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Tectonometamorphic evolution of the Eastern Pennine Alps during Tertiary continental collision: Structural and petrological relationships between Suretta, Tambo, Chiavenna and Gruf units (Switzerland/Italy).

Evolution tectonométamorphique des nappes Penniques orientales pendant la collision continentale Tertiaire: relations pétrologiques et structurales entre les unités de Suretta, Tambo, Chiavenna et Gruf (Alpes Suisses et Italiennes).

Thèse

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Rachel K. Huber

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Tectonometamorphic evolution of the Eastern Pennine Alps during Tertiary continental collision: structural and petrological relationships between Suretta-, Tambo-, Chiavenna and Gruf units (Switzerland/Italy)

de Mme Rachel Huber

UNIVERSITÉ DE NEUCHÂTEL

FACULTÉ DES SCIENCES

La Faculté des sciences de l'Université de Neuchâtel sur le rapport des membres du jury,

MM. F. Persoz (directeur de thèse), D. Marquer,
M. Burkhard, M. Engi (Berne) et N. Mancktelow (Zürich)

autorise l'impression de la présente thèse.

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Le doyen:

F. Stoeckli

F. Stoeckli

Résumé

Les nappes de Tambo et Suretta, comme les unités de Gruf et Chiavenna font partie des nappes penniques orientales. Les unités sont situées dans la zone des "racines", dans la région de Val Bregaglia à l'Est de la Suisse. Les nappes de Tambo et Suretta représentent les nappes supérieures de la pile des nappes penniques. Elles appartiennent paléogéographiquement au domaine de Briançonnais. L'unité de Chiavenna est située sur la marge amincie nord du Briançonnais et l'unité de Gruf provient de la marge continentale Européenne. Les deux nappes sont essentiellement constituées d'un socle polycyclique et polymetamorphique composé de métasédiments, métagranitoides et amphibolites. Elles sont intrudées par des granitoïdes Varisques et recouvertes par des sédiments Mesozoiques. L'unité sous-jacente, l'unité de Chiavenna, montre primordialement des roches basiques et ultrabasiques d'origine subcontinentale et océanique. L'unité la plus basse, l'unité de Gruf, est formée par des migmatites alpines et préalpines avec des reliques de métamorphisme granulitique.

La déformation et la cinématique Tertiaire et les assemblages métamorphiques associés ont été défini dans les quatres unités, ce qui permet de proposer une évolution tectonométamorphique de la collision Tertiaire et de séparer cette evolution alpine de l'histoire préalpine. Les quatre phases Tertiaires se résume de la manière suivante:

La première phase de déformation (D1) est hétérogène et ductile. Les structures majeures sont des zones de cisaillement avec un mouvement chevauchant vers le NW. La schistosité et sa lineation plonge vers le NW. Les assemblages minéralogiques associés montrent des conditions HP (ex: nappe de Tambo: ~13-10 kb, ~500°C).

A la déformation D1, se superpose une deuxième phase de déformation (D2), ductile et hétérogène. Sa schistosité est la schistosité principale de la région, peu inclinée vers le NNE avec une lineation subhorizontale E-W. A toute échelle, des zones de cisaillement indiquent un mouvement normal vers l'E. Cette phase décale les contacts lithologiques et tectoniques. Elle est responsable de l'amincissement des unités vers le SE. L'étude métamorphique de D2 dans la zone des racines démontre l'existence d'une décompression avec un maximum thermique au début de cette phase (ex: la nappe de Tambo: ~11-6 kb, ~610°C), cependant que dans la partie nord des nappes de Tambo et Suretta une décompression isotherme est enregistrée. Pendant le refroidissement, la déformation se poursuit, comme en témoignent des structures de style différent: aux structures ductiles de HT succèdent des structures fragiles de BT. Les conditions PT augmentent en traversant la pile de nappes depuis le haut vers le bas (la nappe de Suretta: ~10-5 kb, ~550°C et l'unité de Gruf: ~10-4 kb, ~730°C).

La troisième phase de déformation (D3) ne s'imprime au N, que dans des zones restreintes orientées E-W, tandis qu'au sud, toute la région est plissée d'une manière isoclinale. La schistosité et la linéation plongent fortement vers le S et elles sont associées à des plis orientés E-W. Pendant la même phase segénèrent des failles ductiles-cassantes chevauchantes vers le N et fortement inclinées vers le S. Des failles mineures conjuguées montrent une géométrie et une cinématique opposées. Cette phase est responsable de la réorientation et du redressement de S2 dans la zone des racines, ainsi que du soulèvement de la région de l'intrusion de Bergell. Au nord, les conditions PT indique la limite inferieure du faciès des schistes verts à la limite ductile-cassante, pendant qu'au sud, dans l'unité de Gruf, les conditions PT de D3 commencent à ~4 kb et ~550°C. Pendant cette phase, l'intrusion de Bergell se met en place, ce qui provoque

une auréole de métamorphisme de contact au toit et une fusion partielle in-situ à la base du pluton.
La quatrième phase de déformation (D4) est caractérisée par des failles normales plongeant vers le NE, parallèles à la faille de Forcola et des mylonites et failles sénestres parallèle à la Ligne d'Engadine.

La première phase est interprétée comme la phase principale d'empilement des nappes durant la subduction Éocène. La formation des nappes avec une direction de transport vers le NW est liée à la subduction du domaine Briançonnais et à la fermeture du basin Valaisan.

La deuxième phase est due à une extension ductile syn-collision, orienté E-W, parallèle à l'axe de l'orogène Alpin. L'épaisseur anormale de la croûte, suite à l'empilement des nappes pendant la subduction, représente un déséquilibre isostatique. Ce déséquilibre conduit à une décompression isotherme pendant l'extension Eocène-Oligocène. Un lien entre la température maximale pendant D2, la formation du magma de l'intrusion de Bergell et l'initiation de l'uplift de D3 pourrait être établi avec un modèle du détachement progressif de la plaque lithosphèrique vers l'Ouest (slab break-off).

La troisième phase a lieu pendant la collision continentale tardive et implique un soulèvement différentiel avec une composante maximale dans la région de l'unité de Gruf. L'érosion induite par le soulèvement mène à l'exhumation de cette région et à une augmentation du taux de refroidissement. L'intrusion de Bergell a lieu pendant cette phase Oligocène.

Pendant la quatrième phase se forme des failles parallèles aux failles majeures de la Ligne d'Engadine, de Forcola et de la Ligne Insubrienne. La Ligne de Forcola pourrait présenter l'équivalent symétrique de la faille du Simplon à l'Ouest des Alpes Centrales. Cette phase est due à l'échappement latéral des blocs lithosphèriques.

Ce fascicule correspond à une forme réduite d'une partie de la thèse.

Le texte intégral de cette thèse a été déposé à la bibliothèque principale et à la bibliothèque de l'Institut de Géologie de l'Université de Neuchâtel

Liste des publications majeures

Publications:

1. Huber, R.K. & Marquer, D. (1996): Tertiary deformation and kinematics of the southern part of the Tambo and the Suretta nappes (Val Bregaglia, Eastern Swiss Alps). Schweiz. Mineral. Petrograph. Mitt., 76, 383-397.

2. Huber, R.K. & Marquer, D. (1998): The tectonometamorphic history of the peridotitic Chiavenna unit from Mesozoic to Tertiary tectonics: a restoration controlled by melt polarity indicators (Eastern Swiss Alps). Tectonophysics, 296, 205-223.

Résumés étendus:

1. Huber, R.K. & Baudin, T. (1995)a: The relationship between extension and uplift-erosion processes in the root zone of the Eastern Pennine Nappes (Val Bregaglia). Terra nova, 7, 123.

2. Huber, R.K., Baudin, T. & Marquer, D. (1995)b: Alpine tectonic and metamorphic evolution of the root zone of the Eastern Pennine nappes (Val Bregaglia, Central Swiss Alps). Journal of the Czech geological Society, 40, 3.

3. Huber, R.K. (1997): The tectonometamorphic evolution of the continental crust and the upper mantle during the Alpine Tertiary continental collision shown at the example of the Eastern Penninic nappes (Val Bregaglia, Switzerland). EUG9-Abstracts, Terra Nova, 9, 85.

4. Huber, R.K. & Marquer, D. (1998): Tectonometamorphic evolution of the Eastern Pennine Alps during Tertiary continental collision: Structural and petrographical relationships between the Suretta-, Tambo-, Chiavenna and Gruf units (Switzerland). Mem. Sci. Geol., 50.

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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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[1] Institut de Géologie, Université de Neuchâtel, rue E. Argand 11, CH-2007 Neuchâtel, Switzerland.
E-mail: huber@geol.unine.ch.

