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Tertiary deformation and kinematics of the southern part of the Tambo and Suretta nappes (Val Bregaglia, Eastern Swiss Alps)

by *Rahel K. Huber*[1] and *Didier Marquer*[1]

Abstract

The southern part of the Tambo and Suretta nappes (Eastern Swiss Alps) records several structural phases during Tertiary orogenesis. Based on micro- and mesostructural methods and kinematic indicator analysis, a tectonic model with four deformation phases is proposed: (i) A top to the NNW shearing (D1) correlated to the nappe stacking event. (ii) The strongest deformation of the area forming the main schistosity (D2), with vertical shortening and E–W extension showing a top to the E shear sense. This phase may be responsible for the bulk reduction of thickness in the SE part of the nappe pile. (iii) Localized deformation creating open N-verging folds and N-thrusting steep shear zones during differential uplift of the Penninic domain. This D3 deformation causes reorientation and steepening of nappe contacts and main S2 schistosity in the southern part of the Suretta and Tambo nappes. (iv) Normal faulting (D4) to the NE corresponding to a late tectonic event under brittle conditions.

Keywords: deformation, tectonic evolution, extension, shear sense, Penninic domain, Central Alps, Switzerland.

Introduction

The aim of this work is to establish the tectonic evolution of the southern part of the Tambo and Suretta nappes (Eastern Swiss Alps) during Tertiary collision between European continent and Apulian microplate. The knowledge gained from this area may lead to a better understanding of the geometry of collision belts and of the kinematics and deformation during ongoing continental collision. We focus on the geometrical description of the different deformation phases and the structural correlation between the Penninic and Austroalpine units in the Eastern Swiss Alps. Particularly interesting is the link of the deformations and kinematics in the studied area to the tectonic evolution established further north for the Tambo and Suretta nappes (MARQUER et al., 1994, 1996), to the Turba Mylonite Zone (LINIGER, 1992; NIEVERGELT et al., 1996), as well as to the ductile deformation associated with the Tertiary Bergell intrusion (ROSENBERG et al., 1994, 1995; DAVIDSON et al., 1996). Structural cross cutting relationships of the Bergell intrusion with the country rocks allow to deduce the relative timing of the deformation phases. Special attention is given to the following points: the geometry and kinematics of the syn-collision deformation phases; the reduction of thickness of the nappe pile towards the SE; the reorientation of both tectonic contacts and main schistosity from N–S to E–W; and the steepening of the main tectonic contacts.

To distinguish between Alpine and pre-Alpine structures, the Alpine structural phases were defined in the Permian intrusive complex (Truzzo granite, Tambo nappe) and in the autochthonous and allochthonous Mesozoic sedimentary cover of the Tambo and Suretta nappes (BAUDIN et al., 1995). The internal consistency of the deformation phases, the kinematics within the nappes and the intensity of deformation was studied at all scales. The geometry of the nappes is shown in cross-sections which were constructed from structural maps. A deformation history has been established taking into account the superposition of all observable structures and their deformation type (brittle/ductile). For all schistosities and lineations, trajectory maps are presented to illustrate

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the superposition of deformation phases. The trajectories were drawn by extrapolation of the strike of each schistosity measurement. The kinematics of each deformation phase were investigated, using mainly the shear sense from shear bands (C/S relationships, discrete shear zone [C] and penetrative schistosity [S]: BERTHÉ et al., 1979; Extensional Crenulation Cleavage [ECC]: PLATT and VISSERS, 1980).

In the last part of this paper, a tectonic model is proposed to integrate the structural data, at the scale of the Tambo and Suretta nappes, with continental collision processes related to mountain building, such as syn-collision extension, vertical extrusion and uplift.

Geological setting

The field area in the Val Bregaglia extends E–W from Chiavenna in Italy to Löbbia in Switzerland, and includes the two slopes of the Val Bregaglia with a range in altitude from 300 to 3000 m. Its coordinates define a rectangle between [769–748] and [132–140] (Swiss federal topographic coordinategrid) (Fig. 1).

The Tambo and Suretta nappes belong to the upper Penninic nappes in the eastern Swiss Alps (Figs 1 and 2) (TRÜMPY, 1980). Their basement rocks, as well as their autochthonous and allochthonous sedimentary covers (Starlera and Schams nappes), showing a typical stratigraphy of internal Briançonnais sediments, belong to the Briançonnais domain (STAUB, 1924; BAUDIN et al., 1995). The Starlera nappe, recently defined by BAUDIN et al. (1995), is a sedimentary nappe, emplaced by thin skin tectonics on the top of the Tambo and Suretta Mesozoic cover prior to thrust tectonics affecting the Tambo and Suretta basement. At the top of the Suretta nappe (Fig. 2), the Starlera nappe is tectonically overlain by the Schams nappes (SCHREURS, 1993), the Avers schistes lustrés, the Arblatsch flysch, the Mesozoic Platta ophiolites, and covered by the orogenic lid of the Austro- and South-Alpine units (TRÜMPY, 1969; MILNES and SCHMUTZ, 1978; LINIGER and GUNTLI, 1988; GUNTLI and LINIGER, 1989). The Chiavenna ophiolites (DAL VESCO, 1953;

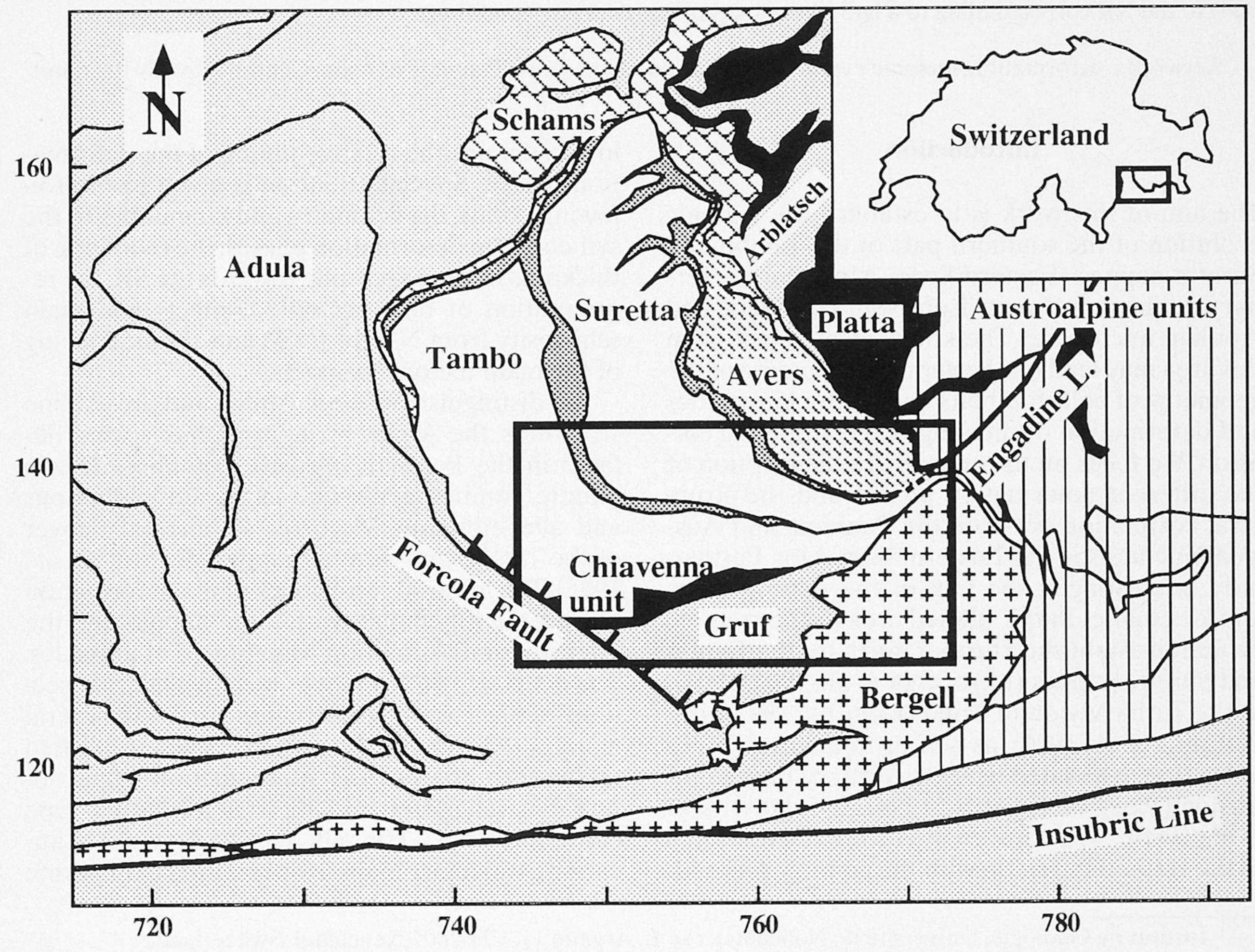


Fig. 1 Location of the study area on a sketch map of the eastern Alps. Numbers refer to the Swiss coordinate grid.

