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From pre-Alpine extension to Alpine convergence: the example of the southwestern margin of the Margna nappe (Val Malenco, N-Italy)

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Abstract

The Austroalpine Margna nappe exposes lower crustal rocks such as the Fedoz gabbro and the paragneisses of the Fedoz Series. Equivalent rocks are present in the Penninic Malenco unit (Braccia gabbro and Senevedo gneiss). Pre-Alpine structures and metamorphic relics preserved in the Fedoz gabbro and Fedoz Series closely match those of the Malenco unit and indicate a common pre-Alpine evolution. The pre-Alpine structures in the Fedoz gabbro suggest that the lower crustal rocks of the Margna nappe were juxtaposed with the upper crustal granitoids, the Fora gneisses, by a ductile large-scale extensional shear zone with an original top-to-the-E or -SE movement, the so called Margna normal fault. A relict pre-Alpine cleavage in the Fora gneisses is interpreted to be related to this extension.

Amphibolite bodies within the Fora gneisses of the Margna nappe display a fine-grained texture and have no pre-Alpine relics. They have a transitional-type MORB chemical signature and are very similar to the metabasalts, which form parts of the adjacent ophiolithic Forno unit. It is suggested that these amphibolites are co-genetic with the Forno metabasalts and represent MORB dykes intruding the hangingwall of the asymmetric rift system leading to the opening of Tethys.

Metaarkoses occur below the Margna thrust contact and probably represent metamorphosed Cretaceous flysch units covering the Forno basalts and associated Jurassic sediments. However, the heavy-mineral spectrum of these metaarkoses is characterised by the lack of chromium spinel, which is normally present in Lower-Austroalpine Cretaceous sediments.

The Alpine regional metamorphic grade in the southwestern Margna nappe reached epidote-amphibolite facies conditions (T ~ 450–500 °C, P ~ 0.7 GPa), identical to the metamorphism of the Forno-Malenco units. Additionally all units shared a common Alpine structural evolution. The Margna nappe and Malenco-Forno units were thus in a neighbouring position in the supra-subduction wedge during Alpine convergence.

Keywords: Margna nappe, Forno-Malenco unit, extensional tectonics, Alpine metamorphism, Central Alps, basaltic dykes, Jurassic rifting.

Introduction

The border-region between the Penninic and Austroalpine nappes in the Eastern Central Alps is a key area for the understanding of the transition from pre-Alpine rifting to Alpine convergence. Detailed structural and sedimentological work permits insight into timing and geometry of Jurassic rifting and Cretaceous nappe stacking occurring in upper-crustal levels (FURRER et al., 1985; FROITZHEIM and EBERLI, 1990; FROITZHEIM and MANATSCHAL 1996; HANDY, 1996; MANATSCHAL and NIEVERGELT, 1997). The same processes are documented in the Penninic Malenco-Forno units and the Austroalpine Margna nappe (Fig. 1). In this area, lower-crustal gabbros, granulites and peridotites have been exhumed, giving constraints on the behaviour of the lowermost crust and the upper mantle during continental rifting (TROMMSDORFF et al., 1993; MÜNTENER and HERMANN, 1996; HERMANN and MÜNTENER, 1996). Gabbros and granulites have been regarded as belonging to

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a single unit until HERMANN and MÜNTENER (1996) demonstrated that the Braccia gabbro and lower crustal granulites (Senevedo gneiss) are incorporated in the Malenco unit whereas the Fedoz series and the Fedoz gabbro are part of the Margna nappe. While there is detailed information about the structural and petrological pre-Alpine evolution of these rocks in the Malenco unit (MÜNTENER and HERMANN, 1996; HERMANN and MÜNTENER, 1996; HERMANN et al., 1997; MÜNTENER et al., 1999), much less is known of similar rocks in the Margna nappe. We present new petrographic and structural information from the Fedoz gabbro and the Fedoz series from the Val Muretto (Western Val Malenco, N-Italy, Fig. 1) which contribute to the understanding of lower crust-upper mantle exhumation during Jurassic rifting.

Rifting was followed by formation of oceanic crust, which is partly preserved in the ophiolitic Forno unit (FERRARIO and MONTRASIO, 1976; PERETTI, 1985; PUSCHNIG, 1998; Fig. 1). Basaltic dykes with MORB-character crosscut the denuded Malenco ultramafic rocks, demonstrating their intrusive character (TROMMSDORFF et al., 1993; PUSCHNIG, 1998). New field, textural and chemical data from mafic dykes in the Margna nappe are presented here. It will be discussed if these dykes are co-genetic to the Forno-MORB's. This is important because MORB dykes in rifted continental crust provide information on the asymmetry of rifting (e.g. VOGGENREITER et al., 1988).

The Forno basalts are overlain by an oceanic sedimentary sequence of inferred Jurassic-to-Cretaceous age (PERETTI, 1985; WEISSERT and BERNOULLI, 1985; PUSCHNIG, 1998). The meta-

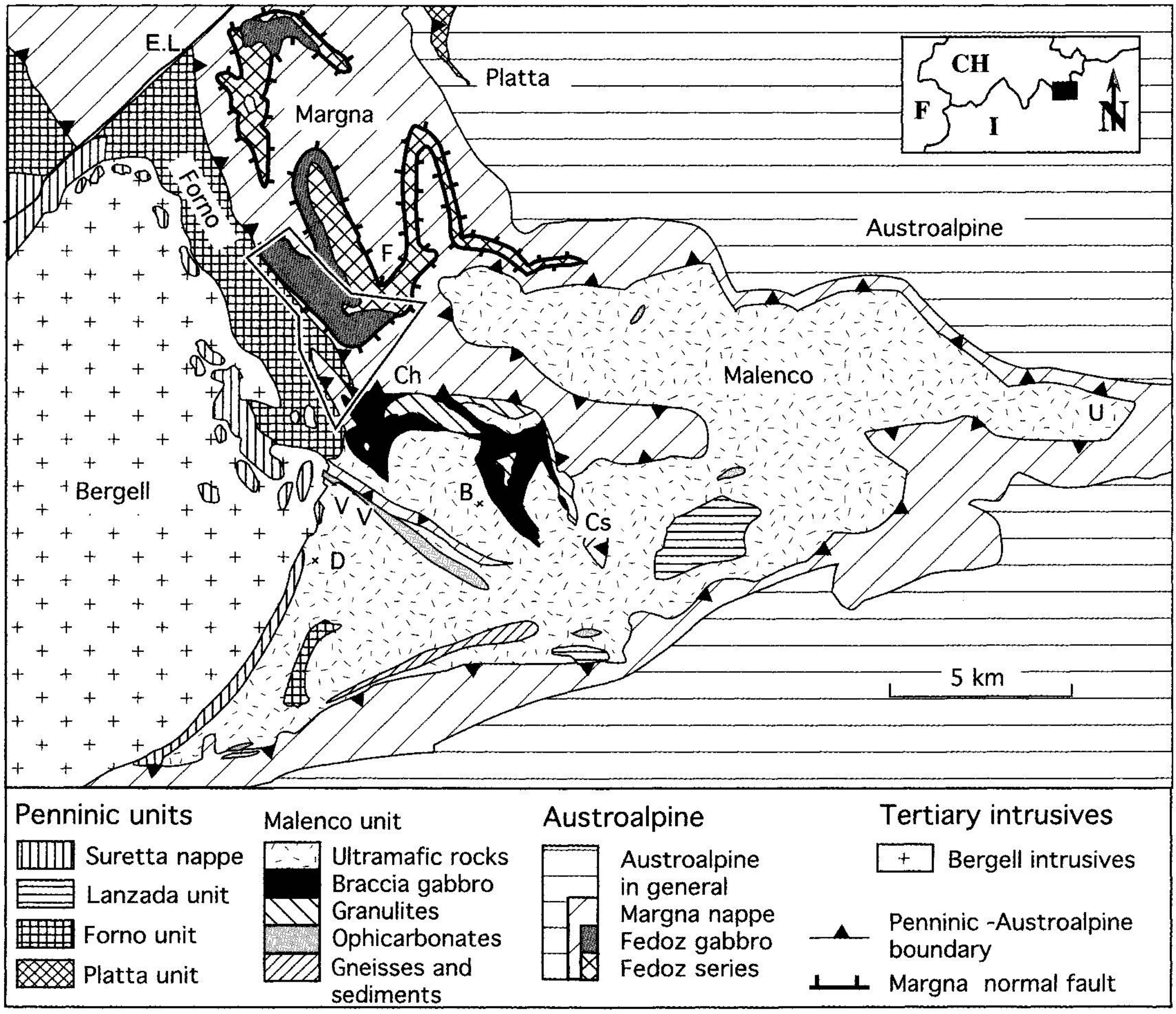

Fig. 1 Tectonic map of the Austroalpine-Penninic border region. The study area is outlined. Ch = Chiareggio, Cs = Chiesa, B = Mt. Braccia, F = Piz Fora, E.L. = Engadine Line, U = Pass d'Ur, D = Monte Disgrazia.

arkoses occurring in the Val Muretto were interpreted to be the uppermost stratigraphic level in this sedimentary sequence. We report heavy mineral spectra of these metaarkoses in order to compare them to spectra reported from other lower Austroalpine Cretaceous sediments.

The transition from continental rocks (Margna) to oceanic rocks (Forno-Malenco) is an important geologic boundary along which subduction may have been initiated during Alpine compression. Data on the Alpine metamorphic evolution of the Fedoz gabbro (Margna nappe) is compared to that of the Braccia gabbro (Malenco unit). This information, together with a comparison of the structural evolution in Margna nappe and Malenco-Forno units helps to define the tectonic positions of these units during Alpine convergence.

The observations presented in this study fill some important gaps in the understanding of Jurassic rifting and subsequent Cretaceous convergence at the former Adriatic passive continental margin. The implications of the new data for rifting and subduction models will be discussed.

Geological setting

The Val Muretto (uppermost-Val Malenco, Figs 1, 2) is situated at the Penninic-Austroalpine boundary in the eastern Central Alps. The predominant tectonic units are the Penninic Forno/Malenco unit and the overlying Austroalpine Margna nappe (Fig. 1).