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;

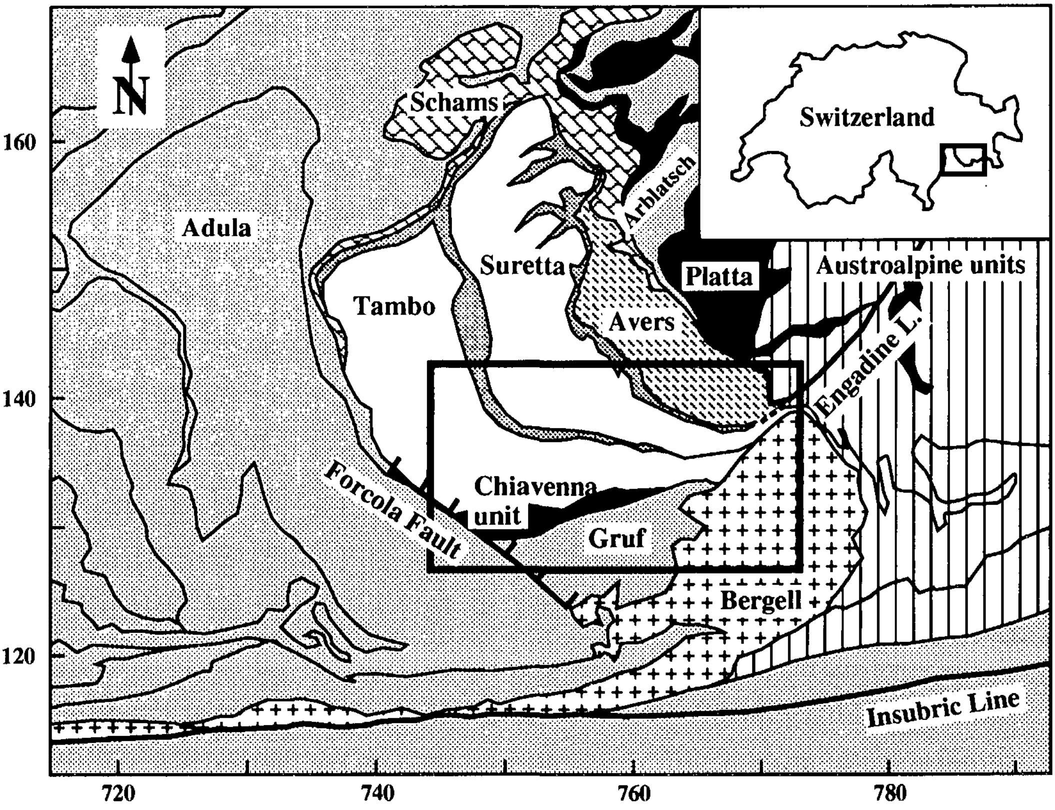


Fig. 1 Location of the study area on a sketch map of the eastern Alps. Numbers refer to the Swiss coordinate grid.

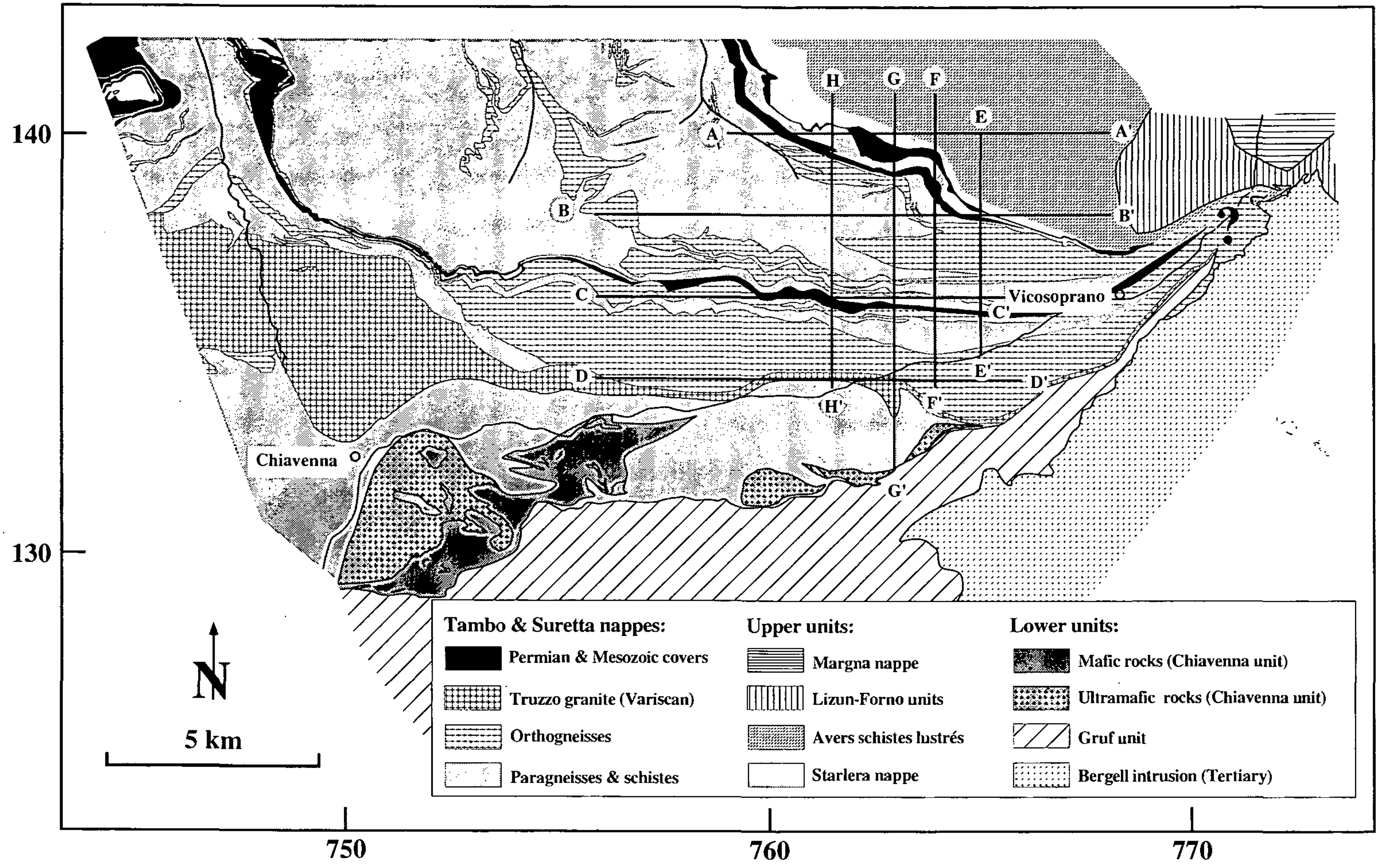


Fig. 2 Tectonic map of the southern part of the Tambo and Suretta nappes and their relationships with the under- and overlying units. Location of the cross-sections (Fig. 4). Numbers refer to the Swiss coordinate grid.

