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On the kinematics of shearing near the top of the Monte Rosa nappe and the nature of the Furgg zone in Val Loranco (Antrona valley, N. Italy): tectonometamorphic and paleogeographical consequences

by *Lukas M. Keller*[1] and *Stefan M. Schmid*[1]

Abstract

This combined structural and petrological study in upper Val Loranco (Italy) examines the contacts between Monte Rosa nappe, Furgg zone, Portjengrat unit and Antrona ophiolites. The Furgg zone is found to be derived from basement and cover lithologies of the continental Portjengrat unit, intruded by post-Triassic mafic dykes. During Alpine D1 and D2 deformation pre-Mesozoic amphibolite facies paragneisses from the top of the Monte Rosa nappe underwent progressive Alpine shearing. Shear zone formation started during Eocene top-N nappe stacking and under eclogite facies conditions (D1). This was immediately followed by fast exhumation to greenschist facies conditions, which occurred within the same kinematic framework of crustal shortening and ongoing top-N shearing (D2). Presently, the early X1 and X2 lineations indicate top-WSW shearing, but these were drastically reoriented due to D3 straining. D3 resulted in backfolding and simultaneous top-ENE (or combined N-side-up and dextral) shearing under greenschist facies conditions (D3) after 35 Ma ago. Because we find that the Furgg zone does not represent an ophiolitic mélange, we propose the following original nappe stack, based on the retrodeformation of the effects of D3. From bottom to top: Antrona ophiolites (Valais ocean), Monte Rosa-Furgg zone-Portjengrat continental fragment (eclogite facies part of the Briançonnais), and Zermatt-Saas ophiolites (Piemont-Liguria ocean).

Keywords: Monte Rosa nappe, paleogeographic restoration, mylonitization, folding, metamorphism.

Introduction

This paper contributes towards understanding a longstanding problem regarding the paleogeographic location of the Monte Rosa nappe situated west of the Lepontine dome (MILNES et al., 1981; FROITZHEIM, 2001). To solve this problem, both lithological and structural evidence must be taken into account. In particular, a lithological and structural re-analysis of the so-called Furgg zone (BEARTH, 1953, 1954a, 1954b, 1956, 1957) is crucial. This complex zone (see WETZEL, 1972 for a detailed petrological analysis) has been regarded either as a sedimentary sequence and part of the cover of the Monte Rosa nappe (JABOYEDOFF et al., 1996), or, as a tectonic mélange (WETZEL, 1972; MILNES et al., 1981; MÜLLER, 1983; FROITZHEIM, 2001). If the Furgg zone represents a Mesozoic ophiolite-bearing tectonic mélange, indeed it can be regarded as a suture zone separating Monte Rosa and Portjengrat continental units (MILNES et al., 1981; FROITZHEIM, 2001). This paper puts a particular focus on the Furgg zone and its lithological composition.

The structural analysis of the kinematic interplay between different events of ductile shearing and folding is equally important for palinspastic restoration. Three types of Tertiary ductile shearing and folding have so far been documented in the Penninic units of Western Switzerland and adjacent Italy (STECK, 1984, 1987; STECK and HUNZIKER, 1994). A first and oldest type of shear zones is associated with stretching lineations, and senses of shear document SE–NW oriented underthrusting of the European plate below the Adriatic margin, contemporaneous with the formation of the nappe pile (e.g., STECK, 1984, 1987; LACASSIN, 1987; STECK and HUNZIKER, 1994). In

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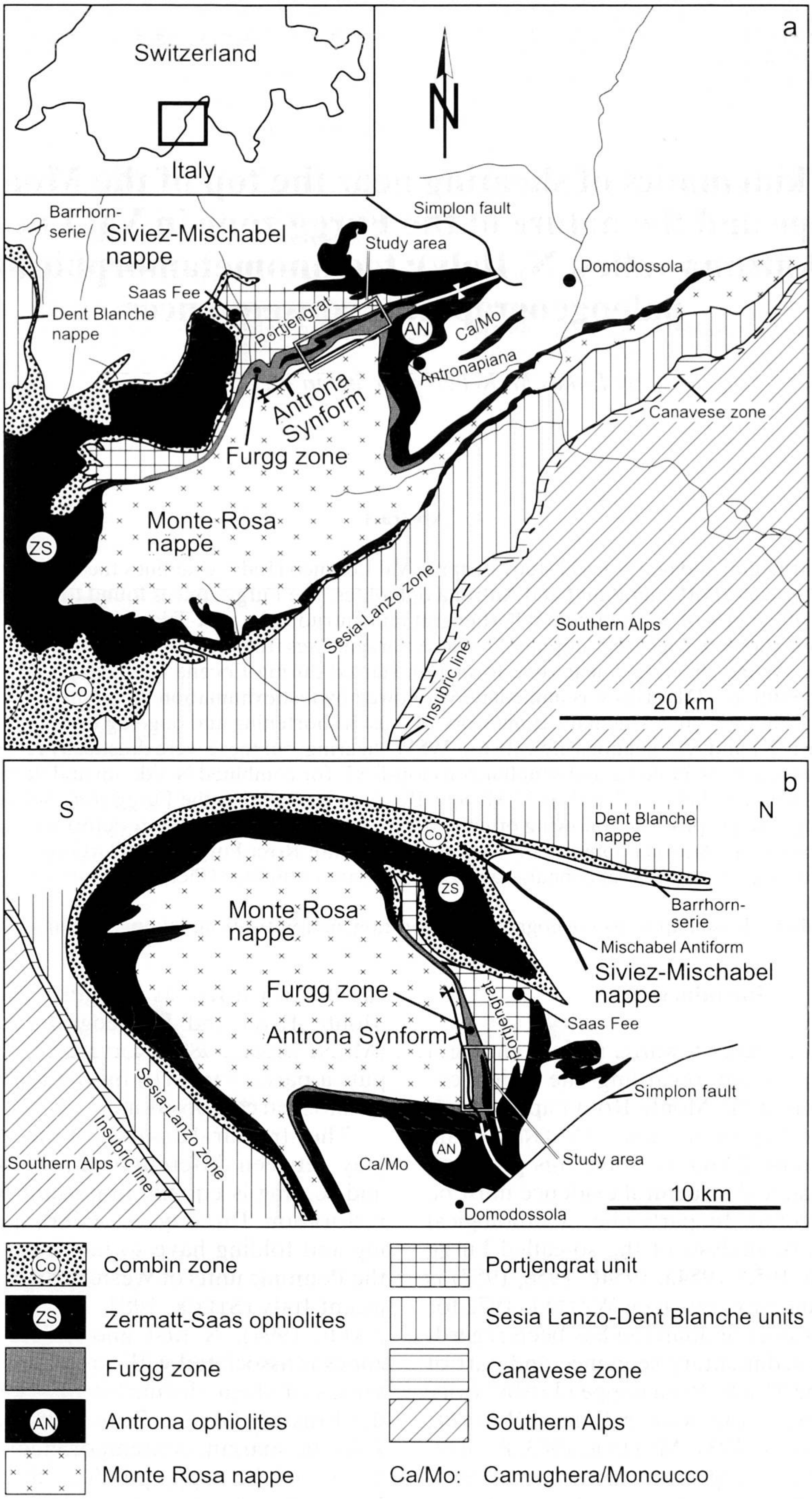

Fig. 1 Location of the study area (outlined by rectangle) within the large scale context. (a) Modified tectonic map of the western part of the upper Penninic Alps after SARTORI (1987), STECK (1989), PFEIFER et al. (1989), RÖSSLER (2000). (b) Synthetic cross section modified after MILNES et al. (1981).

the Mattmark area the top margin of the Monte Rosa nappe is pervasively deformed by such ductile top-NW shearing (LACASSIN, 1987). A second and younger type of stretching lineation with a moderate angle of pitch is associated with shearing parallel to the steeply N-dipping and overturned limbs of megascopic backfolds. This shearing is top-SE in the Mattmark, and top-ENE in the Val Loranco area, respectively (MÜLLER, 1983; STECK, 1984; LACASSIN, 1987; JABOYEDOFF et al., 1996), and it appears dextral in map view. A third type of stretching lineations, also post-dating top-NW stretching, shearing and nappe stacking, is related to the Simplon ductile shear zone (STECK, 1984, 1987, 1990). This shear zone, which started to be active at about 35 Ma (STECK and HUNZIKER, 1994), and the associated Miocene Simplon normal fault (MANCKTELOW, 1992) produced WSW–ENE oriented orogen-parallel extension and top-WSW shearing since the Oligocene.

In the Alpine community, high-pressure metamorphism in the upper Penninic units of Western Switzerland has long been held to be of Cretaceous age (for review see HUNZIKER et al., 1992). Therefore, the observed structures used to be subdivided into Cretaceous and Tertiary structures, the former being related to high-pressure metamorphism, followed by fast exhumation before the Tertiary (STECK and HUNZIKER, 1994). Tertiary greenschist facies lineations were supposed to have overprinted earlier formed Cretaceous stretching lineations (RING and MERLE, 1992). However, recent isotopic studies (BOWTELL et al., 1994; RUBATTO et al., 1997) indicate an early to middle Eocene age for high-pressure metamorphism in the Zermatt-Saas ophiolites. Concerning high-pressure metamorphism in the internal crystalline massifs (Dora Maira) ages ranging from the middle Eocene to the early Oligocene have been obtained (e.g. DUCHENE et al., 1997). Greenschist facies re-equilibration and backthrusting immediately follows and is dated as late Eocene to early Oligocene (BARNICOAT et al., 1995; MARKLEY et al., 1998). This suggests extremely fast exhumation during the Tertiary. In this paper we will discuss which Tertiary structures and contacts formed during the high-pressure stage and which are related to fast exhumation and/or later deformation stages. Furthermore, this study also analyzes the kinematic and metamorphic evolution of early mylonitization within the Monte Rosa basement, as well as the deformation postdating this early mylonitization.

Backfolding and related top-SE to ENE dextral shearing overprint earlier top-NW ductile shear zones and re-oriented the earlier stretching lineations and related transport directions. We attempt to restore the original orientation of the earliest shear directions, which differ from those measured in the field today.

Geological setting

The geometry of pre-Mesozoic crystalline rocks of the Monte Rosa nappe is defined by strong S-vergent backfolds (Fig. 1) with a pronounced axial plunge towards SW (e.g. KLEIN, 1978; MILNES et al., 1981; ESCHER et al., 1997). Zermatt-Saas ophiolites and Antrona ophiolites lie structurally above and below the Monte Rosa nappe, respectively. These ophiolitic units envelop the Monte Rosa nappe almost completely. The Furgg zone mainly consists of paragneisses interleaved with basic rocks and separates the Monte Rosa nappe from the Portjengrat unit.

Further north the Siviez-Mischabel nappe forms the main part of the Grand St-Bernard nappe system. There, the metasedimentary cover predominantly comprises late Carboniferous, Permian and Triassic rocks. The "Barrhornserie", however, contains a complete stratigraphic sequence up to the Eocene (SARTORI, 1987). After its emplacement the nappe pile was overprinted by backfolding. The area studied (Fig. 1) is situated on the northeastern border of the Monte Rosa nappe and comprises the northern limb of the Antrona synformal backfold.

Lithological characterization of the mapped units

A simplified version of the lithostratigraphic units mapped in the working area is given in figure 2. This lithostratigraphy forms the base of the structural maps presented in figures 7 and 9 (details in KELLER, 2000).