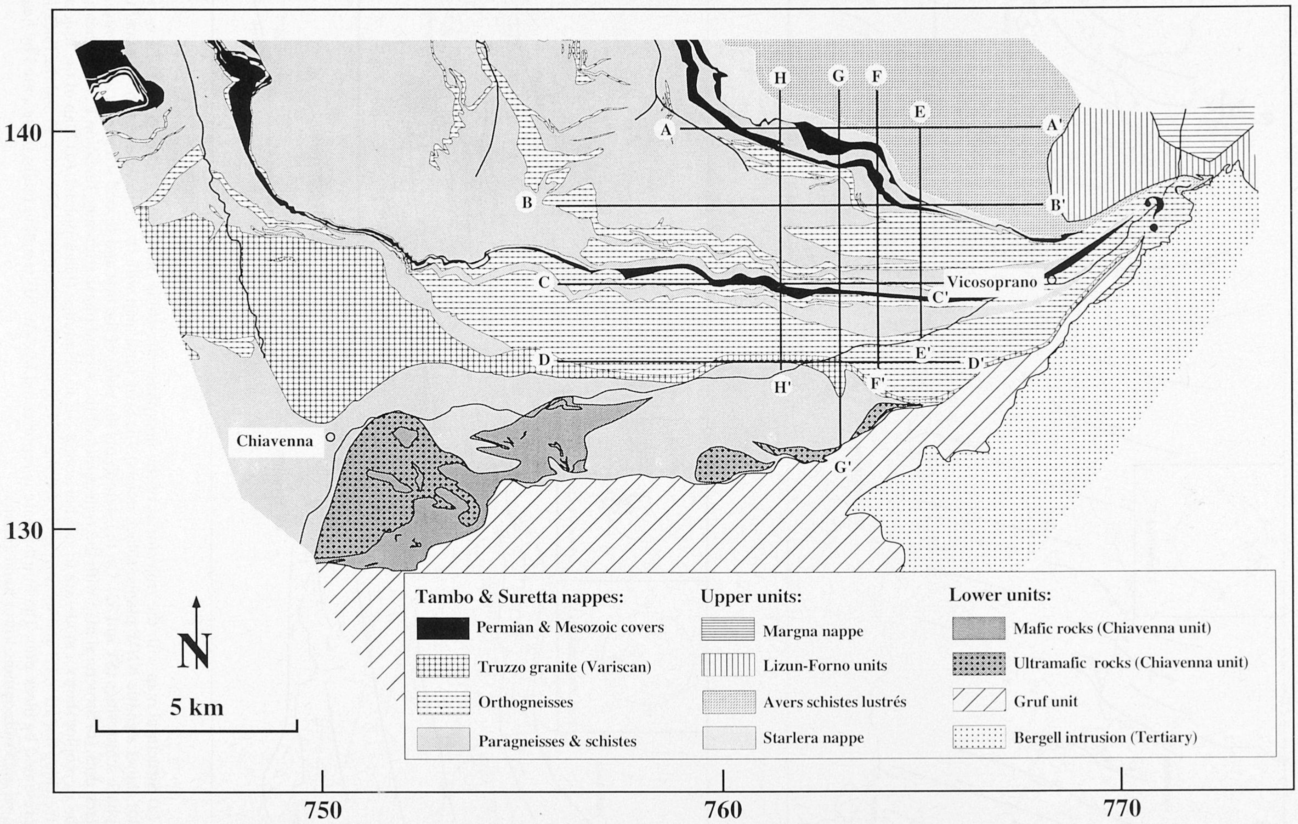


Fig. 2 Tectonic map of the southern part of the Tambo and Suretta nappes and their relationships with the under- and overlying units. Location of the cross-sections (Fig. 4). Numbers refer to the Swiss coordinate grid.

