.74	1.49	1.12	1.96	2.50	1.44
Al_2O_3	17.22	16.06	19.56	18.04	15.40	16.93	16.26	19.28	17.35	16.02	15.99	16.65	16.58	16.05	16.42	18.35	11.03	15.58
Fe_2O_3	7.99	9.07	9.77	8.37	11.18	9.28	9.99	10.91	9.47	11.59	10.05	10.17	9.44	9.31	8.94	10.79	13.15	9.13
MnO	0.14	0.17	0.11	0.15	0.18	0.14	0.26	0.21	0.14	0.20	0.27	0.19	0.15	0.16	0.13	0.16	0.18	0.13
MgO	6.02	7.22	9.58	6.38	7.55	9.40	7.33	7.70	9.10	6.52	7.47	5.38	6.78	7.98	4.09	4.27	11.22	7.67
CaO	10.14	15.99	7.56	9.12	7.89	10.21	11.83	12.22	8.84	6.18	12.64	9.55	10.87	10.67	15.30	13.85	13.96	10.16
Na_2O	2.81	0.87	1.18	4.46	4.48	2.74	3.57	3.17	3.09	4.59	3.55	5.02	3.80	3.83	2.67	3.51	2.31	3.96
K_2O	0.73	0.23	3.66	0.33	0.16	0.63	0.17	0.18	0.30	1.45	0.19	0.22	0.11	0.14	0.70	0.30	0.45	0.12
P_2O_5	0.07	0.21	0.09	0.2	0.25	0.13	0.21	0.03	0.07	0.24	0.22	0.31	0.18	0.14	0.10	0.35	0.64	0.17
Cr_2O_3	0.03	0.03	0.04	0.03	0.02	0.04	0.03	0.02	0.04	0.03	0.03	0.02	0.02	0.04	0.02	0.02	0.05	0.04
NiO_2	0.00	0.00	0.03	0.00	0.00	0.03	0.00	0.00	0.03	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00
L.O.I.	0.57	1.12	1.72	1.42	0.67	1.16	0.24	0.43	1.59	0.60	0.53	0.55	0.53	0.55	9.84	0.47	1.35	0.72
Σ	98.42	98.44	98.47	98.18	99.86	98.83	98.58	98.87	99.16	99.79	98.24	98.79	98.58	99.77	99.60	100.55	98.24	98.33
trace elements (ppm)																		
F	600	516	774	425	335	365	409	249	371	534	314	389	342	433	1346	209	309	137
Ba	194	40	648	24	17	122	<10	18	23	164	13	16	10	13	38	70	33	<10
Rb	21	<8	103	<8	<8	8	<8	<8	<8	34	<8	<8	<8	<8	9	<8	<8	<8
Sr	663	464	263	417	116	348	334	602	294	176	358	249	193	178	326	622	97	168
Pb	7	<5	6	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	8	<5	<5
Th	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
U	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Nb	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	<4	5	17	9
La	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Ce	<15	<15	<15	<15	<15	<15	<15	27	<15	<15	<15	<15	<15	<15	<15	17	44	<15
Nd	<25	<25	<25	<25	<25	<25	<25	26	<25	<25	<25	<25	<25	<25	<25	<25	27	<25
Y	14	26	20	5	19	5	13	24	4	28	27	37	27	27	22	41	45	35
Zr	54	155	94	119	156	79	138	203	81	177	155	208	134	116	95	234	248	118
V	220	318	170	228	259	151	267	350	158	308	298	276	268	255	118	243	317	227
Cr	185	219	324	177	156	324	202	173	322	200	142	44	96	257	88	122	396	256
Ni	60	88	225	71	71	216	68	71	215	97	62	52	77	94	127	46	191	89
Co	36	73	67	36	45	49	53	60	47	51	50	36	42	39	30	42	100	35
Cu	12	<3	59	101	<3	36	<3	285	56	36	<3	38	42	52	4	81	54	8
Zn	66	53	64	49	92	51	87	81	71	98	87	75	49	60	37	68	84	64
Ga	14	18	12	11	10	9	12	19	10	14	16	15	14	14	14	24	8	13
Sc	31	47	37	34	39	34	44	46	35	41	42	35	34	38	27	28	58	41
S	<50	<50	539	<50	<50	<50	<50	<50	779	<50	<50	<50	<50	<50	<50	<50	<50	279
M.I.	0.54	0.53	0.48	0.54	0.57	0.47	0.55	0.56	0.48	0.62	0.55	0.63	0.56	0.51	0.66	0.69	0.51	0.52

when compared with the other Margna amphibolites. AP 9562 has a markable positive Eu anomaly and lower total REE content with respect to the other samples and probably represents a gabbro with fractionation of plagioclase. The REE patterns of samples AP 9505, AP 9603 and AP 9538 overlap with the field of REE patterns of other Margna amphibolites of Bissig (1997) and the field of REE patterns from the Forno amphibolites.

In the Ti-Zr diagram of Pearce & Cann (1973) and the Ti-V diagram of Shervais (1982) the Margna amphibolites lie in both diagrams in the range of the values of Forno and Cassandra amphibolites (Fig. 16).

3.4 *The pelagic sedimentary sequence*

The sedimentary cover of the Forno unit consists of a pelagic sedimentary sequence which can be subdivided into the Rossi Series, consisting of sediments of a silicious-carbonatic and pelitic facies and the Muretto Series, characterized by flysch-type sediments (Peretti 1985).