LITHOSTRATIGRAPHY OF THE MONTE ROSA NAPPE

The Monte Rosa nappe consists of pre-Permian, dominantly metapelitic paragneisses with rare boudins of mafic rocks, intruded by granites at around 310 Ma and 270 Ma (HUNZIKER, 1970; FREY et al., 1976). In the following context these granites will be referred to as orthogneiss due to their subsequent deformation. The relict pre-Alpine mineral assemblages are predominantly biotite–sillimanite–garnet–quartz–K-feldspar–plagioclase, or, garnet–biotite–muscovite–silliman-

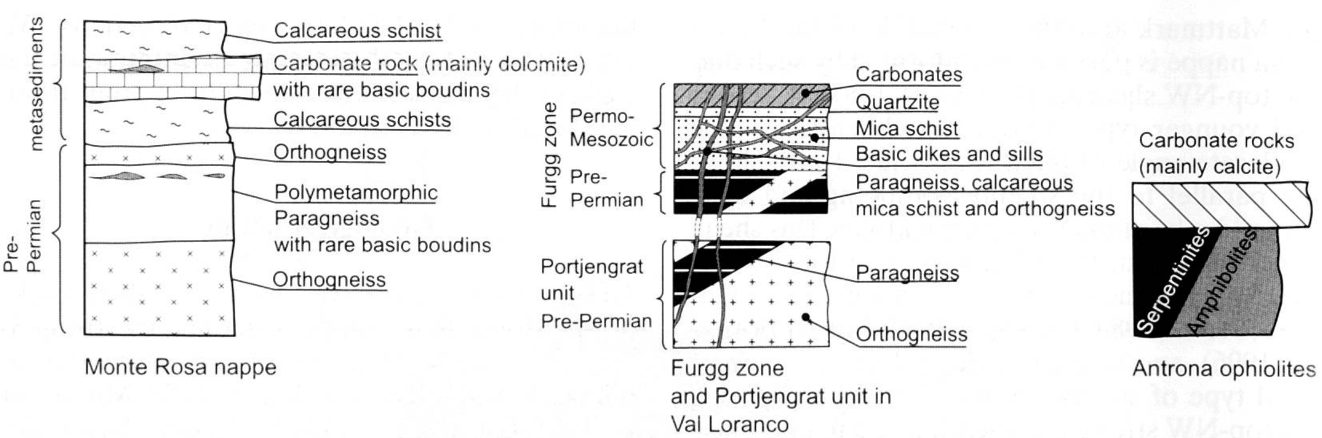

Fig. 2 Synthetic lithostratigraphic profiles of the major tectonic units mapped in Val Loranco.

ite–plagioclase, both indicating high-temperature metamorphic conditions (Bearth, 1957; Dal Piaz and Lombardo, 1986). The change from pre-Alpine to Alpine mineral assemblages is intimately related to deformation processes, as described below in more detail.

At the front of the Monte Rosa basement, strongly deformed lenses of metasedimentary rocks (Bearth, 1954b) occur. Carbonate rocks, containing mainly dolomite with interlayers rich in white mica, are associated with calcareous micaschists. Rare retrogressed eclogitic mafic boudins are found within these carbonate rocks (Keller, 2000). Recent dating on zircon from one of these mafic boudins, erroneously attributed to the Furgg zone, yielded an age of 510 ± 0.5 Ma, interpreted as time of crystallization of the mafic protolith (Liati et al., 2001).

LITHOSTRATIGRAPHY OF THE FURGG ZONE

The exact definition and significance of the Furgg zone (Bearth, 1956; Wetzel, 1972) still are a matter of debate. It is a high-strain zone of heterogeneous composition with paragneiss predominating. It generally, but not always, contains abundant mafic (amphibolitic) boudins and separates the Monte Rosa nappe from the Portjengrat unit. Such boudins, however, are also found outside the Furgg zone. In our study, the term "Furgg zone" simply denotes all those lithological associations, which could not be unambiguously attributed to either the Portjengrat, Monte Rosa, or Antrona ophiolite unit.

– Most of the Furgg zone consists of leucocratic or melanocratic schists, associated with variable amounts of amphibolitic bands or boudins ("Upper Furgg zone" in Jaboyedoff et al., 1996). Parts of the leucocratic schist are interpreted as former Permo–Triassic? arkose and/or mylonitic orthogneiss. Zircons from orthogneiss (granite or acid volcanic rock), which also belong to the Furgg zone (Mattmark area), have been dated as 272 Ma by Liati et al. (2001), who interpreted the age as the crystallization age of the magmatic protoliths. The amphibolite boudins contain white mica with coronas of zoisite. This indicates early nucleation of white mica during the metamorphic history. Colombi (1989) interprets the white mica as a relic of a former high-pressure mineral assemblage. The latter is only rarely preserved in mafic boudins (Wetzel, 1972).

– A second type of lithology found in the Furgg zone consists of Mesozoic (?) (Triassic?) calcite and dolomite marbles, intruded by basic dykes ("middle Furgg zone" in Jaboyedoff et al., 1996).

– A third type consists of paragneiss or calcareous micaschist with rare amphibolite boudins only. Calcareous micaschists consist of the same mineral assemblages as the metasediments found at the front of the Monte Rosa basement. They are exposed in the southern face of the Btta. del Bottarello. Furthermore, a band of paragneiss stretches from Alpe del Gabbio to Monte della Preja and was interpreted as the eastern termination of the pre-Mesozoic basement of the Monte Rosa nappe ("lower Furgg zone") by Jaboyedoff et al. (1996) and Steck et al. (1999). In this work this gneissic band is regarded as an isolated lens within the Furgg zone.

LITHOSTRATIGRAPHY OF THE PORTJENGRAT UNIT

The Portjengrat unit consists mainly of orthogneiss. These include rare paragneiss lenses and amphibolite-bearing micaschists similar to the paragneiss that make up a major part of the Furgg zone. There is no evidence that Permo–Mesozoic cover rocks of the Portjengrat unit are preserved along the contact with what was mapped as "Furgg zone" in the working area. At the northern rim of the Portjengrat unit, however, a cover consisting of quartzites and metacarbonates is preserved. There, both basement and cover are crosscut by basic dykes (CARRUPT and SCHLUP, 1998).

LITHOSTRATIGRAPHY OF THE ANTRONA OPHIOLITE COMPLEX

Mappable volumes of lithologies that undoubtedly derived from the Antrona ophiolites are interlayered with lithologies attributed to the Furgg zone in Val Loranco. Due to extremely intense ductile shearing the metasedimentary cover (calcite marbles) of the mafic and ultramafic lithologies shows a large variation in thickness, ranging from some decimetres up to ten meters. Calcite marbles systematically accompany mafic and ultramafic bands or boudins. Calcschists and metaradiolarites are absent. However, within the main part of the Antrona ophiolites east of the study area, the Antrona ophiolites are reported to comprise quartzites (metaradiolarites?) and calcschists (CARRUPT and SCHLUP, 1998). If radiolarites are indeed present outside our study area this may imply that both Antrona ophiolites and Zermatt-Saas ophiolites belong to the Piemont-Liguria paleogeographic domain. However, the slightly different chemical composition of the two ophiolitic zones (PFEIFER et al., 1989) indicates a different paleogeographic origin (Valaisan?) for the Antrona ophiolites. The interpretation of the Furgg zone discussed below points in a similar direction.

Definition of tectonic units

According to MILNES et al. (1981) tectonic contacts separate units that displayed coherent crustal segments of either continental or oceanic crust before Alpine orogeny. In principle tectonic contacts can be clearly defined where Permo–Mesozoic cover rocks or remnants of oceanic crust are found to separate larger bodies of continental basement. Table 1 characterizes the contacts between units in the study area and indicates which of these contacts are definitely regarded as tectonic.

Following BEARTH (1957) and based on table 1, a subdivision of the study area into the following three tectonic units is proposed: Monte Rosa nappe, Portjengrat-Furgg unit and Antrona ophiolites. The contact between Monte Rosa nappe and the Portjengrat-Furgg unit is either defined by metasediments of the Monte Rosa nappe or by ultramafics derived from the Antrona ophiolites. The main body of the oceanic Antrona ophiolites is structurally below the continental Monte Rosa and Furgg-Portjengrat continental units. The attribution of the Furgg zone to the continental Portjengrat unit will be discussed in a subsequent chapter.

Deformation history

This section discusses the characteristics of the three major ductile deformation phases found in the study area and presents related microstructures and metamorphic conditions.

CRITERIA OF CORRELATION BETWEEN DIFFERENT PHASES OF DEFORMATION

Structural analysis within high-grade gneiss areas lacks many correlation tools available in areas where Mesozoic stratigraphic sequences are preserved. The rare and extremely deformed lenses of metasediments in the study area often do not preserve younging directions, and therefore facing directions cannot be used as a correlation tool.

Tab. 1 Characterization of contacts between different units.

adjacent units	contact characterization	major tectonic contact
Monte Rosa unit vs. Furgg zone/Portjengrat unit	Ultramafic lenses of Antrona ophiolites (east) or metasedimentary cover of the Monte Rosa nappe (west)	yes
Furgg zone vs. Portjengrat unit	No sediments nor remnants of oceanic crust	no
Furgg zone/Portjengrat unit vs. Antrona ophiolites	Marbles or serpentinites	yes

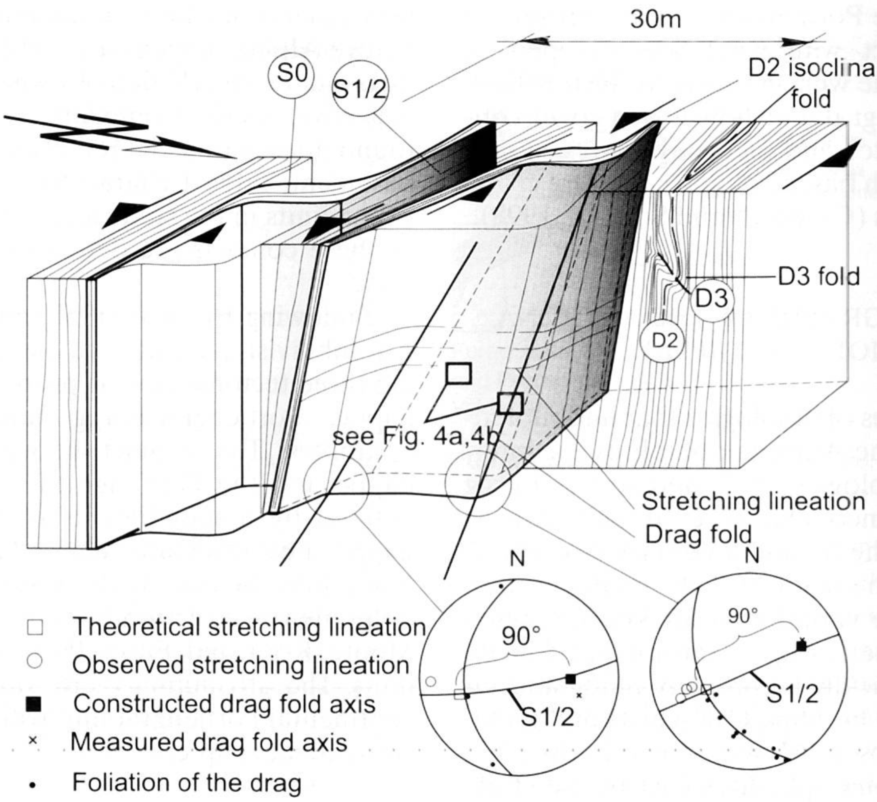

Fig. 3 Anastomosing top-WSW shear zones partly preserve pre-Alpine foliation (S0) in metapelite. Pole figures show construction of "theoretical" stretching lineations X1, assuming that S0 is dragged by simple shear into parallelism with the shear zone around an axis perpendicular to the shearing direction. Agreement between "theoretical" and observed stretching lineations indicates that shearing, starting under eclogite facies conditions, was top-WSW.