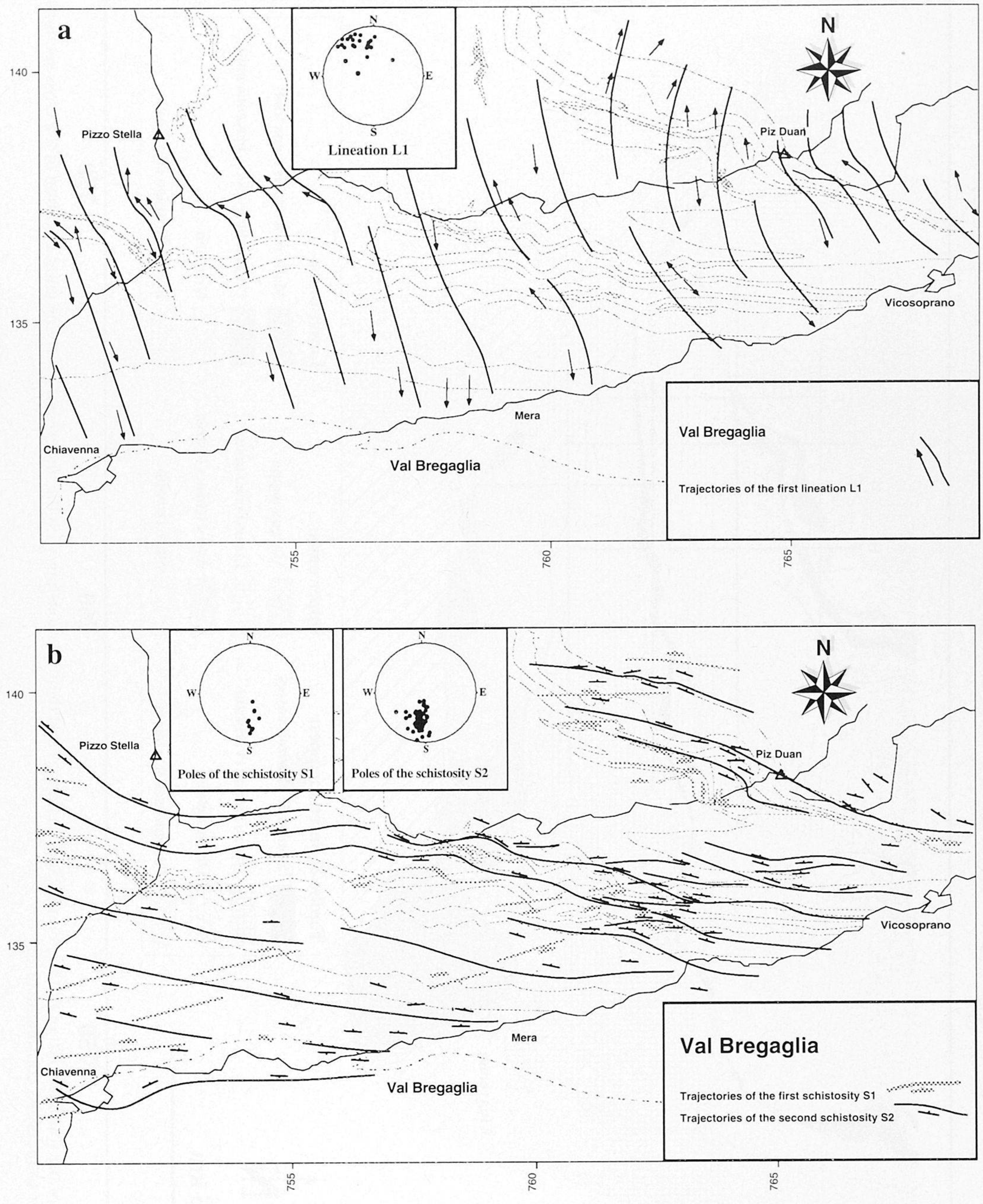
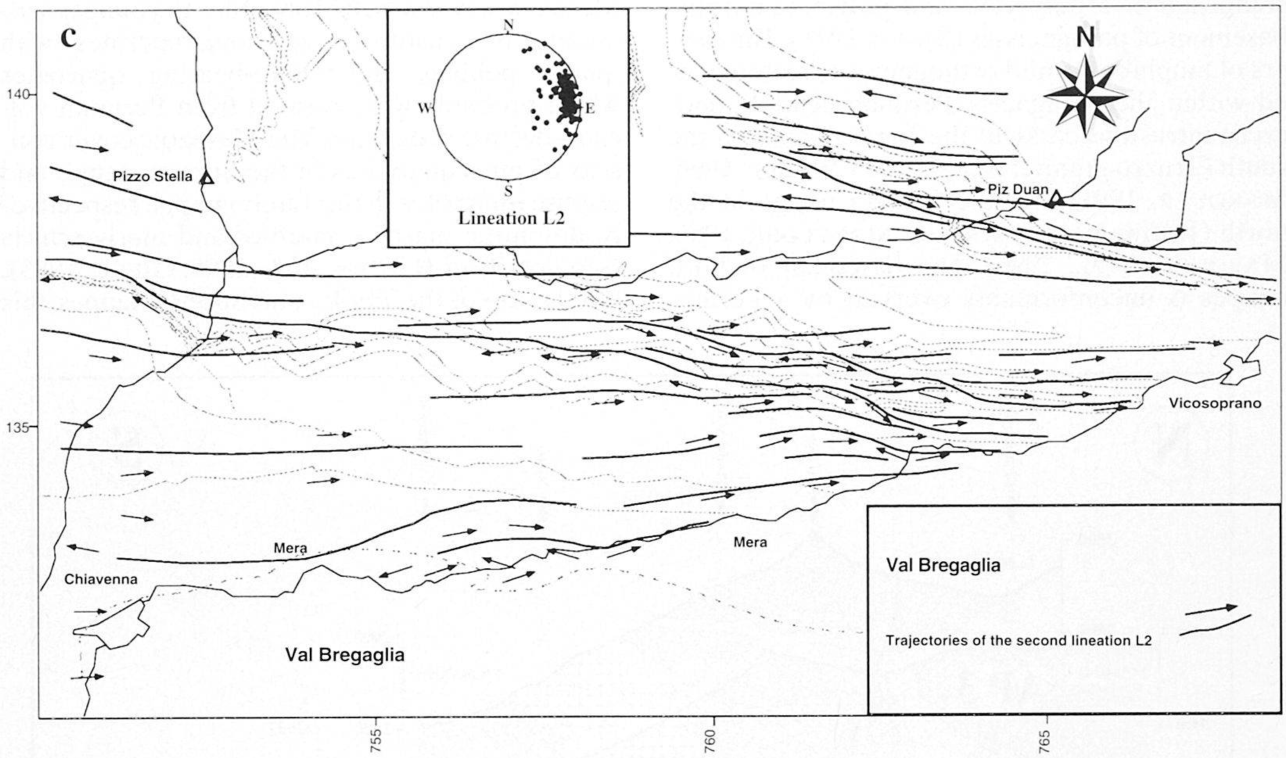
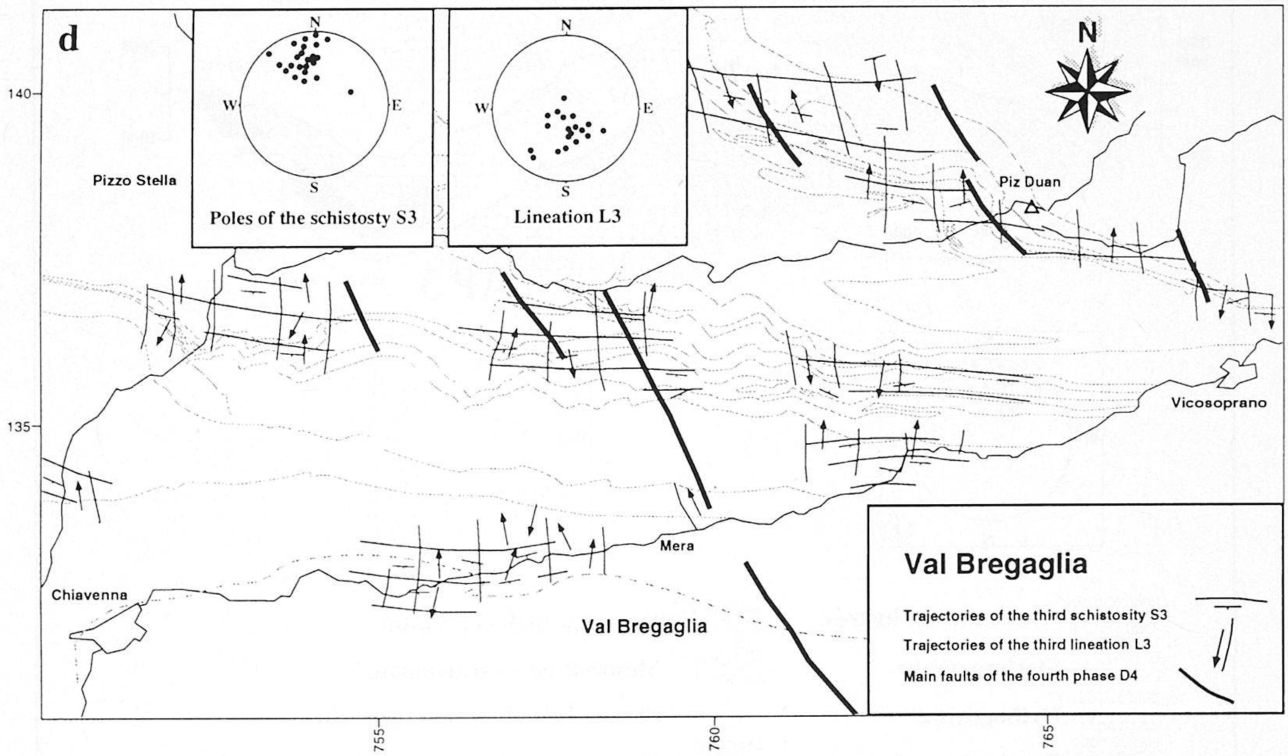


Fig. 3 (a) Structural map with the trajectories of the first phase stretching lineation L1. The lineation L1 on the stereoplot shows a gentle NNW plunge (black points). (b) Structural map with the trajectories of the first and the second phase schistosities (S1 and S2). On the stereoplots the poles of the first and second schistosity are represented by black dots. (c) Structural map with the trajectories of the second phase stretching lineation L2. The lineation L2 on the stereoplot shows a moderate to sub-horizontal NE to SE plunge (black points). (d) Map of the trajectories of stretching lineation L3 and schistosity S3. On the stereoplots the poles of the schistosity S3 and the lineation L3 are presented by black dots. The fourth phase is represented by NW–SE trending faults, represented by heavy lines (equal area stereograms, lower hemisphere).





SCHMUTZ, 1976), addressed as the Chiavenna unit in this paper on the basis of the lack of a typical ophiolitic sequence, are located between the Tambo nappe and the Gruf unit (Fig. 2). The Gruf unit has been correlated with the Adula nappe (BLANC, 1965; PFIFFNER et al., 1990a, 1990b). In the south, the Gruf unit is crosscut by the Tertiary Bergell intrusion (WENK, 1970, 1973; MOTICSKA, 1970; GULSON, 1973; WAGNER, 1979; TROMMSDORFF and NIEVERGELT, 1983; ROSENBERG et al., 1994, 1995; DAVIDSON et al., 1996).

