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Regional and emplacement-related structures at the northeastern border of the Bergell intrusion (Monte del Forno, Rhetic Alps)

by *André R. Puschnig* [1]

Abstract

The Forno unit in the Rhetic Alps represents a South-Penninic ocean floor sequence, overlain by the Lower Austroalpine Margna nappe. Structural observations in the Margna nappe, Forno-Malenco unit and Suretta nappe reveal within the studied area, that the Forno unit has the same structural evolution as the Lower Austroalpine units, but contrasts with that of the Suretta nappe. The Margna nappe and the Forno-Malenco unit were already deformed in the Upper Cretaceous (W-directed nappe stacking), whereas the deformation in the Suretta nappe started in the Tertiary. The extensional Turba phase separates these two stacks. It is characterized in the Forno unit and the Margna nappe by localized shear zones with a top to SE movement, and in the Suretta nappe by a penetrative deformation.

Crosscutting relationships between the Bergell granodiorite and the Forno unit allow for a relative timing of deformation. Field relations indicate that the Turba phase is overprinted by the second phase of backfolding. Both phases precede the tonalite intrusion (32 Ma). The transverse folding, a regional deformation phase, deforms minerals of the tonalite contact metamorphism and can be observed in country rock xenoliths within the granodiorite (30 Ma). Therefore, the transverse folding can be constrained between the two intrusions. As a consequence, the tonalite intrusion can be considered a syn-tectonic intrusion with respect to post-nappe refolding. The granodiorite intrusion however is post-tectonic.

Local deformation, not affecting the entire Penninic-Austroalpine border region in Valmalenco, can be attributed to the emplacement of the intrusives.

Keywords: deformation, contact metamorphism, structural evolution, Austroalpine-Penninic boundary, Forno unit, Bergell (Bregaglia) pluton, Central Alps.

Riassunto

L'Unità del Forno nelle Alpi Retiche rappresenta una sequenza oceanica Sud-Pennidica, sovrapposta dalla Falda Austroalpina inferiore Margna. Osservazioni strutturali nelle Falde Margna e Suretta, e nell'Unità Forno-Malenco rivelano che, all'interno dell'area di studio, l'Unità del Forno ha avuto la stessa evoluzione strutturale delle unità Austroalpine inferiori, ma contrastante rispetto a quella della Falda Suretta. Mentre la Falda Margna e l'Unità Forno-Malenco furono deformate nel Cretaceo Superiore (sovrapposizione delle falde in direzione ovest), la deformazione nella Falda Suretta iniziò soltanto nel Terziario. Queste due pile sono separate dalla fase di estensione Turba, caratterizzata nell'Unità del Forno e nella Falda Margna da zone di taglio con movimento di top verso sud-est, mentre nella Falda Suretta la fase estensiva si esprime con una deformazione penetrativa.

Relazioni di taglio tra la granodiorite del Bregaglia e l'Unità del Forno permettono di caratterizzare le fasi relative di deformazione. Osservazioni in terreno indicano come la fase Turba sia sovrapposta da una seconda fase di retropiegamento. Entrambi le fasi precedono l'intrusione della tonalite (32 milioni di anni). Il piegamento trasversale, fase di deformazione regionale, deforma i minerali del metamorfismo di contatto della tonalite e può essere osservato in xenoliti presenti nella granodiorite (30 milioni di anni). Perciò, il piegamento trasversale può venir situato tra le due intrusioni, e l'intrusione della tonalite può venir considerata come sintettonica rispetto al retropiegamento susseguente la formazione delle falde. L'intrusione della granodiorite, comunque, risulta essere post-tettonica.

La deformazione locale, che non si ripercuote sull'intera regione limite tra Pennidico e Austroalpino nella Valmalenco, può venir attribuita alla messa in posto delle rocce intrusive.

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1. Introduction

The Forno unit plays a key role for understanding Alpine kinematics in the Central Alps, because of its tectonic position between the Lower Austroalpine and the Middle Penninic units and because of its proximity to the Bergell intrusives.

Previous structural investigations in the Penninic-Austroalpine border region south of the Engadine Line showed that the Lower Austroalpine nappes and the South-Penninic Malenco unit have the same structural evolution starting in Upper Cretaceous (SIDLER and BENNING, 1992; HERMANN and MÜNTENER, 1992; LINIGER, 1992; SPILLMANN, 1993). Previous authors working outside the contact area of the intrusives speculated on the timing of post-collisional deformational events with respect to the Oligocene Bergell intrusives. SPILLMANN (1993) was the first, who described clear relations between regional structures and the intrusives for the eastern part of the Bergell intrusives. The intrusive contacts of the Bergell granodiorite to the Forno unit clearly display that the Bergell granodiorite is an excellent time marker for the structural evolution in the Malenco area (see BERGER and GIERÉ, 1995).

The Lower and Middle Penninic units exhibit an Alpine structural evolution starting in the Tertiary (SCHMID et al., 1990; MARQUER et al., 1994; FROITZHEIM et al., 1994), which is distinct from the evolution in the Austroalpine and South-Penninic units. The Turba Mylonite Zone, an E-dipping normal fault north of the Engadine Line, separates these two stacks of units, namely the Middle Penninic Suretta nappe (including the Avers Bündnerschiefer) and the South-Penninic Platta-Lizun unit (including the Lower Austroalpine Margna nappe; LINIGER, 1992).

The aim of this study is to provide constraints on the structural evolution of the Penninic-Austroalpine border region south of the Engadine Line. The relationship of structures of the Forno unit to those of the Lower Austroalpine Margna nappe are examined. In addition, the temporal and spatial relations of the structures to the Bergell granodiorite are studied in detail in a restricted area of approximately 20 km^2 at the northeastern border of the Bergell granodiorite.

The re-examination of this area leads to a separation of regional deformation phases (pre-, syn- and post-intrusive) from local, and therefore emplacement-related deformation phases. Finally, the structural evolution of the Middle Penninic units, represented by the Suretta nappe, and the role and influence of the Turba Mylonite Zone in the study area will be evaluated.

2. Geological setting

The studied area is situated south of Maloja (Fig. 1). The tectonic stack consists, from top to bottom, of the Lower Austroalpine Margna nappe, the South-Penninic Forno-Malenco unit and the Middle Penninic Suretta nappe. Together with the Suretta nappe, the Forno unit is intruded by the Bergell granodiorite.

The basement of the Lower Austroalpine Margna nappe consists of metapelites, carbonates and amphibolites which locally preserve pre-Alpine amphibolite facies metamorphic assemblages (GUNTLI and LINIGER, 1989). This association is intruded by a Permian gabbro complex (Fedoz gabbro, HANSMANN et al., 1995). Late-Variscan granitoid rocks, without traces of pre-Alpine metamorphism, show a close geochemical affinity to the late-Variscan intrusive rocks of the Bernina nappe (GUNTLI, 1987; BENNING, 1990; SPILLMANN, 1993). The Permo-Mesozoic cover of the Margna nappe consists of Permian phyllites ("detritische Basis"), Triassic evaporites and carbonates, Liassic silicious marbles (LINIGER and GUNTLI, 1988), and Upper Jurassic to Lower Cretaceous radiolarites and Calpionella Limestones (LINIGER, 1992).

The Margna nappe can be subdivided into two tectonic subunits, the Maloja sub-nappe above and the Fora sub-nappe below. These sub-nappes represent flat-lying SW-facing, large-scale isoclinal folds. They are separated by a mylonite horizon containing relics of Triassic sediments. The cores of the sub-nappes consist of basement rocks surrounded by Permo-Mesozoic sediments. These sub-nappes are thrust over the South-Penninic Malenco-Forno unit (LINIGER and GUNTLI, 1988).

Although affected by an Alpine polyphase deformation, by Alpine regional metamorphism and by contact metamorphism related to the Bergell intrusives, the Forno unit still shows many features of an ocean floor sequence. It consists of metabasaltic rocks and their metamorphosed sedimentary cover (FERRARIO and MONTRASIO, 1976). Intrusive relationships between the Forno mafics and the ultramafic rocks of the Malenco unit are documented by basaltic dikes crosscutting the Malenco ultramafic rocks (TROMMSDORFF et al., 1993; ULRICH and BORSIEN, 1996). These dikes have subsequently been rodingitized. Pillow lavas and pillow breccias are locally preserved within the metabasaltic sequence (MONTRASIO, 1973). A several km long zone with Fe–Cu–Zn sulfide mineralization represents a hydrothermally altered section of the oceanic crust (PERETTI and KÖPPEL, 1986). Major and trace element geochemical data (GAUTSCHI, 1980) as well as the Pb-isotopic signatures of the mafic rocks (PERETTI and KÖPPEL, 1986) reveal a MORB character. The sedimentary cover of the Forno unit (PERETTI, 1985) consists of quartzitic layers at the base, locally containing metamorphosed manganese ore deposits (PETERS et al., 1973; FERRARIO and MONTRASIO, 1976), which are interpreted as Jurassic radiolarian cherts. The quartzite