The *Margna nappe* is subdivided into an upper Maloja- and a lower Fora sub-nappe, separated by a thrust-fault with relics of Permian-to-Mesozoic sediments in the shear plane (LINIGER and GUNTLI, 1988). Much of the studied area is situated within the Fora sub-nappe, which represents a flat-lying thrust-fold closing to the west (STAUB, 1920; LINIGER and GUNTLI, 1988). From sedimentological arguments (FURRER et al., 1985) and radiometric age determinations (FREY et al., 1974; HANDY et al., 1996), a Cretaceous age for the Lower Austroalpine nappe stacking can be assumed. The Alpine main foliation (S1) corresponds to the axial plane of the nappe-fold. The Fora sub-nappe has a composite basement. The core comprises paragneisses of the Fedoz Series and the Fedoz gabbros (Fig. 2), both preserving relics of pre-Alpine high-grade deformation and metamorphism (GUNTLI and LINIGER, 1989). These rocks are surrounded by two-mica gneisses, the so-called Fora gneiss, considered to correspond to the calc-alkaline Late Variscan Bernina intrusives (SPILLMANN, 1993). The Fora gneiss is covered by Mesozoic sediments, indicating that the Bernina intrusives represented the uppermost crust at the time of deposition. The contact between Fora gneiss and Fedoz series / Fedoz gabbro is of pre-Alpine origin and most probably represents a low-angle normal fault (Margna normal fault) which was active during Jurassic rifting (HERMANN and MÜNTENER, 1996).

The *Forno unit* consists of amphibolites and metasediments which represent former ocean-floor basalts and overlying sediments of an oceanic environment, considered to be Late Jurassic-to-mid-Cretaceous in age (FERRARIO and MONTRASIO, 1976; PERETTI, 1985; PUSCHNIG, 1998). The most dominant sedimentary unit in the studied area comprises metaarkoses, occurring directly under the Margna nappe (Fig. 2). They are isolated from the sediments overlaying the metabasalts, which complicates the interpretation of the metaarkoses.

The *Malenco unit* is the lateral tectonic equivalent of the Forno unit and consists mainly of ultramafic rocks, metagabbros (Braccia gabbro) and some paragneisses (Senevedo gneiss) with relict pre-Alpine granulite facies assemblages (MÜNTENER and HERMANN, 1996). This sequence of rocks represents a fossil crust-to-mantle transition (HERMANN et al., 1997) which was formed during the intrusion of the Braccia gabbro in Permian times (HANSMANN et al., 1996). This mafic underplating caused granulite facies metamorphism (800 °C, 1.0 GPa) in the Senevedo gneiss. Isobaric cooling to 600 °C, at 0.8 GPa, reflects extension and thermal relaxation after the gabbro intrusion (HERMANN et al., 1997). Near-isothermal decompression is associated with increasing hydration of these rocks and documents the exhumation of the former crust-to-mantle transition to the ocean floor during Jurassic rifting (MÜNTENER et al., 1999). Dykes of Forno basalts cut the ultramafic rocks of the Malenco unit, revealing the close relationship of the two units (TROMMSDORFF et al., 1993). Widespread serpentinisation of the ultramafic rocks, the occurrence of sedimentary ophicarbonates and the rodingitisation of mafic dykes within the ultramafic rocks indicate that these rocks were emplaced near the ocean floor prior to the Alpine orogeny (TROMMSDORFF et al., 1993; HERMANN and MÜNTENER, 1996).

Southwest of the studied area, the Forno unit is crosscut by the Oligocene Bergell intrusion. This caused a contact metamorphic aureole (TROMSDORFF and NIEVERGELT, 1983) which destroyed much of the evidence for collision related Alpine metamorphism in the Forno amphibolites and led to recrystallization of the metaarkoses.

Studied rock-types

ROCK-TYPES OF THE MARGNA NAPPE

The *Fedoz* Series consists of reddish-to-brownish-weathering metapelites, commonly garnet-bearing chlorite- two mica gneisses. In metapelites without Alpine deformation, pre-Alpine kyanite-garnet felses are locally preserved. Grey-weathering titanite-bearing potassium feldspar-diopside-garnet-calcsilicate rocks are intercalated in the metapelites. Garnet amphibolites are subordinate (GUNTLI and LINIGER, 1989).

Two major rock-types can be distinguished within the *Fedoz gabbro:* a grey- to slightly reddish-brown-weathering clinozoisite-bearing chlorite-actinolite-gneiss (magnesio-gabbro), occurring as large bodies; and a surrounding titanite- and apatite-bearing chlorite-amphibolite (ferro-gabbro) (Fig. 2). The ferro-gabbro widely forms dykes within the magnesio-gabbro. In addition, a few dykes of biotite-muscovite-actinolite-chlo-

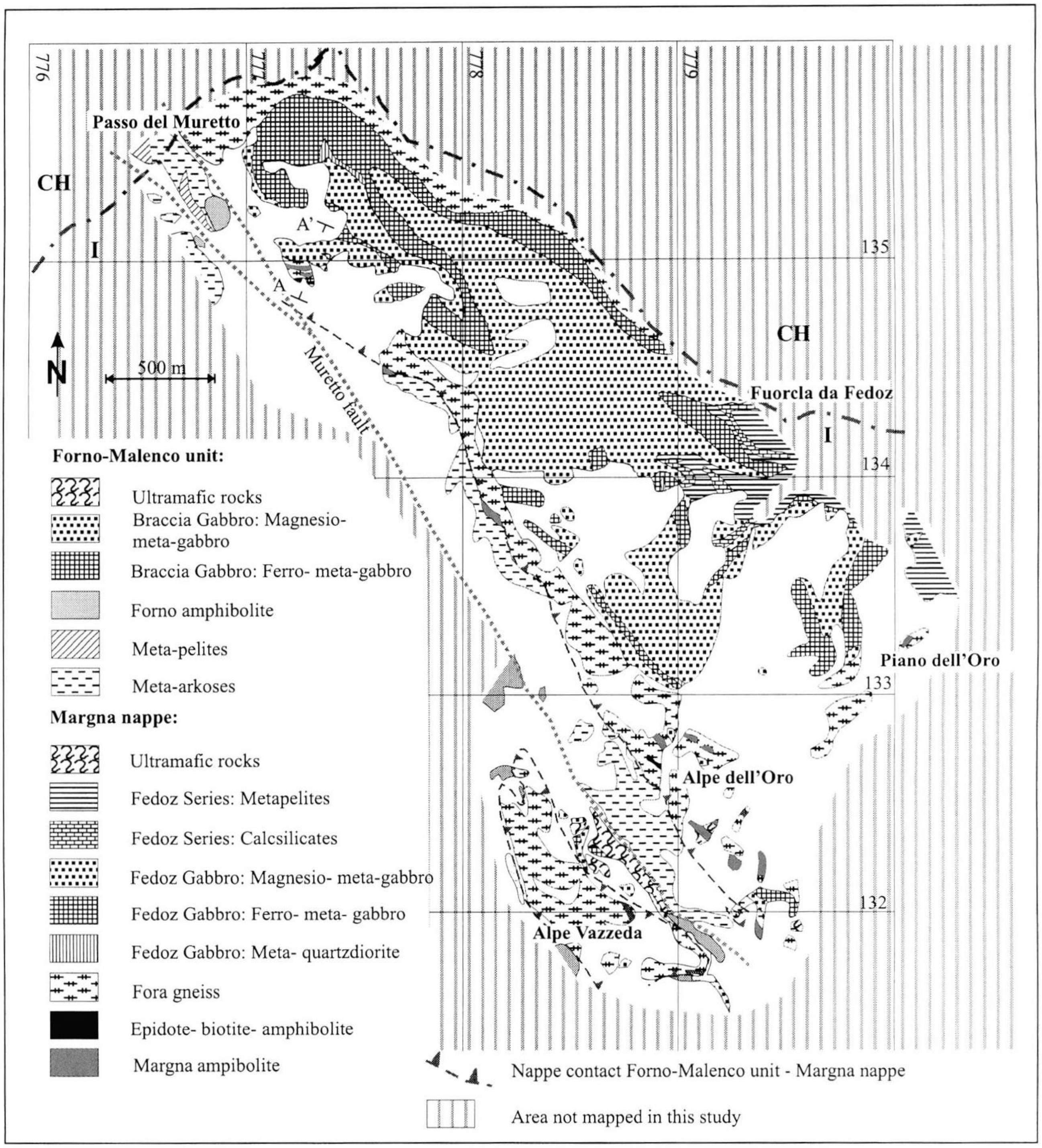

Fig. 2 Geologic map of the Val Muretto (uppermost Val Malenco).