The Tambo and Suretta nappes are mainly

composed of a polycyclic and polymetamorphic basement of paragneisses (STAUB, 1921). Thin layers of amphibolite and orthogneiss are intercalated within the paragneiss. Permian acidic monocyclic intrusions crosscut the Tambo nappe in the south (Truzzo granite: BLANC, 1965; WEBER, 1966; MARQUER, 1991) and the Suretta nappe in the north (Roffna porphyries: GRÜNENFELDER, 1956; MARQUER et al., 1996). The basement of both nappes is unconformably overlain by a Permo-Mesozoic cover which, from older to younger sediments, is constituted of: conglomerates with quartz pebbles and albite-bearing quartzites which probably were formed from Permian volcano-detritic sediments. The Mesozoic cover consists of pure quartzites in the Suretta nappe and impure quartzites in the Tambo nappe respectively, dolomitic marbles, marbles and marly schists (see details in BAUDIN et al., 1995; GIERÉ, 1985). On the top of the Tambo and Suretta nappes, this

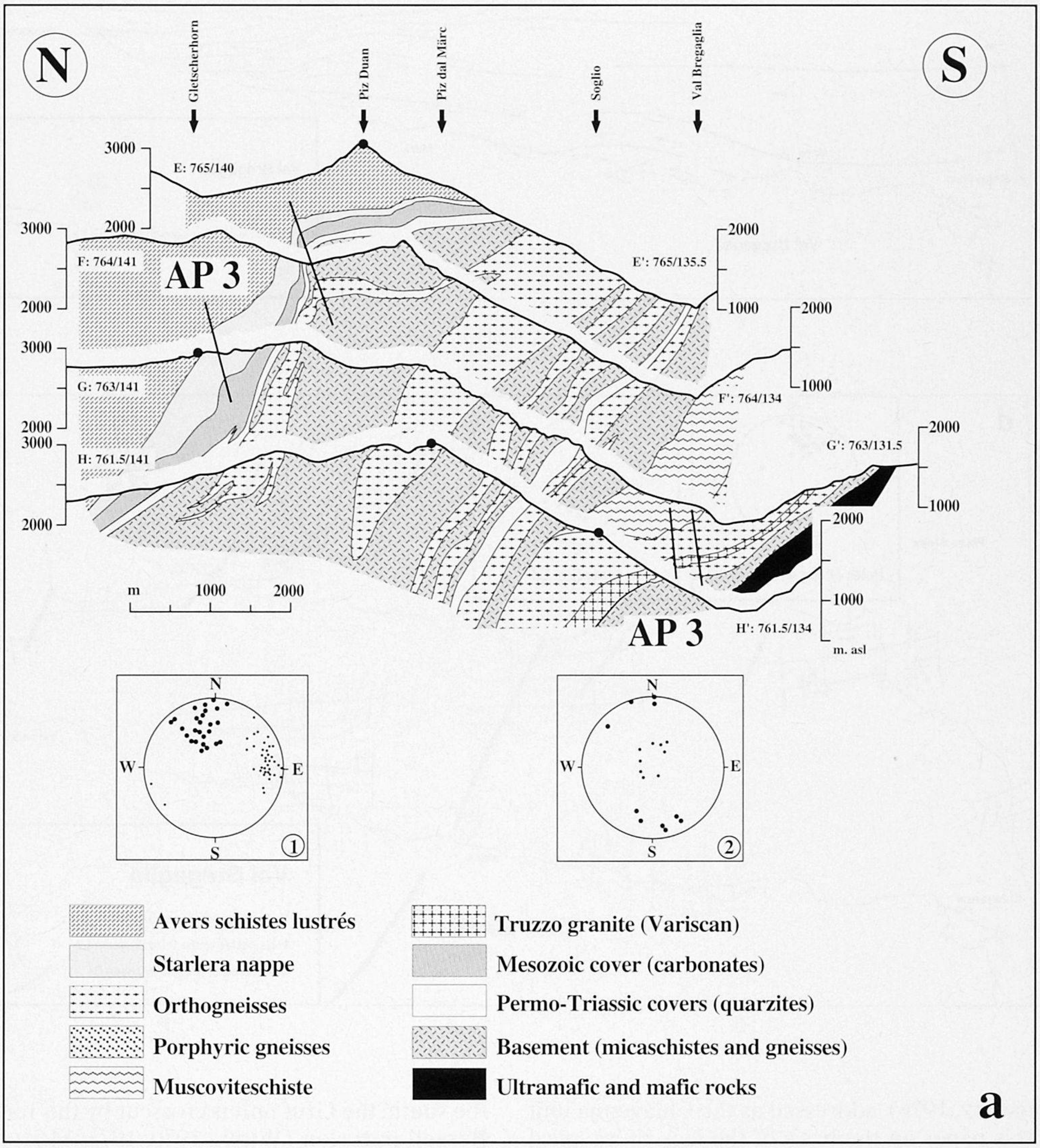


Fig. 4 (a) The N–S profiles (see location on Fig. 2) show the steepening of the root zone due to the D3 folding (black lines = axial plane traces: AP3). Stereogram 1: poles of the fold axial plane of the third phase are indicated as large dots and the fold axes as small dots. Stereogram (2): poles of the brittle-ductile D3 shear zones (large dots) and the adjacent stretching lineation (small dots) (equal area stereograms, lower hemisphere).

reduced autochthonous cover is overlain by a more complete allochthonous cover, the Starlera nappe (Fig. 2), consisting of Mesozoic banded marbles and dolomites, dark stink marbles, white marbles, thick polygenic breccias, and dark calc-schists (BAUDIN et al., 1995).

The Alpine metamorphic grade increases from the top of the Suretta nappe to the bottom of the Tambo nappe and from the North to the South of the nappes from greenschist facies to amphibolite facies (see review in BAUDIN and MARQUER, 1993). High temperature pre-Alpine mineral relics are preserved in basement domains poorly affected by Alpine deformation. From the root zone of the two nappes to the adjacent units in the south (Gruf and Chiavenna units) a metamorphic gradient unusually high for regional metamorphism exists (BUCHER-NURMINEN and DROOP, 1983; DROOP and BUCHER-NURMINEN, 1984).