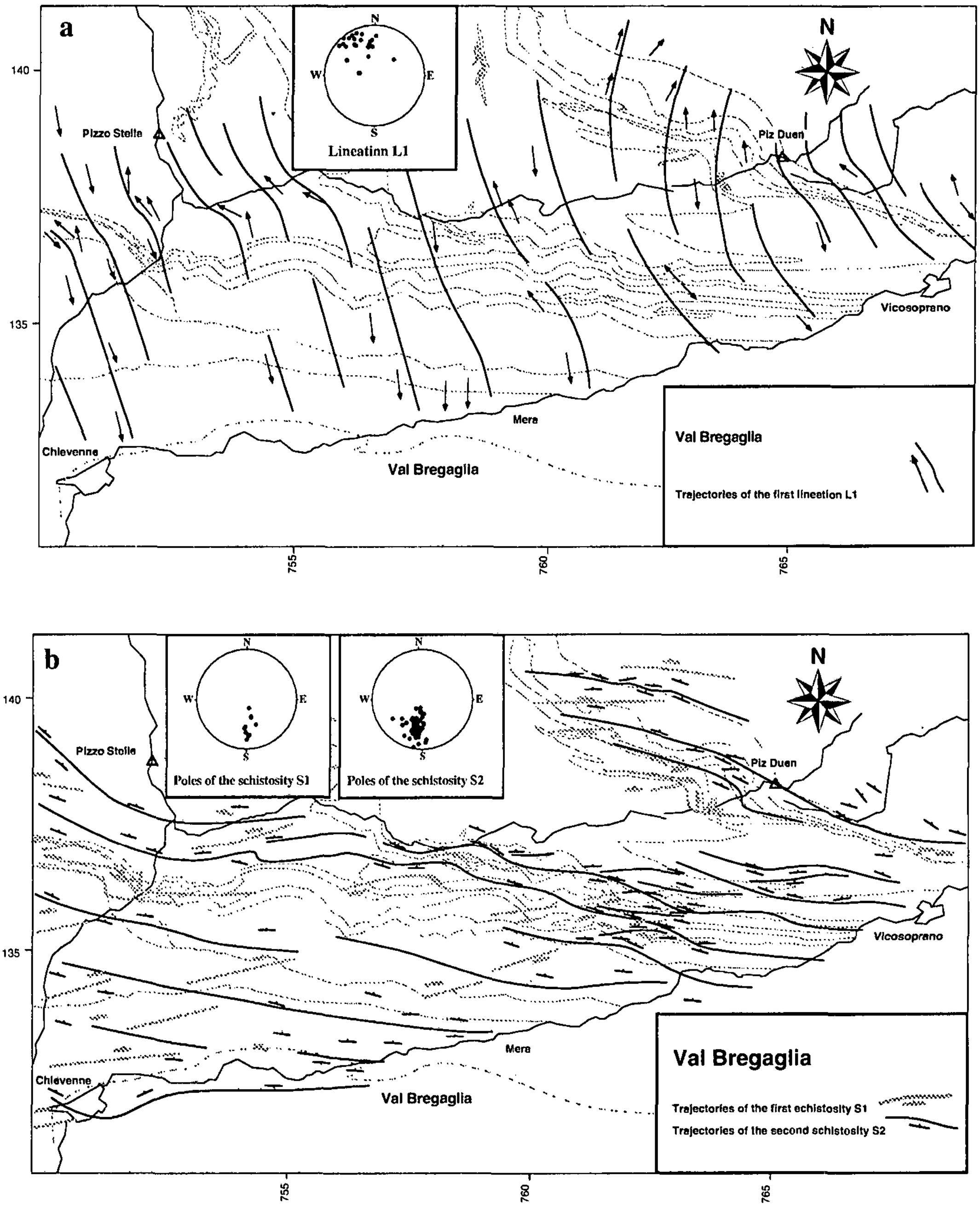
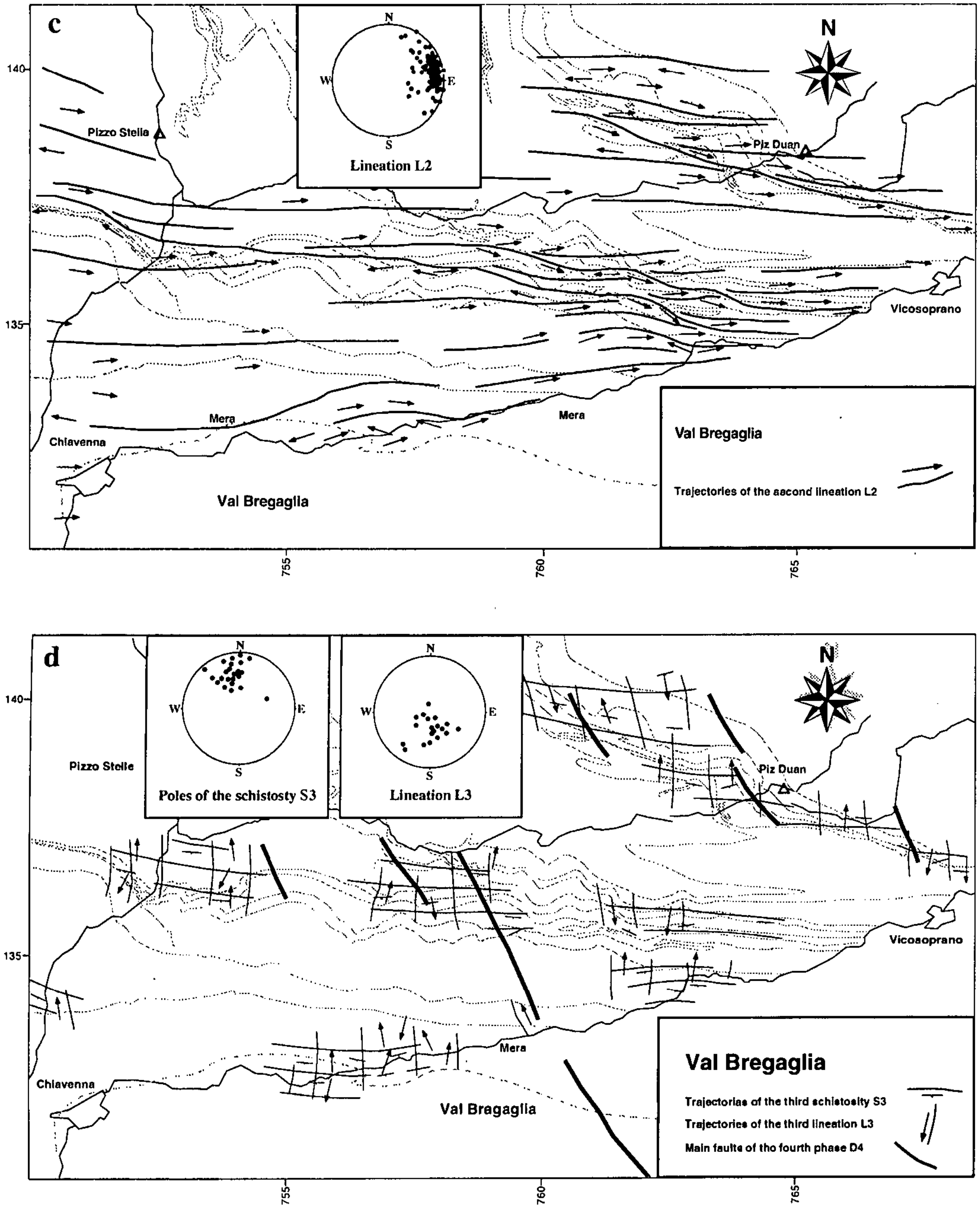


Fig. 3 (a) Structural map with the trajectories of the first phase stretching lineation L1. The lineation L1 on the stereoplot shows a gentle NNW plunge (black points). (b) Structural map with the trajectories of the first and the second phase schistosities (S1 and S2). On the stereoplots the poles of 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

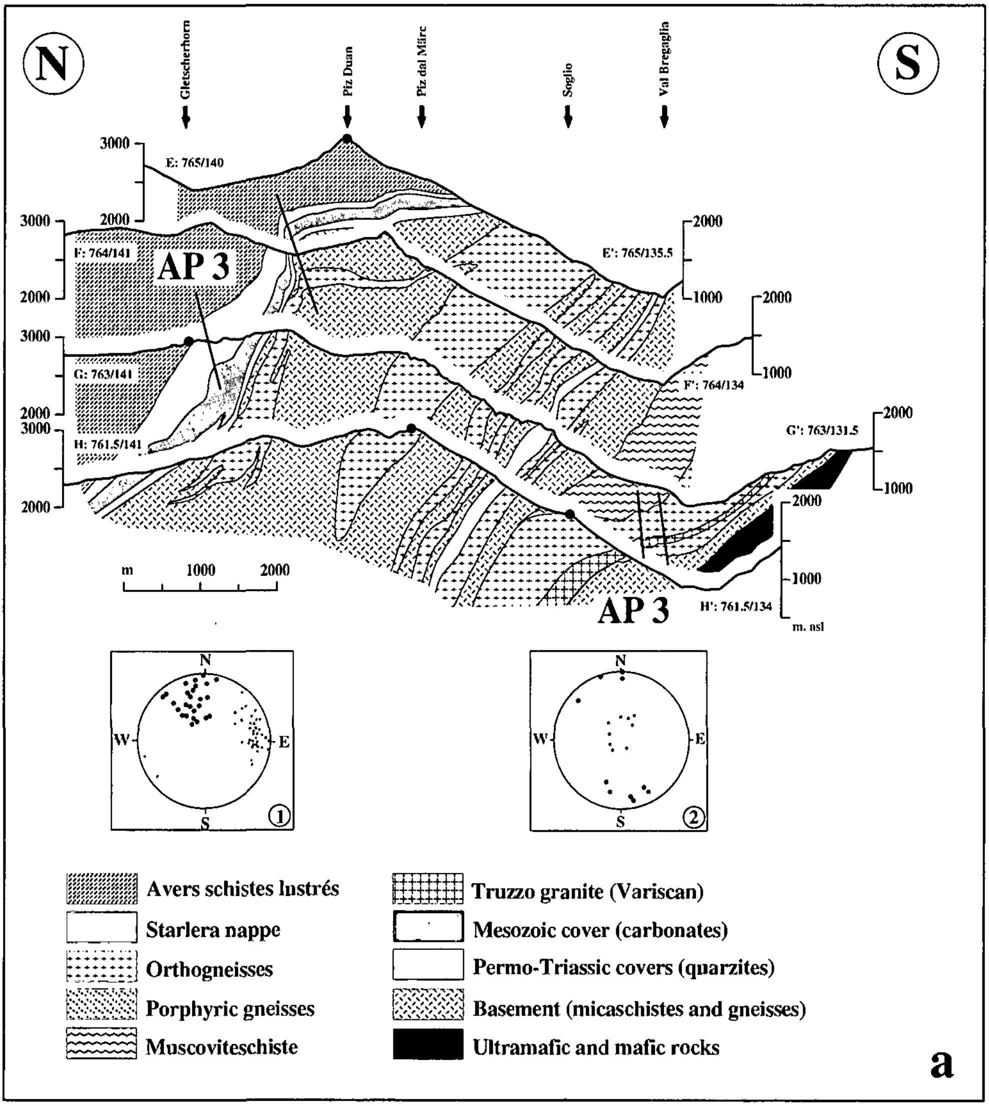


Fig. 4 (a) The N–S profiles (see location on Fig. 2) show the steepening of the root zone due to the D3 folding (black lines = axial plane traces: AP3). Stereogram 1: poles of the fold axial plane of the third phase are indicated as large dots and the fold axes as small dots. Stereogram (2): poles of 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 calcschists (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).