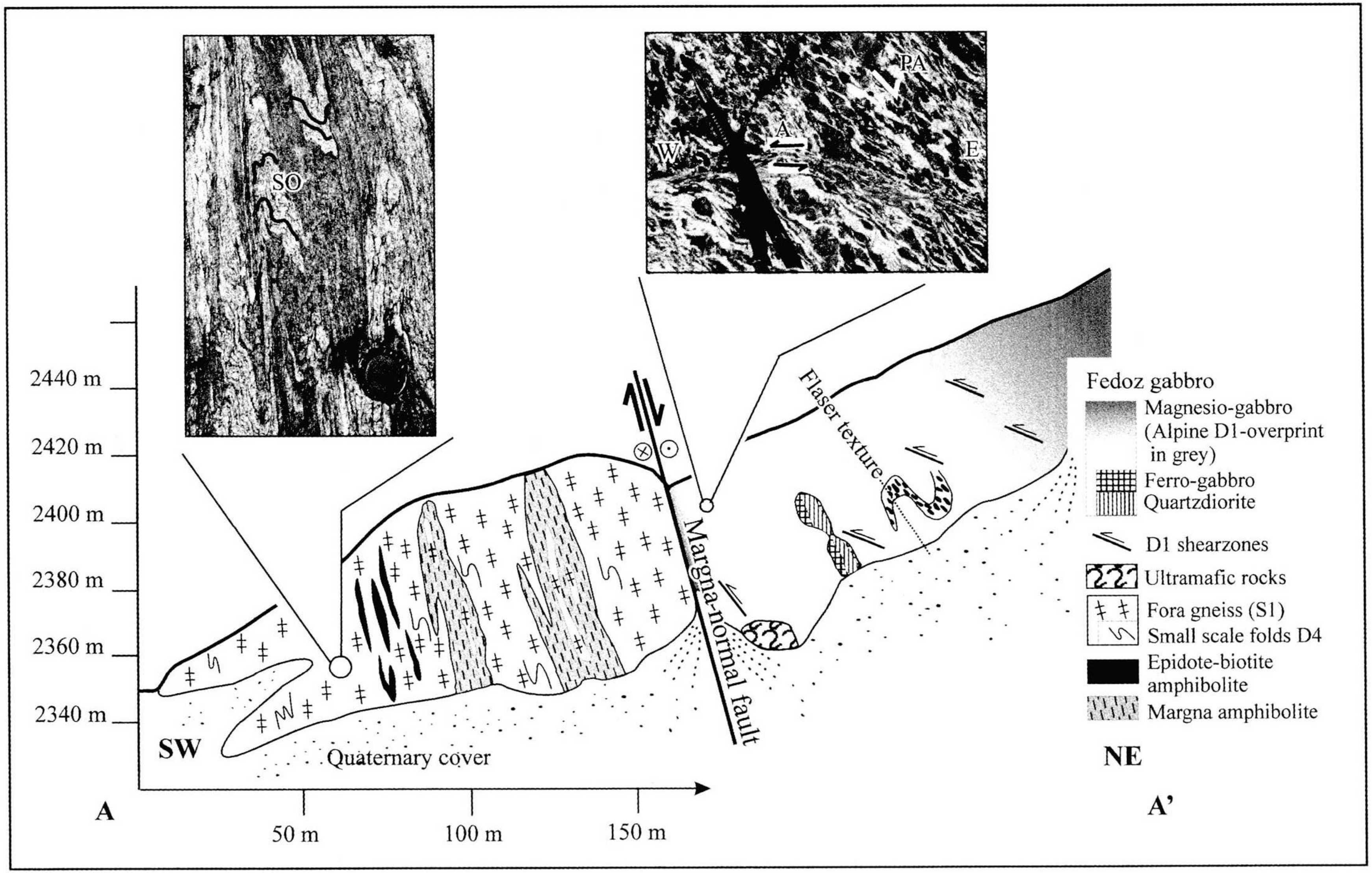

Fig. 3 Profile A–A', approx. 900 m south of Passo del Muretto (for trace see Fig. 2). Various pre-Alpine and Alpine features can be observed: left inset shows pre-Alpine foliation (S0) in the Fora gneisses (coin diameter: 2.5 cm), right inset shows a discrete Alpine D1 shear-zone (A) overprinting ductile pre-Alpine (PA) fabric (pencil for scale; note that the orientation of the foto does not match the orientation of the profile). A pre-Alpine fold and primary intrusive relationships in the Fedoz gabbro are sketched. Discrete D1 shear-zones crosscut the pre-Alpine features (sketched only schematically). The relationships between Fora gneisses and Margna amphibolite are shown in detail in figure 4. The steep inclination of the main foliation is due to verticalization (D5) close to the Bergell contact (PUSCHNIG, 1996). The whole section is situated on a normal limb of a large scale D4 fold.

rite- and epidote-bearing quartz-albite rocks are spatially related to the ferro-gabbros and may represent highly differentiated quartz-diorites. Pre-Alpine mineral relics such as plagioclase and pargasitic amphibole are rare and only locally found, whereas pre-Alpine structures and fabrics are common.

This rock association is identical to the mafic suite of the Malenco unit. Additionally, chemical analyses of the Fedoz gabbro are indistinguishable from the Braccia gabbro (ULRICH and BORSIEN, 1996; BISSIG, 1997; HERMANN, 1997)

The Fora gneisses are pale reddish-to-brownish-weathering chlorite- and potassium-feldspar-bearing quartz-albite-two-mica gneisses. They represent orthogneisses of granodioritic-to-granitic composition (LINIGER and GUNTLI, 1988). A relict pre-Alpine foliation is locally preserved in these gneisses.

At least two different kinds of *mafic rock-units* occur in the Fora gneisses: (I) an apatite- and titanite-bearing *epidote-biotite amphibolite,* which occurs as narrow, but several meter long bodies parallel to S1 exhibiting the same pre-Alpine foliation as the Fora gneisses. (II) The *Margna amphibolite* is a porphyritic biotite-chlorite amphibolite, which occurs as elongated bodies close to the nappe contact (Fig. 2). The pre-Alpine foliation evident in the Fora gneisses and in the epidote-biotite amphibolites is not observed in the Margna amphibolite and no relics of pre-Alpine metamorphism are present. The Margna amphibolite is very similar in the field to the Forno amphibolite (PUSCHNIG, 1998).

METAARKOSES IN THE FORNO UNIT

The metaarkoses in the Val Muretto consist of muscovite-bearing calcite-biotite-plagioclase-quartz-gneisses. Diopside has been observed in only a single layer (Swiss grid co-ordinates: 778.100/133.800), whereas the similar-looking rocks in the Val Forno are generally rich in diopside and poor in calcite (MÜTZENBERG, 1987). The detrital heavy minerals of samples from the Val Muretto suggests a continental provenance. Two distinct populations have been identified: one contains, in order of decreasing abundance: apatite, tourmaline, allanite/clinozoisite, zircon and TiO_2-group minerals, the second lacks tourmaline and includes significantly more zircon. On all of these minerals a metamorphically grown rim is common.

Structural evolution

PRE-ALPINE STRUCTURES

Although the Alpine deformation and metamorphism strongly overprinted the studied rocks, various structural features considered to be pre-Alpine are preserved (Fig. 5). They occur in the pre-Alpine metamorphic Fedoz series, Fedoz gabbro and Fora gneisses, but are absent in the Forno amphibolite, Margna amphibolite and metaarkoses. The structures in the Fedoz gabbro are particularly well preserved and help to clarify the pre-Alpine history of the Margna nappe.

The most important feature is a flaser texture in the gabbroic rocks. The flasers consist of unoriented amphibole pseudomorphs after pyroxene. The former plagioclase matrix is statically overgrown by albite and clinozoisite. The absence of strain in the Alpine metamorphic assemblage demonstrates that the deformation is of pre-Alpine age. The flaser fabric defines an axial-plane cleavage in folded magmatic layers of the gabbro. Within the Braccia gabbro of the Malenco unit, a similar flaser texture occurs in rocks with pre-Alpine minerals preserved (HERMANN and MÜNTENER, 1996).

Ductile, meter-wide shear zones affect the flaser texture in different localities and display a systematic top-to-the-east or -southeast move-

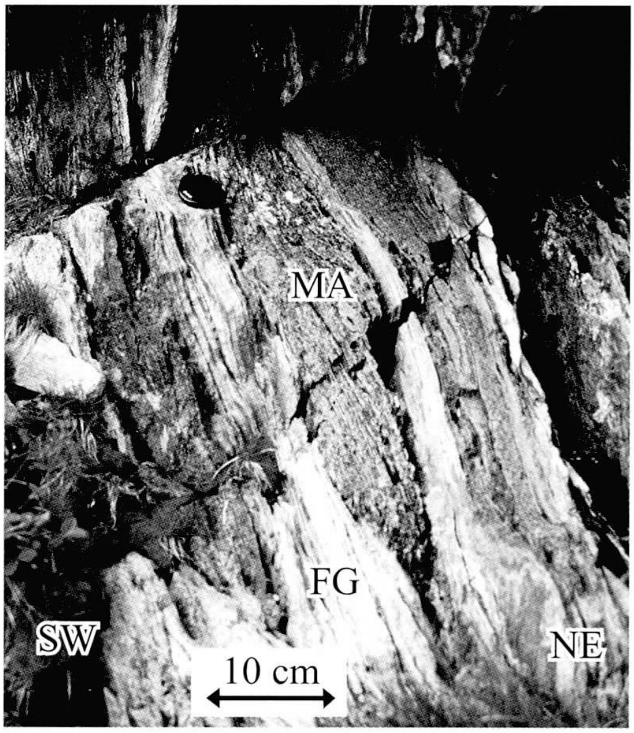

Fig. 4 Isoclinally folded (D1) contact between Fora gneiss (FG) and Margna amphibolite (MA). Swiss grid coordinates: 777.290/134.920 (see also Fig. 3).

ment. Clinozoisites in the feldspar matrix are generally not oriented, indicating that deformation took place prior to the Alpine breakdown of plagioclase to clinozoisite and albite. Pre-Alpine structures and fabrics can be well studied at an outcrop 1 km SW of Passo del Muretto (Fig. 3). Pre-Alpine ductile shear zones with a top-to-the-east movement are clearly cut by a discrete, cm-wide, Alpine shear zones with a top-to-the-west sense of movement. This relationship supports a pre-Alpine origin of the meter-wide shear zones. The contact between the Fora gneisses and the Fedoz gabbro is strongly mylonitized and, on the large scale, folded by the eo-Alpine D1 nappe