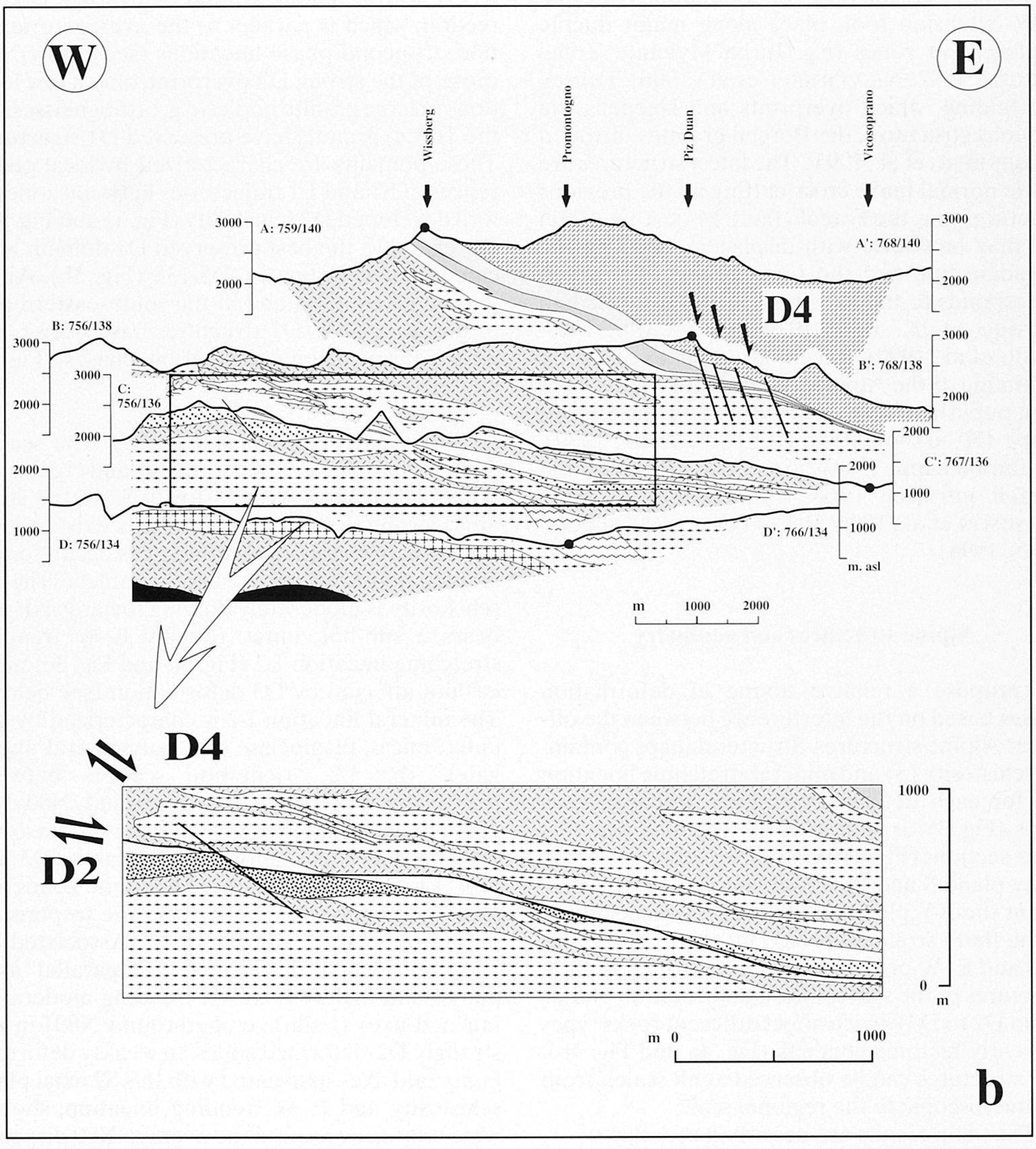


Fig. 4 (b) The E–W cross-sections (see location on Fig. 2) show the offset of the tectonic and lithologic contacts due to the D2 mylonites and D4 faults. The area in the rectangle of the upper cross-section is enlarged to emphasize the D2/D4 geometric relationships on the lower cross-section where heavy lines represent D2 mylonite zones and D4 normal faults.

The Alpine nappe pile was created in a subduction zone environment during the closure of the Piemontais and Valaisan oceans. The Austroalpine nappes were thrusted toward the west during the upper Cretaceous, whereas the Penninic units were emplaced by thrusting toward the northwest in the early Tertiary (see review in FROITZHEIM et al., 1994). The upper Penninic units are considered to be an orogenic wedge consisting of underplated basement and sedimentary slices during the Valaisan subduction (see MARQUER et al., 1994). After the onset of continental collision, E–W extension took place along major ductile displacement zones (e.g. Turba Mylonite Zone: LINIGER, 1992; NIEVERGELT et al., 1996). During late folding, which overprints and steepens the previous structures, the Bergell granites intruded (ROSENBERG et al., 1995). The latest structures are brittle normal faults cross-cutting all the previous structures (e.g. the Forcola fault: MARQUER, 1991) and may be coeval with displacement along the Engadine line and the Iorio-Tonale line, which corresponds to the late stage of the Insubric line (SCHMID et al., 1987, 1989; HEITZMANN, 1987; ZINGG et al., 1990). Recent attempts to constrain the timing of the Alpine deformation events have been published by several authors for the Suretta nappe (HURFORD, 1986; HURFORD et al., 1989), the Tambo nappe (MARQUER et al., 1994) and the Bergell intrusion (VON BLANCKENBURG, 1992; DAVIDSON et al., 1996; OBERLI et al., 1996; HANSMANN, 1996).

Alpine structures and geometry

We propose a relative timing of deformation phases based on the interference between the different Alpine structures. Structural maps containing schistosity (S) and mineral stretching lineation (L) for each deformation phase and trajectory maps (Fig. 3), as well as E–W and N–S trending cross-sections (Fig. 4) were constructed. The schistosity plane S and the stretching lineation L represent the XY plane and the X axis, respectively, of the finite strain ellipsoid (RAMSAY, 1967). The N–S and E–W profiles depict the geometry of the structures of the syn-collision deformation phases (from D2 to D4) which affect different rocks types and early tectonic contacts (Fig. 4a and Fig. 4b). The structures can be observed at all scales, from the microscopic to the regional scale.

The main results are described as follows:

First deformation phase (D1): The first lineation (L1) plunges to NNW and the schistosity (S1) dips gently to the NNW (Fig. 3a and Fig. 3b). The lineation is defined by mineral and aggregate preferred orientations and long axes of quartz pebbles in Permo-Triassic conglomerates. This ductile deformation phase shows heterogeneous deformation at all scales. In the basement rocks, this behaviour leads to deformation gradients and shear zones surrounding weakly deformed domains where pre-Alpine structures and mineral relics are preserved (MARQUER, 1991). In the Mesozoic cover, isoclinal folds have an axial planar schistosity parallel to S1. The fold axes related to D1 scatter mainly around an average N80 direction, which is parallel to the average orientation of second phase lineations (see below). Because of the strong D2 overprint, only a few locations in large granite bodies, e.g. orthogneisses and the Truzzo granite, have preserved D1 structures. These domains are characterized by local occurrences of S1 and L1 trajectories between zones of well developed D2 schistosity (Fig. 3a and Fig. 3b). For example, the best preserved D1 domain is located near coordinates 755/135 (Fig. 3b). Along the nappe contacts and in the south-eastern part of the study area, D1 structures have been reoriented during later deformation phases (Fig. 3a and Fig. 3b).

Second deformation phase (D2): The second ductile phase D2 is heterogeneous and creates the dominant penetrative schistosity S2 in the study area. Strong deformation gradients exist at locations where rheological differences occur, for example along cover-basement contacts. The S2 schistosity is moderately dipping towards NE and bears a sub-horizontal, roughly E–W trending stretching lineation L2 (Fig. 3b and Fig. 3c) in areas not affected by D3 deformation (see below). The mineral lineation L2 is characterized by oriented micas, plagioclase and polymineral aggregates. The L2 orientation scatters between N20–N130 with a clustering around N80–N90 (Fig. 3c). This scattering is due, in part, to the overprint by the latest deformation phases (D3 and D4). The development of D2 mylonite zones and local heterogeneities in the rocks are responsible only for a slight scattering of L2. Associated SE vergent isoclinal folds have S2 parallel axial planes and mainly E to NE trending moderately inclined axes (bulk average around N80) in the strongly D2-deformed zones. In weakly deformed areas, fold axes, associated with this S2 axial plane schistosity and E–W trending lineation, show a wide scattering around the average N80 direction with values ranging from N0 to N100. This scattering of the F2 fold axes can be explained by folding of inhomogeneously oriented, early foliations (D1 or pre-Alpine) and reorientation of fold axes during progressive D2 deformation, which tends to bring them into a parallel orientation with the E–W stretching lineation. BAUDIN et al. (1993) described the same phenomena in the middle and northern part of the Tambo nappe.

Third deformation phase (D3): The third lineation L3 is moderately (45–50°) to steeply (80–90°) south-plunging (Fig. 3d) and is mostly observed on oriented chlorites and quartz pressure shadows around feldspars. The S3 schistosity also dips moderately to steeply south (45–85°) and is axial planar with non cylindrical, stair-case-like, north-verging folds with E-NE trending, moderately inclined axes (Fig. 4a, stereogram 1). On the basis of field geometry, the S3 schistosity and the stair-case-like folds are considered to be coeval with a set of steeply, south dipping, but north directed, brittle-ductile shear zones localized in basement rocks. This dominant set of shear zones is conjugated with a north dipping, south thrusting, minor set (Fig. 4a, stereogram 2). These brittle-ductile structures only appear in restricted E–W trending belts where older schistosities become folded and steep (Fig. 3d). In the N–S trending cross-sections, these belts appear periodically with a wave-length of about 5 km (Fig. 3d and Fig. 4a, AP3). The steep fold limbs and the local thrusts are responsible for the steepening of pre-existing structures such as nappe contacts (Fig. 4a).