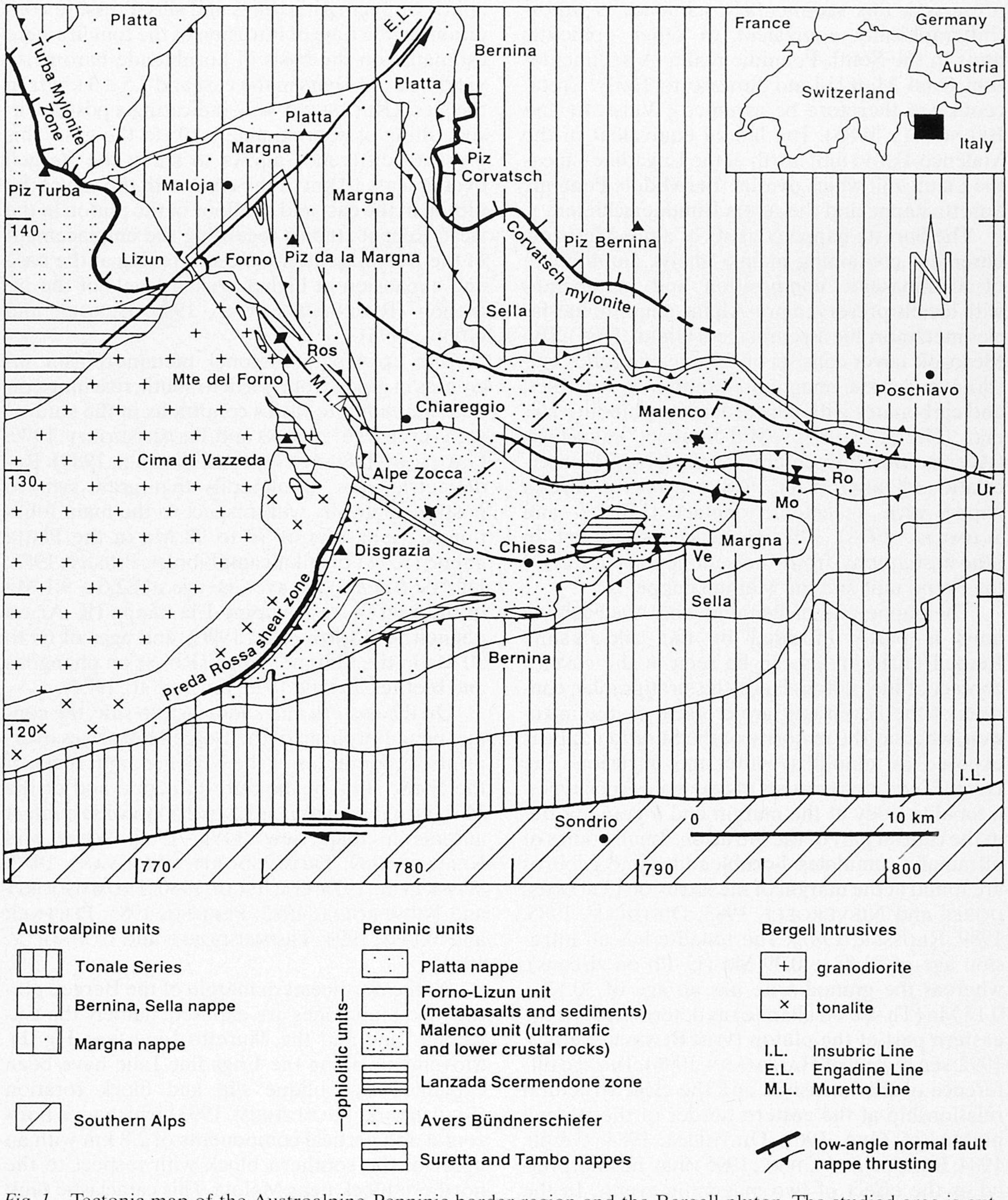

Fig. 1 Tectonic map of the Austroalpine-Penninic border region and the Bergell pluton. The studied area is outlined. Some axial traces of important structures of the Malenco region (SPILLMANN, 1993) such as the second phase of backfolding (thick lines; Ur: Pass d'Ur antiform, Ro: Roggione synform, Mo: Motta antiform, Ve: Ventina synform; Ros: Rossi antiform) or the transverse folding (stippled lines) are indicated.

is overlain by thin layers of calcsilicates and calcite marbles, which may represent metamorphosed Aptychus or Calpionella Limestone. Further sedimentation is documented by metapelites and meta-arkoses with pelitic and carbonate intercalations. Although no fossil records have been preserved, this sedimentary sequence is lithostratigraphically equivalent to other ophiolitic units in the South-Penninic realm. A sedimentation from Mid(?)-Late Jurassic to Early Cretaceous can therefore be assumed (WEISSERT and BERNOULLI, 1985). The lateral equivalent of the Malenco-Forno unit north of the Engadine Line is the Lizun unit which overlies the Middle Penninic Suretta nappe and the Avers Bündnerschiefer.

The Suretta nappe consists of a pre-Mesozoic basement containing mainly gneiss, amphibolite of alkalibasaltic composition and metapelites with locally preserved pre-Alpine amphibolite-facies metamorphic assemblages (GIERÉ, 1985). The Mesozoic cover consists of Triassic quartzites, calcareous schists, magnetite-amphibole marbles, and carbonates with concordant amphibolite layers (GIERÉ, 1985). Mid-Jurassic calcschists (Averser Bündnerschiefer) with ophiolitic intercalations (OBERHÄNSLI, 1978) overlay the Suretta nappe with a tectonic contact (MILNES and 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 Bergell intrusion, as can be seen at the eastern contact of the pluton. Here, the stratigraphic contacts of the Forno unit are crosscut by the intrusion, whereas the majority of the Suretta nappe is exposed as xenoliths within the intrusion. The Bergell intrusion consists of two major rock types: a tonalite body at the margin and a granodiorite in the central part of the intrusion. Small bodies of ultramafic cumulates, hornblendites and gabbros are found at the margin of the intrusion (TROMMSDORFF and NIEVERGELT, 1983; DIETHELM, 1985, 1989; REUSSER, 1987). The tonalite has an intrusion age of 31.88 ± 0.09 Ma (U–Pb on zircons), whereas the granodiorite has an age of 30.13 ± 0.17 Ma (Th–Pb on allanite) as determined for the eastern part of the pluton (VON BLANCKENBURG, 1992; see review of HANSMANN, 1996). The age difference of the intrusives and the clear structural relationship at the eastern border of the Bergell pluton (cf. GYR, 1967; DIETHELM, 1984; GIERÉ, 1984; BERGER and GIERÉ, 1995) may be interpreted as the effect of two magmatic events. In the southern and southwestern part of the pluton mingling and mixing processes can explain the alternating occurrence of tonalite and granodiorite ("Übergangszone", MOTICSKA, 1970; WENK and CORNELIUS, 1977). DRESCHER and STORZ (1926) studied the fabric of the granodiorite and recognized concentric foliation trajectories parallel to the surrounding rocks. The intrusives are later crosscut by several types of aplitic granites and aplitic or pegmatitic dikes and sills. Pressure conditions at the time of intrusion of the tonalite were estimated on the basis of hornblende barometry yielding 5 ± 3 kbars in the east and 7.5 ± 3 kbars in the west (REUSSER, 1987), indicating a post-intrusive tilting of approximately 10° to the east. This pressure difference allows to study the Bergell over at least 10 km of the crust with the top of the pluton in the east and the floor of the pluton in the west. Recent studies regarding the emplacement of the Bergell pluton yield shortening at the base and expansion at higher crustal levels of the intrusion (ROSENBERG et al., 1995; BERGER and GIERÉ, 1995).

The eo-Alpine regional metamorphism increases in grade from north to south, reaching epidote-amphibolite-facies conditions in the studied area (GYR, 1967; EVANS and TROMMSDORFF, 1970; GAUTSCHI, 1980; GUNTLI and LINIGER, 1989). Radiometric ages of minerals that grew syn- to postkinematically with respect to the main foliation S_1 yield ages of 70 to 90 Ma in the Platta nappe (K–Ar on alkali amphiboles, PHILIPP, 1982; DEUTSCH, 1983), an average age of 82.6 ± 9.1 Ma in the Lower Austroalpine Ela nappe (K–Ar on phengites, HANDY et al., 1996), and ages of 60 to 80 Ma in the Margna nappe (Rb–Sr on phengites and biotites, JÄGER, 1973; FREY et al., 1974).

On the eastern and southeastern side, the contact metamorphism of the Bergell intrusives overprints serpentinites of the Malenco unit, rocks of the Forno unit, of the Suretta nappe and of the Margna nappe within a 1.5 to 2.5 km wide contact aureole in map view (GYR, 1967; WENK and KELLER, 1969; TROMMSDORFF and EVANS, 1972; WENK et al., 1974; GAUTSCHI, 1980; TROMMSDORFF and NIEVERGELT, 1983; PERETTI, 1985; PFIFFNER and WEISS, 1994; TROMMSDORFF and CONNOLLY, 1996).

At the northeastern margin of the Bergell pluton, two fault zones are exposed, namely the Engadine Line and the Muretto Line (see Fig. 1). Movements along the Engadine Line have been explained by oblique slip and block rotation (SCHMID and FROITZHEIM, 1993) which give horizontal and vertical components of 2.8 km with an uplift of the southern block with respect to the northern block near Maloja. This cataclastic fault zone postdates the Bergell granodiorite (LINIGER, 1992; SCHMID and FROITZHEIM, 1993). The Muretto Line is a distinct brittle fault with numerous

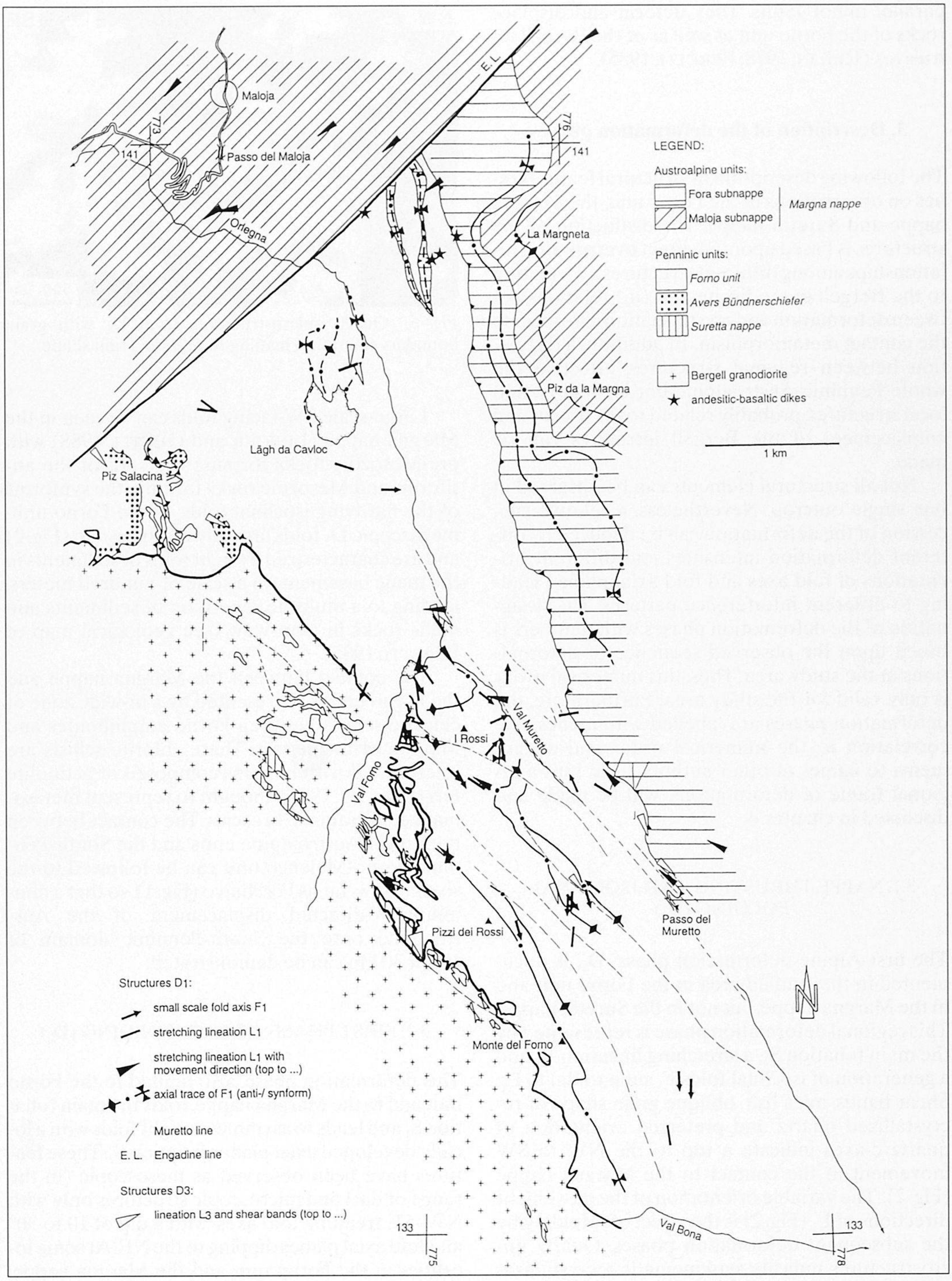

Fig. 2 Map of deformation phases D_1 and D_3 including fold axes (F_1), lineations L_1 and L_3, D_3 shear bands (with sense of shear, some additional data of L_1 in the Margna nappe are from LINIGER, 1992 and SPILLMANN, 1993), and F_1 axial traces (structures from the Margna nappe are from LINIGER and GUNTLI, 1988).

parallel minor faults. They deform and displace rocks of the Forno unit as well as of the Bergell intrusives (RIKLIN, 1978; PERETTI, 1985).