The Rossi Series forms the lower part of the sedimentary sequence of the Forno unit with an up to 2 m thick horizon of quartzites and quartz schists overlying pillow basalts and metahyaloclastites (Fig. 4, e.g. Passo del Muretto). The boundaries between the sedimentary cover and the metavolcanic rocks are frequently gradual or alternating and are thought to be stratigraphic (see also Ferrario & Montrasio 1976, Peretti 1985). The garnet- and magnetite-bearing quartzites have been interpreted as metaradiolarites ('basal quartzites' of Ferrario & Montrasio 1976). Locally dm-thick bodies of Fe-Mn mineralizations within these quartzites are described, consisting of tephroite, rhodonite, spessartine and Ca-Mn carbonates (Peters et al. 1973, Ferrario & Montrasio 1976, De Capitani et al. 1981, Peretti 1985). The quartzites occur between Monte del

	Fora 2 F.A.	P-FO2 F.A.	P-FO5 F.A.	CH-FS2 F.A.	A-C14 C.A.	A-C15 C.A.	A-C16 C.A.	A-C17 C.A.	AP 9621 C.A.	AP 9622 C.A.	AP 9623 C.A.	AP 9624 C.A.	AP 9443 M.A.	AP 9504 M.A.	AP 9505 M.A.	AP 9538 M.A.	AP 9562 M.A.	AP 9603 M.A.
major elements (wt%)																		
SiO_2	34.14	49.76	49.59	47.62	47.77	48.50	50.50	47.14	45.76	44.47	47.05	47.92	49.67	50.93	48.98	47.40	49.10	42.45
TiO_2	3.43	1.69	1.65	1.50	0.96	0.84	1.24	1.31	1.93	1.85	1.05	1.79	1.66	1.56	1.50	1.67	1.20	1.56
Al_2O_3	10.80	17.04	16.07	16.23	16.98	17.79	15.83	16.53	17.79	17.68	16.94	16.81	16.94	15.71	16.75	13.21	15.51	12.12
Fe_2O_3	11.44	10.53	9.96	9.81	7.94	8.81	9.09	9.48	8.13	9.68	8.49	10.34	9.93	8.87	8.65	13.27	9.72	9.34
MnO	0.19	0.13	0.16	0.15	0.12	0.11	0.19	0.18	0.19	0.21	0.22	0.17	0.19	0.16	0.17	0.20	0.18	0.25
MgO	6.86	5.55	7.41	8.34	9.33	8.35	7.81	8.50	4.87	4.46	9.49	7.54	7.55	7.46	7.25	7.63	9.09	5.49
CaO	22.25	8.56	9.55	10.44	11.41	9.93	8.72	12.76	16.70	16.77	11.78	9.82	9.83	8.58	8.64	9.05	7.55	14.85
Na_2O	1.57	4.13	3.39	3.24	2.22	2.82	3.52	1.78	1.53	1.28	2.29	3.98	3.38	4.32	3.79	3.26	3.60	4.18
K_2O	0.55	0.38	0.31	0.23	0.06	0.06	0.04	0.04	0.02	0.02	0.09	0.09	0.11	0.08	0.48	0.24	1.05	0.51
P_2O_5	0.79	0.16	0.22	0.08	0.10	0.08	0.14	0.13	0.22	0.25	0.11	0.20	0.16	0.20	0.20	0.13	0.02	0.22
Cr_2O_3	0.05	0.03	0.03	0.04	0.06	0.04	0.04	0.04	0.02	0.02	0.04	0.03	0.03	0.04	0.03	0.02	0.04	0.02
NiO_2	0.02	0.00	0.00	0.01	0.03	0.02	0.01	0.01	0.00	0.00	0.02	0.02	0.01	0.00	0.00	0.00	0.01	0.00
L.O.I.	7.17	0.32	0.67	0.75	1.56	1.07	0.86	1.09	1.45	1.72	1.51	1.12	0.67	2.06	1.81	2.24	1.76	8.82
Σ	99.26	98.28	99.01	98.44	98.54	98.42	97.99	98.99	98.61	98.41	99.08	99.83	98.22	99.97	98.25	98.32	98.83	99.81
trace elements (ppm)																		
F	1437	46	172	208	26	<10	433	<10	589	693	226	218	428	829	825	458	424	1349
Ba	251	14	<10	24	<10	<10	<10	<10	31	24	<10	<10	12	<10	79	76	113	61
Rb	14	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8	<8	30	21
Sr	533	213	229	249	142	121	145	136	164	284	173	249	240	286	363	148	376	126
Pb	14	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	10
Th	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
U	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
Nb	108	<4	<4	<4	<4	<4	<4	<4	12	11	10	13	<4	<4	<4	<4	<4	18
La	32	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20	<20
Ce	168	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15
Nd	68	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25	<25
Y	41	21	23	<3	10	5	5	26	50	50	31	47	15	26	24	29	4	38
Zr	355	135	136	21	53	53	66	108	169	165	79	150	110	141	141	95	17	132
V	347	217	216	218	166	163	188	221	325	305	170	258	255	197	209	400	187	145
Cr	435	195	180	299	430	283	301	320	103	107	315	210	210	232	132	81	328	37
Ni	174	64	70	120	191	163	106	119	84	79	183	154	135	64	86	60	96	54
Co	113	13	27	48	30	38	22	46	47	73	43	164	44	31	25	54	16	41
Cu	88	68	43	<3	42	<3	22	<3	54	280	9	22	<3	105	32	26	10	67
Zn	111	72	65	64	51	36	57	74	62	60	90	83	73	140	73	106	73	92
Ga	16	12	12	11	9	8	7	12	36	35	14	18	13	13	13	16	13	14
Sc	23	36	37	35	27	22	36	30	27	30	30	41	37	34	31	47	36	33
S	<50	<50	<50	<50	<50	<50	<50	<50	51	309	<50	<50	<50	1099	3594	903	<50	957
M.I.	0.60	0.63	0.55	0.51	0.43	0.49	0.51	0.50	0.60	0.66	0.45	0.55	0.54	0.52	0.52	0.61	0.49	0.60

Forno and Val Forno over a total distance of about 2 km, being an important key horizon for stratigraphic and tectonic reconstructions.

The quartzites are overlain by calcsilicates and calcite marbles with a gradational transition from quartzites to calcsilicates by a change in the carbonate content (Peretti 1985). The calcite marbles and calcsilicates, represented by garnet-diopside-wollastonite-calcite marbles and diopside-vesuvianite-garnet felses, are interpreted as former Aptychus or Calpionella limestones.