It is possible, however, to distinguish between sets of structures associated with distinct synkinematic mineral assemblages. In the study area this principle was used to distinguish between the first two generations of stretching lineations (X1, X2) as well as to separate between a pre-Alpine foliation (S0) and Alpine foliations. The last generation of stretching lineations (X3) is distinguished on the basis of senses of shearing. Overprinting criteria (WILLIAMS, 1985) allow to separate reliably between different generations of folds. Fold style, however, is dependent on rock type and strain intensity, and different generations of folds may exhibit resembling styles. Fortunately, continuity of outcrops often permitted a correlation of different generations of folds with distinct shearing events.

PRE-ALPINE STRUCTURES

Pre-Alpine structures are very rare and preserved in the form of a foliation (S0) preserved between anastomosing D1 shear zones (Fig. 3). S0 was observed in metapelites intruded by and thus predating the Monte Rosa granites. In its present form S0 is defined by garnet–biotite–muscovite–sillimanite–plagioclase. However, in most cases sillimanite is replaced by small kyanite needles, which show no preferred orientation, indicating static recrystallization from pre-Alpine sillimanite to kyanite during the Alpine metamorphic cycle (DAL PIAZ and LOMBARDO, 1986). S0 (Fig. 4a) represents a high temperature, low-pressure foliation whose age is controlled by geochronological data: Rb–Sr dating on muscovite from sample KAW 91, containing an identical mineral assemblage gives ages around 255 Ma (HUNZIKER, 1969). The orientation of S0 found between the anastomosing shear zones differs strongly from the NW-dip of the main Alpine D1/D2 foliation.

D1/D2 MYLONITIZATION IN THE MONTE ROSA NAPPE

One shear zone situated north of the D3 Antrona synform is described here in detail (Swiss coordinates 647.15/102.75). Anastomosing top-WSW shear zones overprint the pre-Alpine S0-foliation of the metapelites. As S0 bends into parallelism with the shear zones, the metastable pre-Alpine mineral assemblage is replaced by an Alpine high-pressure mineral assemblage. Pre-Alpine

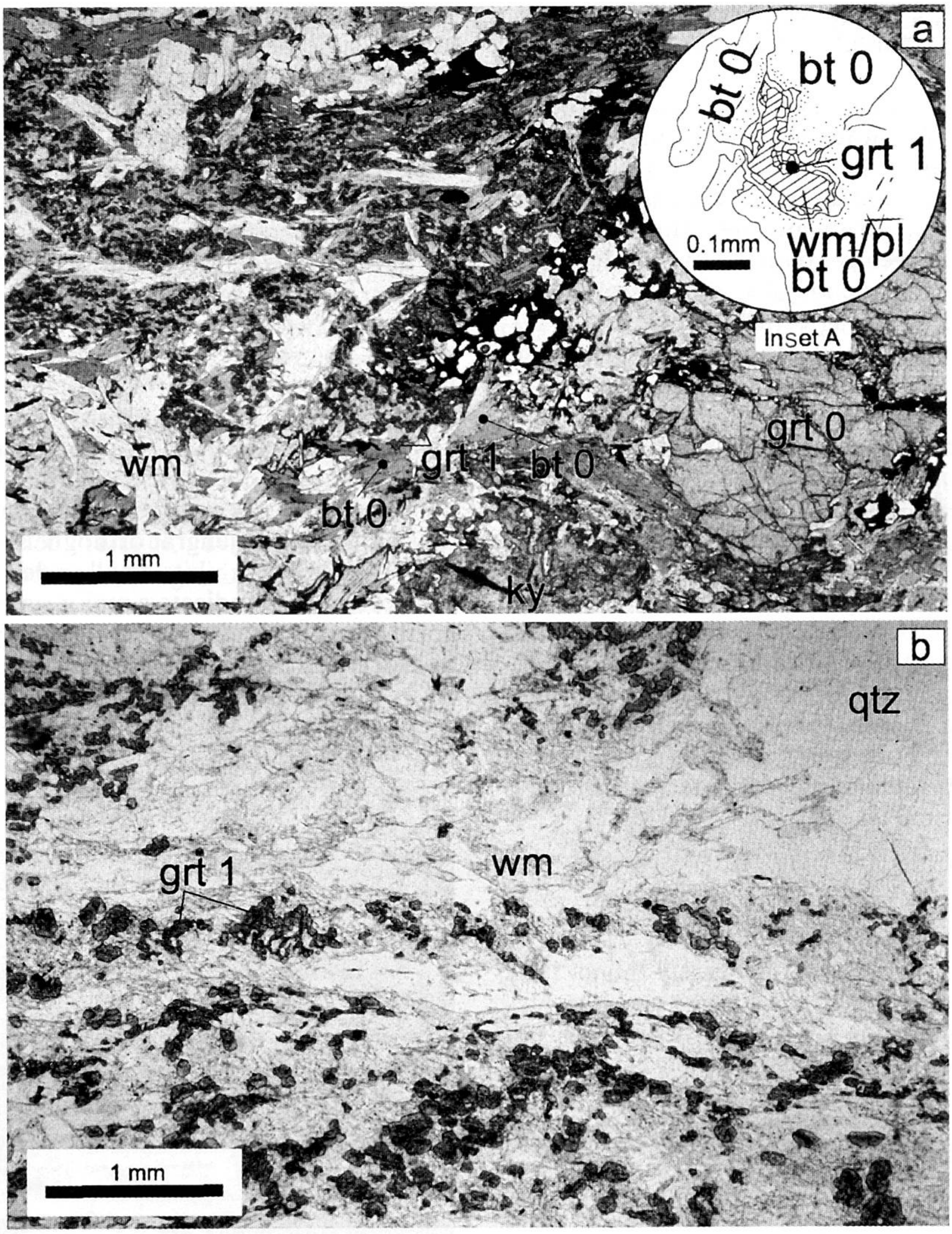

Fig. 4 Micrographs of optical thin sections from the Monte Rosa nappe illustrating metamorphic conditions prevailing during D1. 4a and 4b are from an anastomosing D1 shear zone (locality indicated in Fig. 3). (a) S0 foliation: Pre-alpine biotite (bt 0) and plagioclase decompose to form a new generation of garnet (grt 1) and white mica (see inset A). (b) S1 foliation: Biotite and plagioclase completely decomposed which lead to an eclogite facies mineral assemblage of garnet, white mica, and quartz. Note that volume fraction and grain size of the new garnet generation increased with respect to figure 6a.

biotite and plagioclase are almost completely decomposed according to the following reaction:

plagioclase + biotite = garnet + white mica

As pressure and temperature increase this reaction produces a second generation of garnet and white mica. It is apparent in the field that deformation induces this reaction since the rock changes to a lighter colour as the foliation bends into the shear zone. This observation is confirmed in thin section where the amount of second generation garnet and muscovite is seen to increase as the reaction progresses. During further straining kyanite also partly decomposes as the aluminium is used to store divalent cations (Fe + Mg) in garnet and univalent cations (K + Na) in white mica and the following reaction can be formulated:

plagioclase + biotite ± kyanite + water =
garnet + white mica

This leads to a high-pressure assemblage of metapelites, which consists of garnet, white mica, ±kyanite and quartz (NAGEL et al., 2001) (Figs 4a–b).

The Alpine stretching lineation is defined by recrystallized quartz aggregates. This X1 stretching lineation gently plunges WSW. Figure 3 presents the construction of a "theoretical stretching lineation". Good agreement between "theoretical" and observed lineation indicates that the anastomosing shear zones indeed started to form during D1 mylonitization and under high pressures (Fig. 3). However, the high-pressure mylonitic foliation is preserved only within the marginal parts of the shear zones. In the very central parts of the shear zones the mylonitic foliation is defined by white mica, chlorite, garnet, plagioclase, zoisite and epidote. There the associated greenschist facies stretching lineation X2 also gently plunges WSW. In addition to these anastomosing shear zones top-WSW transport north of the Antrona synform is also indicated by shear bands, asymmetric porphyroclasts systems and preferred crystallographic orientation in recrystallized quartz (Figs 5, 9).

D1 FOLDING

Small-scale D1 folds are only rarely found. They are observed mainly in the Furgg zone (Fig. 6b). However, no major D1 fold structure was observed in the study area.

D2 FOLDING

Mesoscopic isoclinal folds, which refold an earlier foliation and clearly display a greenschist facies axial plane foliation, are regarded as D2 folds. In general, the formation of the main foliation occurs during D2. Only in D2 fold hinges is S1 distinct from S2, transposition of S1 by S2 being complete in the limbs (Figs 6a–b). Overprinting criteria, often also fold style, allow an easy distinction between D2 and D3 folds (Fig. 6c). Where D2 folds are directly associated with D1/D2 shear zones, the contemporaneous activity of these shear zones with associated D2 folding is indicated during the late stages of mylonitization, under greenschist facies conditions.

Discrete top-WSW mylonites are absent and top-WSW shear indicators are rare within the Portjengrat unit, Antrona ophiolites and the Furgg zone, where D2 folding is the predominant D2 feature. This illustrates the difference in deformation style between these units and the Monte Rosa nappe, which is characterized by shear zone formation during D2. Within the Portjengrat unit, Antrona ophiolites and the Furgg zone D2 fold axes generally exhibit a steep NW-plunge, differing from the WSW-plunge of the X1/X2 stretching lineations (Fig. 10a).

In map view (Fig. 7) large scale D2 folding is marked by a band of rocks derived from the Antrona ophiolites stretching from Passo della Preja towards the southern face of P. Bottarello. Marbles of the Antrona ophiolite complex mark a large-scale parasitic antiform-synform pair south of Btta. del Bottarello. This pair exhibits a vergence pointing to a major synform further to the north within the Portjengrat unit (Figs 7, 11). Further east, the Portjengrat orthogneiss adjacent to the Furgg zone exhibits small-scale D2 parasitic folds, which also indicate a major synform further north (see also KLEIN, 1978). This major synform was localized at Alpe Colonna and shows that the entire Portjengrat unit forms a large-scale D2 synform (see Fig. 11).