3. Description of the deformation phases

The following description of structural features relies on observations in the Forno unit, the Margna nappe and Suretta nappe. The distinction of the structures is based upon: (i) direct overprinting relationships among different structures, (ii) relation to the Bergell granodiorite and (iii) relations between deformation and crystallization in respect to the contact metamorphism. In addition, a distinction between regional structures, affecting the whole Penninic-Austroalpine border region, and local structures, probably related to the ascent and emplacement of the Bergell intrusives can be made.

Not all structural elements can be observed in one single outcrop. Nevertheless, a relative succession of the deformation can be deduced by different deformation intensities and different orientations of fold axes and fold axial planes, leading to different interference patterns. The designation of the deformation phases with numbers is based upon the observed sequence of deformations in the study area. Thus, this numerical order is only valid for the study area. Furthermore, the deformation phases are labelled with names. The correlation to the numerical order and assignments to names of other authors, to fit into a regional frame of deformations, will be made and discussed in chapter 4.

3.1. NAPPE THRUSTING AND ISOCLINAL FOLDING (D_1)

The first Alpine deformation phase, D_1, is documented in the studied area in the Forno unit and in the Margna nappe, but not in the Suretta nappe. This regional deformation phase is represented by the main foliation S_1, a stretching lineation L_1 and a generation of isoclinal folds F_1 subparallel to L_1. Shear bands, mica fish, oblique grain shape of recrystallized quartz and preferred orientation of quartz c-axes indicate a top to the NW to SW movement at the contact to the Margna nappe (Fig. 2). The variable orientation of the movement directions of L_1 (Fig. 2) is the effect of refolding by the subsequent deformation phases. Quartz microstructures indicate synkinematic recrystallization by grain boundary migration, associated with grain growth and bulging nucleation, leading to a wide spectrum of grain sizes (20–900 μm, Fig. 3).

Fig. 3 Quartz microstructures from D_1 with grain boundary migration leading to oblique grain shape.

Large-scale SW-facing folds can be seen in the Margna nappe (LINIGER and GUNTLI, 1988) with pre-Mesozoic rocks forming the core of the antiforms and Mesozoic rocks forming the synforms of the flat-lying isoclinal folds. In the Forno unit, megascopic D_1 folds are only rarely visible (Fig. 2) and are characterized by tight folds of sediments in the mafic basement on a scale of hundred meters, leading to a multiple repetition of sediments and mafic rocks in map view (see geological map of PERETTI, 1985).

The contact between the Margna nappe and the Forno unit is represented by a m-wide zone of chlorite schists between Forno amphibolites and Margna orthogneisses. These chlorite schists are intercalated with boudins composed of actinolite fels (PERETTI, 1983), thought to represent metasomatized ultramafic breccias. The contact between the Lower Austroalpine units and the South-Penninic Forno-Malenco unit can be followed to the southeast as far as Poschiavo (Fig. 1), so that a minimum W-directed displacement of the Austroalpine onto the South-Penninic domain of about 30 km can be demonstrated.

3.2. FIRST PHASE OF BACKFOLDING (D_2)

This deformation phase, also limited to the Forno unit and to the Margna nappe, folds the main foliation S_1 and leads to asymmetric tight folds with a locally developed axial planar foliation S_2. These features have been observed as mesoscopic (in the range of dm) and microscopic structures only with NW–SE trending fold axes, with a dip of 10 to 30° and fold axial planes dipping to the NE. At some localities in the Forno unit and the Margna nappe, small-scale folds can be unequivocally attributed to D_2 only, where such minor folds have the wrong vergence with respect to their position on the limb of the later folds formed during D_4 (Fig. 4a). Folds of this regional deformation phase can be interpreted for the study area as originally southwest vergent folds, as supported by the fact that the observations of wrong vergence are restricted to the southwestern steep to overturned limb of D_4 (Fig. 4 b and c).

3.3. TURBA PHASE (D_3)

The Suretta nappe and the Avers Bündnerschiefer consist very often of mylonitic basement rocks (Suretta) and Mesozoic sediments with isoclinal folds and associated penetrative foliation and a stretching lineation. The lineations (L_3) are trending NW–SE. Shear sense determinations of shear bands on the normal limb of the following F_4 folds indicate a top to SE movement (Fig. 2). Shear bands of mylonitic calcschists (Avers) probably correspond to calcite mylonites, reported by LINIGER (1992).

In the Forno unit and the Margna nappe, stretching lineations and shear bands at different scales indicate the same top to the SE movement (Figs 2 and 5). This is documented by asymmetric quartz segregations in metapelites, mica fish, shear bands and oblique grain shape of recrystallized quartz on the normal limb of F_4 folds. Quartz microstructures with old grains surrounded by small synkinematically recrystallized grains with a grain size of about 100–300 μm are typical of a subgrain rotation mechanism for recrystallization. Muscovite and chlorite growing in shear bands in metapelites indicate greenschist-facies conditions for this regional deformation phase.

The foliation observed in the Suretta nappe and the Avers Bündnerschiefer is parallel to the main foliation in the Forno unit and the Margna nappe and also parallel to the contact between these units. This contact is represented by a mylonite horizon. This mylonite zone is located at Piz Salacina at the Avers-Forno contact and west of

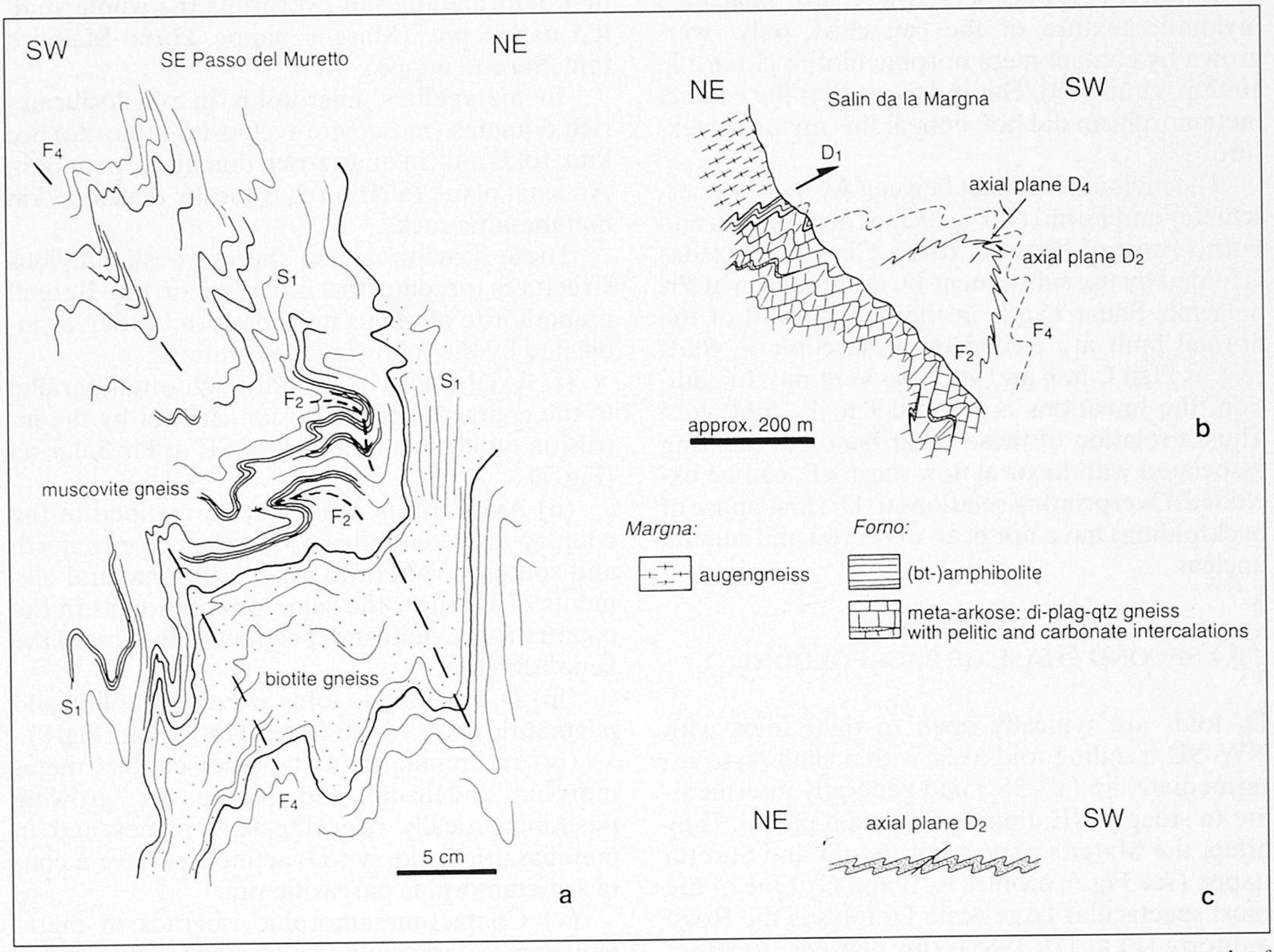

Fig. 4 (a) Overprinting relationships in outcrop-scale of D_2 and D_4 in a orthogneiss of the Margna nappe south of Passo del Muretto (Swiss grid coordinates 777.270/135.900). F_2 folds are recognizable locally as folded axial planes near F_4 axial planes. (b) Schematic overprinting relationship of the co-axial deformation phases D_2 and D_4 from Salin da la Margna south of Piz da la Margna based upon vergences. (c) Retrodeformation results in southwest vergent folds (D_2).

Fig. 5 D_3 shear bands in a metapelite indicate a top to the SE movement with muscovite and chlorite growing in shear bands.

Pizzi dei Rossi and Cima di Vazzeda at the Suretta-Forno contact. Therefore, disappearance of the Avers Bündnerschiefer between Piz Salacina and Val Forno can be assumed.

LINIGER (1992) observed near Piz Salacina a mylonitic texture of the calcschist, only overgrown by contact metamorphic biotite (LINIGER, 1992, p. 91 and 93). This indicates, that the contact metamorphism did not anneal this mylonitic texture.

The mylonitic contact beween Avers Bündnerschiefer and Forno (Piz Salacina) and Suretta and Forno (west of Pizzi dei Rossi, Cima di Vazzeda) is folded by the subsequent D_4 deformation at Piz Salacina. Shear bands in the hangingwall of the normal fault are folded by mesoscopic F_4 folds (e.g. at Plan Canin and at Passo Ventina). In addition, the lineations are parallel to F_4 fold axes. Thus, a relation of these shear bands to shearing associated with flexural flow during F_4 can be excluded. Overprinting relations to D_2 (first phase of backfolding) have not been observed and remain unclear.