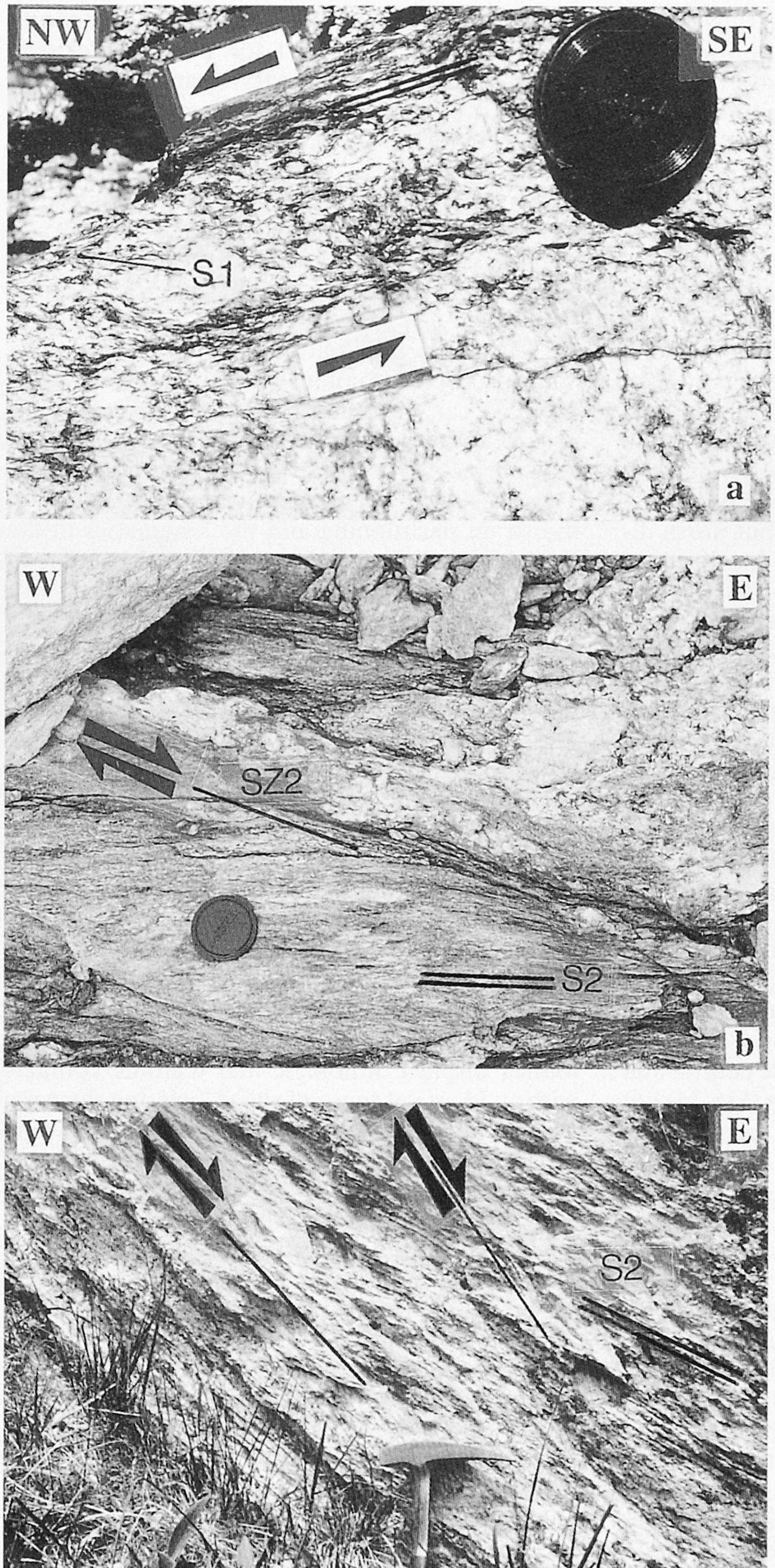
Fourth deformation phase (D4): These late structures are brittle and correspond to localized normal faults with a NW–SE orientation (Fig. 3d). The northeastern side is down thrown (Fig. 4b). These faults are well developed in the central and north-eastern part of the studied area (Fig. 3d) but cause only minor reorientation of pre-existing structures.

Kinematics

For each deformation phase, the kinematics have been investigated using shear sense indicators such as schistosity-shear plane relationships (C/S: BERTHÉ et al., 1979), extensional crenulation cleavage (ECC: PLATT and VISSERS, 1980) and asymmetric microstructures related to non-coaxial deformation of mineral aggregates (see review in HANMER and PASSCHIER, 1991). Special attention was given to the analysis of shear zone patterns. For every deformation phase defined by its schistosity and lineation, the distribution, geometry and asymmetry of the shear zone pattern gives information about the bulk sense of shear (GAPAIS et al., 1987). The shear zone patterns in metagranites were analyzed and compared with the kinematics described for the late Variscan Truzzo granite in the western part of the study area (MARQUER, 1991). The characterization of the kinematics of the different deformation phases was carried out in the basement as well as in the cover. Observation of asymmetric schistosities and lineation trajectories in map view (Fig. 3 b and c), in cross-section (Fig. 4b), at the outcrop (Fig. 5), and in thinsection are coherent for each deformation stage.

D1 shear sense indicators are scarce, however, a few preserved domains (Fig. 3b, e.g. coordinate: 755/135) can be found in the metagranites (e.g. Truzzo granite). Non-coaxial ductile shear bands indicate mainly a top to NW thrusting (Fig. 5a). These results are consistent with recent studies of the strain partitioning and the kinematics in the Roffna intrusive complex in the northern part of the Suretta nappe (MARQUER et al., 1996).

D2 deformation is dominant in the study area and leads to greenschist facies mylonites in the strongly deformed part of the nappes. In the basement, these mylonite zones are grey and fine-grained with a strong schistosity. This penetrative schistosity is mainly defined by quartz, phengites, chlorite and albite. Mylonite zones and non-coaxial shear bands associated with the D2 E–W extension, indicate a top to the E sense of shear as shown, for example, by the angular relationship between the schistosity and the shear zones (Fig. 5b). The non-coaxiality can be demonstrated by the dominance of mylonitic shear zones with top to the E movement. Conjugate shear bands with a top to the W shear sense are less frequent. The mylonites displace lithologic and tectonic contacts with an identical sense of shear lowering the eastern domains (e.g. Permo-Triassic cover and porphyric gneisses on Fig. 4b). These mylonites are highly strained zones preferentially which are located close to the contacts between Mesozoic sediments and the underlying basement of the nappes. The heterogeneous mylonite zones with top to the E movement cause the undulation of the trajectories of S2 and L2, leading to large-scale asymmetric structures (Fig. 3 b and c), and induce a reduction of the thickness of the nappe pile towards the SE. This decrease of thickness is particularly well observed in W–E cross-sections: the Suretta nappe, for example, exhibits a thickness of more than 3 km in the western part and less than 2 km in the eastern part (Fig. 4b). In map view, the initial top to the E shearing yields an apparent dextral strike slip component of the shear zones, indicated by the undulating D2 trajectories (Fig. 3 b and c) and the offset of the Tambo sedimentary cover (Fig. 4b). This apparent sense of