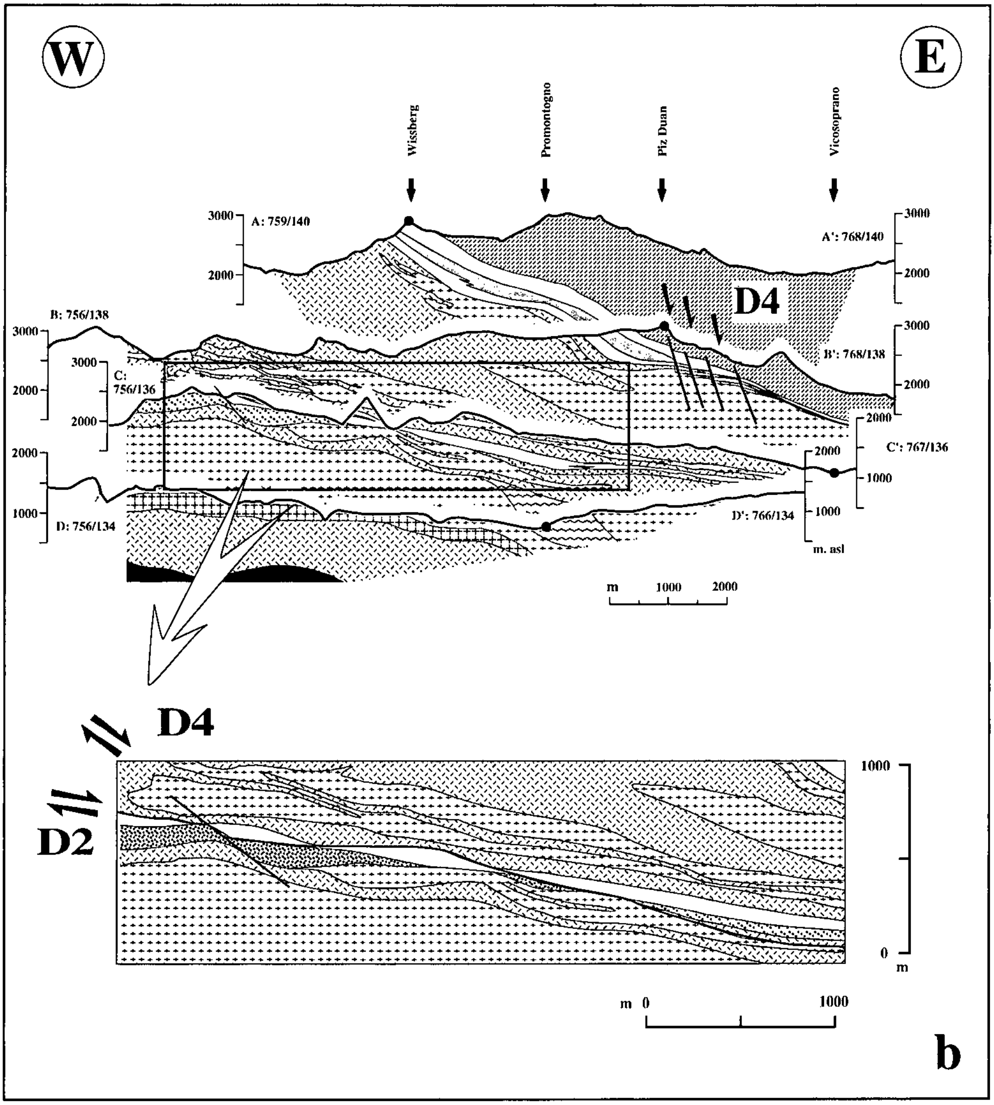


Fig. 4 (b) The E–W cross-sections (see location on Fig. 2) show the offset of the tectonic and lithologic contacts due to the D2 mylonites and D4 faults. The area in the rectangle of the upper cross-section is enlarged to emphasize the D2/D4 geometric relationships on the lower cross-section where heavy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

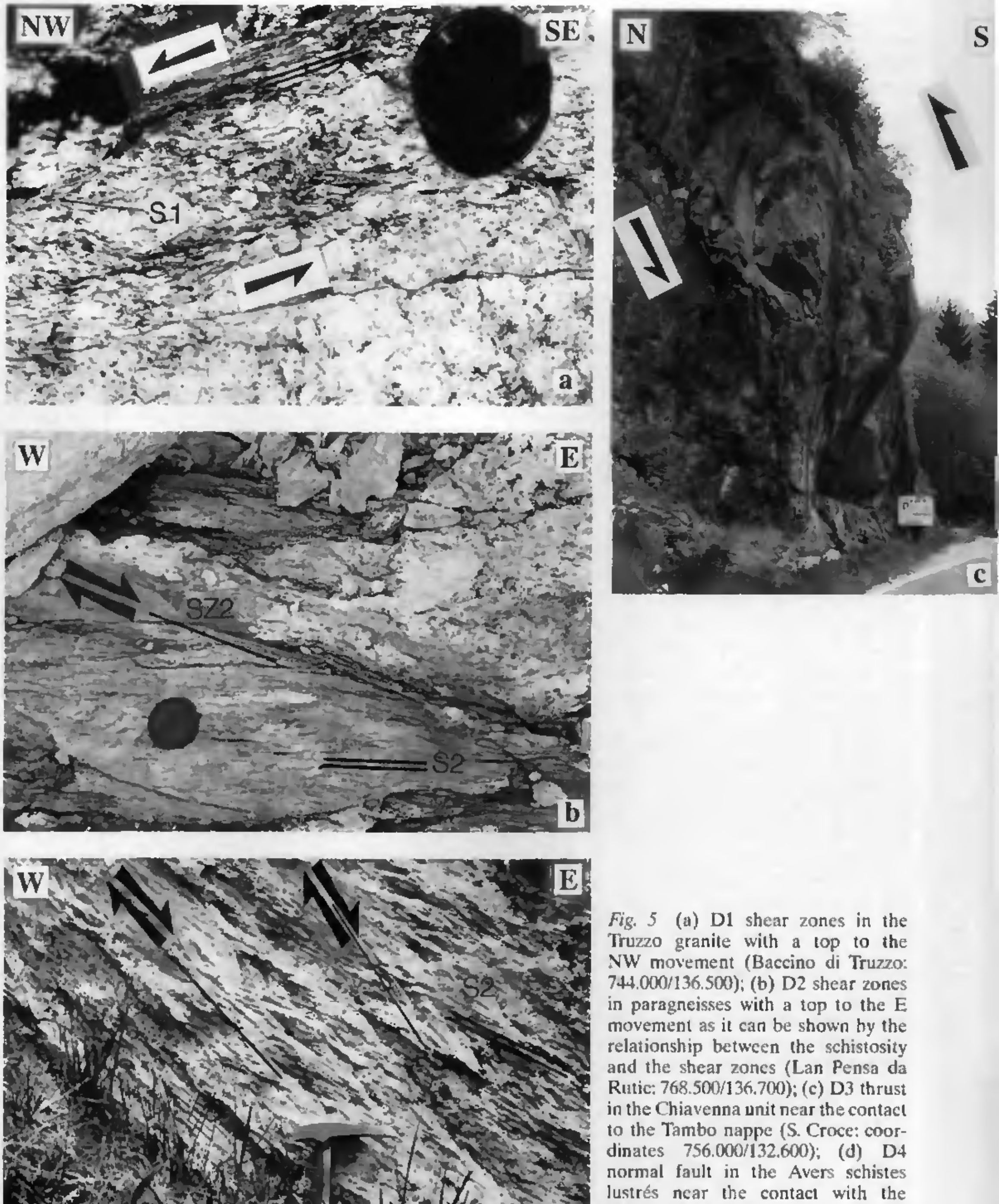


Fig. 5 (a) D1 shear zones in the Truzzo granite with a top to the NW movement (Baccino di Truzzo: 744.000/136.500); (b) D2 shear zones in paragneisses with a top to the E movement as it can be shown by the relationship between the schistosity and the shear zones (Lan Pensa da Rutic: 768.500/136.700); (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.