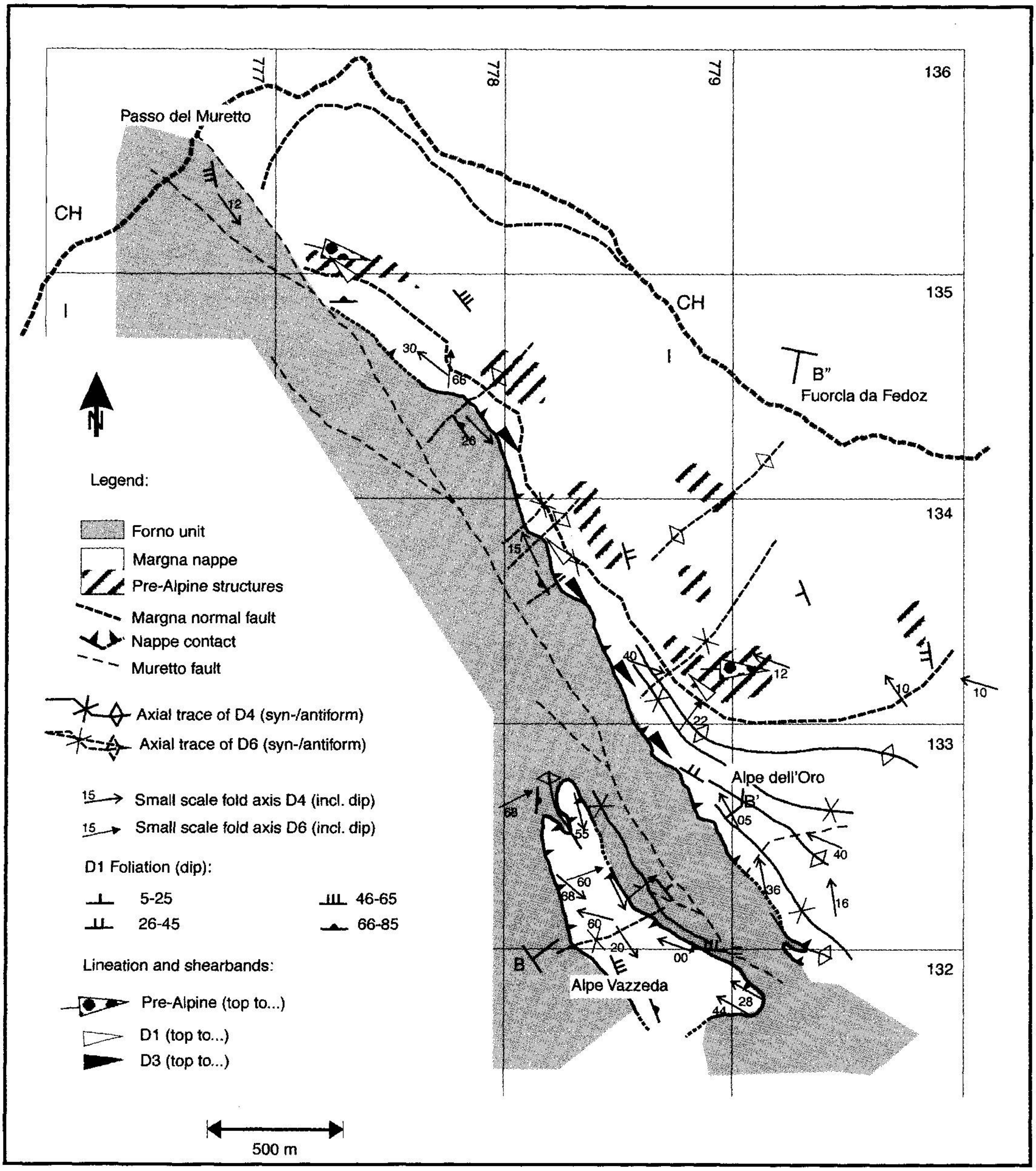

Fig. 5 Structural map of the Val Muretto. The Margna-klippe at Alpe Vazzeda can be explained by a basin structure due to overprinting D4 and D6 synclines (see Fig. 6).

folding, indicating a pre-Alpine origin for this contact. The transition from the magmatic- to the mylonitic fabric of the gabbro is gradual, the mylonite being only weakly overprinted by Alpine structures. The pre-Alpine top-to-the-east movement juxtaposed high-grade metamorphic lower-crustal rocks against relatively low-grade upper-crustal granitoids (Fig. 3, referred to as Margna normal fault).

The Fora gneisses adjacent to the gabbros of this locality have a relict foliation preserved in fold hinges of Alpine D1 folds (Fig. 3). The epidote-biotite amphibolites are also affected by this pre-Alpine cleavage, whereas the Margna amphibolites are deformed by the Alpine D1-folds (Fig. 4), but do not contain relics of an older foliation. This older foliation has never been found in the Forno unit or in the Mesozoic cover of the Margna nappe (LINIGER and GUNTLI, 1988; HERMANN and MÜNTENER, 1992; PUSCHNIG, 1996).

ALPINE STRUCTURES

The structures mapped in the Val Muretto are in conformity with those in adjacent sectors of the Margna nappe (LINIGER and GUNTLI, 1988; HERMANN and MÜNTENER, 1992; SPILLMANN, 1993) and correspond nearly completely to the evolution of the entire Forno unit as described by PUSCHNIG (1996). Therefore only a short description of the relevant structures in the studied area is given (Figs 5 and 6). To prevent confusion, the notation of PUSCHNIG (1996) was used for the described structures (Tab. 1).

D1: Nappe thrusting: This deformation caused isoclinal folding and a related penetrative axial-plane cleavage, representing the main-foliation (S1) in the study-area. Evidence for top-to-the-west to -northwest sense of shear occurs along the nappe contact and in cm-wide shear zones cutting the pre-Alpine fabric within the Fedoz gabbro (Fig. 3).

D3, Turba phase: Top-to-the E or SE shear-sense indicators along the Forno-Margna contact are probably related to the Turba extension (Fig. 5). It post-dates the nappe thrusting but pre-dates the second phase of backfolding (D4), because the latter folds the nappe contact in a large scale.

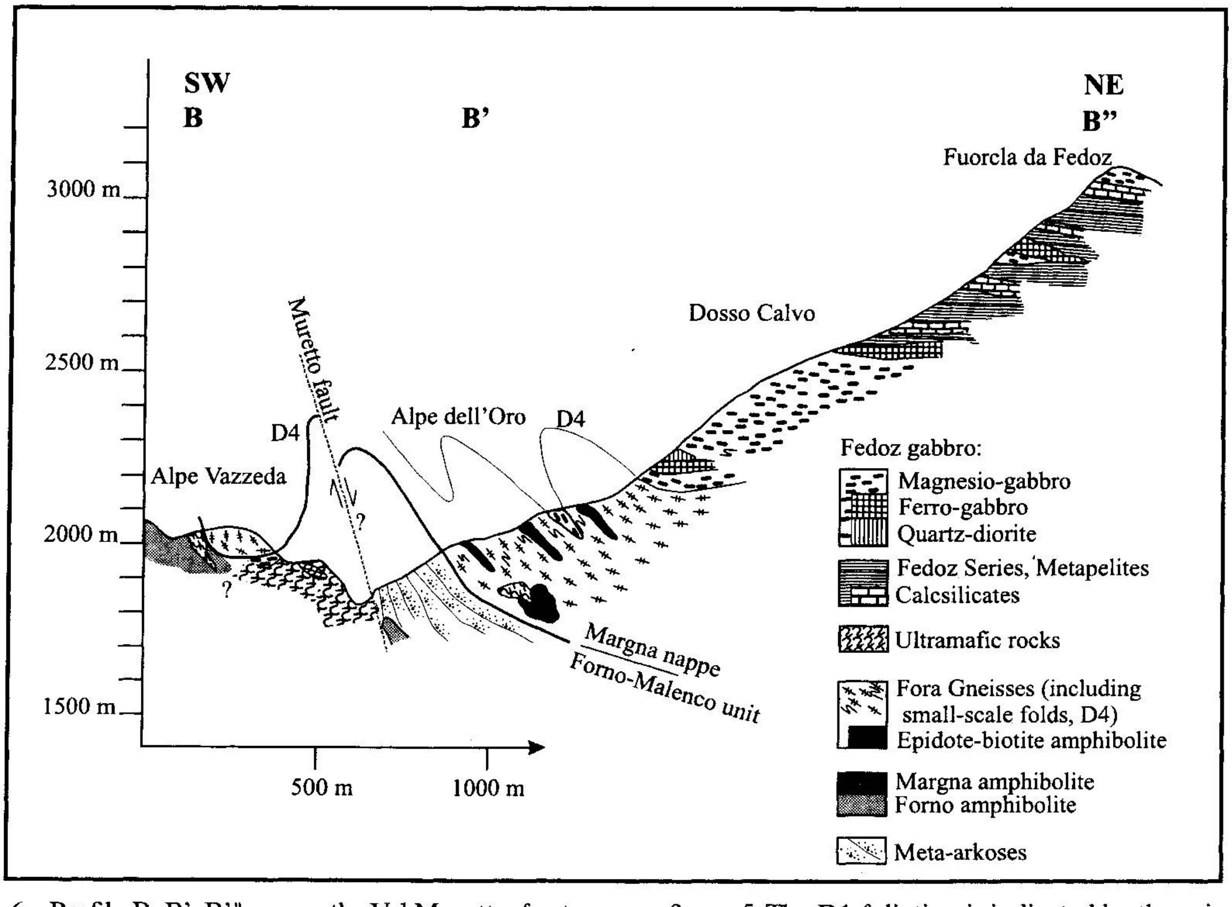

Fig. 6 Profile B–B'–B'" across the Val Muretto; for trace see figure 5. The D1-foliation is indicated by the orientation of the pattern, D4-folds have been outlined.

Tab. 1 The deformation sequences in the Forno unit and southwestern Margna nappe, regional deformation is indicated in bold italics (modified after PUSCHNIG, 1996).