3.4. SECOND PHASE OF BACKFOLDING (D_4)

D_4 folds are typically open to tight folds with NW–SE trending fold axes, with a shallow to intermediate dip (10–35°) and generally intermediate to steeply NE dipping fold axial planes. They affect the Margna nappe, Forno unit and Suretta nappe (see Fig. 6, profiles A, B and C). One of the most spectacular large-scale D_4 folds is the Rossi antiform (PERETTI, 1985). This phase is (together with D_1) the dominant regional deformation phase in the studied area, resulting locally in a type 2 interference pattern (RAMSAY, 1967) between D_1 and D_4 (Fig. 7). This fold generation clearly overprints D_1 in the Forno unit and the Margna nappe (lineation L_1 curving around the fold hinge of D_4) and also folds D_3 shear bands (e.g. at Plan Canin).

Mesoscopic D_4 folds deform the nappe contact between the Forno unit and the Margna nappe. Large-scale D_4 folds on the western flank of La Margneta (Fig. 7) are responsible in general for a repetition of rocks of the Forno unit and the Margna nappe (MÜTZENBERG, 1986; Fig. 6, profile A). However, a retrodeformation of F_1 and F_4 of this repetition cannot bring the ultramafics and amphibolites from the F_4 fold hinge onto the same tectonic level as the Forno rocks. After such a retrodeformation a sliver of ultramafic rocks and amphibolites is overlying the Margna. The tectonic and paleogeographic position of this association is therefore unclear. At Piz Salacina, the nappe contact between the Suretta nappe and the Forno unit is folded by D_4, producing two windows of Suretta and Avers rocks in the Forno unit (Figs 6, 7). This indicates that D_4 represents the first deformation that overprints the whole studied nappe pile (Margna nappe, Forno-Malenco unit, Suretta nappe).

In metapelites, microfolds in phyllosilicate-rich domains (muscovite + chlorite ± biotite) are kink folds and, in quartz-rich domains, open folds. An axial plane foliation S_4 is locally developed in metabasaltic rocks.

These structures, and therefore all previous structures, predate the intrusion of the Bergell granodiorite along its northeastern border, as indicated by the following observations:

(i) Axial traces of D_4, although often parallel to the contact of the intrusion, are cut by the intrusion on its northern border SE of Piz Salacina (Fig. 7).

(ii) Axial traces of D_4 can be mapped in the country rock xenoliths in the granodiorite north and south of Val Forno, where all structural elements of D_4 show the same orientation as in the country rocks, quite independent of the size of the xenoliths (Fig. 7).

(iii) D_4 small-scale folds are cut by aplitic and pegmatitic dikes of the Bergell intrusion (Fig. 8).

(iv) In crenulated metapelites contact metamorphic andalusite and biotite are growing postkinematically over D_4 axial planes and in metabasaltic rocks syn-D_4 actinolites have a contact-metamorphic pargasitic rim.

(v) Contact-metamorphic isograds in metapelites, meta-arkoses and ultramafic rocks are discordant to the large-scale structures of D_4 and are not folded.

(vi) Andesitic-basaltic dikes, undeformed and postdating the regional metamorphism (WENK,

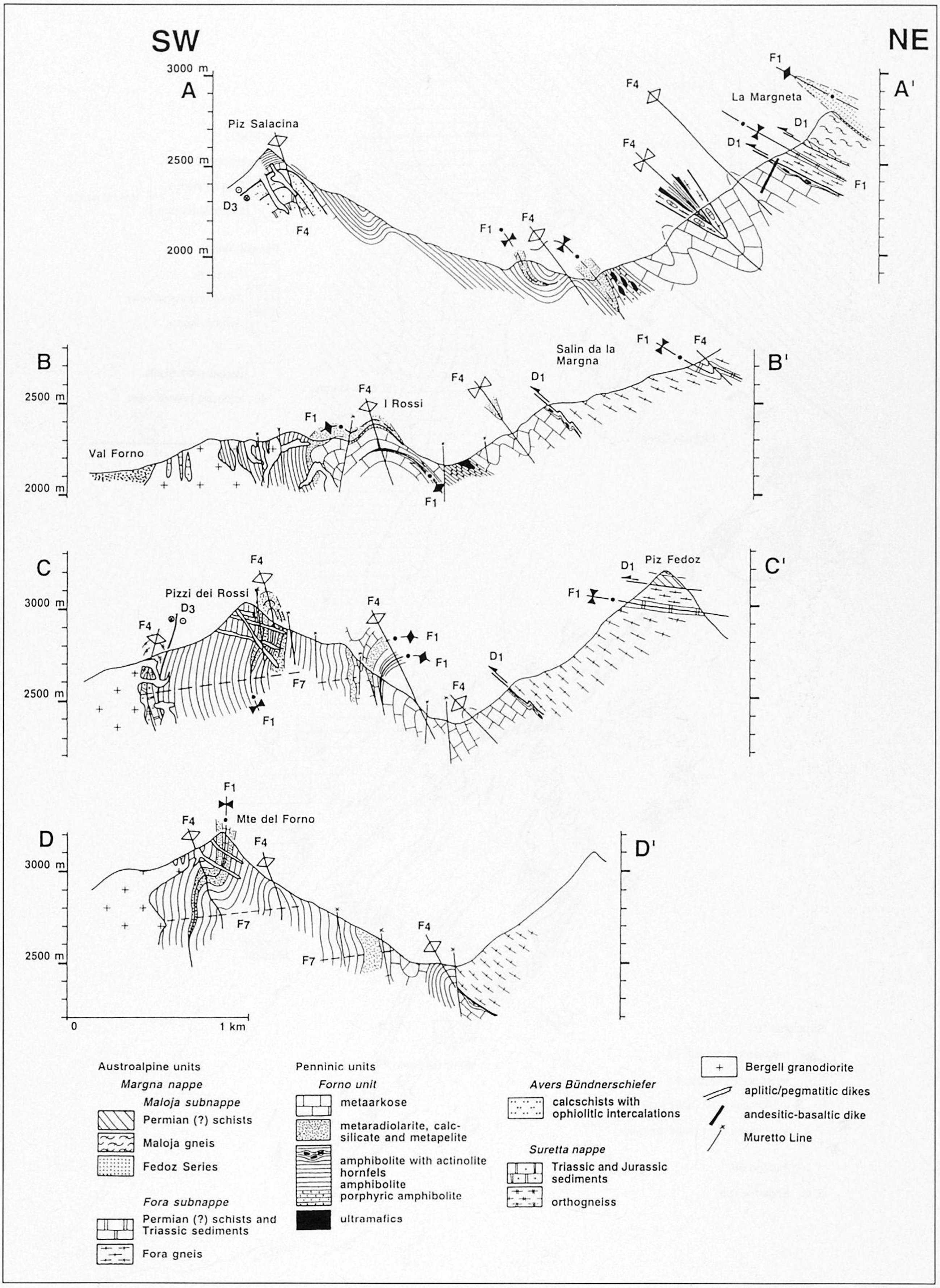

Fig. 6 Profiles across the northeastern border of the Bergell intrusives (including data from the Margna nappe from MÜTZENBERG, 1986 and LINIGER and GUNTLI, 1988). For traces of the profiles see figure 7.

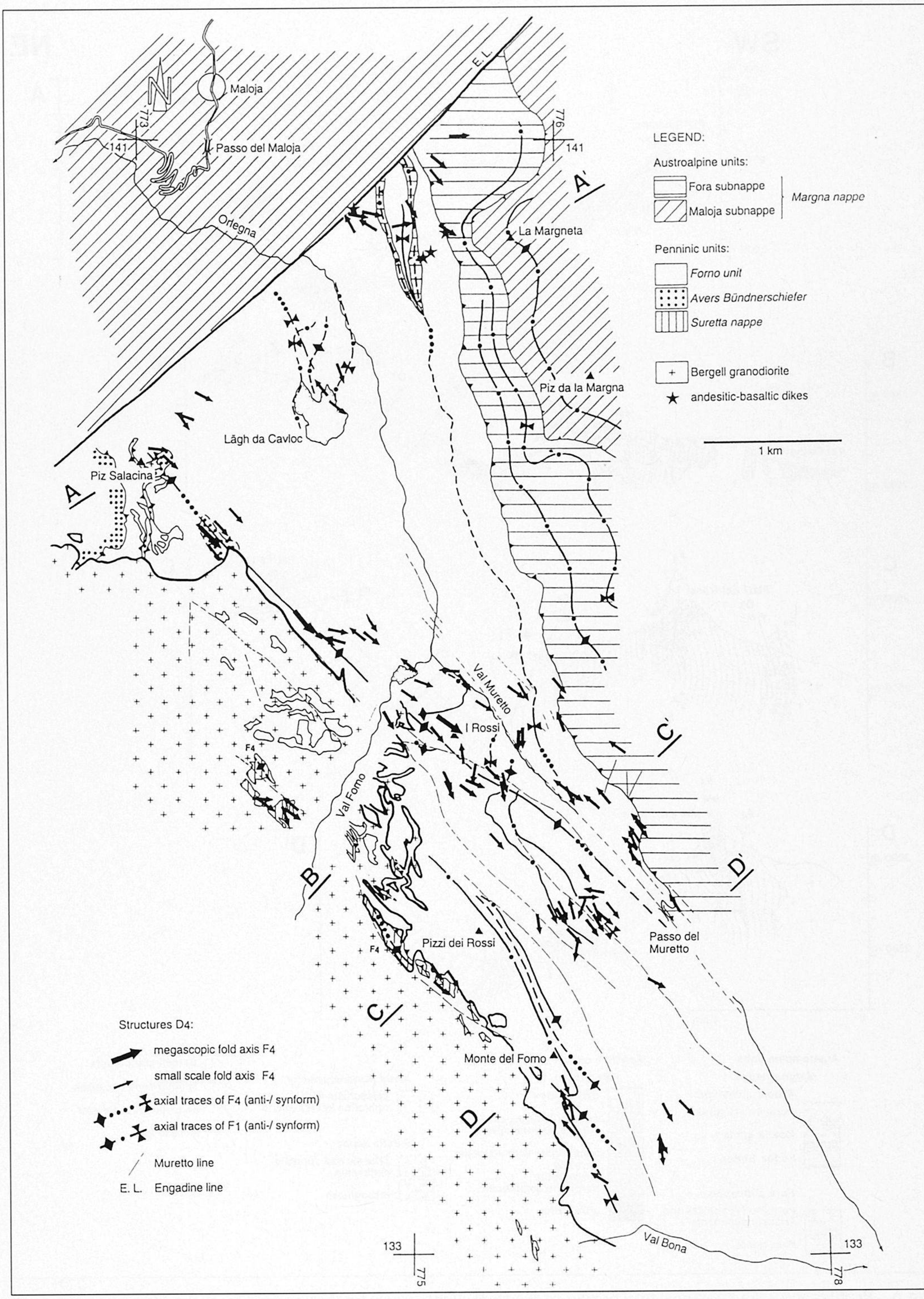

Fig. 7 Map of deformation phase D_4 including fold axes and axial traces.