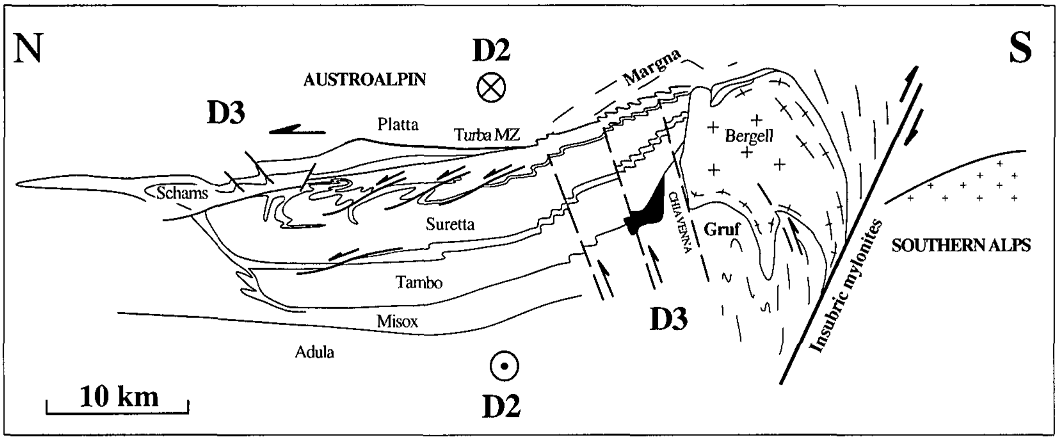


Fig. 6 Schematic N–S cross-section showing the type, geometry, and kinematics of the D3 structures at a regional scale: The differential uplift with its highest elevation is created above the Gruf unit. During D3 deformation, low angle normal faults develop as collapse structures in the northern part 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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R.K. Huber *, D. Marquer

Geological Institute, Neuchâtel University, E.-Argand 11, 2007 Neuchatel, Switzerland

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J.-P. BURG ETH-Zentrum, Institut für Mineralogie und Petrographie, Sonneggstraße 5, CH-8092, Zürich, Switzerland. Phone: +41.1.632 6027; FAX: +41.1.632 1080; e-mail: jpb@erdw.ethz.ch

T. ENGELDER Pennsylvania State University, College of Earth & Mineral Sciences, 336 Deike Building, University Park, PA 16802, USA. Phone: +1.814.865.3620/466.7208; FAX: +1.814.863.7823; e-mail: engelder@geosc.psu.edu

K.P. FURLONG Pennsylvania State University, Department of Geosciences, 439 Deike Building, University Park, PA 16802, USA. Phone: +1.814.863.0567; FAX: +1.814.865.3191; e-mail: kevin@geodyn.psu.edu

F. WENZEL Universität Fridericiana Karlsruhe, Geophysikalisches Institut, Hertzstraße 16, Bau 42, D-76187 Karlsruhe, Germany. Phone: +49.721.608 4431; FAX: +49.721.711173; e-mail: fwenzel@gpiwap1.physik.uni-karlsruhe.de

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The tectonometamorphic history of the peridotitic Chiavenna unit from Mesozoic to Tertiary tectonics: a restoration controlled by melt polarity indicators (Eastern Swiss Alps)

R.K. Huber *, D. Marquer

Geological Institute, Neuchâtel University, E.-Argand 11, 2007 Neuchatel, Switzerland

Accepted 24 June 1998

Abstract

Occurrences of mantle and lower crustal rocks are often preserved in mountain ranges. When they occur in the internal part of collision belts, their initial geometry and palaeogeography are sources of debate. The mafic–ultramafic Chiavenna unit is one example in the Pennine units located in the Eastern Swiss Alps. Because of strong deformation and metamorphism during Tertiary collision tectonics, the pre-collision geometry of this unit can only be restored using a qualitative geometrical analysis of the successive ductile deformation phases (D1–D4). In-situ melting and melt migration during the main Alpine deformation phase (D2) is a way-up indicator and is of special importance to this restoration. The restored Prealpine geometry of the Chiavenna unit indicates that a sub-continental mantle close to a thinned continental margin becomes denuded during the Mesozoic extension and subsequently covered by carbonate sediments. Taking into account the position of the Chiavenna unit in the nappe pile and its *PT*-path, a northern Briançonnais situation during Mesozoic time becomes most probable. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Chiavenna unit; Eastern Switzerland; Pennine unit; subcontinental mantle; thinned continental margin; melt way-up criterion

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1. Introduction

Petrology and structures of upper mantle rocks and their relationships with the lower crust lead to a better understanding of the geometry at the mantle–crust boundary, the tectonic evolution of the mantle at the lower crustal level and their subsequent exhumation. Mantle peridotites occur as xenoliths in volcanic rocks, at the boundary of thinned continental margins (Boillot et al., 1995) or in ophiolites involved in collision belts. Only the later two allow the structural studies that are necessary to define the geometrical relationships of the crust–mantle boundary and the tectonic evolution. Mantle rocks are often involved in orogenic processes as small peridotite bodies. Such ultramafic bodies of diverse origin occur in the Alps. They are recognized as subcontinental mantle, like the Malenco unit (Trommsdorff et al., 1993; Müntener, 1997; Hermann, 1997), or as ophiolite sequences, like the Zermatt zone or the Platta nappe (Trümpy, 1980; Pfeifer et al., 1989; Manatschal and Nievergelt, 1997).

This work focuses on the origin and significance

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* Corresponding author. Fax: +41 (32) 718 2601; E-mail: rachel.huber@geol.unine.ch

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of the Chiavenna unit in the Eastern Swiss Alps. The Chiavenna unit is a mafic–ultramafic body of unresolved origin with a poorly established Alpine collision history. The aim of this work is to define the tectonic evolution during collision tectonics, to deduce the initial geometry at the mantle–crust boundary and to propose a Prealpine scenario for the Chiavenna unit. Because the Chiavenna unit underwent strong deformation and recrystallization during Alpine tectonics, the Alpine tectono-metamorphic history needs to be established first.

Four main Alpine deformation phases have been distinguished on the basis of structural and microstructural field work and deformation-metamorphism analysis. Huber and Marquer (1996) correlated the four deformation phases to the overlying tectonic units confirming their regional relevance. In the peridotite, *PT*-conditions are estimated using the stable mineral assemblages in the microstructures of each deformation phase. The structural phases and the *PT*-path in the peridotites are compared with those in the overlying Tambo and Suretta nappes and the underlying Adula nappe. The similarities and differences in *PT*-history in the different units limit the proposed Alpine tectonic evolution of the Chiavenna unit.

Qualitative, step-by-step restoration of the structures of each deformation phase leads to a reconstruction of the Prealpine initial geometry. Of particular aid to the geometrical reconstruction are polarity indicators. Local partial melting forms leucosomes which may exhibit way-up criteria (Burg, 1991). Therefore, special attention was paid to melt produced in the meta-gabbros and intruding the overlying peridotites during D2-deformation. These melt-related structures were used to restore these rocks in their original position. The initial Prealpine geometry of the Chiavenna unit is discussed in terms of palaeotectonics and palaeoenvironment.

2. Geological setting

The Chiavenna and adjacent units belong to the Eastern Pennine units situated in the Eastern Swiss Alps and northern Italy (Figs. 1 and 2) (Trümpy,

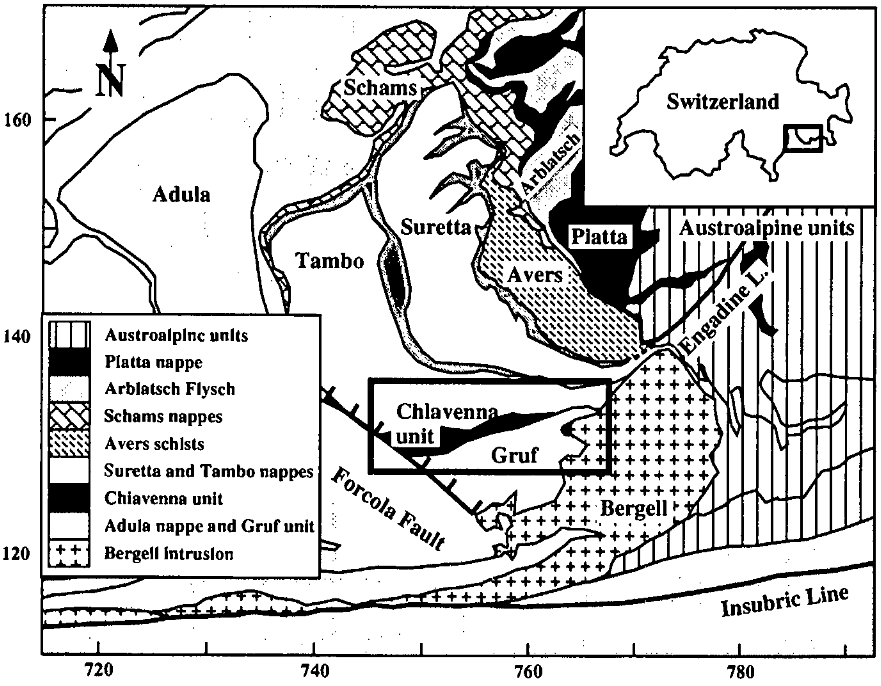


Fig. 1. Location of the study area on a sketch map of the Eastern Swiss Alps. Numbers refer to the Swiss coordinate grid (E–W coordinates: 745–768; N–S coordinates: 127–137).