The radiolarites and the Calpionella limestones are the first sediments overlying the syn-rift sediments in the Lower Austroalpine domain (Furrer et al. 1985, Liniger 1992, Spillmann 1993).

The predominant rock type of the Rossi Series are the stratigraphically higher metapelites (kinzigites of Staub 1946, andalusite-garnet-biotite schists of Gyr 1967), with an original thickness of probably 50 to 100 m. These andalusite-garnet-biotite schists contain locally Fe-Mn mineralizations, now documented as knobs of quartz and spessartine within quartz-rich pelitic horizons. In several places the pelites contain graphite-bearing layers which probably represent Cretaceous black shales (Weissert & Bernoulli 1985).

The upper part of the sedimentary sequence of the Forno unit, the Muretto Series, consists of carbonate-bearing metasandstones. The metasandstone (Muretto quartzites of Staub 1946, diopside-plagioclase-quartz schists of Drescher-Kaden 1940 and Gyr 1967) has probably an original thickness of several hundred meters. Cm- to dm-thick intercalations of calcsilicate-bearing marbles and metapelites occur in the metasandstones. These sediments are thought to mark the change from pelagic to clastic sedimentation of continent-derived material (Trommsdorff & Nievergelt 1983). The original composition of these arkoses most probably was an immature

Table 2. Rare earth element variation of Forno, Cassandra and Margna amphibolites (ICP-MS). F.A.: Forno amphibolites, C.A.: Cassandra amphibolites, M.A.: Margna amphibolites.

	AP 9429 F.A.	**AP 9438** F.A.	**AP 9458** F.A.	**AP 9466** F.A.	**AP 9467** F.A.	**P FO5** F.A.	**CH FS2** F.A.	**A C14** C.A.	**A C15** C.A.	**A C16** C.A.	**A C17** C.A.	**AP 9505** M.A.	**AP 9538** M.A.	**AP 9562** M.A.	**AP 9603** M.A.
(ppm)															
La	7.520	6.420	6.050	7.410	10.100	5.480	3.860	2.740	1.980	3.290	3.860	4.946	3.326	1.259	6.392
Ce	20.300	20.300	12.500	21.700	28.600	17.300	8.620	7.310	6.710	10.800	12.100	16.907	11.355	4.188	17.524
Pr	2.940	3.230	2.010	3.320	4.450	2.830	1.530	1.350	1.290	1.960	1.950	2.638	2.026	0.790	2.532
Nd	14.200	16.600	9.650	16.700	22.400	14.800	8.470	7.430	7.040	10.400	10.000	12.807	10.584	3.625	11.785
Sm	4.180	5.270	2.950	5.140	6.740	4.890	2.810	2.770	2.460	3.680	3.390	3.878	3.889	1.471	3.431
Eu	1.610	1.850	1.180	1.860	2.450	1.780	1.410	1.180	1.010	1.460	1.340	1.305	1.415	0.892	1.049
Gd	4.850	6.440	3.810	6.300	8.230	6.140	3.440	3.710	3.100	4.810	4.410	4.574	5.447	1.967	4.071
Tb	0.701	1.070	0.565	0.921	1.170	1.030	0.443	0.498	0.560	0.815	0.788	0.766	0.975	0.313	0.669
Dy	4.690	7.180	4.140	6.200	7.870	6.160	3.140	3.660	3.040	4.770	4.610	5.373	6.632	2.056	4.672
Ho	0.987	1.500	0.906	1.300	1.640	1.280	0.648	0.786	0.629	0.995	0.983	1.141	1.428	0.409	0.998
Er	2.740	4.220	2.540	3.580	4.630	3.670	1.750	2.210	1.830	2.830	2.820	3.118	4.078	1.047	2.838
Tm	0.387	0.606	0.380	0.508	0.677	0.508	0.250	0.322	0.253	0.396	0.397	0.443	0.584	0.137	0.416
Yb	2.400	3.870	2.250	3.190	4.090	2.740	1.510	2.040	1.460	2.320	2.360	2.502	3.531	0.792	2.501
Lu	0.325	0.505	0.323	0.433	0.610	0.430	0.218	0.284	0.221	0.344	0.349	0.345	0.531	0.121	0.384

feldspar-bearing quartz sand with a dolomitic cement. As these arkoses are contact metamorphosed, the original composition can only roughly be estimated. K-feldspar and plagioclase are the metamorphic products of the original feldspar or mica and diopside and calcite products of the original dolomite. Relics of lithic fragments have not been found. A heavy mineral study on these arkoses by Bissig (1997) yielded an association of zircons, apatite, tourmaline, allanite, brookite, rutile and titanite. This association is common for sandstones derived from a continental crust. Cr-spinel as it is reported for Albian to Cenomanian clastic series in the Arosa zone (Lüdin 1987, Winkler 1988) has not been found. The absence of Cr-spinel suggests that the Muretto sandstones do not represent sediments with reworked oceanic components. Such features would be typical for the obduction of oceanic crust (Winkler 1996).

Outcrops where pelagic and clastic sediments overlie the serpentinized ultramafic ocean floor have not been observed in the Malenco region.

4. Discussion

4.1 Relation between ultramafic rocks and Forno basalts

The ultramafic rocks occurring as bodies of different size within the Forno basalts represent a heterogeneous mantle with a complex mantle history. This is documented by the presence of dunites, lherzolites, peridotites (Alpe Sissone) and pyroxenites (Alp da Cavloc). The pyroxenites have a high-grade, subsolidus overprint of upper mantle conditions. These metamorphic conditions are much higher than the conditions of the Cretaceous regional and Oligocene contact metamorphic overprint. This demonstrates that this mantle sequence had a pre-Alpine, most probably Permian, sub-solidus evolution.