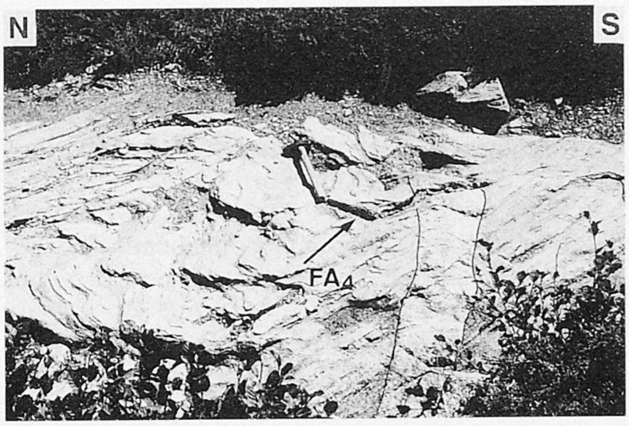

Fig. 8 A small-scale D_4 fold in meta-arkoses of the Forno unit is cut by an aplitic dike of the Bergell intrusion (Swiss grid coordinates 775.100/137.590).

1980), crosscut the F_4 fold at La Margneta (TROMMSDORFF and NIEVERGELT, 1983; MÜTZENBERG, 1986), but are overprinted by the contact metamorphism.

3.5. VERTICALIZATION (D_5), TRANSVERSE FOLDING (D_6) AND VERTICAL SHORTENING (D_7)

The temporal bracketing of the subsequent following structures is closely associated with the orientation of structures in the country rock xenoliths which were studied in particular. However, it cannot be determined whether these xenoliths are true xenoliths or roof pendants, i.e. connected with the country rocks. A primary, not reoriented position of the xenoliths in the study area, is supported by the following observations:

(i) The granodiorite shows an alignment of K-feldspars megacrysts (up to several cm long) representing a magmatic foliation (BERGER and GIERÉ, 1995). Minor solid-state deformation produces only tails of feldspar and quartz around K-feldspar megacrysts and recrystallization of feldspars and quartz. This weak solid-state deformation produced a foliation which is parallel to the main foliation of the country rocks (BERGER and GIERÉ, 1995). Solid-state deformation within the granodiorite capable of reorienting the xenoliths and of producing a gneissic texture, has not been observed around the xenoliths.

(ii) K-feldspar megacrysts are often accumulated between closely spaced xenoliths. These K-feldspars do not exhibit a recognizable solid-state deformation, so that a primary position and orientation of xenoliths and granodiorite can be assumed. However, small xenoliths (< m) are often reoriented probably due to magmatic flow.

(iii) Additionally, preexisting structures within the xenoliths, as the main foliations in Suretta nappe and Forno unit (DRESCHER and STORZ, 1926) and fold axes and axial planes of D_4, are not reoriented with respect to structures in the country rocks (see Fig. 9). Apart from this feature, an F_4 axial trace can be followed from the country rocks at Monte del Forno into the xenoliths in Val Forno (Fig. 7).

The verticalization (D_5) is documented by bending of the contacts between Suretta, Forno and Margna nappes and the associated foliations from a moderate NE dip in the east to an upright position in the west (see Fig. 6, profiles B, C, and D). This monoclinal type of fold or flexure on a km-scale ("Muretto-Querfalte" of STAUB, 1919; "Chiesa synform" of SPILLMANN, 1993; "Muretto monocline" of BERGER and GIERÉ, 1995) strikes NNW–SSE and shows no mesoscopic or microscopic structures so that the relation to the contact metamorphism is unclear. This local fold leads to the rotation of D_4 fold axial planes from a moderately inclined towards NE orientation at the Forno-Margna nappe contact to a subvertical orientation near the contact to the granodiorite and to a vertical orientation of the Forno-Suretta contact (Fig. 6, profile C). A probably pre-granodiorite verticalization can be assumed by the following observations:

(i) A subvertical to vertical orientation of the penetrative foliations in the Suretta nappe and the Forno unit and a subvertical orientation of the fold axial plane D_4 can also be observed within the xenoliths (Fig. 9).

(ii) A mylonitized contact affecting both granodiorite and country rocks as effect of the verticalization due to the ascent of the granodiorite is lacking. However, a development of this structure related to the emplacement of the Bergell intrusives can be assumed, because this verticalization is only documented in a narrow distance (approx. 2 km) from the eastern contact of the Bergell intrusives.

(iii) The contact between the Suretta nappe and the Forno unit near Cima di Vazzeda (Fig. 1) is a subvertical contact, which is cut towards the north by the Bergell granodiorite.

The transverse folding (D_6), with generally subhorizontal NE–SW trending fold axes and subvertical axial planes, is best seen in incompetent rocks such as metapelites and serpentinites, leading to an undulation or kinking on a scale of cm to hundreds of meters. Interference between the second phase of backfolding (D_4) and transverse folding leads to regional dome-and-basin structures of different intensities in the Suretta nappe, the Forno unit and the Margna nappe. This structure predates the granodiorite intrusion, because D_6 small-scale structures overprint F_4 fold axes (NW- and SE-dipping) in xenoliths of the Val Forno (see Fig. 9). In addition, they have the same orientation as country rocks outside the granodiorite. The granodiorite is not affected by this deformation phase. This phase is younger than the contact metamorphism of the Bergell tonalite, because small-scale D_6 structures in ultramafic rocks of the Malenco unit overprint the contact metamorphic paragenesis olivine + talc near the tonalite at Alpe Zocca (south of Valle Sissone: REBER, 1995) and in Valle Airale (south of M. Disgrazia: FORNERA, 1996).

Folds accommodating a vertical shortening or collapse (D_7) are only recognizable in zones with preexisting steep orientations of stratigraphic contacts and foliations. This locally developed shortening leads to an undulation of the foliations in the Suretta nappe and Forno unit, on a wavelength of several tens of meters, with the development of a crenulation in phyllosilicate-rich domains of metapelites. This undulation is documented by steeply inclined NE- and SW-dipping foliations and F_4 axial planes. The F_7 fold axes plunge moderately southeast and axial planes are horizontal to shallowly SW-dipping, clearly distinct from the steep orientation of D_4 axial planes in this zone (F_7, see Fig. 6, profile C). This deformation is pre-to syn-granodiorite and post-

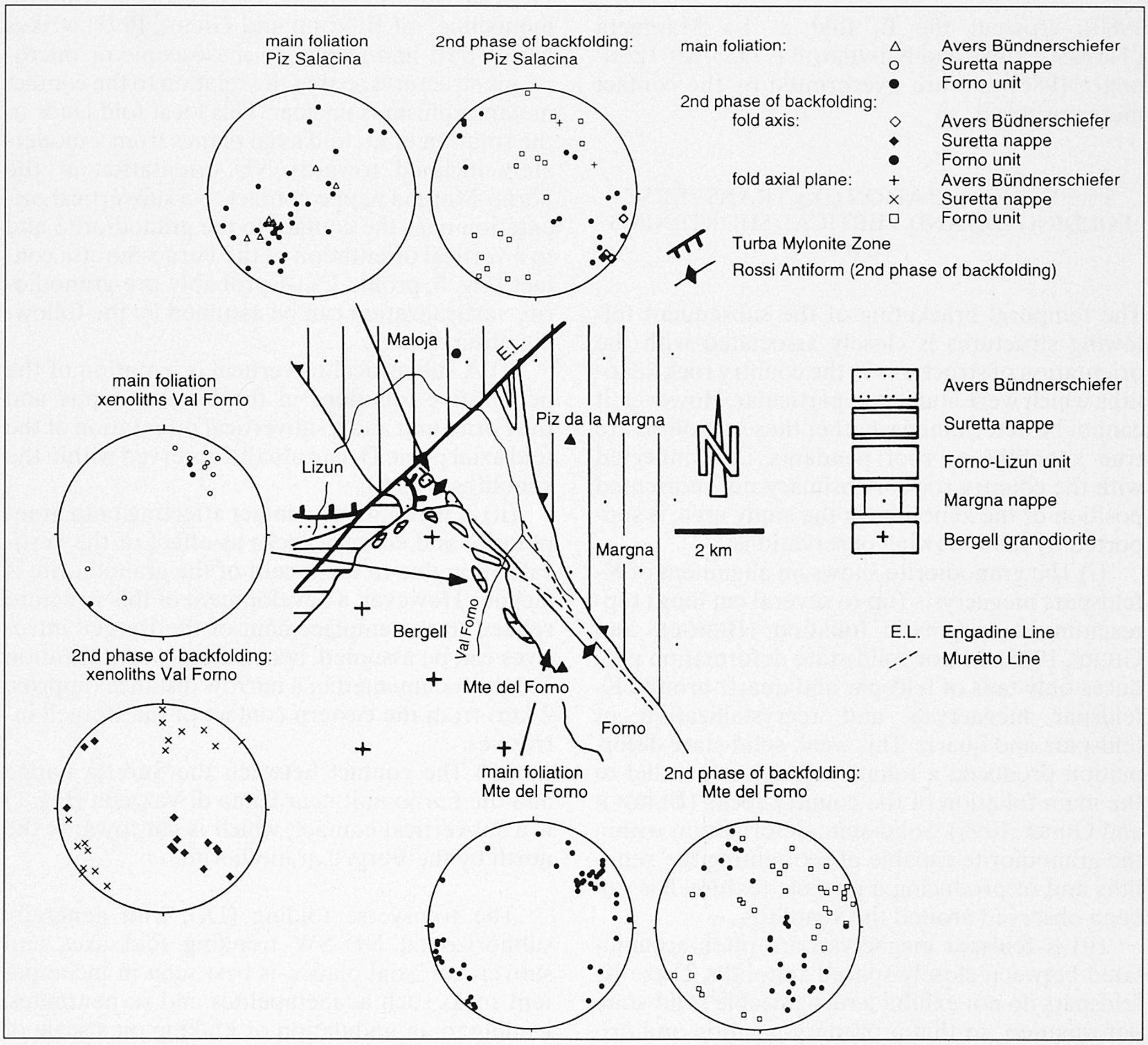

Fig. 9 Comparison between structural elements in xenoliths and country rocks (e.g. main foliations and fold axes and axial planes of the second phase of backfolding D_4). NW- and SE-dipping F_4 fold axes are the effect of the transverse folding (D_6), whereas the variable orientation of F_4 axial planes is the effect of the vertical shortening (D_7).