Deformation Sequences (PUSCHNIG, 1996)	**Observed features in the southwestern Margna nappe**	**Age scale and interpretation (PUSCHNIG, 1996)**
Nappe thrusting: Top to W (D1)	Isoclinal folds, main foliation, shearbands top to W	Cretaceous nappe stacking (Cenomanian-Santonian)
1st phase of backfolding (D2)	Small scale southwest-vergent folds	Early tertiary north-south shortening (Eocene)
Turba phase: Top to SE (D3)	Shearbands along the contact Margna nappe and Forno unit	East-west extension (Early Oligocene)
2nd phase of backfolding (D4)	Mappable southwest-vergent folds, locally a secondary axial plain cleavage	
Verticalisation (D5)	Increasing angle of dip towards the Bergell contact	Emplacement of tonalite (32 Ma)
Transverse folding (D6)	Small- and large-scale folds perpendicular to D4 fold axis	Northwest-southeast shortening
Vertical shortening (D7)	Only minor evidence within the discussed area	Emplacement of the granodiorite (30 Ma)
Final emplacement of the granodiorite (D8)	Only minor evidence within the discussed area	

D4, Second phase of back-folding: These structures constitute the most obvious folds within the studied area. They clearly deform the main foliation and locally develop a new axial-plane cleavage. Northwest-southeast striking, southwest-vergent synforms and antiforms with wavelengths of several hundred meters are mappable (see Fig. 5). These structures appear in the Margna nappe as well as in the Forno unit, folding the nappe contact, and are of regional importance in the Val Malenco (SPILLMANN, 1993). The second phase of backfolding is partly crosscut and overprinted by the contact aureole of the tonalite (SPILLMANN, 1993; REBER, 1995; PUSCHNIG, 1996), of the Bergell intrusion (32 Ma, VON BLANCKENBURG, 1992).

D6, Transverse folding: In contrast to all the previous phases of folding, these structures have NE–SW striking axes and subvertical axial planes. The folds form open synforms and antiforms and, together with the second phase of backfolding, a pronounced dome-basin pattern. The gneisses belonging to the Margna nappe at Alpe Vazzeda lie in such a basin structure (Fig. 5). This deformation is of regional importance (SPILLMANN, 1993) and intervened between the two intrusive phases of the Bergell pluton (PUSCHNIG, 1996).

Brittle deformation along the Muretto Fault: The position of the gneisses at Alpe Vazzeda can be explained by D4 and D6 folding and no obvious signs of a major fault can be observed in the valley between Alpe Vazzeda and Alpe dell'Oro (Figs 5 and 6). These observations indicate that the Muretto Fault had only a limited offset in the lower Val Muretto and supports the studies of RING (1994) and SPILLMANN (1993) who suggested that vertical displacement does probably not exceed 200 m (NE block down-thrown) at the Passo del Muretto.

Metamorphism

PRE-ALPINE HIGH TEMPERATURE AND HIGH PRESSURE METAMORPHISM

Definition of the pre-Alpine metamorphic conditions within the Margna nappe is difficult, because of the strong Alpine overprint. Although the Fedoz gabbro and the Fora gneisses exhibit pre-Alpine structures, little or no mineralogical evidence for contemporaneous metamorphism is preserved (GUNTLI and LINIGER, 1989; BISSIG, 1997). However, in the metapelites of the Fedoz Series, garnet, kyanite and rutile-bearing quartz constitute relics of a pre-Alpine high-temperature and -pressure metamorphism (Fig. 7). Paragonite overprints the relict minerals and is assumed to belong to a retrograde stage of the pre-Alpine metamorphism (Fig. 7). In the associated calc-silicate rocks, the paragenesis calcite + quartz + grossular + diopside + titanite + microcline ± ap-

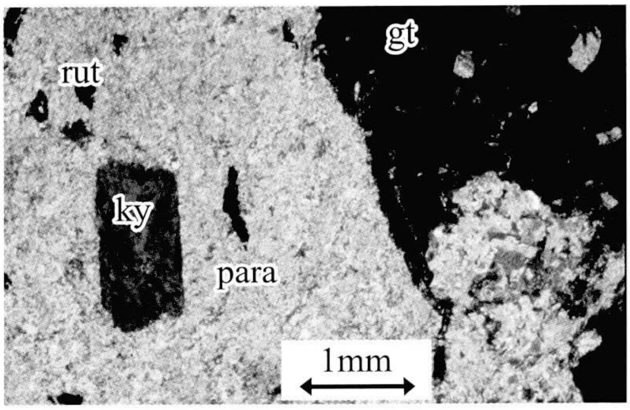

Fig. 7 Photomicrograph of a metapelite of the Fedoz Series containing large garnets (gt), kyanite (ky) and rutile (rut) in a matrix of paragonite (para). Swiss grid coordinates: 779.130/133.860.

atite is present. This assemblage is similar to that of granulite facies calc-silicates in the Malenco unit (HERMANN, 1997) and is clearly of pre-Alpine origin, because diopside and garnet are nowhere found in the Mesozoic cover of the Margna nappe (HERMANN and MÜNTENER, 1992).

ALPINE REGIONAL METAMORPHISM

The Alpine metamorphism overprints the pre-Alpine relics and affects also the Forno unit and the Mesozoic sediments covering the Margna nappe (PERETTI, 1985; HERMANN and MÜNTENER, 1992). The best constraints on the Alpine regional metamorphism in the study-area are found in iron-rich gabbros where no pre-Alpine relics are preserved. Only samples from northeast of Alpe dell'Oro are suitable, because further southwest the later contact metamorphism of the Bergell intrusion affects all lithological units.

Generally the paragenesis, albite + epidote/clinozoisite + chlorite + actinolitic hornblende + titanite, is stable in the mafic rocks, indicating that Alpine metamorphism reached upper greenschist to epidote-amphibolite facies conditions. In most of the samples titanite is the stable titanium phase, usually postkinematic to D1 and overgrowing rutile (Fig. 8). However, in one sample from Piano dell'Oro, titanite is overgrown by ilmenite (Fig. 8). In this sample, small zoned garnets coexist with zoned amphiboles. The rims are clearly post-kinematic with respect to D1. The cores are assumed to be synchronous with, or slightly post-kinematic to, D1. The assemblage is iron-buffered due to its content of magnetite. The apparent cores of the garnets and the amphiboles yield temperatures of 500 ± 50 °C, and the rims 530 ± 50 °C, using garnet-amphibole thermometer (GRAHAM and POWELL 1984). This is in agreement with the transition from titanite to ilmenite, which was probably caused by the reaction:

chlorite + titanite + actinolite ± albite ± epidote = hornblende + ilmenite + quartz + H_2O,

experimentally constrained to 500–550 °C (Fig. 9; APTED and LIOU, 1983). However, the fact that ilmenite, garnet and albite + oligoclase are present only in iron-rich varieties of the gabbro, has to be considered. In more magnesium-rich gabbros, titanite and albite + clinozoisite are stable and no garnet is present. Realistic values for the metamorphic temperatures are therefore probably

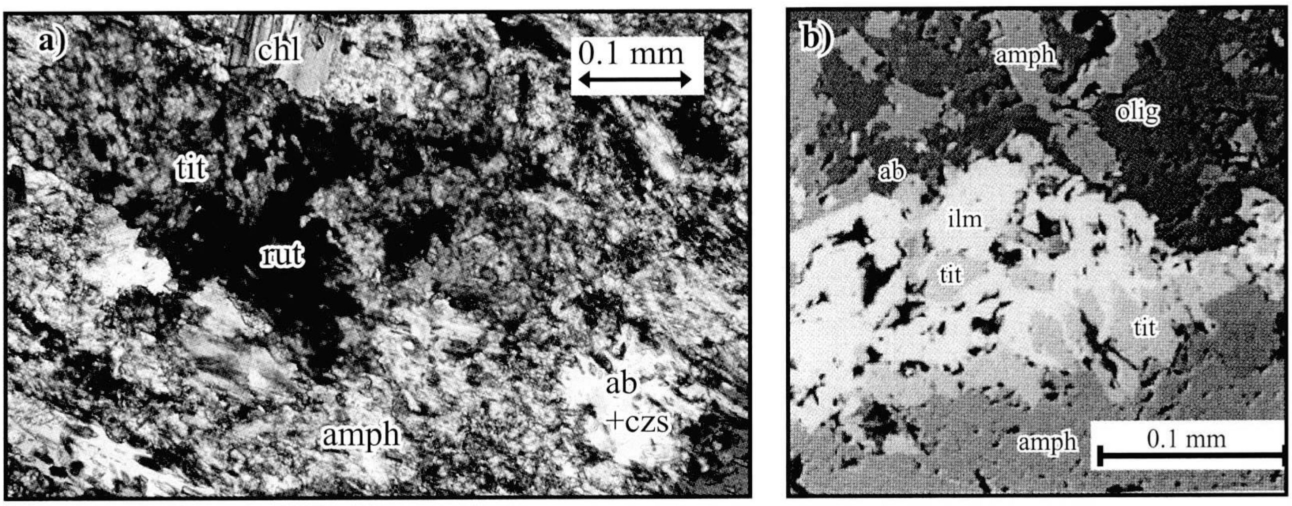

Fig. 8 Alpine paragenesis of the Fedoz gabbro: (a) Photomicrograph of a ferro-gabbro. Rutile (rut) is overgrown by titanite (tit). Further abbreviations: amph: green hornblende; chl: chlorite; ab: albite; czs: clinozoisite. Swiss grid coordinates: 779.580/133.190. (b) Backscatter-electron image of a ferro-gabbro. Ilmenite (ilm) replaces titanite (tit). Further present are green hornblende (amph), albite (ab) and oligoclase (olig). Sample CH-F 205, location: Piano dell'Oro, Swiss grid coordinates: 779.770/133.480.

closer to 450 °C for the cores and 480 °C for the rims.

The Na in the M4 crystal site (Na^{M4}) in the cores of the amphiboles indicates a pressure during D1 metamorphism of about 0.6–0.7 GPa (Fig. 10), using the semi-quantitative calibration of BROWN (1977). The Na^{M4} in the cores are similar to values obtained by GUNTLI and LINIGER (1989) from other ferro-gabbros in the Margna nappe. One thin amphibole rim displays significantly lower Na^{M4} and Al(IV)-contents than the cores (Fig. 10), and represents amphibole recrystallization during late Alpine deformation or contact metamorphism.

The paragenesis of the metagabbros in the Margna nappe is identical to similar rock types in the Braccia gabbro of the Malenco unit. In the Braccia gabbro, titanite overgrow on rutile can also be observed, the garnets display the same chemical trends from core to rim (Tab. 2), and the amphibole compositions cover the same range (Tab. 2, Fig. 10). Garnet-amphibole thermometry (GRAHAM and POWELL, 1984) yields temperatures of 485 ± 50 °C for the garnet cores and 495 ± 50 °C for the garnet rims. Alpine metamorphism therefore reached the same grade in the Penninic Malenco unit and the Austroalpine Margna nappe.