The lithological units and the history are identical to those of the Malenco mantle of Mt. Braccia (Müntener & Hermann 1996). The Malenco mantle is a heterogeneous mantle with a pre-Alpine sub-solidus equilibration in the spinel lherzolite field (Müntener 1997). This suggests that the ultramafic bodies within the Forno basalts represent parts of the denudated Malenco mantle.

Dunite layers in the Cassandra area, sometimes discordant to the layered mantle fabric and with fragments of country rocks correspond to observations of Müntener & Hermann (1996) in the Braccia area. There, the dunites have been interpreted as 'replacive dunites' in the sense of Kelemen et al. (1995).

Field relations between ultramafic rocks and Forno basalts show rodingitized dikes and rodingitized rims of basaltic bodies. These rodingites occur in the Malenco region at all contacts between ultramafic and basaltic rocks (see Fig. 2) and are not reactivated during Alpine deformation. The rodingitization process is a metasomatic event concomitant with the serpentinization of ultramafic rocks (Coleman 1977). As the serpentinization is an oceanic event (field relations with ophicarbonates, stable isotope signature) the rodingitization of the basaltic rocks can be considered as an ocean floor process. The rodingitized contacts represent primary contacts. This demonstrates a primary association of the Malenco mantle and the Forno basalts, where the Malenco mantle is the basement or the substratum for the Forno oceanic sequence.

A primary association of basaltic and ultramafic rocks is also given in the Cassandra area, where the body is accompanied by rodingitized basaltic dikes.

The relations of ultramafic rocks, ophicarbonates and basaltic rocks (Alpe Sissone) shows that the volcanic basement was formed after the formation of ophicarbonates. An analoguous relative succession of serpentinized ultramafic rocks, ophicarbonates and metabasalts has been reported for the Ligurian ophiolites (Lemoine et al. 1987), for the Platta nappe (Manatschal & Nievergelt 1997) and for the Mid-Atlantic Ridge (Lagabrielle & Cannat 1990).

The rodingitized basaltic dikes most probably represent the feeder dikes of the basaltic layer and the pillows of the Forno volcanic basement. Basaltic dikes within ultramafic rocks not affected by Ca-metasomatism (rodingitization) have not been observed. As these dikes act for a long time as feeder of upcoming MORB melts, the rodingitization of these dikes must have outlasted the magmatic activity as well as the serpentinization of ultramafic rocks outlasted the dike activity. The occurrence of ophicarbonates prior the basaltic crust suggests that the serpentinization of the ultramafic rocks started with the exhumation and denudation of the subcontinental Malenco mantle. Therefore, it is suggested that the serpentinization was a long-term process that outlasted the formation of ophicarbonates and basaltic crust.

The field relations of the lenses of ultramafic rocks within the Forno volcanic basement (crosscut by rodingitized dikes, rodingitized rims) suggest a primary position within the basement. The ultramafic blocks most probably were preserved because only a thin and discontinuous oceanic crust was formed, not covering all ultramafic rocks.

The mafic and ultramafic rocks of the Forno and Malenco units exhibit no relics of a high-pressure metamorphic overprint. High-pressure relics have been found in the underlying Avers schists (Dietrich & Oberhänsli 1976, Oberhänsli 1978). The schists are interpreted as part of the oceanic Piemont accretionary wedge (Schmid et al. 1996). Most probably the location of the E-dipping subduction zone was in the ocean and not in the continental margin (Froitzheim et al. 1996). This may explain why the features of a primary association of Forno mafic and Malenco ultramafic rocks have not been erased or disrupted.

4.2 The magmatic evolution of the Forno and Cassandra basalts

Forno and Cassandra basalts present a tholeiitic character as already mentioned by Gautschi (1980) and Peretti & Köppel (1986). The REE patterns of the metabasalts show a T-MORB signature. A T-MORB character for ophiolitic metabasalts is described for ophiolites from Corsica (Balagne), the Western Alps (Montgenèvre) and for the External Ligurides (Venturelli et al. 1981, Piccardo et al. 1992, Vanucci et al. 1993). Metabasalts of a transitional character are interpreted to represent lavas erupted either during early stages of opening of a small ocean basin or lavas erupted along the continental margin of a larger basin (Venturelli et al. 1981). By contrast, basalts of a mature basin, e.g. at mid-ocean ridges, display a N-MORB signature (Basaltic Volcanism Study Project 1981).

4.3 Relation between continental crust and mafic rocks

Different types of mafic rocks occur in the Margna continental margin: (1) mafic rocks with a pre-Alpine history and (Variscan) metamorphic overprint. These are the (garnet)-amphibolites of the Fedoz Series and the Fedoz Gabbro, both lithological units most probably of Permian age. (2) Mafic rocks without a pre-Alpine metamorphic overprint occur only in the Late-Variscan meta-intrusives. One group of mafics is of alkaline character and is genetically related to the suite of the Late-Variscan intrusives (lamprophyres, Spillmann 1993). A second group of mafics has a tholeiitic character. Field relations of these rocks show that they occur as layers parallel to the mylonitic main foliation. D_1-folded contacts between mafics and metagranites indicate a contact prior to the Alpine deformation (Fig. 11). Field relations pointing to an intrusive character of these mafics – due to the strong tectonic overprint – have not been observed.

The mafic rocks within the Margna Gneiss show the same trends on main, trace and rare earth elements as the Forno and Cassandra basalts. They represent tholeiitic basalts with a T-MORB character. These amphibolites contain no relics of pre-Alpine texture or metamorphism. They occur as boudins and layers only within the Margna Gneiss and roughly at the same tectonic level (see Fig. 10). The contact is folded by D_1. A pre-D_1 tectonic imbrication is not likely, because Mesozoic sediments in stratigraphic contact with the Margna amphibolites have not been observed. The coincidence of textures and chemistry and the similar relative age with respect to the Alpine structural evolution suggests a genetic relationship between amphibolites of the Margna domain and the Jurassic Forno and Cassandra amphibolites. Therefore, it is suggested that the basalts in the Margna domain are Forno-type basalts that most probably intruded into the distal part of the continental margin (see also Bissig & Hermann 1999).