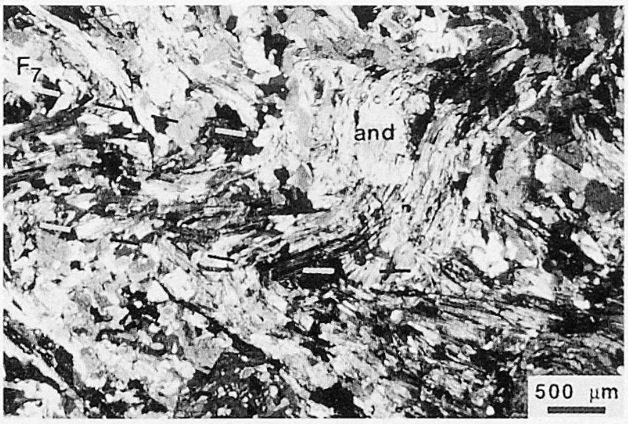

Fig. 10 D_7 microstructures are postkinematically overgrown by andalusite (and) and biotite.

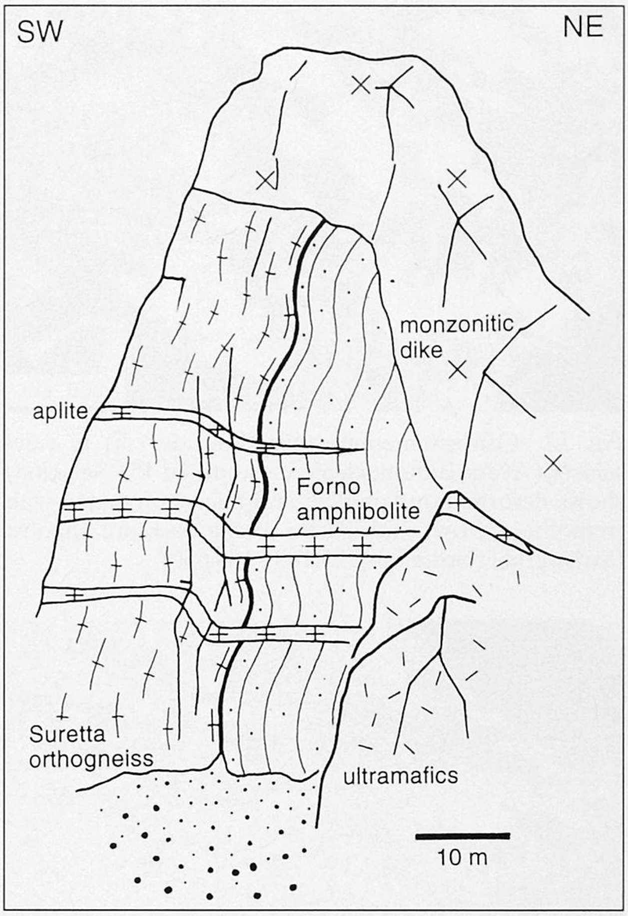

Fig. 11 Schematic drawing of a view to the subvertical contact between Suretta nappe and Forno unit on the crest southeast of Cima di Vazzeda. This contact is undulated by D_7 and cut by Bergell aplites.

tonalite, as suggested by the following observations:

(i) D_7 structures can be observed in Suretta xenoliths in the granodiorite (see Fig. 9).

(ii) D_7 microstructures in metapelites are overgrown by contact metamorphic andalusite and biotite (Fig. 10).

(iii) The subvertical contact between Suretta nappe and Forno unit southeast of Cima di Vazzeda is undulated and cut by Bergell aplites (Fig. 11). Towards the north, the Suretta-Forno contact is cut by the Bergell granodiorite (Fig. 1), where the latter is not showing a folding of the magmatic foliation.

(iv) An undulation of a foliation of an already vertically oriented and strongly foliated tonalite in Val Sissone (west of Chiareggio) indicates a solid-state deformation within the tonalite.

(v) F_7 folds can also be observed in ultramafic rocks at Piano di Preda Rossa near the tonalite. There, the contact metamorphic mineral paragenesis talc + olivine is folded.

Direct field observations in the studied area for the temporal succession of these three deformation phases are lacking. Direct overprinting relationships of D_4, the local verticalization (D_5) and the regional transverse folding (D_6) in Val Scermendone (south of M. Disgrazia) reveal that the verticalization precedes the transverse folding (HERMANN, pers. comm.). This is documented by an increasing inclination of F_4 fold axes towards the west, where D_6 fold axes and axial planes are not changing their orientations. The structures of a vertical shortening are probably the youngest of these three phases, restricted to D_5 verticalized units.

3.6. STRUCTURES RELATED TO THE FINAL EMPLACEMENT OF THE BERGELL GRANODIORITE (D_8)

Information on the relationship of the final emplacement of the Bergell granodiorite to deformation in the surrounding rocks is summarized in this section.

Granodioritic, aplitic and pegmatitic dikes in xenoliths and in the country rocks are folded, whereas sills are weakly boudinaged and show a chocolate-tablet structure (BERGER and GIERÉ, 1995). This indicates that the dikes represent the competent layers during this deformation, and thus have to be solid during deformation (BERGER and GIERÉ, 1995). The axial planes of the folded dikes are often parallel to the penetrative foliations in Forno and Suretta xenoliths. These penetrative foliations clearly predate D_4, thus indicating that the axial plane of the folded dikes is a composite foliation (D_5 of BERGER and GIERÉ, 1995). The axial plane foliation in the dikes is the result of

Fig. 12 Contact metamorphic diopside (di) in calcschists (Avers Bündnerschiefer south of Piz Salacina) shows deformation lamellae and microboudinage with tremolite (arrow) and calcite in the pressure shadow (Swiss grid coordinates 773.180 / 138.650).

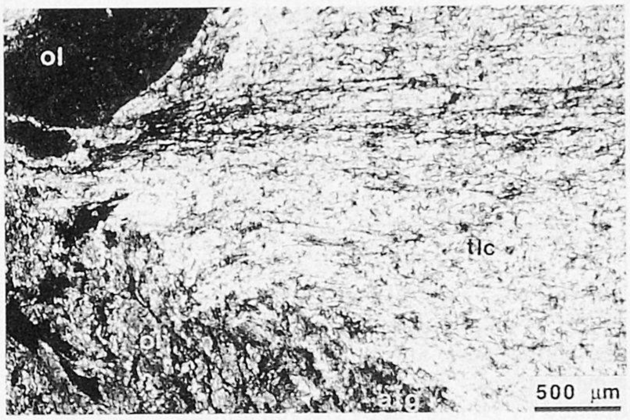

Fig. 13 A local talc foliation is developed overgrowing static talc in a talc-olivine hornfels (near Lägh da Cavloc), which is then overgrown by retrograde antigorite (atg) (Swiss grid coordinates 774.870 / 138.610).

solid-state deformation whereby grains of feldspar and quartz recrystallized.

Intrusion-related metasomatic veins in Suretta marbles, crosscutting isoclinal folding in the marble, are boudinaged and folded (RIKLIN, 1977; CONFORTO-GALLI et al., 1988; RIED, 1994).

Deformation of contact metamorphic minerals can be observed in the surrounding rocks (KUBLI, 1983; PERETTI, 1983; MÜTZENBERG, 1986; BERGER and GIERÉ, 1995). Andalusites are stretched in metapelites of the Forno unit. The cracks are sealed with quartz. The width of the cracks varies from 20 μm to 1 mm in a direction generally perpendicular to the main foliation. Contact metamorphic minerals in calcsilicates of the Suretta nappe are fractured, whereas garnet porphyroblasts have asymmetric garnet tails (BERGER and GIERÉ, 1995). Contact metamorphic diopside in calcschists (Avers Bündnerschiefer) south of Piz Salacina exhibits deformation lamellae and microboudinage, with tremolite and calcite in its pressure shadows (Fig. 12). At a distance of 1.5 km from the granodiorite intrusion, ultramafic talc-olivine rocks develop a local foliation within the talc matrix (Fig. 13).

All these observations can be summarized and interpreted as syn- to post-intrusive flattening. A careful analysis of thin sections of the diploma theses of KUBLI (1983); PERETTI (1983); GIERÉ (1984); MÜTZENBERG (1986) and own thin sections leads to figure 14. This figure summarizes the macroscopic and microscopic observations of these features related to the final emplacement of the Bergell granodiorite. Syn- to post intrusive deformation is only visible in the metasediments and ultramafic rocks. In amphibolites, the contact metamorphism leads to topotactic replacement of actinolitic hornblende by pargasitic hornblende. There is a deformation gradient from the contact of the intrusion, documented by macroscopically deformed metasomatic veins and Bergell sills and dikes, outwards to the surrounding rocks, documented by microscopically deformed contact metamorphic minerals. This local deformation is restricted to a distance of 2–2.5 km away from the intrusion, since andesitic-basaltic dikes near La Margneta show no evidence for deformation (WENK, 1980; TROMMSDORFF and NIEVERGELT, 1983; MÜTZENBERG, 1986).

The growth of tremolite and calcite in the pressure shadows of diopside and a new talc foliation in contact metamorphic ultramafics indicate slightly retrograde conditions with respect to peak metamorphic conditions during contact metamorphism.

3.7. BRITTLE DEFORMATION

The Muretto line is an important fault in the study area. It is accompanied by a system of subsidiary faults. This fault system displaces and deforms both the rocks of the Forno unit and the Bergell granodiorite and postdates the ductile deformations D_1 to D_8. Characteristic of this fault zone is the rusty red alteration colour of the surrounding rocks and the precipitation of Fe-rich dolomites and Fe–Cu–Zn(–Pb–As) sulphide deposits within fault breccias (PERETTI, 1983).

The faults strike generally NNW–SSE with a steep dip to the ENE. Striations dip moderately or steeply to SE. The associated sense of shear indicates a relative uplift of the western block (RING, 1994). RING (1994) interpreted this fault as a dextral oblique normal fault with a calculated maxi-