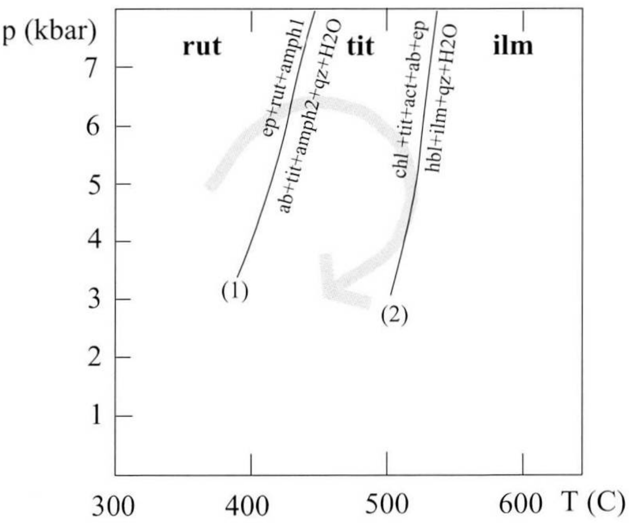

Fig. 9 PT path that would explain the Alpine paragenesis in the Fedoz ferro-gabbros. Reaction 1 is based on metamorphic assemblages in the Braccia gabbro (HERMANN, 1997) and is most probably continous. Reaction 2 is experimentally determined in mafic rocks by APTED and LIOU (1983). During reaction 1 Al- and Ca-content of amphibole increase whereas Na(M4) decreases (schematically shown as amph1 and amph2). The southwestern margin of the Margna nappe barely reaches the reaction 2. Abbreviations: rut: rutile; tit: titanite; ilm: ilmenite; ep: epidote; amph: amphibole; qz: quartz; chl: chlorite; act: actinolite; ab: albite; hbl: hornblende.

The geochemical characteristics of the mafic rocks in the Fora-Gneisses of the Margna nappe

The Margna amphibolites are fine-grained and occur in dyke/sill like configurations. They have a basaltic composition and can be characterised on the basis of the immobile elements Ti, Y, Zr or Nb (Tab. 3). In a Ti–Y/Nb diagram the Margna amphibolites predominantly plot into the tholeiite fields, whereas the epidote-biotite amphibolites have a stronger alkalic affinity (Fig. 11). The Margna amphibolites show the same range of composition as the Forno-metabasalts (PUSCHNIG, 1998) but differ clearly from the Fedoz and Braccia gabbros, which display chemical characteristics of cumulates (ULRICH and BORSIEN, 1996; HERMANN, 1997).

The REE patterns of the Margna amphibolites are flat and display no Eu-anomaly (Fig. 12), indicating the absence of cumulus plagioclase. This observation provides evidence that the

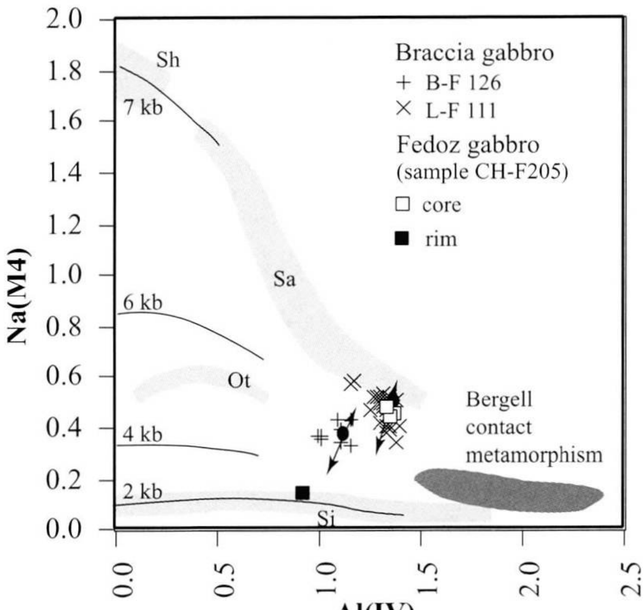

Fig. 10 Semi-quantitative pressure determination after BROWN (1977) of Alpine metamorphism on the basis of the Na(M4) content of amphiboles in samples from the Fedoz and the Braccia gabbro. The composition of amphibole cores in the Fedoz gabbro overlaps with D1 amphibole composition in the Braccia gabbro and indicate a pressure during D1 metamorphism of 0.6–0.7 GPa. Arrows indicate possible range of Al(IV) and Na(M4) due to different normalisation procedures. For comparison the composition of amphiboles formed during the Bergell contact metamorphism are shown (BORSIEN, 1995). The terrains which BROWN (1977) used for calibrating the plot are shown: Sh = Shuksan, Sa = Sanbagawa, Ot = Otaga, Si = Sierra. (Samples: CH-F 205, Swiss grid coordinates: 779.770/133.480, B-F 126: 784.300/128.390, L-F 111: 783.500/130.350.)

Tab. 2 Electron microprobe data of amphiboles and garnets from the Fedoz and the Braccia gabbro. Data are given in wt%. Cations calculated on the basis of 23 oxygens and Fe^{3+}/Fe^{tot} = 0.3 (amphiboles) and 8 cations and 12 oxygens (garnet). Important site distributions and ratios for amphiboles are given.
Mineral compositions were analyzed using a Cameca SX-50 microprobe, equipped with five crystal spectrometers. Samples were coated with 200 Å of carbon. Operating parameters include an acceleration potential of 15 kV, a beam current of 20 nA and a beam size of 10 Å. Data collection time was 20 s. Natural and synthetic oxides and silicates were used as standards. A ZAF type correction procedure was applied to the data.

	Fedoz gabbro					Braccia gabbro		
	Amphibole			Garnet		Am	Garnet	
	Core	Rim1	Rim2	Core	Rim1		Core	Rim
SiO_2	46.69	46.35	48.82	37.66	37.45	47.51	37.08	36.94
TiO_2	0.38	0.39	0.18	0.03	0.08	0.29	0.08	0.08
Al_2O_3	12.37	13.24	7.27	22.25	22.02	10.68	21.62	21.54
Fe_2O_3	5.74	5.87	6.02	1.23	1.02	4.25	2.05	2.03
FeO	12.06	12.31	12.64	31.07	28.88	8.93	26.23	26.01
MnO	0.09	0.08	0.22	0.56	1.26	0.16	1.70	1.04
MgO	10.01	10.17	11.41	1.97	1.94	12.72	2.08	2.12
CaO	8.84	8.94	11.52	7.61	8.73	10.09	9.85	10.32
Na_2O	2.38	2.14	0.65	< 0.03	< 0.03	2.12	< 0.03	< 0.03
K_2O	0.26	0.27	0.27	< 0.03	< 0.03	0.26	< 0.03	< 0.03
H_2O	2.08	2.09	2.07			2.06		
Total	100.9	101.9	101.1	102.4	101.4	99.2	100.7	100.0
Si	6.741	6.635	7.086	2.941	2.945	6.88	2.93	2.93
Ti	0.042	0.042	0.019	0.002	0.005	0.03	0.00	0.00
Al	2.104	2.234	1.244	2.048	2.041	1.83	2.01	2.01
Fe^{3+}	0.624	0.632	0.658	0.072	0.060	0.46	0.12	0.12
Fe^{2+}	1.456	1.473	1.534	2.029	1.900	1.08	1.73	1.73
Mn	0.011	0.009	0.018	0.037	0.084	0.02	0.11	0.07
Mg	2.153	2.170	2.468	0.230	0.227	2.73	0.25	0.25
Ca	1.368	1.372	1.792	0.637	0.736	1.57	0.83	0.88
Na	0.665	0.595	0.182	0.000	0.000	0.59	0.00	0.00
K	0.048	0.050	0.050	0.000	0.000	0.05	0.00	0.00
H	2.000	2.000	2.000			2.00		
x_{Mg} (Fe_{tot})	0.509	0.507	0.530			0.64		
Al (IV)	1.259	1.365	0.914			1.18		
Al (VI)	0.845	0.869	0.330			0.65		
Na (M4)	0.502	0.432	0.172			0.38		
Na+K (A)	0.211	0.213	0.060			0.26		

Margna amphibolites represent crystallised basaltic melts. These REE patterns are very similar to the Forno metabasalts and display characteristics of transitional-type MORB (WALKER, 1991; Fig. 12).

The REE patterns of epidote-biotite amphibolites, however, differ clearly from the Margna amphibolite. They are light-REE enriched compared with the Margna and Forno amphibolites and have a composition similar to alkali-basalts (SUN and MCDONOUGH, 1989; Fig. 12).

Discussion

The special tectonic position of the study-area at the boundary between the oceanic Forno unit and the continental Margna nappe constrains the processes involved in the separation as well as the convergence between the Adriatic and European plate.

MARGNA NORMAL FAULT

Pre-Alpine metamorphic relics, such as garnet and kyanite in the Fedoz Series and garnet and diopside in intercalated calcsilicates, correspond to pelitic granulites in the Malenco unit (HERMANN et al., 1997). Additionally the rock-types and chemical characteristics of the Fedoz gabbro in the Margna nappe are identical to the Braccia gabbro in the Malenco unit. Thus a common pre-Alpine evolution of these rocks is suggested. As in the Senevedo gneiss, kyanite was stable at peak

Tab. 3 Representative whole-rock geochemical data for Margna- and epidote biotite amphibolites determined by XRF (major elements in wt%; trace elements in ppm) and solution ICP-MS (REE in ppm).