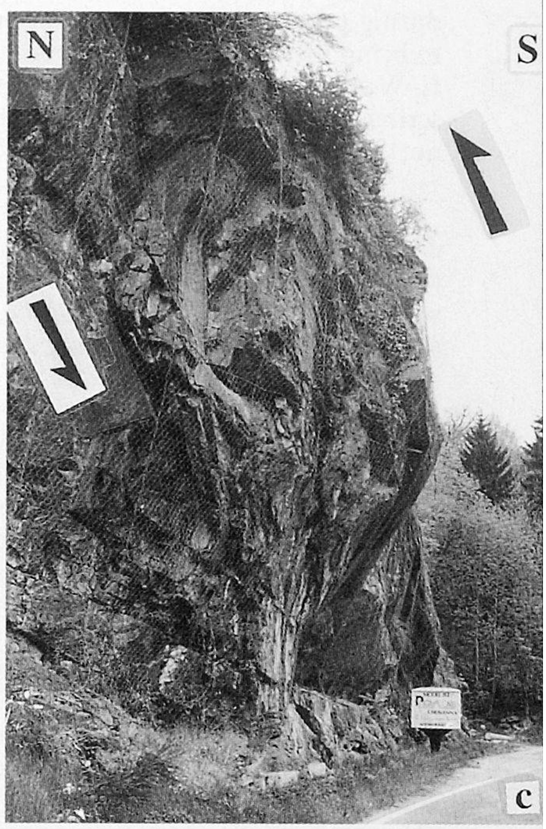


Fig. 5 (a) D1 shear zones in the Truzzo granite with a top to the NW movement (Baccino di Truzzo: 744.000/136.500); (b) D2 shear zones in paragneisses with a top to the E movement as it can be shown by the relationship between the schistosity and the shear zones (Lan Pensa da Rutic: 768.500/136.700); (c) D3 thrust in the Chiavenna unit near the contact to the Tambo nappe (S. Croce: coordinates 756.000/132.600); (d) D4 normal fault in the Avers schistes lustrés near the contact with the Suretta nappe (Nambrun: coordinates 768.700/137.400). S: schistosity; SZ: shear zone or brittle-ductile fault.

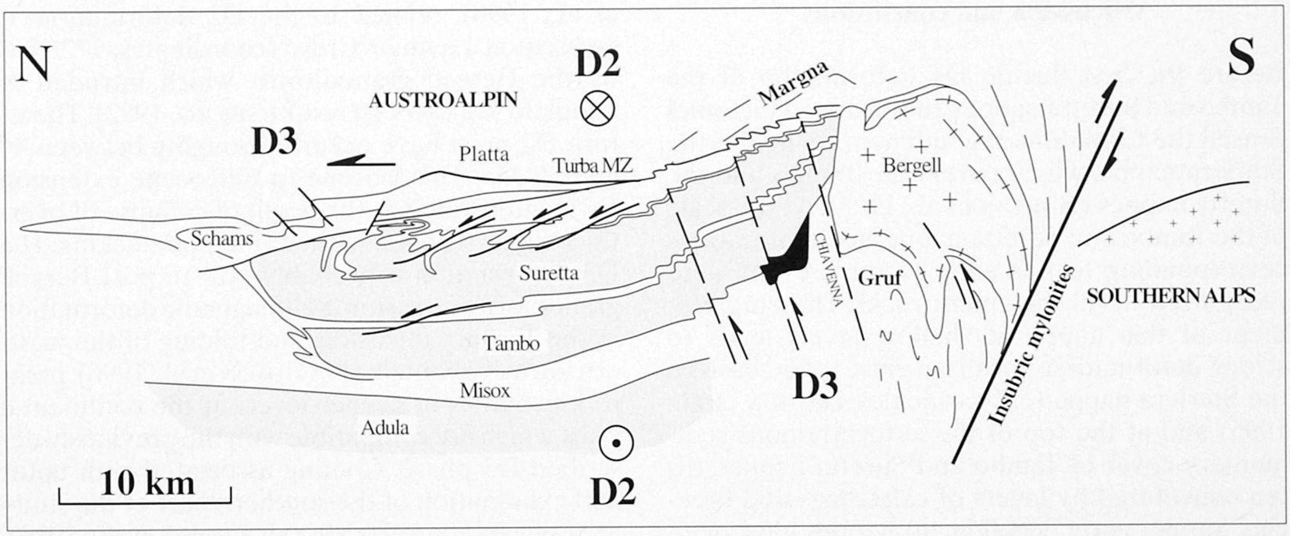


Fig. 6 Schematic N–S cross-section showing the type, geometry, and kinematics of the D3 structures at a regional scale: The differential uplift with its highest elevation is created above the Gruf unit. During D3 deformation, low angle normal faults develop as collapse structures in the northern part at the top of the Tambo and Suretta nappes (extensional structures: from NUSSBAUM [1995] at the top of the Suretta nappe; BAUDIN et al. [1993] at the top of the Tambo nappe). D2 deformation: Turba MZ corresponds to the Turba Mylonite Zone after NIEVERGELT et al. (1996). The position of the Bergell intrusion corresponds to the syn-D3 deformation (modified after SCHMID et al., 1990).

shear is due to a rotation of about 60° around a sub horizontal E–W trending axis and corresponds to the steepening of the previously flat-laying D2 structures during D3 deformation (Fig. 4a). The kinematics deduced in this region is compatible with observations made in the north of the Tambo and Suretta nappes (BAUDIN et al., 1993; MARQUER et al., 1996) and in the overlying units (LINIGER, 1992; NIEVERGELT et al., 1996).

In areas of strong D3 deformation in the basement rocks, south dipping narrow shear zones formed near the brittle-ductile transition are dominant. On these steep shear zones a down-dip lineation is present due to oriented chlorites (Fig. 4a, stereogram 2). The C/S geometrical relationships observed in these shear zones indicate a top to the N movement (Fig. 5c). These localised thrusts are associated with a minor set of steeply north-dipping thrusts. The S3 schistosity and the major fault set (south dipping thrusts) enclose a narrow angle (25–30°), whereas a wide angle (45°) is found between the S3 schistosity and the minor fault set (north-dipping thrusts) (compare Fig. 3d and Fig. 4a, stereogram 2). These geometrical relationships associated with the dominance of south-dipping thrust planes are interpreted as a non-coaxial deformation with a component of simple shear towards the north. These thrusts become more abundant in the southern part of the studied area. In the middle and the northern part of the Suretta nappe (e.g. Lago di Lei), the D3 deformation at the top of the basement, based on relative chronology between D2 folds and D4 faulting (NUSSBAUM, 1995), leads to the appearance of extensional structures corresponding to E–W trending and north dipping low angle normal faults which down throw the hangingwall towards the north (Fig. 6). In summary, the D3 deformation is progressive and partitioned across the strike of the mountain belt, so that the geometry and the kinematics of the D3 deformation in the southern domain indicate a bulk vertical stretching with asymmetric conjugate thrust faults and E–W trending folds, while the D3 deformation in the northern part of the nappe pile is marked by top down to the north extension and E–W north vergent trending folds (BAUDIN et al., 1993; MAYERAT, 1994). (These different types of structures will be interpreted in a tectonic model in the last part of this paper.)

The D4 deformation is marked by brittle NW–SE trending, north-east dipping high angle normal faults with down-dip striae on their fault planes. On the basis of shear criteria, such as asymmetric deformation of older cleavages and crystallization on the lee side of asperities (PETIT, 1987), these brittle faults show a lowering of the NE part of the units (Fig. 4b and Fig. 5d). Being the latest structure they crosscut all the previous ones. For example at Nambrun (coordinates: 768.700/137.400) (Fig. 5d), the Turba mylonite has been reoriented along the D4 fault planes, which are steeper than the mylonite.

Discussion and conclusions

Before the first ductile D1 deformation of the Tambo and Suretta nappes, thin-skinned tectonics caused the formation of a sedimentary nappe, the Starlera nappe, which covers the Tambo and the Suretta nappes (BAUDIN et al., 1995). At the scale of the Tambo and Suretta nappe, no deformations corresponding to this early tectonic event were recognized in the basement rocks. The emplacement of this nappe at shallow levels leads to strong deformations localized close to the basis of the Starlera nappe (e.g. carnieules, BAUDIN et al., 1995) and at the top of the autochthonous sedimentary cover of Tambo and Suretta nappes, often constituted by layers of calcschists and breccias. Similar early décollement nappes have been described in the western French Briançonnais zone (e.g. "Quatrième écaille", BARFÉTY et al., 1992). The first ductile deformation (D1) present in the Tambo and Suretta nappes, is interpreted as the main nappe stacking event and was directed towards NW corresponding to Eocene subduction of the Briançonnais basement during the closure of the Valais trough. The second deformation (D2) is presumably due to syn-collision ductile extension of the nappe pile parallel to the orogenic belt. The third deformation D3 formed during late continental collision implying differential uplift from north to south with the strongest exhumation in the southern parts of the studied area. This deformation event creates stair-case like folds associated with the south dipping local thrusts, which may be interpreted as a conjugate set with respect to the vertical movement along the Insubric mylonites (HEITZMANN, 1987; SCHMID et al., 1987, 1989). North of the area of greatest exhumation, the steepened topography collapsed along local E–W trending normal faults with N–S extension during the latest stages of this deformation phase. This fourth deformation involves late orogenic normal faulting compatible with the movements along the SSW–NNE striking sinistral Engadine Line and the E–W striking dextral Insubric Lines (Tonale Line s.s.) (HEITZMANN, 1987; SCHMID et al., 1987, 1989). The strike-slip bulk kinematics associated with the two lines imply a major extension towards the NE and a NW–SE compression which is compatible to the offset direction of the D4 normal faults.