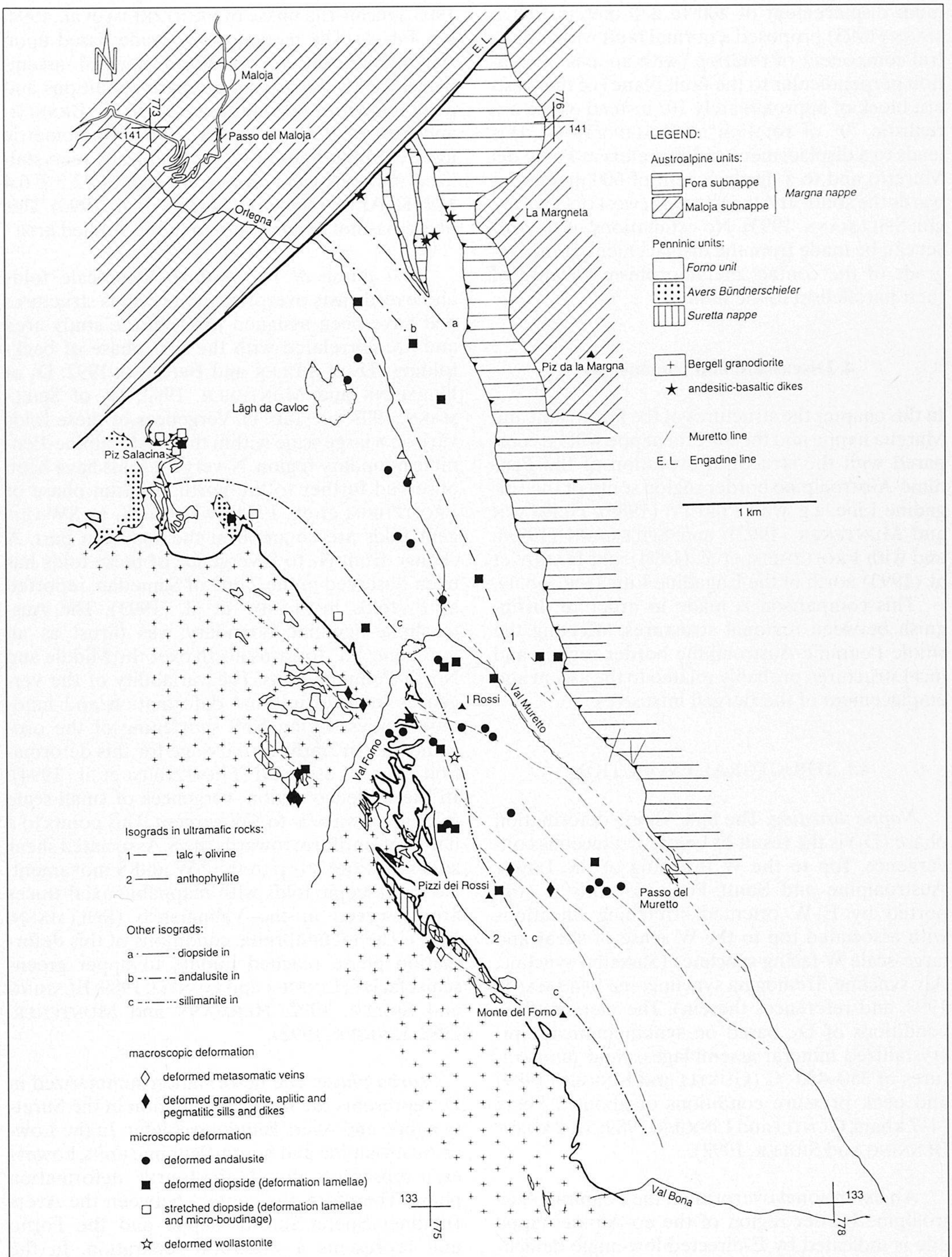

Fig. 14 Deformation related to the final emplacement of the intrusion with deformation of metasomatic veins, sills and dikes and deformation of contact metamorphic minerals.

mum displacement of 200 to 270 meters. SPILLMANN (1993) proposed a normal fault with a sinistral component of rotation (with an axis of rotation perpendicular to the fault plane) of the western block of approximately 10° instead of the unrealistic 70° of rotation of RIKLIN (1978). This leads to a displacement of 200 meters at Passo del Muretto and to a displacement of 600 meters towards the south at Alpe Vazzeda (west of Chiareggio; SPILLMANN, 1993). No estimations of the offset can be made from the displacement of the isograds of the contact metamorphism because of their parallelism to the fault.

4. Discussion and conclusions

In this chapter the structures of the Forno unit, the Margna nappe and the Suretta nappe will be compared with the structural evolution of the Penninic-Austroalpine border region south of the Engadine Line, e.g. with PERETTI (1985), HERMANN and MÜNTENER (1992), and SPILLMANN (1993), and with FROITZHEIM et al. (1994) and HANDY et al. (1993) north of the Engadine Line (see Tab. 1).

This comparison is made in order to distinguish between regional structures, affecting the whole Penninic-Austroalpine border region, and local structures, probably related to the ascent and emplacement of the Bergell intrusives.

4.1. STRUCTURAL EVOLUTION

Nappe thrusting: The first Alpine deformation phase (D_1) is the result of Upper Cretaceous convergence. Top to the W thrusting of the Lower Austroalpine and South-Penninic units is supported by E–W oriented stretching lineations with associated top to the W sense of shear and large-scale W-facing synclines (Sassalbo syncline, Alv syncline, Tremoggia syncline; see SPILLMANN, 1993, and references therein). The metamorphic conditions of D_1, based on synkinematically recrystallized mineral assemblages, yield temperatures of 350–450 °C (GUNTLI and LINIGER, 1989) and peak pressure conditions of about 5 kbars (4–7 kbars, GUNTLI and LINIGER, 1989; 5 ± 2 kbars, BENNING and SIDLER, 1992).

An extensional overprint in the Penninic-Austroalpine border region of the eo-Alpine nappe pile is indicated by E-directed low-angle detachments (e.g. the Corvatsch mylonite, Fig. 1), interpreted as due to gravitational collapse of the eo-Alpine thickened crust (F_2 of LINIGER, 1992; D_2 of HERMANN and MÜNTENER, 1992 and SPILLMANN, 1993, Ducan-Ela phase of FROITZHEIM et al., 1994, see Tab. 1). The metamorphic grade based upon synkinematically recrystallized mineral assemblages yields decreasing pressure conditions and peak temperature conditions (≥ 450 °C, BENNING and SIDLER, 1992; LINIGER, 1992). Radiometric age determinations of synkinematically recrystallized minerals yield an average age of 72.5 ± 6.4 Ma (K–Ar on phengites, HANDY et al., 1996). This phase has not been observed in the studied area.

First phase of backfolding: Mesoscale folds and overthrusts overprint the previous structures and have been assigned to D_2 in the study area and are correlated with the first phase of backfolding (D_2 of SIDLER and BENNING, 1992; D_3 of HERMANN and MÜNTENER, 1992; D_3 of SPILLMANN, 1993, see Tab. 1). Vergences of these folds vary on a large scale within the Austroalpine-Penninic boundary region. N-vergent folds have been observed further to the north (Blaisun phase of FROITZHEIM et al., 1994), whereas S- to SW-vergent folds are common in the southern part. A change from N- to S-vergence of these folds has been observed in the Zone of Samedan, reported as F_3 folds in HANDY et al. (1993). The Austroalpine-Penninic boundary was thrust as an "orogenic lid" towards north over the Middle and North Penninic units. The variability of the vergences indicate internal deformation and inhomogeneities during N–S shortening of the orogenic lid. An Early Tertiary age for this deformation phase is assumed (FROITZHEIM et al., 1994). In the Malenco region, vergences of small-scale folds are always S- to SW-vergent. This points to a flat-lying antiform towards the S. Associated shear zones indicate a top to the SW and S movement. No megascopic folds with mappable axial traces are observed in the Valmalenco (SPILLMANN, 1993). The metamorphic conditions of this deformation phase reached middle to upper greenschist facies (LINIGER and GUNTLI, 1989; BENNING and SIDLER, 1992; HERMANN and MÜNTENER, 1992; LINIGER, 1992).

Turba phase: The deformation summarized in D_3 represents the main deformation in the Suretta nappe and Avers Bündnerschiefer. In the Lower Austroalpine and South-Penninic units, however, it represents already the fourth deformation phase. Therefore, the contact between the Avers Bündnerschiefer/Suretta nappe and the Forno unit represents a structural separation. In the footwall of this contact, the deformation is characterized by (synmylonitic?) isoclinal folds, a penetrative foliation and a lineation with top to SE movement. In the hangingwall, it is only charac-

Tab. 1 Correlation of deformation sequences in the Penninic-Austroalpine boundary region. Regional deformation in the studied area is indicated bold and in italics, whereas local deformation is indicated in italics. Note that this correlation combined with age scale is only valid for the eastern part of the Bergell intrusives.

	south of the Engadine Line				north of the Engadine Line	
	this study:	PERETTI (1985)	HERMANN and MÜNTENER (1992):	SPILLMANN (1993):	FROITZHEIM et al. (1994):	HANDY et al. (1993):
	Forno unit, Margna nappe	Forno unit	Malenco unit, Margna and Sella nappes	Austroalpine-Penn. boundary region (southern part of Bernina massif)	Silvretta, Ela, Err	Samedan zone
Cretaceous nappe stacking (Cenomanian-Santonian)	***Nappe thrusting:*** top to W (D_1)	F_1	D_1: top to W	D_1: top to W	Trupchun phase (D_1)	F_1: top to W
Late Cretaceous east-west extension (Campanian-Mastrichtian)			D_2: top to ESE	D_2: top to E	Ducan-Ela phase (D_2)	F_2: top to E
Early Tertiary north-south shortening (Eocene)	***1st phase of backfolding*** (D_2)		1st phase of backfolding: D_3	1st phase of backfolding: D_3	Blaisun phase (D_3)	F_3: top to N
			D_4: folds			
east-west extension (Early Oligocene)	***Turba phase:*** top to SE (D_3)		D_5: top to ESE		Turba phase (D_4)	steep, E-dipping normal faults
	2nd phase of backfolding (D_4)	F_2	2nd phase of backfolding: D_6	2nd phase of backfolding: D_4		
emplacement of tonalite (32 Ma)	*Verticalization* (D_5)					
	Preda Rossa shear zone					
northwest-southeast shortening	***Transverse folding*** (D_6)		D_7	D_5: 'Querfaltung'	Domleschg phase ? (D_5)	F_4 ?
	Vertical shortening (D_7)					
emplacement of granodiorite (30 Ma)	*final emplacement of granodiorite* (D_8)					

terized by shear bands showing the same top to SE movement. The movement beween the structurally different units did not lead to a doubling of these units, but to the disappearence of the Avers Bündnerschiefer between Piz Salacina and Pizzi dei Rossi, where the Suretta nappe is in direct contact to the Forno unit. These features point at an E–W extension. The disappearence of units can be explained by a E-dipping normal fault between the Forno unit and the underlying units, where the Avers and Suretta represent the highly deformed footwall, and the Forno the locally deformed hangingwall.

These observations fit well in the kinematics of the Turba Mylonite Zone (LINIGER and NIEVERGELT, 1990; LINIGER, 1992). This E-dipping normal fault can be followed from north of Piz Platta to the northern border of the Bergell intrusives, where it is cut by the Bergell granodiorite (Fig. 1; LINIGER and NIEVERGELT, 1990; LINIGER, 1992; NIEVERGELT et al., 1996). LINIGER (1992) and NIEVERGELT et al. (1996) observed top to the SE movement in the Avers Bündnerschiefer, in the Arblatsch Flysch and in the southern part of the Schams nappes (D_2 deformation of LINIGER, 1992, and NIEVERGELT et al., 1996). An older deformation phase affecting the Avers Bünderschiefer and the Suretta nappe and corresponding to D_1 of LINIGER (1992) and NIEVERGELT et al. (1996) with associated foliation and lineations with a top to NW movement in the footwall of the mylonite zone has not been observed in the study area. The Suretta-Forno contact at Cima di Vazzeda (see Fig. 1) is cut by the Bergell tonalite towards the south and the Bergell granodiorite towards the north. Therefore, a pre-tonalite age for the Turba Mylonite Zone can be assumed.

The distribution of mesoscopic extensional features above the Turba Mylonite Zone (Forno and Margna) is restricted to incompetent lithologic units (metapelites) and to the nappe contact between the Forno-Malenco unit and the Margna nappe, thus probably representing a reactivated contact. This observation indicates a localized minor deformation above the Turba Mylonite Zone in the Forno unit and Margna nappe. Top to the ESE movement in the hangingwall of the Margna nappe reported by HERMANN and MÜNTENER (1992) probably belongs to the same deformation phase.