	Margna amphibolite			Ep-bi amphibolite	
Sample no.	F44x	F45	F136	F143	F146
SiO_2	48.97	46.84	48.24	44.2	49.09
TiO_2	0.68	1.85	1.17	3.47	1.89
Al_2O_3	16.72	14.45	15.63	12.13	16.91
Fe_2O_3*	11.27	12.4	10.68	13.06	9.57
MnO	0.15	0.21	0.21	0.17	0.17
MgO	7.12	8.4	8.62	8.94	5.05
CaO	4.83	9.3	8.26	9.67	9.75
Na_2O	4.34	3.12	2.9	0.67	0.9
K_2O	1.51	1.18	1.52	3.83	3.99
P_2O_5	0.08	0.22	0.14	0.58	0.23
Volatiles	2.91	1.65	1.31	1.75	1.8
Total	98.58	99.62	98.68	98.47	99.35
F	374	723	621	2123	1458
Ba	210	180	302	836	710
Rb	46	39	51	122	212
Sr	159	229	210	92	345
Nb	5	16	8	64	33
Y	19	41	30	40	26
Zr	46	141	81	341	54
V	308	319	216	275	202
Cr	69	117	219	564	309
Ni	37	54	110	170	94
Co	28	53	37	95	51
Cu	16	49	24	10	31
Zn	142	120	106	179	84
Hf	17	16	16	19	16
Sc	56	56	47	29	44
S	648	59	< 50	< 50	260
Y/Nb	3.8	2.56	3.75	0.63	0.79
La	1.6	8.4	5	50	15
Ce	4.9	21	13	112	33
Pr	0.72	3.3	2	14	4.4
Nd	2.7	15	9.8	57	19
Sm	1.1	4.8	3.1	11	5.1
Eu	0.39	1.7	1.1	3.3	1.7
Gd	1.5	5.8	4	9.1	5.9
Tb	0.27	0.96	0.67	1.3	0.97
Dy	1.9	6.4	4.4	6.5	6.4
Ho	0.4	1.3	0.91	1.2	1.3
Er	1.2	3.7	2.5	2.9	3.6
Tm	0.17	0.53	0.35	0.37	0.52
Yb	1	3.1	2.2	2.1	3.1
Lu	0.15	0.47	0.33	0.29	0.43

* Fe total

metamorphism in the Fedoz series, compatible with granulite facies metamorphism at 800 °C, 1.0 GPa due to mafic underplating of the Fedoz/Braccia gabbro in Permian times (HERMANN et al., 1997). Thermal relaxation after intrusion was followed by near-isothermal decompression, indicating exhumation of the granulites to low p-T conditions (MÜNTENER et al., 1999). Exhumation has been related to Jurassic rifting and occurred along a normal fault (Margna normal fault) cutting through the entire continental crust (HERMANN and MÜNTENER, 1996). Much of this pre-Alpine shear zone was reactivated during later Alpine convergence. However, segments of the fault are preserved within the Margna nappe. The new data presented in this paper help to constrain kinematics along the Margna normal fault.

The pre-Alpine shear zones cutting the flaser texture in the Fedoz gabbro show a consistent top-to-the-(south-)east movement. The intensity of shearing increases towards the Margna normal fault, which constitutes the pre-Alpine tectonic contact between the upper crustal Fora-Gneiss and lower crustal Fedoz series and Fedoz gabbro (Fig. 3). The Margna normal fault is folded on map-scale by the first Alpine deformation. Additionally some of the shear zones clearly display a static mineral growth during Alpine metamorphism. These observations indicate that the top-to-the-southeast shearing occurred in pre-Alpine times and was related to movements along the Margna normal fault. In its present position, the investigated contact is situated on the overturned limb of the Fora subnappe fold. Thus, retrodeformation of the Alpine deformation is required in order to get the original shear sense along the Margna normal fault. Two arguments help to constrain the original movement: (I) Alpine shear zones within the Fedoz gabbro always display a

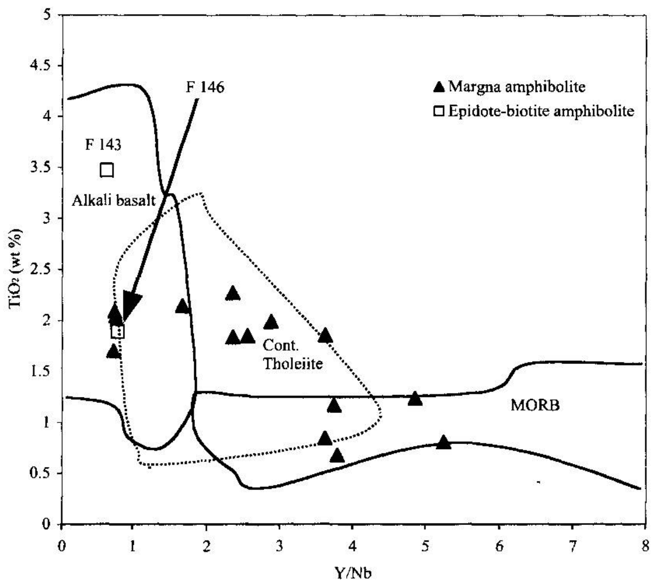

Fig. 11 TiO_2 versus Y/Nb: The Margna amphibolite plots in the tholeiitic basalt fields whereas the epidote-biotite amphibolite shows a more alkalic affinity (after FLOYD and WINCHESTER, 1975).

top-to-the-(north-)west which is in conformity with the overall shear sense during the Margna nappe formation (LINIGER and GUNTLI, 1988; HERMANN and MÜNTENER, 1992; SPILLMANN, 1993), but opposite to the pre-Alpine shear zones. (II) The shear direction is perpendicular to the large scale Fora sub-nappe fold axis and thus retrodeformation does not significantly change the shear sense. From both arguments we conclude that the original shear sense along the Margna normal fault was opposite to Alpine thrusting, i.e., top-to-the-east. This new structural data are in agreement with the hypothesis of HERMANN and MÜNTENER (1996) that the Margna normal fault dipped below the Adriatic continent (Fig. 13).

Generally the late Variscan intrusive units of the Lower Austroalpine nappes are free of pre-Alpine deformation (SPILLMANN, 1993). The pre-Alpine foliation in the Fora gneiss represents an exception, but is restricted to rocks close to the Margna normal fault. It is suggested that this foliation is related to Jurassic movements along the Margna normal fault. However, no systematic mapping of this foliation has been undertaken.

MARGNA AMPHIBOLITES

The Margna amphibolites are metabasalts with a transitional-type MORB chemical signature. In contrast to the Fedoz gabbro, they do not contain relics of pre-Alpine textures or minerals. Margna amphibolites occur only within the Fora gneisses and can be found as boudins and small elongated bodies at roughly the same tectonic level (Fig. 2). The contact of the amphibolites to the Fora gneisses is folded by D1 but not thrusted or faulted. A pre-D1 tectonic integration of amphibolites from the ocean floor sequence is not likely, because no Mesozoic sediments occur in immediate contact with the Margna amphibolites. The Margna amphibolites nowhere display the pre-Alpine foliation which is preserved in the host Fora gneiss. If the deformation of the Fora gneiss were related to the Margna normal fault, this would entail that the Margna amphibolites intruded the continental crust after the fault was active but prior to Alpine thrusting.

The Forno unit exhibits most features of a typical ocean-floor sequence. Pillow structures are locally preserved within the metabasalts (FERRARIO and MONTRASIO, 1976) and the chemical signature corresponds to transitional-type MORB (PUSCHNIG, 1998). The textural and geochemical similarity between the Margna and the Forno metabasalts and the similar relative age with respect to the structural evolution suggests a co-genetic origin. This implies that the Margna continental block was situated in a distal paleogeographic position at the margin of the Adriatic continent, close to the source of the MOR basalts in

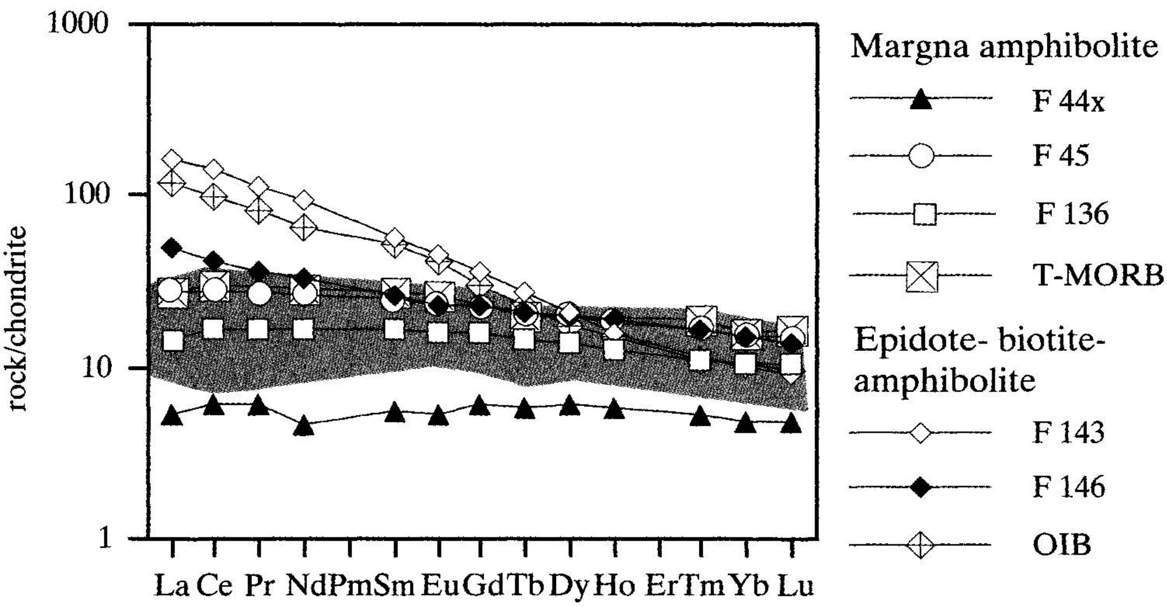

Fig. 12 The distribution of the rare earth elements (REE) in amphibolites within the Fora gneisses (chondrite normalisation after BOYNTON, 1984). The Margna amphibolites show a relatively uniform distribution, whereas the epidote-biotite-amphibolites show an increase of the light REE. The plot-range of the Forno amphibolites is shaded (compiled from PUSCHNIG, 1998) and corresponds well with the Margna amphibolites. A tholeiitic-alkaline transitional type MORB (WALKER, 1991) and an alkaline ocean-island basalt (SUN and MCDONOUGH, 1989) are shown for comparison.