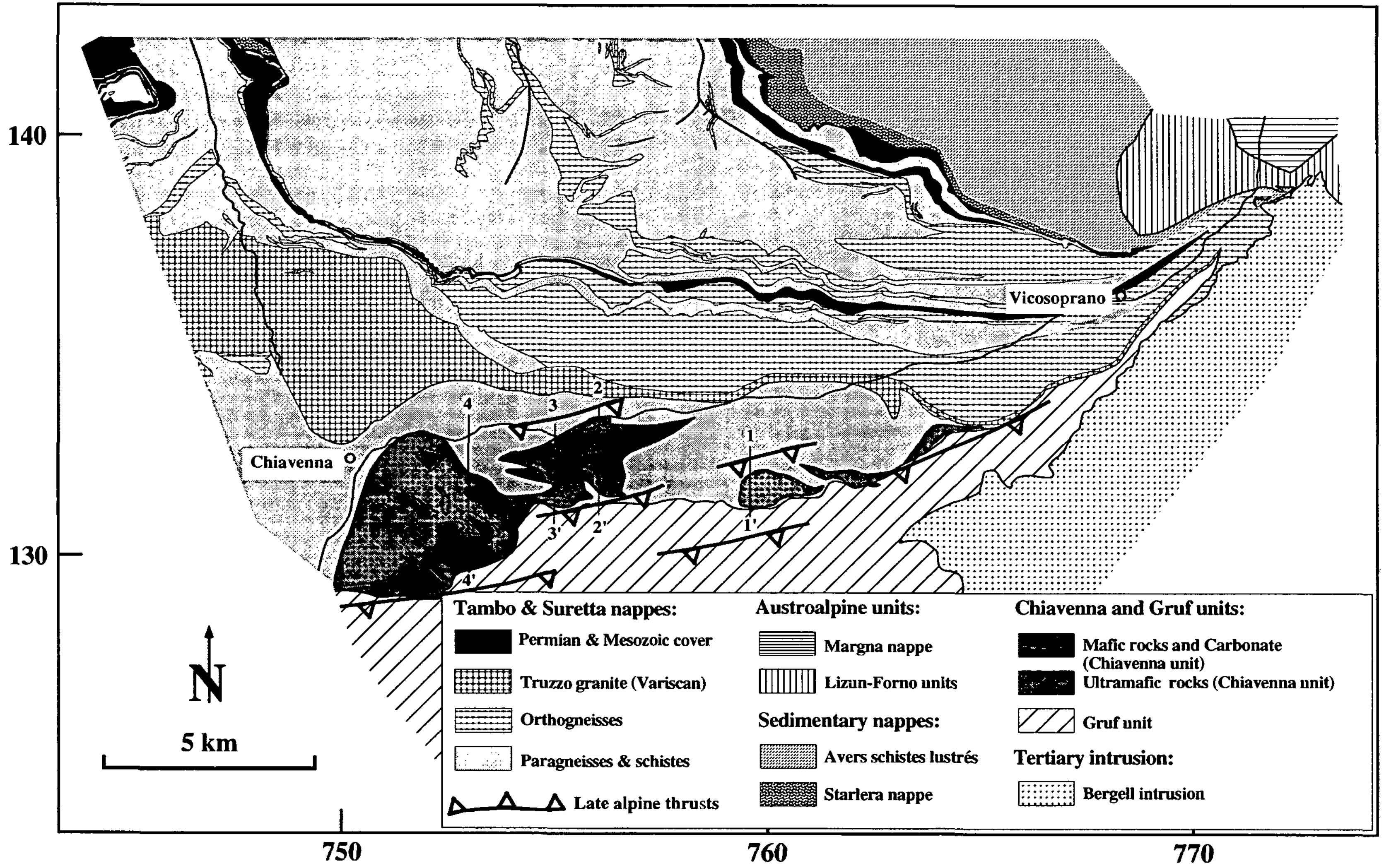


Fig. 2. Tectonic map of the Chiavenna unit and its relationship with under and overlying units. Location of the cross-sections in Fig. 4. Numbers refer to the Swiss coordinate grid.

1980). The investigated area extends from the coordinates 745/128 to 762/131 according to the Swiss coordinate system (Fig. 1). The Chiavenna unit (Dal Vesco, 1953; Schmutz, 1976) is located between the Tambo nappe in the north and the Gruf unit in the south (Fig. 2). The Gruf unit has granulite relics devoid of retrogression (Droop and Bucher-Nurminen, 1984). The imprint of granulite metamorphic facies is considered by them as a metamorphic event of Alpine age. The Gruf unit has been classically correlated with the Adula nappe (Blanc, 1965; Pfiffner et al., 1990a,b). In the south, the Gruf unit is cross-cut by the Tertiary Bergell intrusion (Wenk, 1970, 1973; Moticska, 1970; Gulson, 1973; Wagner et al., 1979; Trommsdorff and Nievergelt, 1983; Rosenberg et al., 1994, 1995; Davidson et al., 1996).

The Tambo and Suretta nappes are composed of polycyclic and polymetamorphic basement rocks (paragneiss, layers of amphibolite and orthogneiss) cross-cut by Permian acidic monometamorphic intrusions (Grünenfelder, 1956; Blanc, 1965; Weber, 1966; Marquer, 1991; Marquer et al., 1996). Their unconformably overlying Permo–Mesozoic autochthonous and allochthonous sedimentary covers show a typical stratigraphy of internal Briançonnais sediments (Staub, 1919, 1924; Baudin et al., 1995) (Fig. 2). At the top of the Suretta nappe, the Starlera nappe is tectonically overlain by the Schams nappe (Schmid et al., 1990; Schreurs, 1993) and the Avers schistes lustrés and is covered by the orogenic lid of the Austroalpine units (Trümpy, 1969; Milnes and Schmutz, 1978; Liniger and Guntli, 1988; Guntli and Liniger, 1989) (Figs. 1 and 3).

The Chiavenna unit consists of meta-peridotites, amphibolites, and carbonates and is regarded as an 'ophiolitic sequence' by Schmutz (1976). Because the peridotites overlie the amphibolites, the sequence was interpreted as an overturned unit (Schmutz, 1976). The Chiavenna ophiolites are addressed as the Chiavenna unit in this paper because of the lack of a typical ophiolitic sequence (Anonymous, 1972) (see Geometrical restoration). The main lithologies of the unit are meta-peridotites and amphibolites present in equal amounts (estimated surface of 50% for each lithology) (Fig. 2). Carbonate occurrences are rare and consist of discontinuous layers with centimetre to metre thicknesses (Figs. 2 and 4). Meta-peridotites have various metamorphic mineral assemblages which recrystallized during the Alpine orogenesis. The mineralogy of the meta-peridotites shows magnetite, chlorite, talc, amphibole, olivine, pyroxene with different degrees of serpentinisation. Essentially monomineralic rocks formed of talc, antigorite, chlorite or amphibole occur in narrow deformation zones. Clinopyroxene and spinel are rare.

Amphibolites are classified according to textural and mineralogical criteria at mappable scales. Fine-grained greenish amphibolites, sometimes layered, show a rich mineralogy with plagioclase, quartz, amphibole, biotite, chlorite, epidote/zoisite, titanite and oxides. Coarse-grained dark massive amphibolites with meta-gabbroic texture, show 'flaser' texture and poor mineral association (plagioclase, amphibole and biotite). Multicoloured, centimetre-scale layered amphibolites associated with small centimetre- to decimetre-scale calc-silicate boudins are in minor abundance and always occur close to the meta-peridotites. Their mineralogy is distinguished from the other amphibolites by the presence of diopside and calcite.

Carbonates are located in or close to the meta-peridotite as veins, discordant to the mantle layering. These calc-silicate veins have undergone at least four deformation phases. In the amphibolites, they occur as calc-silicate boudins parallel to the compositional layering. The third type of carbonates are almost pure calcite-marble. They are layered at a centimetre to decimetre scale. They separate coarse-grained from the fine-grained amphibolites. This layered marble is the only mappable carbonate lithology.