Second phase of backfolding: S- to SW-oriented asymmetrical D_4 folds are described as the second phase of backfolding (D_3 of SIDLER and BENNING, 1992; D_6 of HERMANN and MÜNTENER, 1992; D_4 of SPILLMANN, 1993; see Tab. 1) south of the Engadine Line. These structures with SW–NE compression are deformations related to movements along the Periadriatic Lineament under lower greenschist-facies conditons (BENNING and SIDLER, 1992; HERMANN and MÜNTENER, 1992). Field observations clearly demonstrate a pre-granodiorite age for D_4, but SPILLMANN (1993) and REBER (1995) assume even a pre-tonalite age. REBER (1995) observed, for example, isograds of tonalite contact metamorphism that are oblique to D_4 axial traces at Alpe Zocca (south of Val Sissone) near the tonalite intrusion (Fig. 1).

The F_2 fold generation of PERETTI (1985), LINIGER and GUNTLI (1985) and MÜTZENBERG (1986) has always been correlated with the first phase of backfolding (HERMANN and MÜNTENER, 1992; LINIGER, 1992; SPILLMANN, 1993), based upon shape of folding and orientation of the fold axial planes. Because of the lacking direct relationships between first and second phase of backfolding in the northern part of the Margna nappe LINIGER (1992) stated that the relation to the first or second phase of backfolding is unclear. Direct relationships between D_2 and D_4, however, are documented in the study area by D_2 small-scale folds that are only recognizable due to their wrong vergence on the SW limb of F_4 folds (Figs 4 and 5). This corresponds to relationships of first and second phase of backfolding observed in the Malenco region (SIDLER and BENNING, 1992; HERMANN and MÜNTENER, 1992; SPILLMANN, 1993). Thus, large-scale structures in the study area such as the Rossi antiform (F_2 of KUBLI, 1983; PERETTI, 1983, 1985) can now be interpreted as folds produced during the second phase of backfolding.

Verticalization, transverse folding and vertical shortening: The verticalization (D_5), transverse folding (D_6) and vertical shortening (D_7) probably precede the granodiorite intrusion. The temporal bracketing of these deformations is closely related to the xenoliths and their orientation within the granodiorite. The parallel arrangement and parallel orientation of xenoliths in the Bergell granodiorite, not being reoriented by a stoping process, is not well understood. Nevertheless, the xenoliths can be interpreted as being largely in situ. Such a phenomenon is well known and described, for example, for the Main Donegal Granite (PITCHER and READ, 1959; later discussed by PITCHER, 1970 and PITCHER and BERGER, 1972) and for the Adamello batholith (BRACK, 1983). The features in the Bergell granodiorite can only be interpreted as an indication for the absence of convection in the magma.

The pre-granodiorite verticalization is considered to be syn-tonalite and due to its emplacement. The verticalization can be traced into Valle di Preda Rossa by steeply inclined lithological units, by foliations and by the contact of the Suretta nappe and Forno-Malenco unit at the contact to the Bergell tonalite (WENK, 1973; PFIFFNER and WEISS, 1994). A verticalization postdating the second phase of backfolding has also been recognized by SPILLMANN (1993). A shear zone at the contact between tonalite and country rocks (Preda Rossa shear zone, Fig. 1) has been observed by BERGER and GIERÉ (1993). Microstructures suggest a gradual change from high-temperature deformation (magmatic) in the inner part of the tonalite to deformation under greenschist-facies conditions at the margin (BERGER and GIERÉ, 1993). In the country rocks, contact metamorphic minerals grew during deformation. Sense of shear indicators of subvertical mineral lineations along this shear zone indicate an uplift of the tonalite (BERGER and GIERÉ, 1993), which may have also verticalized the adjacent units. This shear zone along the contact between tonalite and country rocks can be followed further to the north, but seems to end in Valle Sissone at the contact to the granodiorite (BERGER and GIERÉ, 1995). An estimation of the movement between tonalite and country rocks can probably be made by the difference of solidus pressure of the tonalite (5–6 ± 3 kbars, REUSSER, 1987) and the pressure of the contact metamorphism in the country rocks (3.5–4 kbars, TROMMSDORFF and CONNOLLY, 1990; CONNOLLY and TROMMSDORFF, 1991). Although the pressure difference lies within the error limits of the pressure estimation for the tonalite (see REUSSER, 1987), an uplift of the tonalite in a subsolidus state can be assumed.

Based upon field relations, the transverse folding (corresponding to D_4 of SIDLER and BENNING, 1992; D_7 of HERMANN and MÜNTENER, 1992; F_5 of LINIGER, 1992; D_5 or "Querfaltung" of SPILLMANN, 1993; see Tab. 1) can be constrained to have occurred between the tonalite and the granodiorite intrusions. This deformation phase leads to two recognizable antiforms in the Malenco region (Fig. 1), one near M. Disgrazia and a second one northeast of Chiesa. The highest intensity of D_6 folding is reached in the vicinity of the antiform near M. Disgrazia (SPILLMANN, 1993). According to the observations made in the study area, this deformation is considered a regional event due to its extensive appearance over the Malenco region (see Fig. 1).

The folds accommodating a vertical shortening or collapse (D_7) represent a local structure at the eastern border of the Bergell intrusives. Their age can be assumed to be pre-to syn-granodiorite. Whether this folding phase is a passive folding due to gravitational collapse of verticalized units or a syn-intrusive folding due to the upcoming granodiorite intrusion remains unclear.

Final emplacement of the granodiorite: D_8 includes the solid-state deformation of the intrusives (deformed sills and dikes), deformation of intrusion-related metasomatic veins and deformation of the contact metamorphic minerals in the country rocks. All these observations can be viewed in terms of syn- to post-intrusive flattening, which is in accord with observations of BERGER and GIERÉ (1995). They analyzed the aspect ratio of enclaves in granodiorite and tonalite and demonstrated a strain increase towards the margin of the intrusives in the flattening field of a Flinn diagram. The observations of deformed contact metamorphic minerals like diopside as well as synkinematic growth of tremolite and calcite are in agreement with BERGER and GIERÉ (1995), who distinguished between an early static and a younger dynamic contact metamorphism, with the latter related to the final emplacement of the Bergell pluton.

The correlation of the deformation phases across the Engadine Line is partly unclear, because of several deformational events not recorded in the adjacent areas (see Tab. 1). This concerns, for example, the second phase of backfolding, which is only observed in the Malenco region, south of the Engadine Line. The lateral occurrence of this phase is probably restricted to the Southern Steep Belt due to post-collisional movements. Another deformation phase, the Domleschg phase of FROITZHEIM et al., (1994) affects the Austroalpine-Penninic boundary north of the Engadine Line. This structure with NE–SW trending open fold axes can probably be correlated with the transverse folding on the basis of geometric orientation, the development and temporal sucession in the deformation sequence.

4.2. ASCENT AND EMPLACEMENT OF THE BERGELL INTRUSIVES

The structural evolution of the study area reveals that the transverse folding (D_6), interpreted as a regional deformation phase, can be constrained to have taken place between the tonalite and granodiorite intrusions. Thus, the Bergell tonalite can be considered intruding in a frame of regional deformations (between second phase of backfolding and transverse folding). Therefore, the tonalite can be described as a syn-tectonic intrusion with respect to post-nappe refolding. The Bergell granodiorite, however, represents a post-tectonic intrusion with respect to regional deformations. A division into a tonalite and a granodiorite ascent and emplacement is proposed:

(1) A forcible diapiric ascent and emplacement (in the sense of upward movement of a magma) of the tonalite with the development of a foliation in the tonalite and a (partly) dynamic thermal aureole. This is induced by shortening at depth resulting from post-collisional convergence ("vertical escape" of ROSENBERG et al., 1995) with synmagmatic folding at the base of the pluton, i.e. at its western border (ROSENBERG et al., 1995) and verticalization of the surrounding units at the southeastern border along the Preda Rossa shear zone.

(2) A more passive ascent of the granodiorite with respect to the forcible ascent of the tonalite. This is documented by stoping of the surrounding rocks with the development of a static thermal aureole (early static contact metamorphism of BERGER and GIERÉ, 1995). The fact, that xenoliths and their pre-granodiorite structures are not reoriented with respect to structures in the country rocks, gives evidence for a limited magmatic deformation. No mylonitization at the contact to the country rocks nor large-scale syn-intrusive folding could be observed. Further rising of magma lead to the final emplacement and a flattening of the outer, already crystallized margin, producing features similar to "ballooning" plutons, e.g. solid-state deformation in the granodiorite (DRESCHER and STORZ, 1926; BERGER and GIERÉ, 1995), deformation of aplitic sills and dikes, and deformation of contact metamorphic minerals (late dynamic contact metamorphism of BERGER and GIERÉ, 1995).

The ascent and emplacement of the Bergell granodiorite, and associated contact metamorphism did not result in a complete annealing of pre-intrusive microfabrics in the country rocks outside the intrusion, nor in a complete annealing of microstructures within the xenoliths. Thus, sense of shear determinations of oblique grain shapes in quartz- and calcite-rich rocks are still possible (see Fig. 3 and LINIGER, 1992, p. 93).

4.3. CONCLUSIONS

Two different structural evolutions are preserved in the studied nappe pile of the Suretta nappe, Forno unit and Margna nappe. The first governs the evolution of the Penninic-Austroalpine border region (Forno-Malenco, Margna), while the second affects the Middle Penninic units (Suretta, Avers Bündnerschiefer). They are separated by a mylonite zone along the contact between the Suretta nappe and the Forno unit, which probably represents the southern continuation of the Turba Mylonite Zone. A pre-tonalite age for this zone can be assumed based on a discordant relationship between the Suretta-Forno contact and the tonalite at Cima di Vazzeda (Fig. 1). In addition, the second phase of backfolding, which is overprinting the Turba phase, is older than the tonalite. After the Turba phase the entire nappe pile shows an identical overall structural evolution. Local deformation phases, restricted to the border region of the intrusives, are considered to be emplacement-related.

Xenoliths within the granodiorite did not rotate during intrusion and thus allow to constrain the age of deformation within the studied area. The transverse folding, which is considered a regional deformation phase, is constrained by the two intrusions.

A relative timing of the deformation in the Penninic-Austroalpine border region can be established with respect to the intrusions of tonalite and granodiorite: Deformations of pre-tonalite age are nappe thrusting, first phase of backfolding, Turba phase, and second phase of backfolding. The verticalization of the units at the eastern border of the Bergell intrusives is considered to be syn-tonalite due to uplift of tonalite along the Preda Rossa shear zone. Post-tonalitic deformations are transverse folding, which is of pre-granodiorite age and vertical shortening, which is of pre-to syn-granodiorite age. A syn- to post-granodiorite deformation is summarized in D_8. As a consequence of the relative timing of the regional deformation phases, the tonalite intrusion is regarded as syn-tectonic, whereas the granodiorite is post-tectonic with respect to post-nappe refolding.

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