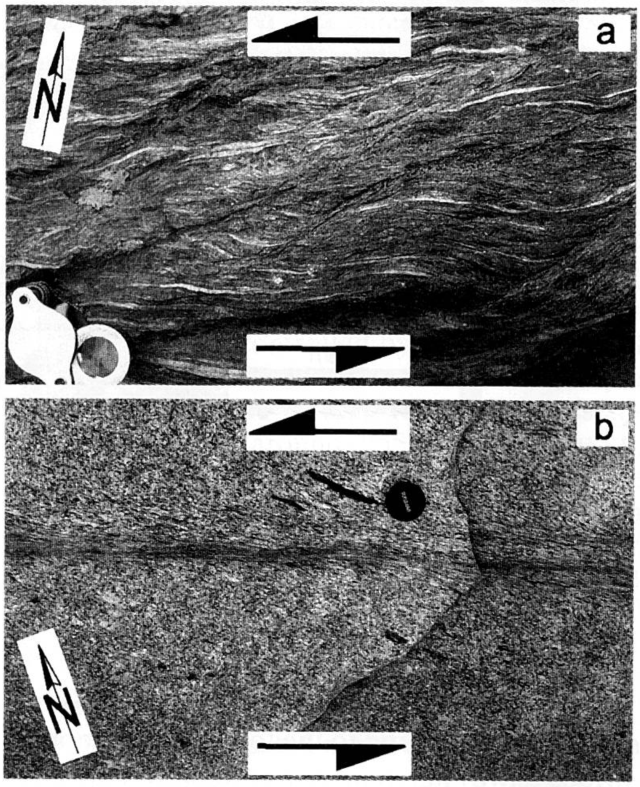

Fig. 5 Mylonitic D1/D2 structures from the Monte Rosa nappe. (a) D1/D2 shear bands indicating top-WSW transport within metapelites. (b) Discrete shear zone within weakly deformed orthogneiss indicating top-NW transport in the internal parts of the Monte Rosa nappe south of the Antrona synform.

D3 FOLDING AND SHEARING

D3 is associated with parasitic folds at different scales, which refold the S1/S2 main foliation. In contrast to the D2 folds with changing vergence, D3 folds exhibit a constant vergence across the Furgg zone and Portjengrat unit, indicating that both units are situated in the northern limb of the D3 Antrona synform.

In the Furgg zone the lithological heterogeneity gives rise to a wide spectrum of wavelengths resulting in tight to open similar folds. Open similar folds predominate in homogeneous lithologies. The mylonitic foliation at the top of the Monte Rosa nappe is not only refolded by D3 folds but also overprinted by top-ENE shear bands (Figs 8a–b). An S3 axial plane foliation is only sporadically established (KLEIN, 1978) and, where present, is associated with greenschist facies conditions. The D3 axial planes plunge steeply NNW, D3 fold axes plunge W to WSW (Fig. 10a). Sense of shear observations in the Furgg zone and Portjengrat unit are predominantly top-ENE as indicated by shear bands, asymmetric boudinage and preferred crystallographic orientation in recrystallized quartz (Fig. 9). Associated X3 stretching lineations gently dip WSW, i.e. they are subparallel to the direction of D3 fold axes (Fig. 10a). This, together with the overprinting of D2 folds by top-ENE shear bands, suggests that this third folding phase is related to combined NE-side-up and dextral shearing.

KLEIN (1978) provides a detailed account regarding the asymmetry of small-scale third generation folds (his "F2") and the consequences that result from this. We essentially confirm his observations that the vergence of D3 parasitic folds points to a major synform situated within the

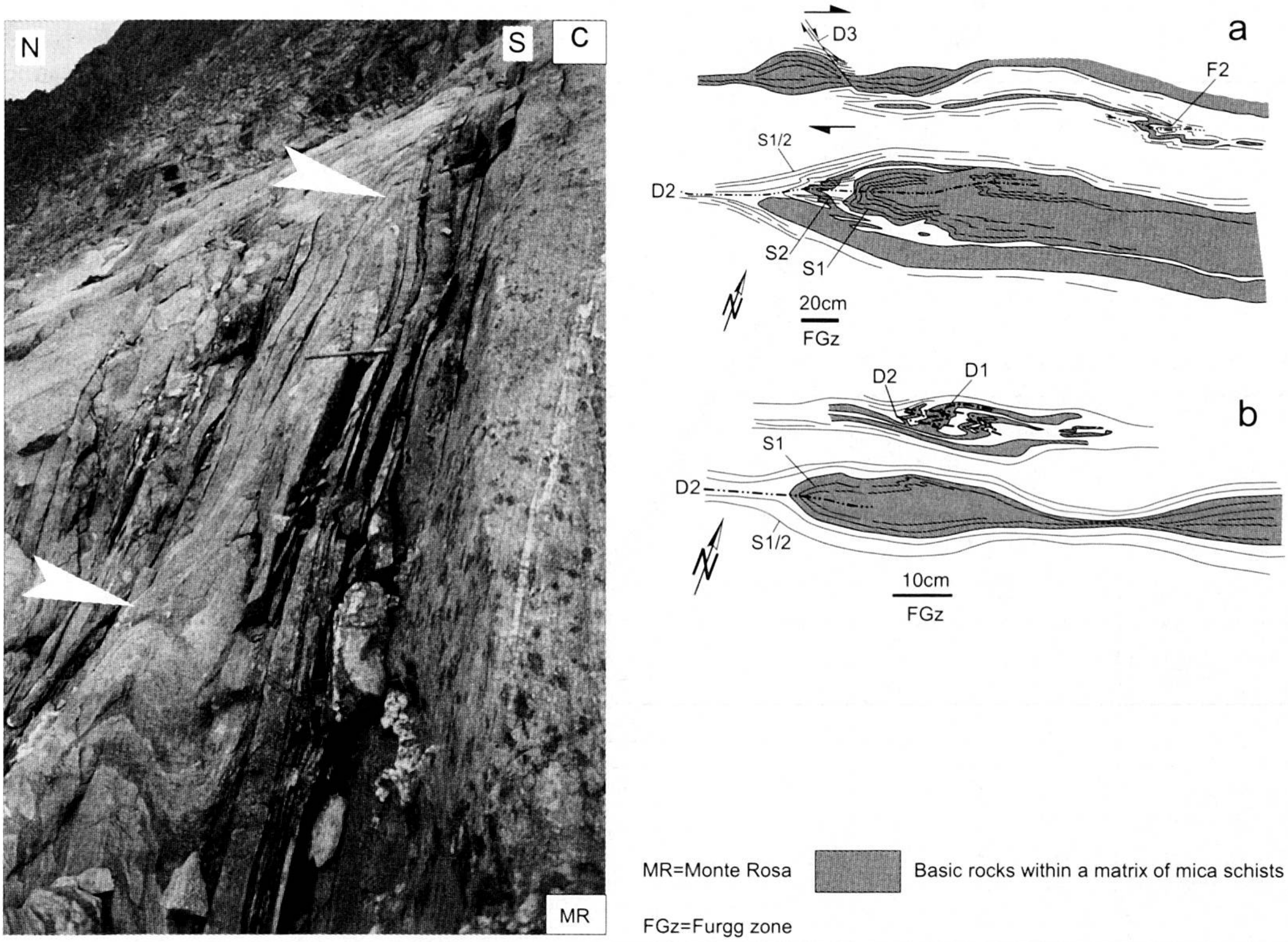

Fig. 6 Examples of fold-overprinting relationships, (a) and (b) in map view, (c) in profile view. (a) In fold hinges of D2 isoclinal folds S1 can be distinguished from S2 in mafic lithologies. D3 is indicated by asymmetric boudinage indicating top-ENE transport. Locality: western part of Alpi di Andolla. (b) Isoclinal D2 fold and evidence for D1 folding. Locality: western part of Alpi di Andolla. (c) Overprinting of an isoclinal D2 fold by an open D3 fold within orthogneiss from the Monte Rosa nappe. Upper arrow indicates a D2 fold hinge defined by S1; lower arrow indicates overprinting of both D2 fold limbs by an open D3 fold. Locality: SW of Lago Ciapivul.

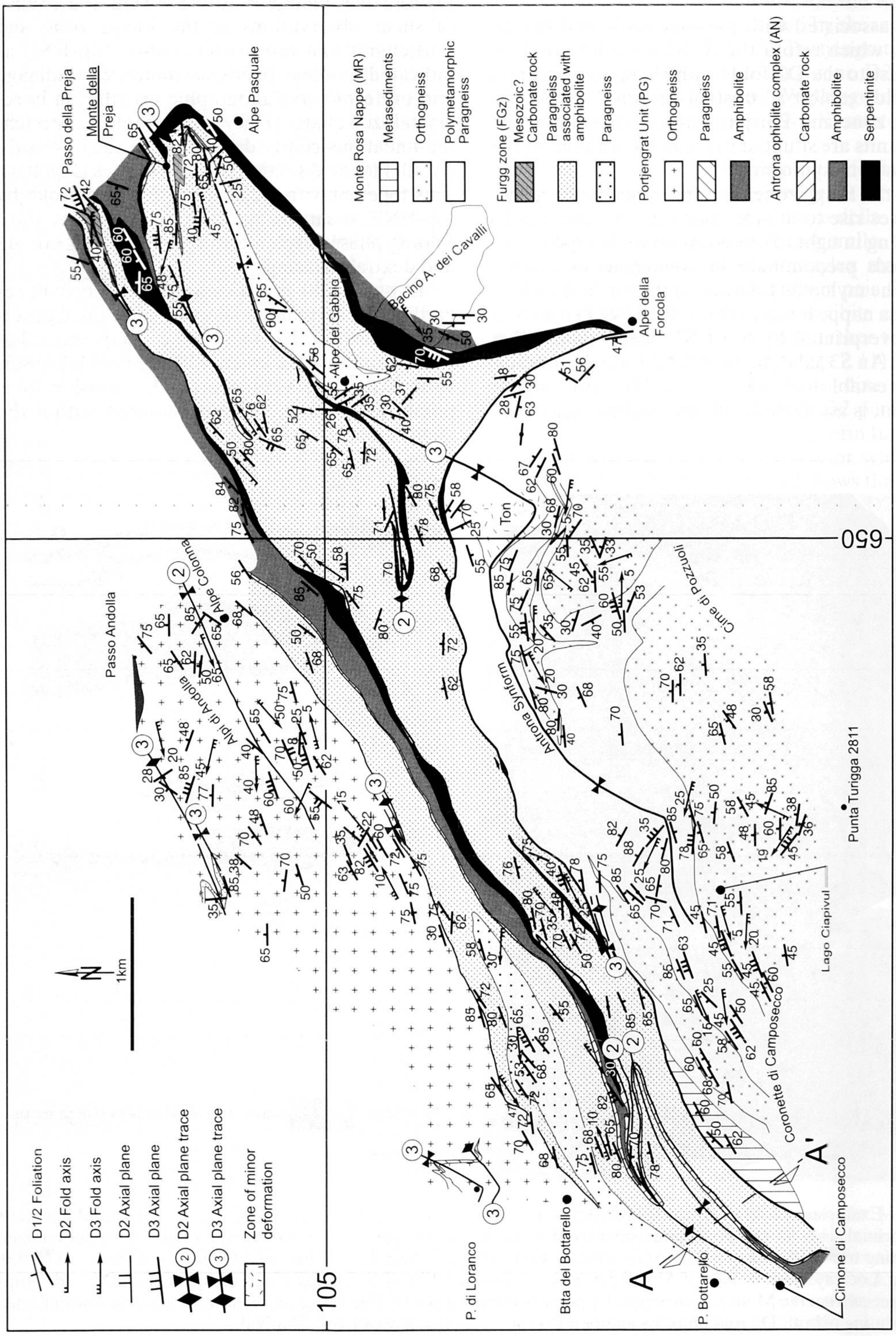

Fig. 7 Tectonic map of the study area indicating the orientation of all structural elements, except for stretching lineations and transport directions (see Fig. 9).

front of the Monte Rosa nappe, the Antrona synform (Fig. 11).