Intrusions of MOR-type basalts into continental basement rocks is not uncommon. It is described in the Apennines by Braga & Marchetti (1969), Molli (1996) and Marroni et al. (1998).

4.4 Petrogenetic evolution of the basalts

Petrogenetic calculations of Puschnig (1998) showed that the MOR basalts of the Forno unit and the basalts of the Margna domain are characterized by a low-pressure fractionation (<10 kbars) of the assemblage plag + ol + cpx. Additionally, all basalts derived from the same source, a light REE depleted mantle, most probably in the spinel-stability field (Puschnig 1998). The REE abundances of the basalts are obtained by 10 to 15 % of partial melting of a lherzolitic mantle.

Field and petrological observations indicate that the Malenco mantle displays a sub-solidus, non-adiabatic uplift from lithospheric mantle to the sea floor, where sub-solidus conditions were already achieved prior to the Permian intrusion of the Braccia Gabbro (Müntener & Hermann 1996). Therefore, the MORB generating melts did not come from the Malenco mantle, but from an adiabatically decompressed asthenospheric mantle in the spinel lherzolite field. The partial melts caused shallower intrusions or a sea floor emplacement of basaltic rocks in the Piemontese Ligurian (Tethys) basin.

Different intrusion and extrusion conditions and ages of the Forno basalts and of the (tholeiitic) Braccia Gabbro suggest that there is no genetic relationship. The Braccia Gabbro intruded a crust-to-mantle interface in a depth of about 35 to 40 km (Hermann 1997) and has a Permian intrusion age (Hansmann et al. 1996). The Forno metabasalts extruded on the ocean floor in Mid(?) Jurassic time. It cannot be excluded however that the parental magma for both mafic rock types originated from the same asthenospheric mantle.

4.5 Sedimentary evolution of the Forno unit

The stratigraphic succession of quartzites, marbles and pelites (Rossi Series) is comparable with other stratigraphical sequences in the Piemontese Ligurian ocean, e.g. of the Platta nappe (Dietrich 1970), the zone of Zermatt-Saas Fee (Bearth 1967) and the Ligurian Apennines (for a correlation see Weissert & Bernoulli 1985). The radiolarites are considered to be of Late Callovian to Aptian age (Middle to Late Jurassic age; Baumgartner 1984, Weissert & Bernoulli 1985, De Wever et al. 1987, De Wever & Baudin 1996). Recent revisions of the biostratigraphy of the radiolarites of the Tethys reveal a time span even from Aalenien to early Aptian (Baumgartner et al. 1995a, Baumgartner et al. 1995b, Baumgartner et al. 1995c). The radiolarites represent a period of an elevated Calcite Compensation Depth (CCD, Baumgartner 1984). Mn-ore deposits within these metaradiolarites (Ferrario & Montrasio 1976, De Capitani et al. 1981, Peretti 1985) indicate hydrothermal activity, probably linked to hydrothermal alteration of the Forno metabasalts and the Malenco serpentinite (Fe-Cu-Zn and Fe-Ni-Cu mineralizations). For the Calpionella limestones a latest Jurassic to Early Cretaceous age may be assumed (Weissert & Bernoulli 1985, Baumgartner 1984, Furrer et al. 1985, De Wever et al. 1987). Silicious shales overlie the Calpionella limestones and mark the change from silicious-calcareous to pelitic facies. The metapelites probably correspond to dark silicious shales and marls, deposited during Early Cretaceous (Valanginian to Albian, Weissert & Bernoulli 1985) and known as Argille a Palombini Formation and Scisti di Val Lavagna. Arkosic sediments with calcareous and pelitic intercalations have a flysch-like character. For the flysch deposition (Muretto Series) an Albian to Cenomanian or younger age is inferred (Weissert & Bernoulli 1985).

Ophicarbonates, interpreted as breccias of tectono-sedimentary origin, occur on top and in fractures of the Malenco serpentinite in Val Scermendone, Val Ventina and Campo Franscia. Oceanic Forno sediments overlying the Malenco serpentinite have not been found.

The influx of siliciclastics into the pelagic marine environment is commonly used as an indicator of tectonic activity and/or as a consequence of a major sealevel drop. Siliciclastics in an area without tectonic activity (convergence) are described with sealevel highstands and greenhouse climate conditions (Weissert 1990). Flysch-type sediments in the Alps were mostly deposited in a convergent tectonic setting. Information about paleogeography of the hinterland and the composition of the source rocks can be gained from the petrography of the sandstones. The arkoses of the Forno unit are locally restricted to the study area. Evidence for a lateral distribution of analogous sediments in the Lizun unit is missing. A heavy mineral study on these arkoses by Bissig (1997) yielded an association common for sandstones derived from a continental crust. The absence of Cr-spinel suggests that the Muretto sandstones do not represent sediments with reworked oceanic components. As the stratigraphic thickness of the arkoses increases to the east, where the arkoses directly overlie the oceanic basement (Peretti 1985; see also Fig. 12 Passo del Muretto), a paleogeographic origin of these sandstones from the Adriatic continental margin seems reasonable. The restriction of the sandstones to the Forno unit is probably the effect of local tectonic activity (convergence, uplift) in the Albian/Aptian in the study area, leading to a local deposition of siliciclastics. Primary structures pointing to a fan-like deposition have not been observed. However, siliciclastic deposition in the Early Cretaceous is not an uncommon feature in the Tethys ocean (see Weissert 1990, Gardin et al. 1994).