3. Tectono-metamorphic setting

The Austroalpine nappes underwent deformation under greenschist facies metamorphic conditions during Late Cretaceous time (Liniger, 1992; Manatschal and Nievergelt, 1997). During Eocene subduction, very high-pressure relics from the eclogite facies occur only locally within of the underlying Adula nappe (Fig. 9) (Heinrich, 1986; Meyre and Puschnig, 1993; Meyre et al., 1997). Other eclogite facies rocks of the upper Pennine region (Tambo and Suretta nappes) are described as Prealpine relics, whereas Alpine pressure-dominated metamorphism

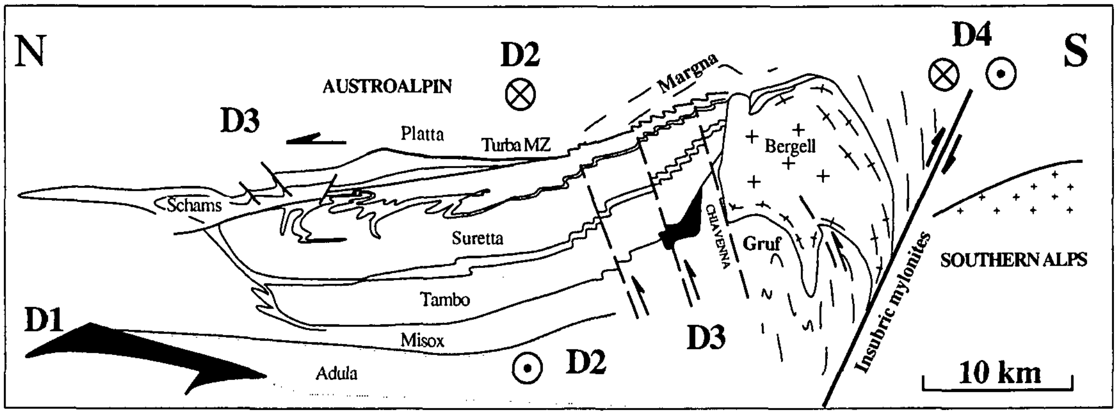


Fig. 3. Interpretative N–S crustal section (modified after Schmid et al., 1990) showing the main Alpine deformations: D1 corresponds to the Tertiary south-directed subduction (black arrow) and is responsible for the stacking of the nappes. D2 represents the ductile E–W extension of the nappe pile. During this stage, major mylonite zones developed along the nappe contacts (e.g. Turba-MZ). The compressive D3-phase shows a differential vertical uplift with the highest elevation created above the Gruf unit. This deformation phase is restricted to the zone north of the Insubric line (Insubric mylonites).

reached conditions not higher than blueschist facies (Biino et al., 1997).

The Oligocene metamorphism is of Barrovian type, increasing through the nappe pile in pressure and temperature from greenschist facies in the uppermost Pennine unit to upper amphibolite facies in the lowermost Gruf and the Chiavenna units (Trommsdorff and Evans, 1969; Niggli, 1970; Wenk, 1974; Todd and Engi, 1997). Only a few granulites exist in the Gruf unit and are suggested to be of Alpine age by Bucher-Nurminen and Droop (1983) and Droop and Bucher-Nurminen (1984). In the Alps, in tectonically higher units, other granulites are present and are interpreted as being of Prealpine age (Gardien et al., 1994; Hermann, 1997; Müntener, 1997). In the underlying Pennine units, Prealpine HT evidence exists in the form of migmatites (Hänny et al., 1975; Romer et al., 1996). Therefore, without geochronological evidence, the age of Gruf unit granulites is still a subject of debate (Romer et al., 1996).

Contact metamorphism due to the Bergell intrusion has been well-documented for the higher units (Gieré, 1985: Austroalpine and Suretta nappes) and recently studied in the Gruf unit (Davidson et al., 1996), but is structurally not well defined in the Chiavenna unit (Schmutz, 1976).

In the upper eastern Pennine units, we have recognized four main Tertiary Alpine deformation phases (D1, D2, D3 and D4) corresponding to four main tectonic events which overprint Prealpine structures (Marquer, 1991; Huber and Marquer, 1996). The four phases are also recognized in our study area and are as follows.

The Pennine units were thrust northwestward during the Eocene (Froitzheim et al., 1994). The Pennine nappes were in a subduction zone environment during the closure of the Valais Pennine basin (Fig. 3: D1). The upper Pennine units which consist of underplated basement and sedimentary slices, an accretionary prism, formed during the Valais subduction (see Marquer et al., 1994). The D2-structures are the most penetrative structures and related to a ductile, syn-collisional E–W extension. Major ductile detachment zones (Fig. 3; D2, e.g. Turba mylonite zone, Liniger, 1992; Nievergelt et al., 1996) cross-cut the tectonic contact of the nappes. Recent attempts to define the timing of Alpine deformation events (Hunziker et al., 1992) have been published by several authors for the Suretta nappe (Hurford, 1986; Hurford et al., 1989), and the Tambo nappe (Marquer et al., 1994), suggesting an Eocene subduction (D1) followed by Oligo–Miocene collision (D2).

The D3- and D4-structures are not penetrative. They are linked to vertical extrusion of the crustal block situated to the north of the Insubric line (D3) and brittle–ductile E–W extension parallel to the Forcola line (D4). During late folding (D3) which overprinted and steepened the previous structures in the southern part of the studied area, the Bergell granite intruded (Fig. 3; D3) (Rosenberg et al., 1995). This intrusion took place between 32 and 30 Ma (von Blankenburg, 1992; Davidson et al., 1996; Oberli et al., 1996). The latest structures (D4), corresponding to a NE–SW extension, are brittle normal faults cross-cutting all previous structures (Fig. 1) (e.g. the Forcola fault: Marquer, 1991). They may have been contemporaneous with displacements along the Engadine line and the late dextral Iorio–Tonale line (Schmid et al., 1987, 1989; Heitzmann, 1987; Zingg and Hunziker, 1990). The Novate intrusion was affected by the D4 normal faults. Therefore, the intrusion age of 25 Ma (von Blankenburg, 1992) limits the maximum age of the D4-phase onset.

4. Alpine structures and geometry in the Chiavenna unit

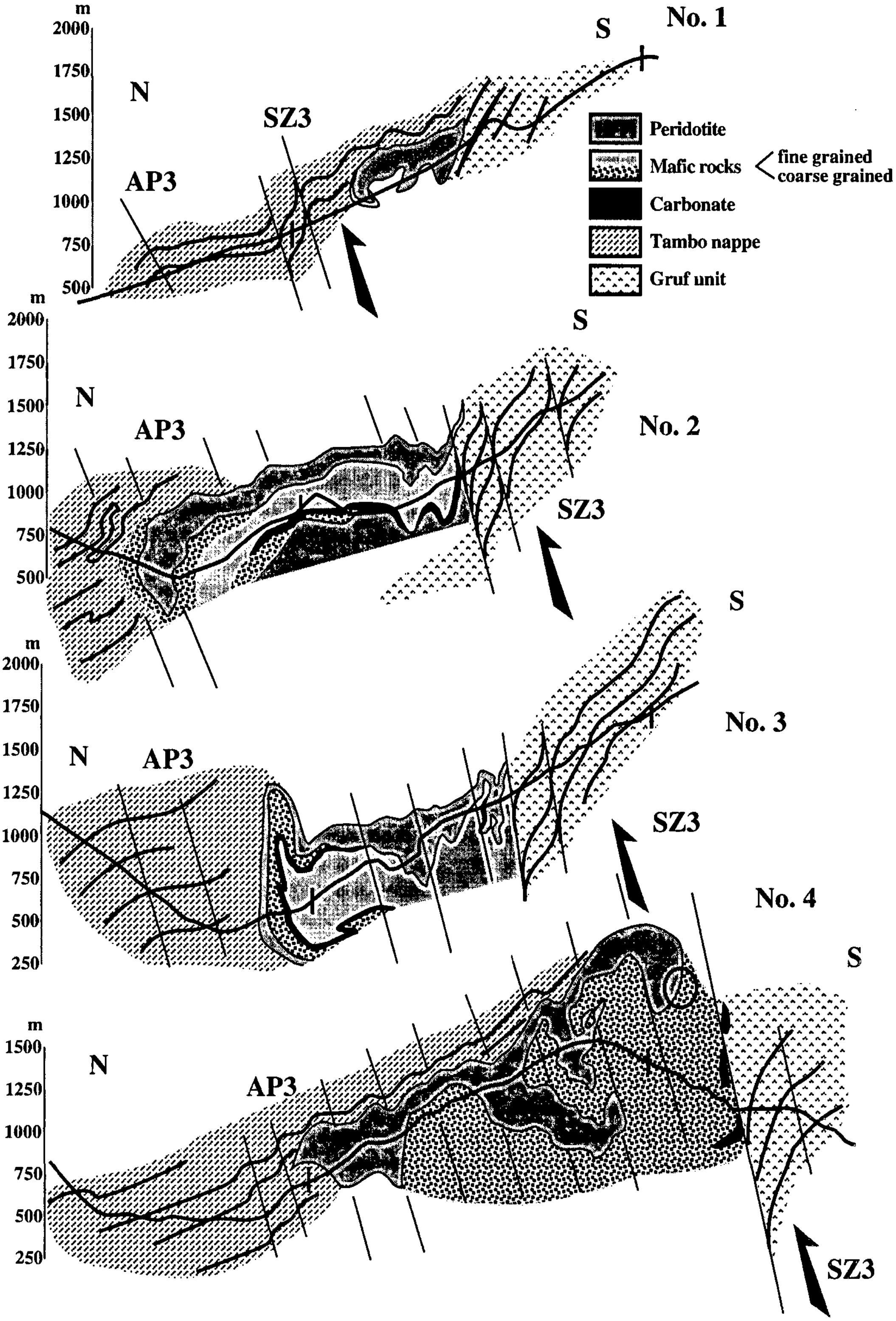
The Alpine deformation history in the study area can be described by four major deformation phases (D1–D4) which correspond to the major structures and tectonic events described above. Only D2 and D3 were well observed in the Chiavenna unit.