Our own observations, as well as those of Klein (1978) suggest that the continuation of the Antrona synform runs within the very frontal part of the Monte Rosa nappe and subparallel to the contact with the Furgg zone, dying out in the Mattmark area as suggested by Klein (1978). However, further investigations are needed in order to definitely exclude the hypothesis that this major axial plane runs into the more internal parts of the Monte Rosa nappe, as proposed by Milnes et al. (1981), Ring and Merle (1992) and Froitzheim (2001).

Near Alpe del Gabbio the large-scale Antrona synform deflects the main S1/S2 foliation from a NE–SW strike to a N–S strike. This deflection within the hinge zone is pronounced within and in the immediate vicinity of the Monte Rosa unit, representing a highly competent body of rocks during D3. The hinge of the Antrona synform is situated slightly north of a gneissic lens mapped as part of the Furgg zone (Fig. 7). In contrast, this same gneissic lens was interpreted as the pinched out eastern synformal hinge of the Monte Rosa nappe in the new tectonic map of the Western Alps (Steck et al., 1999). The orientation of the foliations found immediately west of Alpe del Gabbio and the separation of this gneissic lens from the Monte Rosa by lithologies of the Furgg zone (Fig. 7) preclude its direct connection with the Monte Rosa nappe. This interpretation is further supported by the fact that the Monte Rosa nappe is partly encased by serpentinites, which mark the tectonic contact between Monte Rosa nappe and Furgg zone.

The poles to the main D1/D2 foliation define a great circle whose pole coincides with the orientation of second order D3 fold axes (Fig. 10b). This clearly documents that the Antrona synform in the study area is a D3 structure, which in agreement with larger scale correlations (Klein, 1978), formed contemporaneously with other classical backfolds such as the Mischabel backfold.

LINEATIONS AND SENSE OF SHEARING

All transport directions indicated on the map (Fig. 9) are inferred from either macroscopic or microscopic sense of shear criteria (Simpson and Schmid, 1983). The most remarkable feature is that most stretching lineations (i.e. X1 to X3) in the northern limb of the Antrona synform dip gently WSW. Many of these lineations (i.e. most of them from within the Furgg zone and Portjengrat unit and some from the Monte Rosa unit) formed during D3 and are related to top-ENE, respectively dextral, shearing (see also Steck, 1984; Jaboyedoff et al., 1996). Others, particularly those found at the top of the Monte Rosa nappe, are related to D1/D2 mylonitization (X1 and X2) and indicate a reverse sense of shear (top WSW and sinistral, respectively).

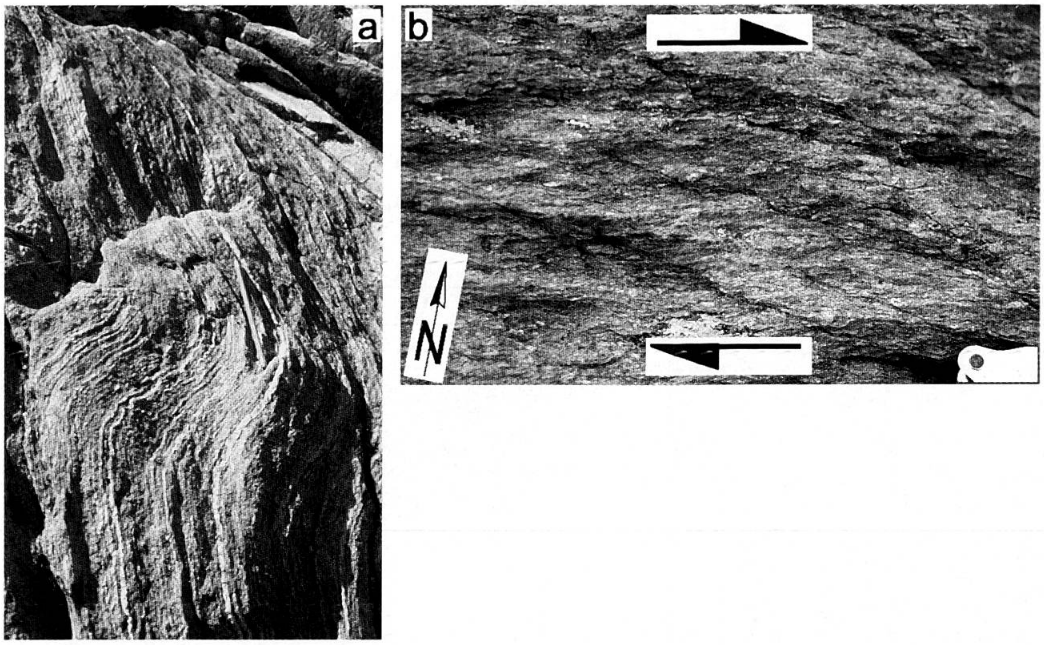

Fig. 8 Illustrations concerning D3 structures. (a) Open D3 folds, overprinting D1/D2 mylonites in metapelites from the top of the Monte Rosa nappe. (b) Top-ENE shear bands overprinting and reactivating former D1/D2 top-WSW mylonites found at the top of the Monte Rosa nappe.

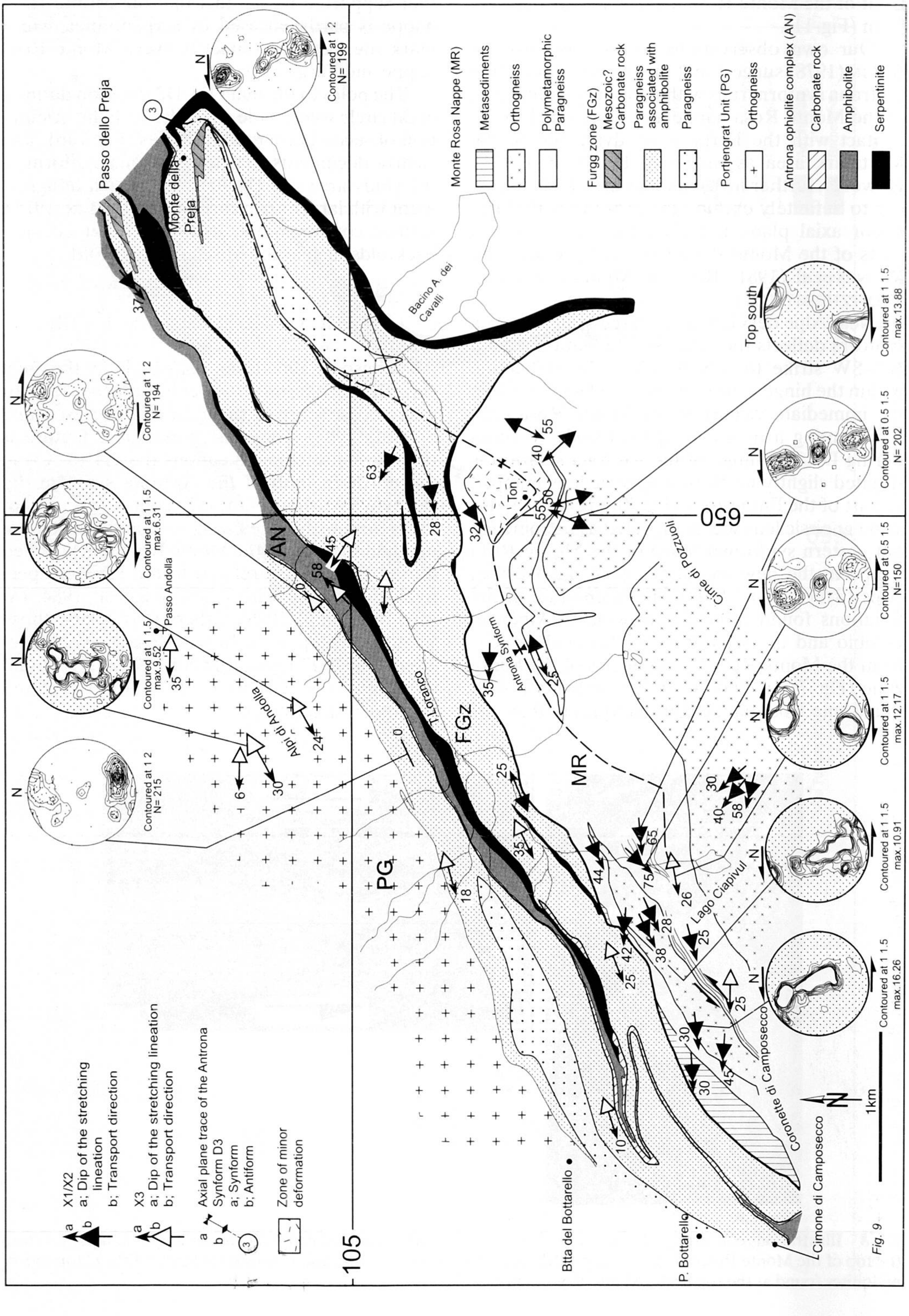
a
b
X1/X2
a; Dip of the stretching lineation
b; Transport direction
a
b
X3
a; Dip of the stretching lineation
b; Transport direction
a
b
③
Axial plane trace of the Antrona Synform D3
a; Synform
b; Antiform
Zone of minor deformation
Monte Rosa Nappe (MR)
Metasediments
Orthogneiss
Polymetamorphic Paragneiss
Furgg zone (FGz)
Mesozoic? Carbonate rock
Paragneiss associated with amphibolite
Paragneiss
Portjengrat Unit (PG)
Orthogneiss
Antrona ophiolite complex (AN)
Carbonate rock
Amphibolite
Serpentinite
105
650
PG
AN
FGz
MR
Passo dello Preja
Monte della Preja
Bacino A. dei Cavalli
Ton
Passo Andolla
Alpi di Andolla
T. Loranco
Antrona Synform
Cime di Pozzuoli
Lago Ciapivul
Coronette di Camposecco
Cimone di Camposecco
Btta del Bottarello
P. Bottarello
3
N
Contoured at 1 2
N= 199
Contoured at 1 2
N= 194
Contoured at 1 1.5
max.6.31
Contoured at 1 1.5
max.9.52
Contoured at 1 2
N= 215
Top south
Contoured at 1 1.5
max.13.88
Contoured at 0.5 1.5
N= 202
Contoured at 0.5 1.5
N=150
Contoured at 1 1.5
max.12.17
Contoured at 1 1.5
max.10.91
Contoured at 1 1.5
max.16.26
37
63
28
32
40
55
55
50
55
45
58
0
35
25
35
24
6
30
0
25
35
18
65
30
40
58
44
75
26
28
38
42
25
25
25
30
45
30
10
N
1km

Fig. 9

↑*Fig. 9* Tectonic map indicating transport directions of the hanging wall. Note northerly dip of all tectonic contacts. Pole figures, whose locations are shown by tie lines, indicate crystallographic preferred orientation of quartz c-axes (X is E–W, while Z is N–S oriented). Pole figures refer to either X-ray goniometer data (dotted background, contour interval is 0.5 of uniform distribution) or U-stage data (blank background, contour interval is 1.0 of uniform distribution). Multiples of uniform distribution are labelled for the first two contours. For X- ray goniometer data maximum of uniform distribution is labelled.