4.6 Comparison with other ophiolites from the Piemontese Ligurian ocean

The Northern Apennine ophiolites formed in the Piemontese Ligurian basin and show associations of peridotites and basaltic rocks in different structural positions (Piccardo et al. 1992). The internal Liguride units are characterized by depleted ultramafics, basaltic intrusives and volcanics and represent the internal, oceanic setting. The external Liguride units are characterized by fertile ultramafics associated with basaltic volcanics representing a pericontinental setting. Basalts from both units show a MORB character. It has been assumed that the primary melt of these basaltic sequences has been generated by low-pressure partial melting of slightly depleted MORB mantle sources (i.e. upwelling asthenospheric mantle; Piccardo et al. 1992). The lherzolites from the external Ligurides record a subsolidus, non-adiabatic uplift from deep lithospheric levels to the sea floor. The lherzolites from the internal Ligurides, however, are considered as the asthenospheric source for MORB basalts which was adiabatically upwelled during rifting stages of the Piemontese Ligurian basin.

The geodynamic evolution of the Piemontese Ligurian basin is characterized by an incipient rifting stage dominated by a passive and asymmetric extension of the lithosphere (Piccardo et al. 1992). This mechanism led to a tectonic denudation and sea floor emplacement of subcontinental lithospheric mantle and a passive, almost adiabatic upwelling of underlying asthenosphere. MORB-type melts intruded the overlying extended lithosphere and were emplaced on the sea-floor to form new oceanic crust.

The Malenco peridotites display a subsolidus, non-adiabatic uplift from lithospheric mantle towards the ocean floor (Müntener 1997). The inferred evolutionary p-T path for the Malenco ultramafics roughly coincides with the p-T path and the chemical signature of the lherzolites from the external Ligurides (Piccardo et al. 1990). The Forno unit and their field relations to the surrounding Malenco ultramafic rocks seem to be comparable to those of the external Ligurides.

For the Platta nappe a stratigraphic sequence equivalent to the Forno unit is reported by Manatschal & Nievergelt (1997). Ultramafic rocks (spinel lherzolites and harzburgites) are intruded by gabbroic rocks. The gabbros have a mylonitic fabric that is interpreted to be of pre-Alpine age. The ultramafic and the gabbroic rocks are both intruded by basaltic dikes. The basaltic cover consists of pillow lavas and breccias. Ophicarbonates are overlain by basalts and post-rift sediments. The sedimentary cover consists of radiolarites, Calpionella limestones and Palombini schists. The field relations and the stratigraphic evolution of the Platta nappe is comparable to that of the Forno unit, with the exception that in the Forno-Malenco unit no intrusive relations for gabbroic and basaltic rocks have been observed.

4.7 Palinspastic reconstruction of a continent-ocean transition

Kinematic inversion

A kinematic inversion of the Alpine deformation leads the present-day situation back to a pre-Alpine geometry. It represents a simplification as only the strongest Alpine deformations are considered for this reconstruction.

An E-W oriented compression led to the Cretaceous nappe stacking D_1, where the higher tectonic units represent the more continent-ward, internal domains. In the Malenco region a westward D_1 displacement of the Margna on the Malenco-Forno domain of at least 30 km can be assumed (Puschnig 1996). Therefore, a first order kinematic inversion of the Alpine structures and a palinspastic reconstruction of the former continent-ocean transition can be derived from E-W oriented profiles.

Another important Alpine structure in the study area affecting the Cretaceous nappe pile is the second phase of backfolding (D_4, Puschnig 1996). A N-S shortening of approximately 5 km for the second phase of backfolding for the base of the Margna nappe from Maloja to Passo Scermendone can be assumed. The complex Alpine geometry of D_1 and D_4 affects the primary orientation of different oceanic structures like fracture zones, oceanic mineralizations and the orientation of the Cassandra body. Therefore, in a second order kinematic inversion original orientations of different important oceanic features can be reconstructed and give important constraints for the opening direction of the Tethys ocean in the studied area. Structures on the normal limb of D_1 and/or D_4 preserve their original orientation or are only marginally reoriented especially when they are parallel to the fold axis of D_1 and D_4. Structures on the overturned limb of D_1 and D_4 are strongly reoriented.

Ventina ophicarbonate zone

The ophicarbonate zone in the Ventina area is situated on the normal limb of a D_4 fold (see Fig. 13). A retrodeformation of D_4 and of the westward D_1-thrusting yields roughly a vertical NW-SE orientation for this ophicarbonate zone (see Fig. 13). This orientation is roughly parallel to the opening direction of the Alpine Tethys in the study area (Weissert & Bernoulli 1985, Dercourt et al. 1986). Although ophicarbonates occur along ridge segments (e.g. at the Mid-Atlantic Ridge Leg 82, Bougault et al. 1985), it is suggested that the Ventina ophicarbonate zone represents a fracture zone, as already mentioned by Pozzorini (1996). Its direction would nicely correspond to a transform-like fracture zone in a NE-SW trending ocean.

Fe-Ni-Cu mineralizations are found along a segment of the serpentinite-ophicarbonate boundary of the Ventina ophicarbonate zone (De Capitani et al. 1981). These mineralizations are thought to reflect hydrothermal activity within the upper part of the fractured sea floor.

Oceanic mineralizations

The oceanic mineralizations within the Forno basalts occur on both sides of a D_4 fold and are parallel to the fold axis D_4 (Fig. 12). A retrodeformation of D_1-thrusting and D_4 folding yields roughly a NW-SE orientation for the mineralization. This primary orientation is identical to the orientation of the Ventina ophicarbonate zone. Therefore, it is suggested that this zone represents a mineralization along a fracture zone.

Additionally, a reconstruction of a continent-ocean transition shows an ocean-ward decrease of the Muretto Series (sandstones). At Passo del Muretto the Muretto Series directly overlie the Forno basalts. West of the Monte del Forno, sediments of the Rossi Series (radiolarites, Calpionella limestones and pelites) overlay the basalts.

The position of the Cassandra body

The Cassandra body lacks evidence for an extrusive setting on the ocean floor, like pillow structures and a metasedimentary cover, but it is characterized by subvertical basaltic layers, that are parallel to the rodingitized dikes. It is suggested that these layers represent basaltic dikes. All these observations suggest a sheeted dike-like, subvolcanic position of the Cassandra body.