The maximum age of the D1 phase in the Tambo and Suretta nappes is constrained by the sedimentation of the Arblatsch flysch (ZIEGLER, 1956; EIERMANN, 1988) and radiometric data at about 50–35 Ma (for review of isotopic data, see MARQUER et al., 1994). The Turba mylonite, an E–W extensional structure (LINIGER, 1992; NIEVERGELT et al., 1996), related to the D2 deformation, is crosscut at Lavinair Crusc (coordinates: 772/138) by the Bergell granodiorite, which intruded at about 30 Ma (VON BLANCKENBURG, 1992). Therefore D2 must have occurred roughly between 40 and 30 Ma. This Eocene to Oligocene extension D2 is interpreted as the result of collapse of overthickened crust due to the D1 nappe stacking. The D3 deformation is probably syn- to post-Bergell granodiorite intrusion. Submagmatic deformation in the Tertiary intrusion, and folding of the western intrusive contact (DAVIDSON et al., 1996), point to kinematics in deeper levels of the continental crust which are compatible with the previously described D3 phase. Cooling associated with uplift and exhumation of the southern part of the study area began about 30 Ma (HURFORD et al., 1989). D3 deformation during cooling is supported by the south dipping and north vergent thrusts which crosscut the intrusion in its solid state (ROSENBERG et al., 1994). Rapid cooling corresponding to the D3 uplift is also reported from the Suretta and Tambo nappes from 30 Ma until about 20 Ma (HURFORD et al., 1989; MARQUER et al., 1994). The timing of the D4 phase is not well constrained. We assume the D4 phase may be around or younger than 20 Ma, probably coeval with the dextral strike slip along the Insubric line, which post-dates the uplift of the whole region. The normal faults, associated with D4 could be the symmetric structural equivalents to the brittle component of the Simplon Fault zone (MANKTELOW, 1985; STECK, 1990) in the western part of the Penninic zone, but they may not be contemporaneous, because of the younging of the cooling ages towards the Simplon area (HURFORD et al., 1989; for review: HUNZIKER et al., 1992).

On the basis of the previously described data and assumptions, a model for the tectonic evolution of the nappe pile can be proposed (Fig. 6). This interpretation is mainly based on the geometry of the structures and the kinematics recorded by the Tambo and Suretta nappes and it leads to an alternative model for the evolution of the D2 and D3 deformations with respect to recent interpretations derived from structural investigations in the Bergell area (ROSENBERG et al., 1995; DAVIDSON et al., 1996). In these recent models, the first stage of the intrusion history of the Bergell pluton implies coeval different shear senses at the top of the Suretta nappe (top to the south) and the bottom of the Tambo nappe (top to the north) leading to an horizontal intrusion of the pluton before a regional N–S compression. But only the second stage proposed for the emplacement of the Bergell pluton, the regional N–S compression, is compatible with the structural observations of

D3 deformation described in the Tambo and Suretta nappes. On the other hand, for the previous stages, a continuous syn-collision lithospheric extension from D2 to D4 can be proposed on the basis of the structural investigations in the Tambo and Suretta nappes. This progressive extension is defined by eastward escaping extensional structures due to relaxation of a buoyancy disequilibrium in an abnormally thickened crust (see review of exhumation processes in PLATT, 1993). The ductile D2 mylonites and shear zones were first created at a deep-crustal level. The progressively shallower tectonic setting of the Tambo and Suretta nappes during D2 deformation, corresponding to isothermal decompression from 1.0 GPa to 0.5 GPa (BAUDIN and MARQUER, 1993), is considered as a syn-collision extension process due to the D2 ductile vertical shortening, low-angle detachments toward the East (Fig. 6) (e.g. Turba Mylonite Zone, NIEVERGELT et al., 1996) and associated erosion. The subsequently cooled units were subjected to brittle-ductile deformations during D3 and D4 under Barrowian metamorphic conditions (MARQUER et al., 1994). At these shallow crustal levels, the D4 normal faults were formed, corresponding to NE–SW extension, parallel to the belt axis. With this interpretation, the ongoing syn-collision extension, leading to D2 and D4 structures, is interrupted by a double event corresponding to the Bergell intrusion and the D3 uplift. The progressive deformation during D3 leads to a succession from ductile to brittle-ductile structures. Isoclinal folds and thrusts, described at the base of the Bergell intrusion (ROSENBERG et al., 1994, 1995; DAVIDSON et al., 1996), and north vergent staircase-like folds in the southern part of the Tambo and Suretta nappes were accompanied by the formation of steep brittle-ductile thrusts in the basement rocks (Fig. 6). The thrust and fold zones might be considered as antithetical to the Insubric mylonites and allow a differential uplift of the southern part of the nappe pile. The fold and thrust zones steepen the pre-existing schistosity in the southern part of the Tambo and Suretta nappes. In the northern, more external areas, the southern highly uplifted area collapses into northwards directed normal faults at the top of the Suretta nappe while D3 north vergent folds are created in the upper sedimentary units, such as the Schams nappes for example (D3 in SCHREURS, 1993) or in the frontal part of the Tambo nappe (D4 in MAYERAT, 1994) (Fig. 6). The geometry of these D3 structures were previously described by BAUDIN et al. (1993) at the top of the Tambo nappe, where these authors interpreted systematic northward vergence of D3 folds and extensional crenulation cleavage as a result of a bulk top to the North shearing. At the scale of the nappe pile, these structures could accommodate the bulk gravitational disequilibrium associated with the vertical extrusion in the most internal part, close to the Insubric line (Fig. 6).

In summary, four deformation phases are described in the southern parts of the Tambo and Suretta nappes: The D1 deformation is associated with nappe stacking towards the NW in a subduction environment. Syn-collision ductile east-west directed extension (D2) creates important mylonite zones leading to a bulk top to the east sense of shear. Syn-collision brittle-ductile uplift (D3) is syn- to post-Bergell granodiorite intrusion and forms steep folds and conjugate thrusts. Later, brittle normal faults indicate NE–SW extension (D4). Taking into account previous works in the Bergell area, a rough timing can be proposed. Constrained by mineral ages and the overthrusting on the Arblatsch flysch, the D1 deformation of Tambo and Suretta took place between 50 and 35 Ma. The Turba mylonite has been crosscut by the granodiorite intrusion (30 Ma, VON BLANCKENBURG, 1992; NIEVERGELT et al., 1996) and is linked to the D2 structures observed in the studied area. This restricts the lower age of D2 to 30 Ma probably indicating a pre- to syn-Bergell tonalite intrusion age for the D2 deformation. The Oligocene high cooling rates are most plausibly associated with the D3-uplift. The rapid cooling in the Tambo and Suretta nappes ends at 20 Ma. This age could be attributed to the beginning of the predominance of D4 deformation, as D4 brittle extension started when the uplift decreased.

The main schistosity (D2) is contemporaneous with and due to an E–W extension strongly overprinting almost all previous structures. The reduction of the thickness of the nappe pile, as observed on the tectonic map, is not caused by the intersection of geological structures with the topography but is rather created by the large scale D2 ductile extension structures, which appears to be strongest in the southeastern parts of the Tambo and Suretta nappes. The turning from a north-south to a west-east direction of the tectonic unit boundaries in the southernmost part of the studied area, as well as the steepening of the main schistosity, are due to differential uplift during the D3 phase leading to a vertical extrusion and a major uplift of the southern part of the nappe pile.

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