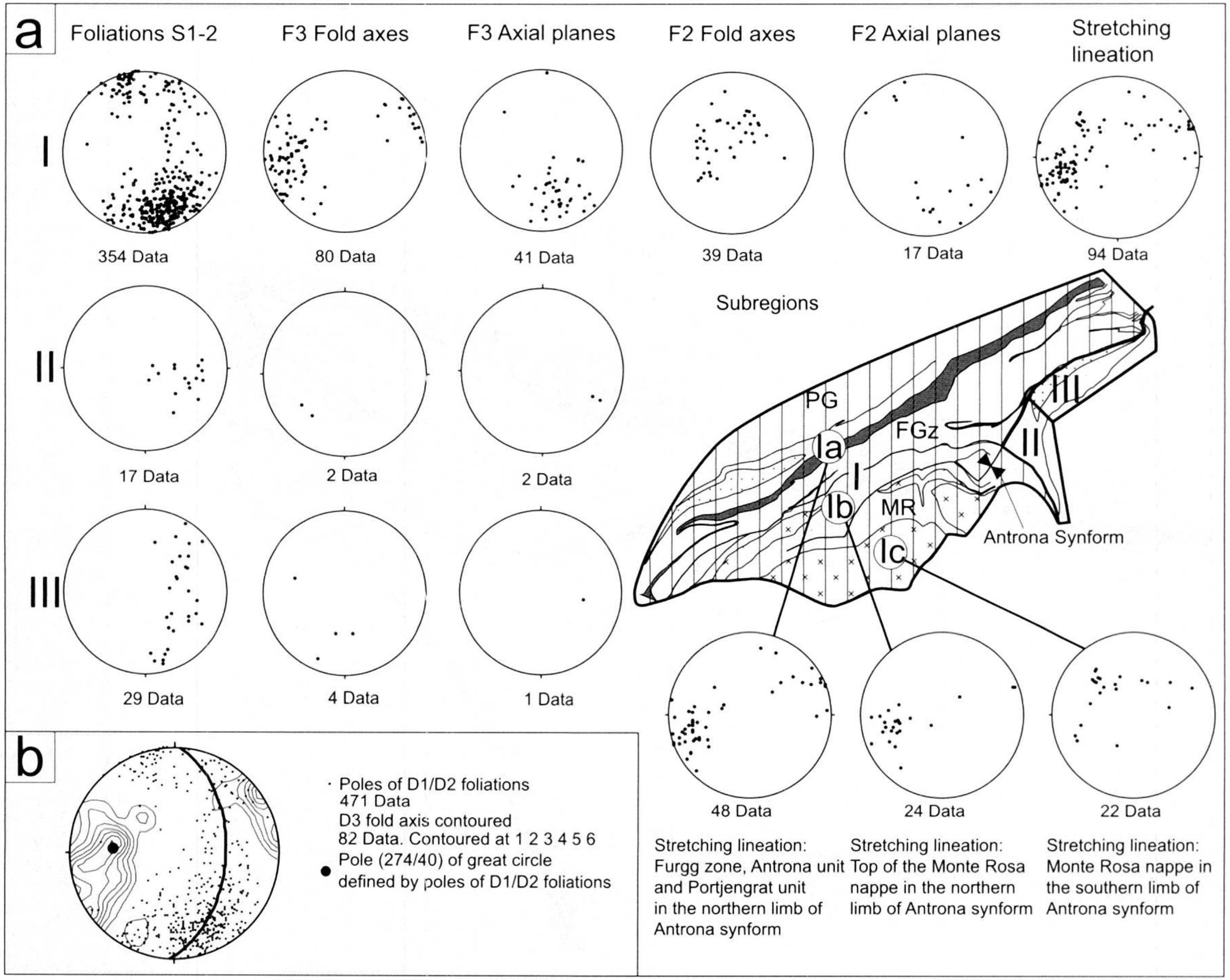

Fig. 10 Orientation data of structural elements. (a) Grouped into subregions. I: Furgg zone, Antrona unit, Portjengrat unit and Monte Rosa nappe. II and III: Furgg zone and Antrona unit in the southern limb of the Antrona synform. Stretching lineations grouped into Ia: Furgg zone, Antrona unit and Portjengrat unit in the northern limb of the Antrona synform. Ib: Top of the Monte Rosa nappe in the northern limb of the Antrona synform. Ic: Monte Rosa nappe in the southern limb of the Antrona synform; there, the stretching lineations show higher orientational spread as compared with the northern limb of the Antrona synform (subregions Ia and Ib). (b) Pole of great circle, defined by poles to the main S1/S2 foliation and comparison with measured D3 fold axes.

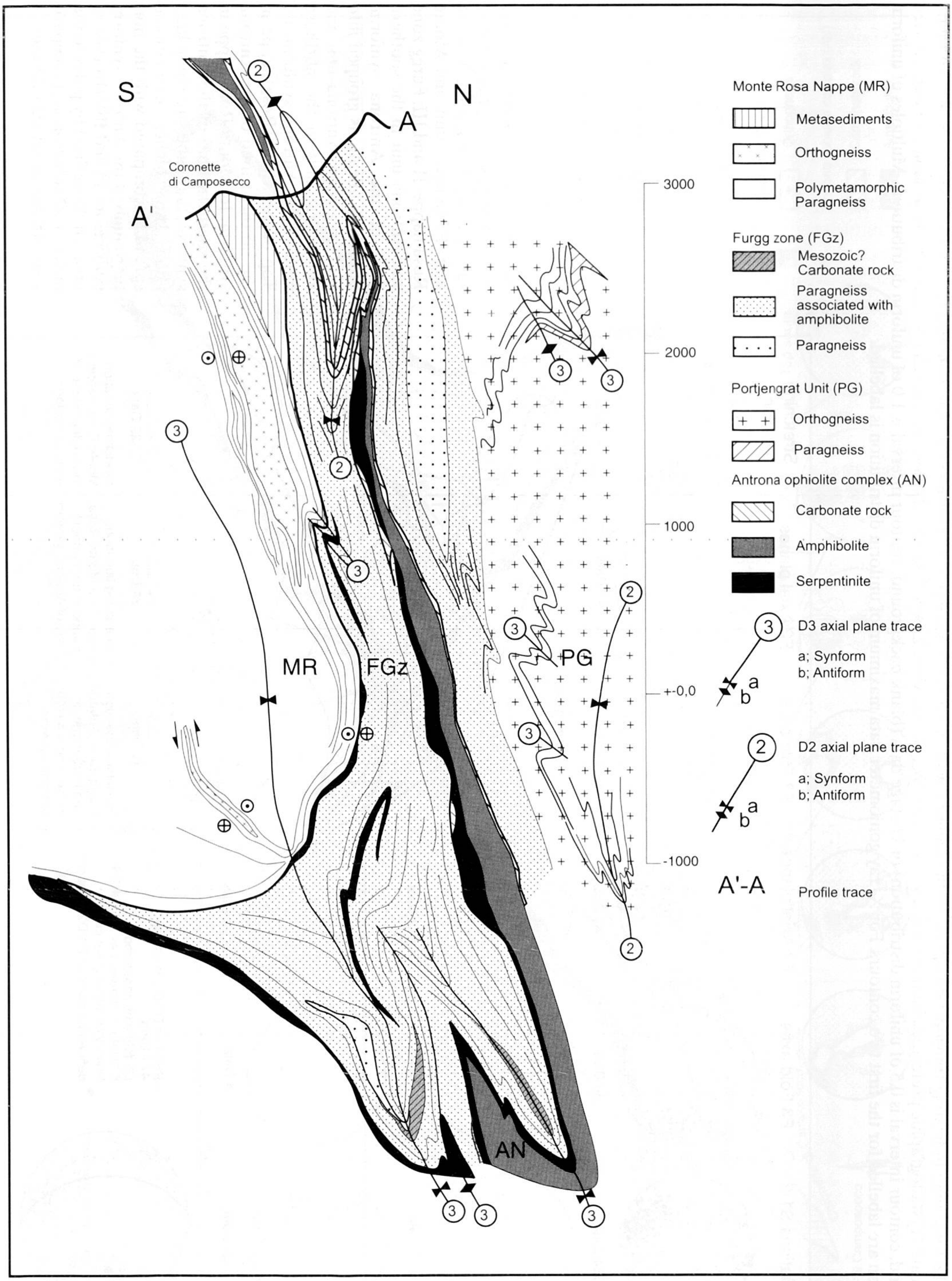

Fig. 11 Composite cross-section A–A' (trace indicated in Fig. 7) from Val Loranco, based on a stack of 9 individual cross sections (striking 143°) by assuming an axial plunge of 30° to the WSW. Note that the vergence of second order D3 folds consistently points to a synform situated within the Monte Rosa nappe (the Antrona synform).

South of the Antrona synform and within the Monte Rosa nappe the orientation pattern of the stretching lineations (X1/X2) and associated senses of shear are far more complex. In many cases top NW sense of shear is found. But south of Ton mountain (Fig. 9) X1/X2 shearing is overprinted by D3 folding and varies from top-S over top-SE to top-ENE. Such shear senses, differing from those found within the northern limb of the Antrona synform, were also described by RING and MERLE (1992). The effect of D3 deformation on the orientation of X1/X2 and related senses of shear is discussed below.

Discussion and conclusions

TECTONOMETAMORPHIC EVOLUTION

Of the three generations of stretching lineations, X1 and X2 are best documented in the frontal part of the Monte Rosa nappe. These lineations formed during progressive shear zone formation, related to top-WSW movements, which appear sinistral in map view. We discuss below that straining during D3 subsequently substantially reoriented X1 and X2. During early stages of shearing under eclogite facies conditions, associated with the formation of X1, pre-Alpine high-grade mineral assemblages were overprinted synkinematically. D1 folding is interpreted to be contemporaneous with the formation of X1, under high-pressure conditions that prevailed during the early stages of mylonitization. Ongoing shearing is limited to the central parts of the same shear zones and, within the same kinematic regime, led to X2-stretching under greenschist facies conditions (Figs 3, 4a–b).

Two conclusions are drawn from this. Firstly, during shear zone formation the active straining was progressively localized in the central parts of the shear zones and enhanced the kinetics of mineral reactions responsible for the greenschist facies overprint. This interpretation implies that more marginal parts of the shear zones preserved earlier and low-strain conditions (MEANS, 1995). Secondly, shear zone formation was related to decompression, and D1 and D2 merely represent progressive stages during the early deformation history, related to nappe stacking (D1) and isoclinal refolding of parts of this nappe stack (D2) during decompression.

X3 clearly reveals a drastic change in terms of transport direction (top-ENE, N-side up and dextral, respectively) during D3, after substantial exhumation during D2, and still under greenschist facies conditions. Such D3-related shear criteria are mainly found in the Portjengrat unit and Furgg zone, but occasionally also at the top of the Monte Rosa nappe (Fig. 9). It is concluded that this top-ENE shearing is directly related to large scale D3 backfolding, such as the formation of the Antrona synformal backfold in the area of study (STECK and HUNZIKER, 1994). The fact that D3 fold axes are oriented subparallel to X3 in the units north of the Antrona synform is interpreted to indicate a contemporaneous SSE–NNW oriented shortening and WSW–ENE oriented extension, reported to have prevailed during the formation of the Simplon ductile shear zone (STECK and HUNZIKER, 1994) as well as during successive Simplon normal faulting (MANCKTELOW, 1992).

Provided that the correlation of the onset of D3 deformation with the onset of the activity of the Simplon ductile shear zone is correct, this major change in kinematics did already occur at around 35 Ma ago (STECK and HUNZIKER, 1994). This leaves little time for Eocene high-pressure metamorphism (D1) and substantial amounts of exhumation (D2).