A gradient of Alpine deformation is documented from SE to NW (Fig. 8). To the NW the rodingitized dikes are undeformed and at some places crosscut a complex pre-Alpine mantle history. Therefore, it is suggested that the Alpine strain was accommodated around the Cassandra body and the ultramafic rocks NW of the body. This association probably forms a lens, being only slightly deformed during Alpine time and preserving pre-Alpine structures and features (dunite layers, mantle layering and undeformed rodingitized dikes). This lense ranges approximately from Corni Bruciati to Pizzo Cassandra

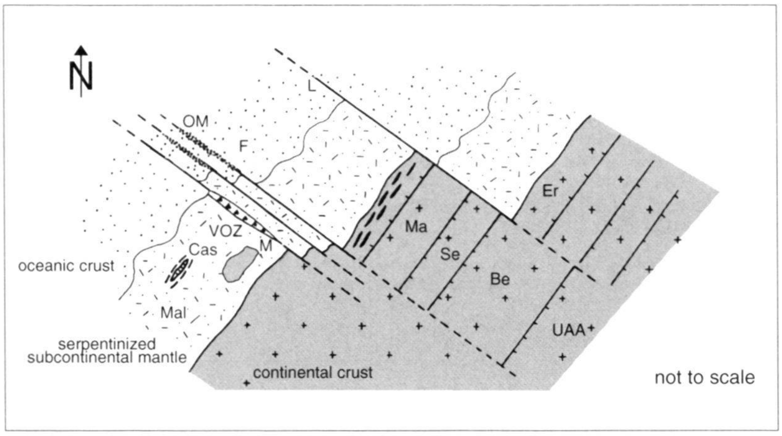

Fig. 17. Schematic paleogeographic reconstruction of the Adriatic continental margin in the Margna domain. Not to scale. Abbreviations: Cas: Cassandra, F: Forno, L: Lizun, P: Platta, Ma: Margna, Mal: Malenco, Se: Sella, Be: Bernina, UAA: Upper Austroalpine. VOZ: Ventina ophicarbonate zone, OM: oceanic mineralizations, M: Mastabia extensional allochthon.

including the Cassandra basaltic body and the ultramafic rocks northwest of this body. Additionally, it is suggested that Alpine tectonics (D_1 and D_4) did not greatly reorient the Cassandra body and their accompanying dikes. A NW-SE oriented opening direction, deduced from the orientation of the basaltic dikes, is compatible with paleogeographic reconstructions of Weissert & Bernoulli (1985) and Dercourt et al. (1986) who propose a NE-SW striking ridge axis for the Alpine Tethys ocean.

The continent-ocean transition

The present-day position from N to S of the Forno basalts, the oceanic mineralizations, the Ventina ophicarbonate zone and the Cassandra body roughly represent their paleogeographic position on the ocean floor. Southeast of the large mass of basalts of the Forno unit the Ventina ophicarbonate zone occurs. This zone is interpreted as fracture filling of a NW-SE striking fracture zone. The oceanic mineralizations within the Forno metabasalts have the same orientation as the ophicarbonate zone and are most probably the result of small transform-like faults situated north of the Ventina ophicarbonate zone. The reconstruction of orientation of ophicarbonates and mineralizations is very similar to geometrical features reported from the Mid-Atlantic Ridge. Ophicarbonates in fracture zones have been described by Bonatti et al. (1974) and hydrothermal deposits along transform faults by Hoffert et al. (1978). Further to the south the Cassandra body is situated (Fig. 17). This body is interpreted as a small sheeted dike-like structure and has a NW-SE orientation.

The huge mass of Malenco ultramafic rocks to the southeast of the Forno basalts and east of the Cassandra body (Fig. 2) has no basaltic cover and no primary relationships to basalts. This suggests that continent-ward to the east ultramafic rocks are exposed on the sea floor, and are not overlain by basalts. A cover of post-rift sediments on the mantle has not been observed, and may have been eroded during invasion or deposited and sheared off during Alpine tectonics. Metabasaltic rocks within the Late Variscan intrusives of the Margna domain are genetically linked to the Forno metabasalts. They are interpreted as basaltic sills (or dikes) intruding the distal part of the Adriatic continental margin. This indicates a relatively narrow distance between the basaltic intrusives and the Forno basalts on the ocean floor and suggests an eruption of metabasalts near the Adriatic continental margin. Jurassic rifting led to the formation of basins and highs at the Adriatic continental margin. Rifting features in the Austroalpine units are documented by sedimentary sequences and Jurassic structures in the Austroalpine units (Eberli 1988, Froitzheim & Eberli 1990, Handy 1996). Proceeding rifting leads to a disintegration of the continental crust and to formation of extensional allochthons. Possible extensional allochthons like the Mastabia zone (see Hermann & Müntener 1996) lie directly on top of serpentinites between the Cassandra body and the continental margin.

In the Alpine nappe stacking the Platta unit is wedged between the Margna and Bernina nappe (Fig. 2). This unit is in a higher tectonic position than the Forno unit, its paleogeographic lateral equivalent. Liniger (1992) and Spillmann (1993) demonstrated by detailed structural work that the Platta unit in this position cannot be explained by Alpine tectonics. Different Jurassic opening and fragmentation directions (NW-SE) and Late Cretaceous closing (E-W, Fig. 17) may result in the present-day complex geometry (Liniger 1992 and Spillmann 1993). Handy (1996) and Froitzheim & Manatschal (1996) interpret the Margna block as an extensional allochthon resulting from asymmetric rifting. It is also possible that a combination of both processes led to the special position of the Platta unit.