Jurassic times (Fig. 13). A low-angle detachment fault with a top-to-the-east movement would explain this fact better than a symmetrical pure shear model or the opposite sense of shear. Basaltic dykes are reported from the hanging wall of the rift system in the southern Red Sea, but not from the footwall (VOGGENREITER et al., 1988). Therefore the position of the Margna amphibolites within the continental basement of the Adriatic plate is in agreement with asymmetric rifting along an east-dipping Margna normal fault (Fig. 13).

METAARKOSES

STAUB (1918, 1921) considered the metaarkoses of the Muretto Series to be pre-Triassic and to belong to the Margna nappe, but more recent studies revealed that the metasediments constitute a stratigraphic sequence overlying the metabasalts of the Forno unit (FERRARIO and MONTRASIO, 1976; PERETTI, 1985). Because no fossils survived Alpine metamorphism, an Upper Jurassic-to-mid-Cretaceous age of the sedimentary series has been assumed from lithostratigraphic correlation (PERETTI, 1985; WEISSERT and BERNOULLI, 1985; PUSCHNIG, 1998).

If the arkoses are the uppermost member of this sedimentary sequence, then they represent metamorphosed flysch and hence the initial closure of the Piemont-Ligurian ocean during the Cretaceous (WEISSERT and BERNOULLI, 1985). However, the whole series differs slightly from other South-Penninic–Lower Austroalpine sediments, both in facies and heavy mineral contents. Chromium spinel is characteristic of lower Austroalpine clastic sediments of Cretaceous age, the source of detritus being a northern Adriatic obduction belt which is completely eroded (WINKLER, 1996). Chromium spinel does not occur in the metaarkoses of the Val Muretto, indicating that the detrital source differed from that of most South-Penninic–Lower Austroalpine Cretaceous sediments. This could be explained by an almost isolated position of the Margna block at the continental margin.

Another possible interpretation is that the metaarkoses in the Val Muretto belong to the overturned limb of the Fora subnappe and hence the contact with the Forno metasediments is of tectonic origin. The metaarkoses could thus represent Jurassic syn-rift sediments (e.g. FROITZHEIM and EBERLI, 1990), containing debris from the continental crust as well as Triassic dolomite

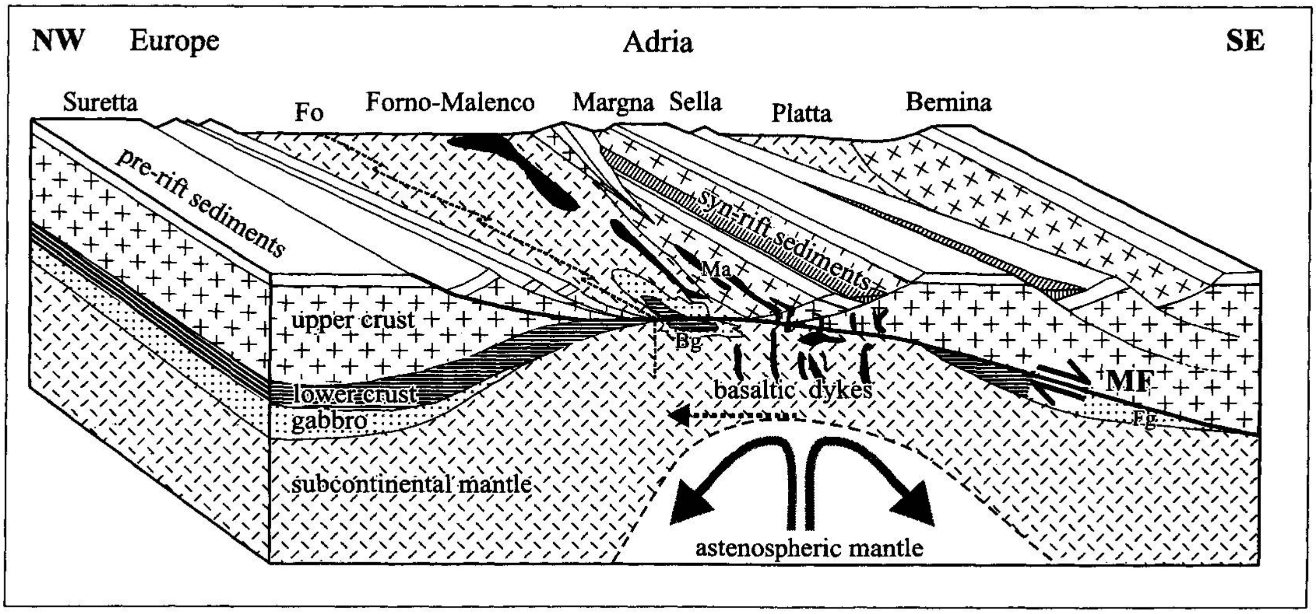

Fig. 13 Reconstruction of the Adriatic passive continental margin formation in Middle Jurassic times. The block diagramm shows the situation prior to the formation of the ocean-floor sequence of the later Forno unit which was emplaced in the Upper Jurassic along the depicted dashed line (Fo). A westward movement of the upwelling asthenosphere (dashed arrow) is required in order to produce the Forno basalts in the observed position. Note the basalts intruding the continental margin of the later Margna nappe as dykes and beginning extrusion at the sea-floor. The position of MORB dykes in the rifted continental crust, the westward shift of the upwelling asthenosphere and the kinematics at the Margna normal fault all indicate asymmetric rifting along a SE-dipping crustal scale shear zone. The metaarkoses discussed in this article may represent syn-rift sediments as indicated in the figure. Suretta, Forno-Malenco, Margna, Sella, Platta, Bernina refer to crustal blocks forming nappes during later Alpine compression. MF: Margna normal fault, Fg: Fedoz gabbro, Bg: Braccia gabbro, Ma: Margna amphibolites.

pebbles which would be the precursor of contact metamorphic diopside. This hypothesis is in agreement with the heavy mineral content of the metaarkoses. However, more detailed structural and sedimentological work has to be done to resolve the origin of these rocks.

ALPINE DEFORMATION AND METAMORPHISM

The comparison of Alpine structures and metamorphism between the Margna nappe and Malenco-Forno units is important because the transition from continental to oceanic crust can act as discontinuity along which subduction is initiated during convergence.

The sequence of Alpine structures in the investigated area agrees completely with the structural evolution of the Forno unit (PUSCHNIG, 1996). Up to now, a detailed comparison of Alpine metamorphic conditions has not been possible because (I) the Forno unit is completely overprinted by the Oligocene contact metamorphism (TROMMSDORFF and NIEVERGELT, 1983); and (II) the Malenco unit was regarded to consist only of ultramafic rocks which do not record metamorphic pressures well. HERMANN and MÜNTENER (1996) demonstrated that the Braccia gabbro belongs to the Malenco unit, which permits to compare the Alpine metamorphic conditions of the Malenco unit to the Margna nappe using equivalent rock-types. In both, the Braccia and Fedoz gabbro, Alpine metamorphism reached epidote-amphibolite facies conditions. Mineral compositions of garnets and amphiboles in Fe-rich metagabbros are identical in both units (Fig. 10, Tab. 2) and yield pressures of 0.5–0.6 GPa and temperatures of about 450–500 °C. These data are consistent with earlier pressure estimates of 0.4–0.7 GPa in the Margna nappe on the basis of amphibole composition (GUNTLI and LINIGER, 1989) and with temperatures of about 450 °C in the Malenco unit estimated by calcite-dolomite solvus thermometry in ophicarbonates (MELLINI et al., 1987; BENNING and SIDLER, 1992). Therefore, the Margna-nappe and the Malenco-Forno unit display the same Alpine structural and metamorphic evolution, indicating that these units were located in the supra-subduction wedge and were buried only to moderate depth. This may explain why the features of the Jurassic passive continental margin are so well preserved in this area.

Conclusions

1) Pre-Alpine structures and metamorphic relics from the Fedoz gabbro and Fedoz Series of the Austroalpine Margna nappe correspond to the pre-Alpine features found in the Braccia gabbro and Senevedo gneiss of the Penninic Malenco unit. A common origin and pre-Alpine evolution of the Fedoz- and Braccia gabbro, as well as of the Fedoz series and Senevedo gneiss, can therefore be assumed.

2) Pre-Alpine shear zones within the Fedoz gabbro are associated to movements along the Margna normal fault and are related to the rifting and break-up of the Adriatic and European continent. Shear sense indicators yield an original top to the E oro SE movement, which is consistent with a dip of the Margna normal fault below Adria. A pre-Alpine cleavage in the Fora gneisses is locally preserved and interpreted to be related to the Margna normal fault.

3) The field relations, textures and geochemistry of amphibolite bodies within the Fora gneisses of the Margna nappe show that they probably represent basaltic dykes with the same origin as the Forno basalts. The dykes intruded the hanging wall of the asymmetric rift-system, which led subsequently to the opening of the Tethys. These interpretations are in agreement with the pre-Alpine extension-related structures showing an eastward-dipping, low-angle, normal fault.

4) The metaarkoses in the Val Muretto are distinct from Lower Austroalpine Cretaceous flysch type sediments, because they do not contain heavy minerals derived from ultramafic rocks, such as chromium spinel. An isolated position of the later Margna nappe at the continental margin can explain the distinct heavy mineral pattern. Alternatively, the metaarkoses may be interpreted as Jurassic rift-graben infill.

5) The Alpine metamorphic and structural evolution of the Margna nappe corresponds to the one of the Forno-Malenco unit. The metamorphic conditions reached epidote amphibolite facies and pressures did not exceed 0.7 GPa. The pressures indicate that both units were buried only to moderate depths, probably situated in the supra-subduction wedge during Cretaceous convergence.

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