THE ORIGIN AND TECTONIC SIGNIFICANCE OF THE FURGG ZONE

The interpretation of the Furgg zone has far reaching consequences. If the Furgg zone represents a continuous ophiolite-bearing mélange zone, including ophiolitic rocks derived from the Zermatt-Saas and Antrona ophiolitic units, these two ophiolitic units are likely to have originally been interconnected. They would now completely envelope the Monte Rosa continental basement unit and completely separate the Monte Rosa nappe from Portjengrat and Siviez-Mischabel. This is the "classical" view (e.g. ESCHER et al., 1997), which lead to paleogeographic restorations of the upper Penninic Alps such as proposed by MILNES et al. (1981) who postulated the existence of an oceanic realm between the Monte Rosa and Portjengrat-Siviez-Mischabel units.

According to a recent hypothesis by FROITZHEIM (2001) the Furgg zone is indeed interpreted as a tectonic mélange incorporating ophiolitic rocks. However, in this case the ophiolitic components are interpreted to be exclusively derived from the Antrona ophiolites, interpreted to have been derived from the Valais ocean. This lead FROITZHEIM (2001) to paleogeographically locate the Monte Rosa continental unit north of the Valais ocean, i.e. within stable Europe. The same author only attributed the units presently found north of his Antrona-Furgg-zone to the Briançon-

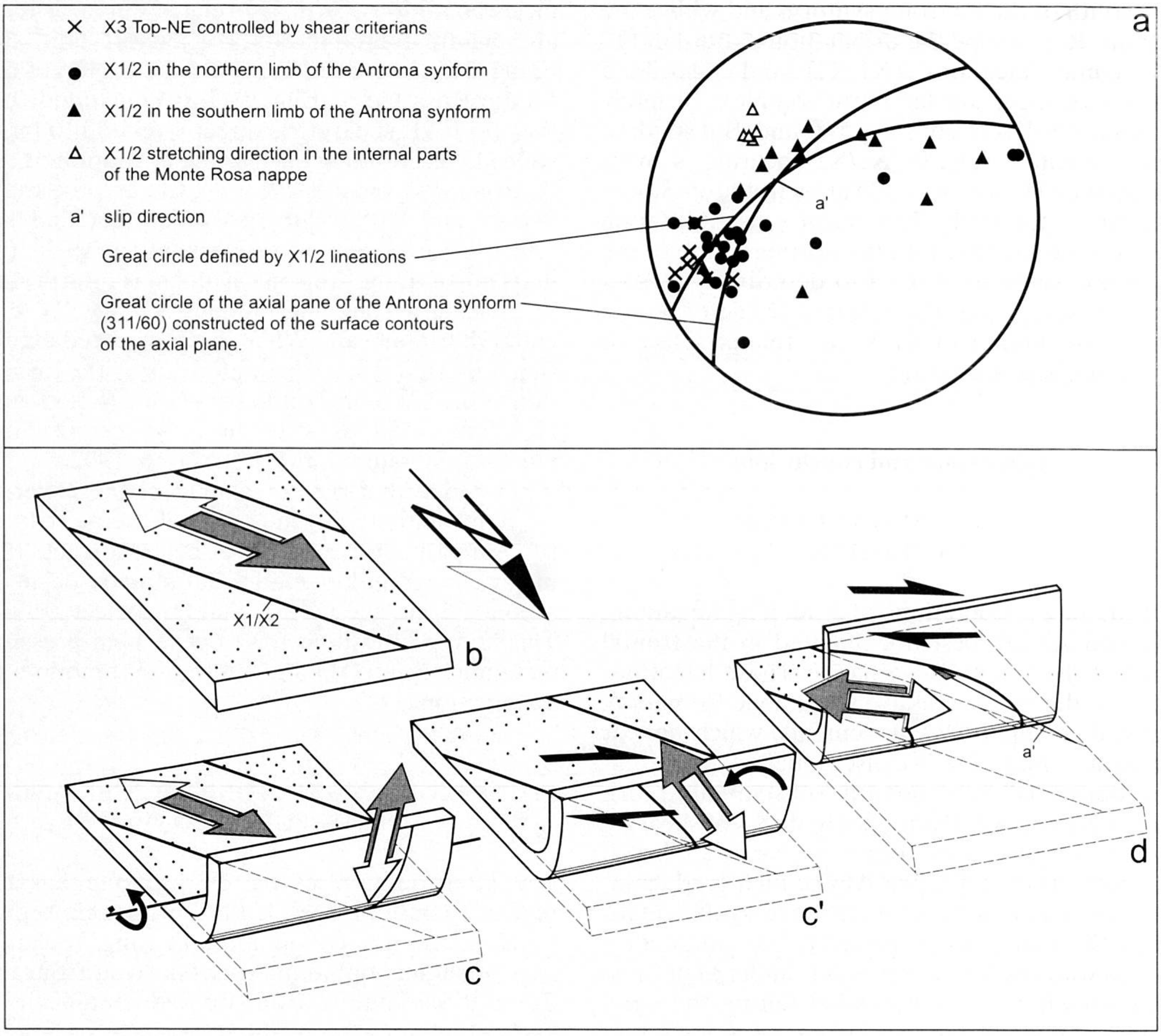

Fig. 12 (a) Pole figure indicating orientation of X1/X2 lineations related to D1/D2 mylonitization from different parts of the Monte Rosa nappe (for transport direction see Fig. 9), as well as orientation of X3 lineations where transport direction (top-ENE) could be determined. X1/X2 lineations exhibit large spread approximating great circle distribition. Point a' denotes intersection point between this great circle distribution and the F3 axial plane. Reorientation of X1/X2 lineations according to the cartoons b–d is discussed in text. (b) Pre-D3 situation and kinematics during D1 and D2. (c) Simultaneous folding and shearing during D3, artificially separated to show their individual effects: folding c, shearing c'. (d) Late stage of D3 folding and shearing. X1/X2 has been dragged into subparallelism with X3 (and F3). Slip direction a' significantly departs from X3.

nais paleogeographic domain. The Monte Rosa nappe would occupy a structurally lower position with respect to the Antrona-Furgg (=Valaisan) zone prior to post-nappe folding.

Many of our data do not support the idea that the Furgg zone represents an ophiolitic mélange, and hence, contradict both hypotheses and interpretations discussed above. The Furgg zone, due to its vicinity to the relatively competent Monte Rosa unit, undoubtedly represents a high-strain zone during all three deformation phases but it exhibits exactly the same deformation history as the surrounding units. The S1 foliation is preferentially preserved in relatively competent amphibolites within the Furgg zone (D2 fold hinges or boudins), documenting that the assemblage of schists and amphibolites, characteristic of the Furgg zone, predates S1. Furthermore, the amphibolitic boudins and lenses, so characteristic of the Furgg zone, do not represent fragments of an ophiolitic suite, as discussed below. However, mapping showed that thin but coherent bands made up of ophiolitic lithologies (serpentinite, amphibolite, and calcite marble), are directly linked to the main body of the Antrona ophiolites and are interleaved with Furgg zone lithologies. Because these Antrona lithologies have been isoclinally folded during D2 they must have been interleaved with the Furgg zone already during D1. Hence, within the area we studied, mappable volumes of continental (Furgg zone) and oceanic series (Antrona ophiolites) appear to have been imbricated during D1.

We conclude that the Furgg zone originally represented a stratigraphic sequence of continental basement and cover rocks, crosscut by mafic sills and dykes, the latter representing the protoliths for the amphibolite boudins of the Furgg zone, as proposed by JABOYEDOFF et al. (1996). During subsequent deformation the sills and dykes were folded and boudinaged. Such sills and dykes are still well preserved within Triassic calcite and dolomite marbles of the Furgg zone near Passo della Preja (Fig. 5 in JABOYEDOFF et al., 1996). Conversely, amphibolitic boudins are not restricted to the Furgg zone but have also been observed within the Portjengrat basement unit. This clearly indicates that the former basic dykes, although post-Triassic in age, must have intruded continental basement-cover series and do not represent parts of an ophiolitic sequence such as the Antrona or Zermatt-Saas ophiolites.

Large parts of the Furgg zone are interpreted to represent the cover of the Portjengrat unit. While the Furgg zone unit is separated from the Monte Rosa nappe either by serpentinites or relics of the cover of the Monte Rosa nappe (see also BEARTH, 1957) there is no evidence that the contact between Furgg zone and orthogneiss of the Portjengrat unit is tectonic. Furthermore, isolated basic dykes also occur within the Portjengrat unit (CARRUPT and SCHLUP, 1998), and we also mapped micaschist-boudin associations, identical to those found in the Furgg zone, within the Portjengrat unit.

A first and predominant lithological association in the Furgg zone consists of mafic boudins, bands and rootless foldhinges, surrounded by a matrix of different types of micaschist. We interpret that at least parts of these micaschists represent Permo–Triassic lithologies, and hence we do not think that this association is Middle Jurassic in age (JABOYEDOFF et al., 1996). A second lithological type, the Mesozoic marbles, are obviously intruded by basic dykes (JABOYEDOFF et al., 1996) and found in the cores of D3 folds (BLUMENTHAL, 1952). We conclude from our mapping that a third type of lithology consists of gneiss (pre-Permian) or calcareous micaschist (Permo–Triassic?). This type contains little or no mafic boudins. As discussed, this third type does not represent the eastern end of the Monte Rosa nappe as proposed by JABOYEDOFF et al. (1996) and STECK et al. (1999). The radiometric data available on the Furgg zone and adjacent areas appear in line with our interpretation of the Furgg zone. The protoliths of orthogneisses (granite or acid volcanic rock) from the Furgg zone are of early Permian age (zircon dating by LIATI et al., 2001). This corresponds well with the Permian age (whole rock Rb–Sr isochron age) given by FREY et al. (1976, their Fig. 2) for the Furgg zone. The pre-Variscan mafic rock found as boudin within the cover of the Monte Rosa nappe, also dated by LIATI et al. (2001), are likely to be part of the pre-Variscan basement of the Monte Rosa nappe. According to the mapping of BEARTH (1954b) and to our mapping this boudin definitely is not part of the Furgg zone. Hence the radiometric data available do not support the interpretation of the Furgg zone as a Mesozoic tectonic mélange incorporating Mesozoic mafic boudins such as proposed by MILNES et al. (1981) and FROITZHEIM (2001).

The western continuation of the Furgg zone near Mattmark was mapped by RÖSSLER (2000), who came to very similar conclusions regarding the nature of the Furgg zone. According to this author and in agreement with the mapping by BEARTH (1954b), the Furgg zone near Mattmark does not contain any ophiolitic slivers derived from the Antrona or Zermatt-Saas ophiolite units at all. However, Zermatt-Saas ophiolites are again found to be interleaved with the Furgg zone near the Stockknubel at the base of the southern slope of Gornergrat (see map of BEARTH, 1953).

In summary, it is proposed that the Furgg zone represents a high strain zone, which consists of both Permo–Triassic cover and continental basement of the Portjengrat unit, intruded by mafic dykes of post-Triassic age. This high strain zone accompanies the contact between Monte Rosa and Portjengrat basement units. During D1 the Furgg zone was imbricated with ophiolitic series derived from the Antrona unit near its eastern, structurally lower termination (our working area) and with ophiolitic series derived from the Zermatt-Saas ophiolites near its western, respectively structurally higher termination (Gornergrat area). Hence, the Furgg zone is not regarded as a continuous ophiolitic mélange zone. It appears that its ophiolite-free middle portion west of the working area (Mattmark) separates two ophiolitic units (Antrona and Zermatt-Saas). In fact, these two ophiolitic units would occupy different structural positions with respect to the Monte Rosa-Portjengrat basement units, as further discussed below.