The reconstruction of a continent-ocean transition presented here is very similar to the geometry reported from the western continental margin of Iberia (Galicia margin, Boillot et al. 1995a, 1995b). In Galicia, blocks of upper continental basement of the margin are separated from mantle rocks by a low-angle normal fault. In the zone between large basaltic flows

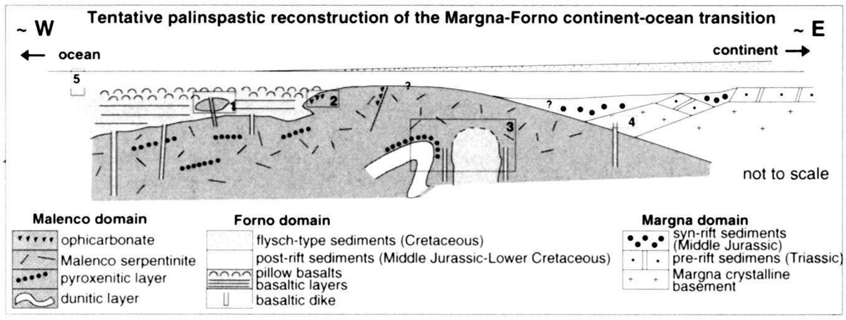

Fig. 18. Schematic sketch of the continent-ocean transition as reconstructed on the basis of the present study. The rectangles document the relations observed directly in the study area.
1: Alpe Sissone/Alp da Carloc,
2: Alpe Sissone,
3: Cassandra area,
4: Passo del Muretto,
5: Passo del Muretto.

and the continental margin, denudated subcontinental mantle is exposed ('peridotite ridge'). Large boudins of lower crust like at the Adriatic continental margin have not been found until now on the Galicia margin.

4.8 Evolution of the continent-ocean transition

Sedimentological and structural data from Austroalpine units (Err, Platta, Bernina; Froitzheim & Eberli 1990, Froitzheim & Manatschal 1996, Manatschal & Nievergelt 1997) as well as petrological and structural data from a crust-to-mantle section in the Malenco region (Trommsdorff et al. 1993, Müntener & Hermann 1996, Hermann & Müntener 1996) give important constraints for the evolution of the Austroalpine margin in the studied area. A possible scenario of this evolution is presented in the following:

Permian situation:

The lower crust of the future Austroalpine domain was welded to subcontinental mantle by a Permian gabbro intrusion (Braccia Gabbro; Trommsdorff et al. 1993, Hermann & Müntener 1996). This magmatic underplating occurred at a depth of about 35 km. The retrograde evolution of this crust-to mantle section is characterized by isobaric cooling during Permian extension, where no major exhumation occurred.

Jurassic rifting:

A two-phase rifting model (Froitzheim & Eberli 1990, Froitzheim & Manatschal 1996) explains the sedimentological and structural features of the Austroalpine realm. During Late Triassic-Early Jurassic extensional faulting affected the proximal parts of the future margin. E-dipping normal faults led to half-grabens, basins and the deposition of syn-rift sediments. In a second rifting phase (Late Toarcien-Middle Jurassic) W-dipping low-angle detachment faults developed in the distal part of the Austroalpine margin. They cut towards the European continent into the mantle.

During the first phase of rifting an E-dipping detachment fault along the crust-to-mantle interface led to the uplift of the subcontinental mantle into a shallow level (< 10 km; Froitzheim & Manatschal 1996, Hermann & Müntener 1996, Manatschal & Nievergelt 1997). The movement is documented by mylonites and shear zones with top-to-E movement in the Malenco region (Hermann & Müntener 1996). During the second phase of rifting the mantle was denudated by W-dipping faults (Froitzheim & Manatschal 1996). This asymmetric extension most probably led to the emplacement of extensional allochthons.

The transition from rifting to the opening of the ocean is marked by extrusions of pillow lavas and the formation of a pelagic sedimentary sequence of the Forno ocean floor sequence. The basaltic volcanism is thereby the result of a passive uplift and decompression of asthenospheric mantle. The intrusion of MOR basalts in the distal parts of the Austroalpine margin and a continent-near extrusion of MOR basalts is most probably the result of relative westward movement of upcoming asthenospheric mantle and therefore to a westward migration of the source of the MOR Forno basalts. This movement most probably caused the intrusion of MOR basalts in the distal part of the Austroalpine margin and a continent-near extrusion of MOR basalts.

5. Conclusions

Detailed mapping in Valmalenco confirmed the existence of an atypical sequence of basaltic and ultramafic rocks. Numerous intrusive contacts of Forno basalts with the denudated subcontinental Malenco mantle demonstrate a Jurassic association, where the Malenco ultramafic rocks form the substratum of the Forno volcanic basement. These contacts are overprinted by an oceanic metasomatic event (rodingitization) and have not been disrupted by Alpine tectonics.

Basaltic rocks in the upper crustal basement of the Margna nappe have a MORB character and are chemically equivalent to the Forno basalts. Most probably they derived from the same source. Field relations give no clear evidence for an intrusive association, but it is suggested that MOR-type basalts intruded the distal part of the Adriatic continental margin.

A reconstruction of a continent-ocean transition (Fig. 18) demonstrates that in the vicinity of the disintegrated passive continental margin the lithospheric subcontinental Malenco mantle has been exposed to the ocean floor during rifting. Subsequently Middle Jurassic MOR basalts (Forno) intruded and extruded the Malenco mantle and formed a discontinuous and thin basaltic oceanic crust on the oceanic side of the continent-ocean transition. The T-MORB character of the Forno basalts and field relations in the study area suggest that the Forno ocean floor sequence was formed during an early stage of ocean formation.

The field relations in Valmalenco do not give evidence for the existence of a gabbroic layer, as it is defined for a Penrose-type ophiolite. Therefore, the observed sequence does not represent an ophiolite sequence in the classical sense. The Forno-Malenco unit consists of different rock types with different ages and origin: (1) the Malenco ultramafic rocks of an Adriatic subcontinental origin and a sub-solidus history starting in the Permian, (2) a Permian (tholeiitic) gabbro intrusion at a crust-mantle boundary (Braccia Gabbro), and (3) Middle Jurassic oceanic Forno basalts intruding the exhumed Malenco mantle, followed by Middle Jurassic to Early Cretaceous pelagic sediments.

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