REORIENTATION OF X1/X2 LINEATIONS BY THE EFFECTS OF D3 STRAINING

The possibility that the X1/X2 top WSW sense of shear, described from the front of the Monte Rosa nappe and within our working area, may have been drastically reoriented by later straining, needs to be seriously considered since nappe stacking is unlikely to have been top-WSW in the Central and Western Alps (e.g. STECK 1990; SCHMID and KISSLING, 2000). In fact, the large spread of X1/X2-lineations approximating a great circle distribution (Fig. 12a) indicates that the effects of this reorientation during D3 were substantial. The questions then arise as to which of these lineations may have been reoriented and what would represent the original orientation of X1/X2. Given the wide distribution of these lineations and the fact that any passive line will rotate towards the principle stretch, it is the X1/X2 lineations presently oriented subparallel to X3 (i.e. the gently WSW-plunging ones), which must have rotated by a maximum angle (i.e. 90°) out of their original orientation during D3. Conversely, the X1/X2 lineations oriented at a right angle to the latter (i.e. roughly N–S) must indicate the original orientation of the X1/X2 lineations. Hence, shearing during nappe stacking must have been top-N, and we suggest that many of the "top NW"-lineations described elsewhere (i.e. STECK, 1990) were also reoriented by later strain increments.

Figure 12a shows that the slip vector "a" constructed for D3 folding (see RAMSAY and HUBER, 1987, Fig. 22.7) does not match the orientation of X3. This indicates that D3 folding is a combined effect of "shear folding" and homogeneous strain. Figures 12b–d visualizes how the X1/X2 lineation progressively rotates into parallelism with X3. It is noteworthy that the senses of shearing related to X1/X2 were preserved during this reorientation. This leads to the interesting fact that opposed senses of shear can still be observed for similarly oriented lineations (i.e. in respect to X1/X2 and X3, respectively) in the northern limb of the Antrona synform of our working area. This scheme presented in figure 12 does not explain many of the X1/X2 shear directions observed south of Ton mountain (Fig. 9). There, an antithetic (i.e. top-S) sense of shear must also be postulated. We attribute this to the fact that this part of the Monte Rosa basement represents a lens of only weakly deformed rocks around or within which conjugate shear zones nucleated.

Interestingly, the early lineations appear to have been most dramatically reoriented in the northern limb of the Antrona synform (Fig. 12a). This indicates that the intensity of D3 straining is much higher north of the Antrona synform. This independently supports the postulate discussed below, namely that it is the northern limb of the Antrona backfold, which exhibits an inverted original nappe stack.

CONSEQUENCES REGARDING PALEOGEOGRAPHICAL RECONSTRUCTIONS

Any paleogeographic reconstruction first needs to undo the effects of the latest major deformation event (D3 in the case of our working area which remained unaffected by D4 folding related to the Vanzone antiform). The famous Mischabel antiformal backfold (MÜLLER, 1983) belongs to the same D3 generation as the Antrona synformal backfold, two more large-scale folds being described in between (KLEIN 1978; Trifthorn Antiform and Mittaghorn synform, respectively; see our Fig. 13). Accepting that the upper limb of the Mischabel backfold exhibits a right-way-up nappe stack, the simplest solution would be to postulate that the northern limb of the Antrona synform exposes an overturned nappe stack (KLEIN, 1978). Unfortunately, this conclusion is only valid provided that D1 and D2 do not produce large-scale inversions of the nappe stack as postulated by MILNES et al. (1981) and FROITZHEIM (2001).

Independent of whether or not such earlier large scale post-nappe folding might occur, we propose that the simple scheme first proposed by KLEIN (1978) and illustrated in figure 13b–d is correct, i.e. that the Monte Rosa unit occupied a structurally higher position with respect to the Antrona ophiolitic unit. This proposition is based on two independent arguments:

(i) After discussing the Furgg zone it was concluded that Antrona and Zermatt-Saas ophiolites originally (i.e. before nappe refolding) occupied different structural positions with respect to the joint Monte-Rosa-Portjengrat continental unit.

(ii) As discussed above, the reorientation of the original orientation of the X1/X2 stretching lineation is most pronounced in the part of the Monte Rosa nappe presently situated north of the Antrona synform. Hence it is this northern rim of the Monte Rosa nappe, which was most significantly reoriented by D3 while the original nappe stack (Monte Rosa over Antrona) was preserved south of the Antrona synform.

We finally conclude that the Antrona ophiolites represent the Valais suture. They are overlain by the Monte Rosa-Portjengrat units, which represent eclogite facies parts of the Briançonnais

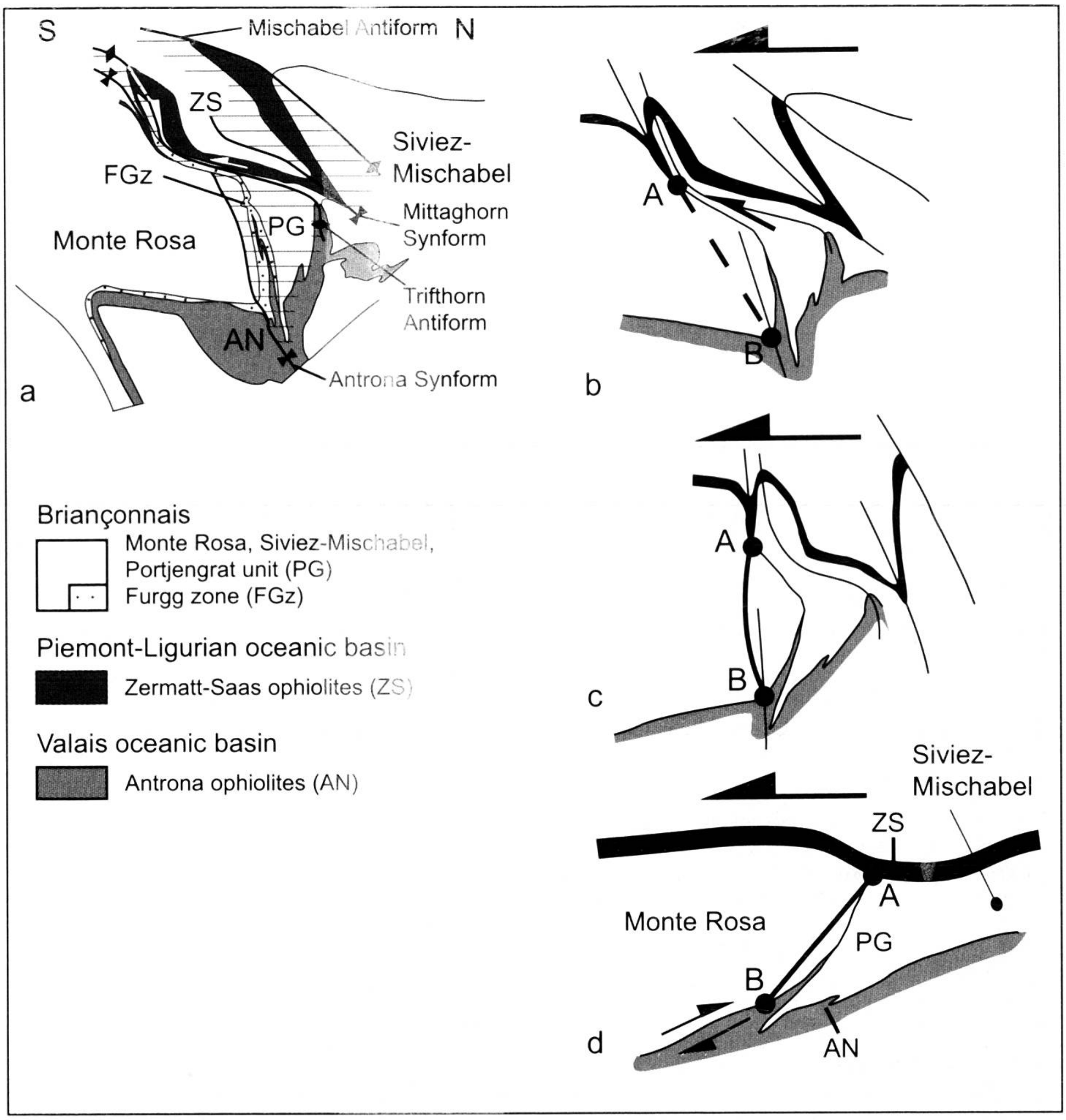

Fig. 13 Proposed retrodeformation of D3, largely after of KLEIN (1978). (a) Simplified present-day N–S profile, horizontal ruling indicates overturned nappe stack. (b–c) Restoration of D3 backfolding phase. This folding is associated with shearing, which is subhorizontal and oblique to the trace of the profile. In map view this shearing is dextral. In profile view it is top-S in the Mattmark area (point A), but top-N in the Val Loranco area (point B) (MÜLLER, 1983; STECK, 1984; LACASSIN, 1987; JABOYEDOFF et al., 1996). Projected onto a N–S oriented profile plane, this implies that the relative position of point B and point A, and hence the orientation of the tie line between these points, must have changed during D3. After fold nucleation (stage c), shear zone formation rather than folding is interpreted to be the dominant deformation process (stage b). Stage (d) shows a qualitative restoration of the original nappe pile according to steps b to d.

microcontinent. Only the structurally highest Zermatt-Saas ophiolites represent the Piemont-Liguria ocean.

Summary

1. The tectonometamorphic evolution in the working area is characterized by Eocene top-N nappe stacking occurring under eclogite facies conditions (D1), immediately followed by fast exhumation to greenschist facies. Exhumation is accompanied by ongoing crustal shortening and D2 top-N shearing according to the same kinematic framework (D2). These structures were then (after 35 Ma ago) affected by backfolding and simultaneous top-ENE (N-side-up in profile and dextral in map view) shearing under greenschist facies conditions (D3).

2. The early top-N lineations formed during D1 and D2 were drastically reoriented due to D3 straining and presently appear as apparent top-WSW lineations in the working area.

3. The Furgg zone does not represent an ophiolitic suture or mélange zone. Instead it is regarded as a high strain zone derived from basement and cover lithologies of the Portjengrat unit, intruded by post-Triassic mafic dykes.

4. The original nappe stack, formed under eclogite facies conditions, consisted of Antrona ophiolites (Valais ocean), overlain by the Monte Rosa-Furgg zone-Portjengrat continental fragment (eclogite facies part of the Briançonnais), and finally the Zermatt-Saas ophiolites (Piemont-Liguria ocean).

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Careful mapping of Peter Bearth provided the firm base for our re-investigations of the geology in Val Loranco. We gratefully acknowledge the contributions of all the other members of the Basel "Monte Rosa group" (Ronan Le Bayon, Kathy Dubach, Martin Frey, Nikolaus Froitzheim, Julia Kramer and Christiane Rössler), which were instrumental for our own thinking. Furthermore we had support from Holger Stünitz, Christian de Capitani, Thorsten Nagel, Michael Stipp, Andrea Loprieno, Stefano Ceriani and Stefan Bucher. The manuscript benefitted from a thorough review by Marco Herwegh, critical comments by Nikolaus Froitzheim and advice by Martin Engi. The second author also acknowledges support from NF-project Nr 20-61814.00. This project was headed by the late Martin Frey. We are grateful for his initiative and continuing support during this study.

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