Prealpine mantle relics in the peridotites and D1 Alpine structures from the subduction event are rare. Despite this, it is possible to reconstruct the geometry of the Chiavenna unit for each phase. The first (D1) phase's schistosity and lineation have been preserved in only a few outcrops. Where there was limited D2-deformation, for example in the neck of large D1-boudins and close to D2-fold hinges, there is weak penetrative second axial-planar schistosity. The average regional D1-orientation (S1: 340/30 in azimuth and dip, L1: 340/30) best shown in the late Variscan Truzzo orthogneiss (Marquer, 1991) cannot be followed into the Chiavenna unit. The most penetrative D2-phase was responsible for the rotation of the S1 and L1 relic into a position sub-parallel to the D2-schistosity. Other preserved D1-structures are large-scale isoclinal folds, which, because of fold style similarity, can only be distinguished from the D2-folds by superimposed fold geometry (Figs. 4 and 5b). After restoring younger phases, D1-folds show isoclinal fold style on a large scale with two main axial planes in the study area (Fig. 5c). The first phase folds affected preexisting structures and the compositional layering of the ultramafic and mafic rocks as well as their lithological contacts.

The D2-deformation is the most penetrative on the regional scale and produced the dominant schistosity. This schistosity and the corresponding lineation can be correlated to zones where they are not affected by younger deformation. At these locations, for example the Tambo and the Suretta nappes in the middle and northern parts, the S2 shows a general N to NE dip of about 20°, while the L2 trends sub-horizontally E–W (Marquer, 1991; Baudin et al., 1993; Huber and Marquer, 1996). Large-scale isoclinal folds show an axial planar schistosity parallel to S2 and affect the entire nappe pile (Fig. 4). They show a general SE vergence, which becomes even more evident after restoring the D3 phase (Fig. 5). Large-scale boudinage during this phase created the actual shape of the Chiavenna unit (Fig. 2). This boudinage was also responsible for the horizontal cut off of the Chiavenna unit demonstrated in the N–S cross-sections (Fig. 4; top of section 1). A tectonic breccia associated with in-situ melting was formed at the base of the mega-boudins (see Section 5 and Figs. 6 and 7). The mega-boudins developed in major mylonite zones. These zones form the contacts to the upper unit, the Tambo nappe and the lower unit, the Gruf unit. Similar zones exist in the whole nappe pile, for example along the Tambo–Suretta contact (Huber and Marquer, 1996) and the greenschist facies Turba mylonite on top of the Suretta nappe (Fig. 3; Liniger, 1992). These mylonites are the last structures in the continuum of the deformation regime of the D2-phase and show bulk top-to-the-east ductile detachments (Fig. 8).

The third deformation phase D3 had less influence than the D2 phase and developed only locally

Fig. 4. Four N–S cross-sections across the Chiavenna unit showing the general geometry (see location in Fig. 1). The contact to the surrounding Tambo nappe and Gruf unit is discordantly cross-cut by the second schistosity (black lines in the Tambo nappe and the Gruf unit). Steep D3-folds (*AP3*: axial planes) and D3-shear zones (*SZ3*) (see thrusts in Fig. 1) represent the last ductile to brittle–ductile structures. The circle on cross-section 4 locates Fig. 6. Scale: no vertical exaggeration.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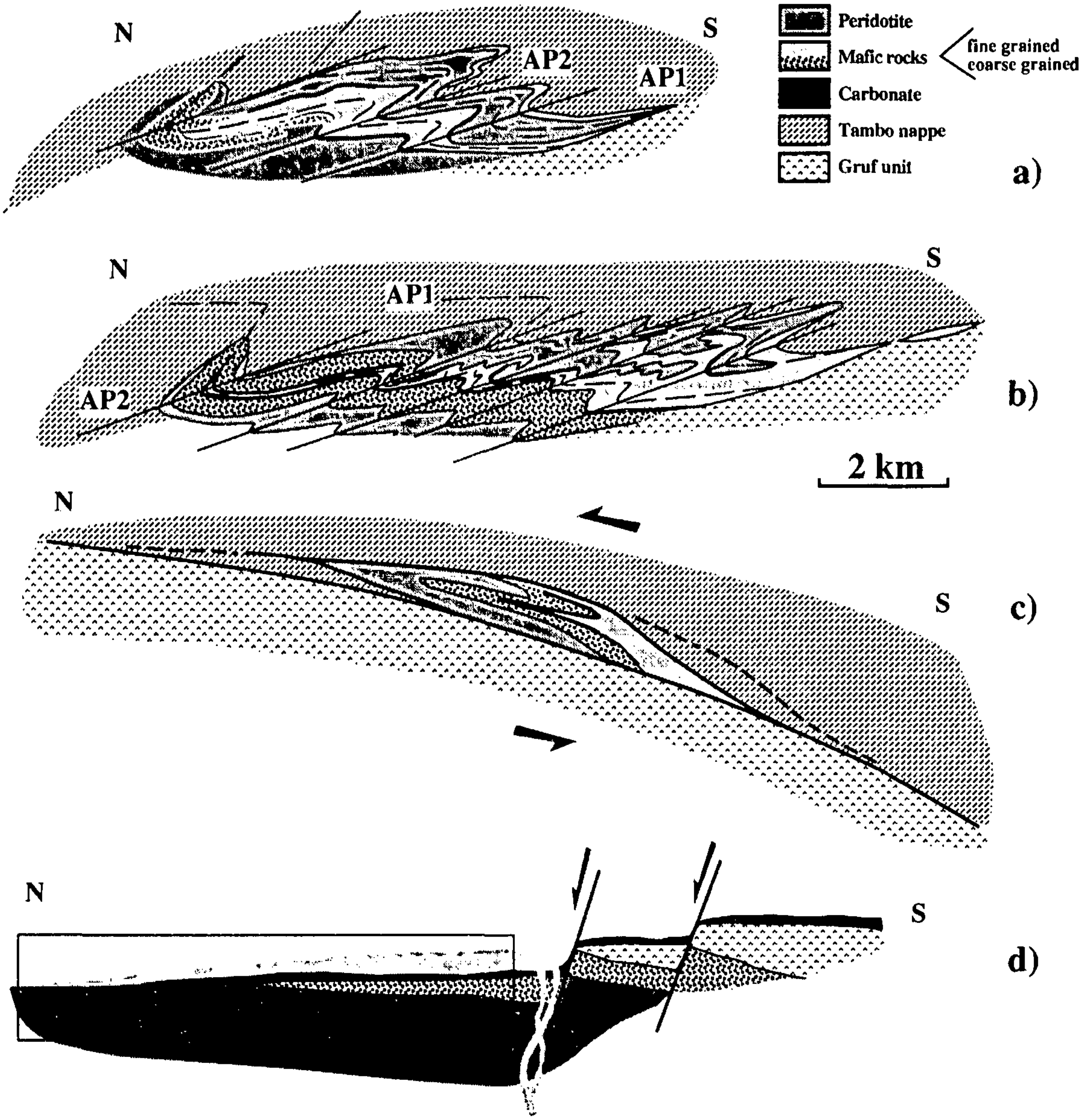

Fig. 5. (a, b) Schematic N–S cross-sections through the Chiavenna unit, structurally restored to before the D3-phase. The D2-folds (*AP2*: axial planes) have deformed an already complex geometry and pre-existing fold axial planes (*AP1*). Cross-section (a): compilation of the sections 1 and 2 (Fig. 4: eastern Chiavenna unit); cross-section (b): compilation of sections 3 and 4 (Fig. 4: western Chiavenna unit). (c) After unfolding the D2-folds, D1-folds (AP1) are shown in a schematic N–S cross-section through the Chiavenna unit. The major thrust plane represents the subduction zone. The figure is not to scale. (d) Palaeogeographic interpretation after restoration of the D1-phase shows discordant contacts between the topping basalt and the carbonate and the carbonate and the gabbro–peridotite complex. Note the lack of the carbonate in the north and the irregular shape of the gabbro. Basalt extruded from dikes, following Mesozoic normal faults. The black frame surrounds today's outcrop area. The figure is not to scale.

in an E–W-trending 20 km wide belt just north of the Insubric line (Fig. 3). In the study area, staircase-like E–W-trending folds with steeply S-dipping axial planes are the main geometrical structures of this phase (Fig. 4). There is a deformation gradient increasing towards the south (Figs. 3 and 4).

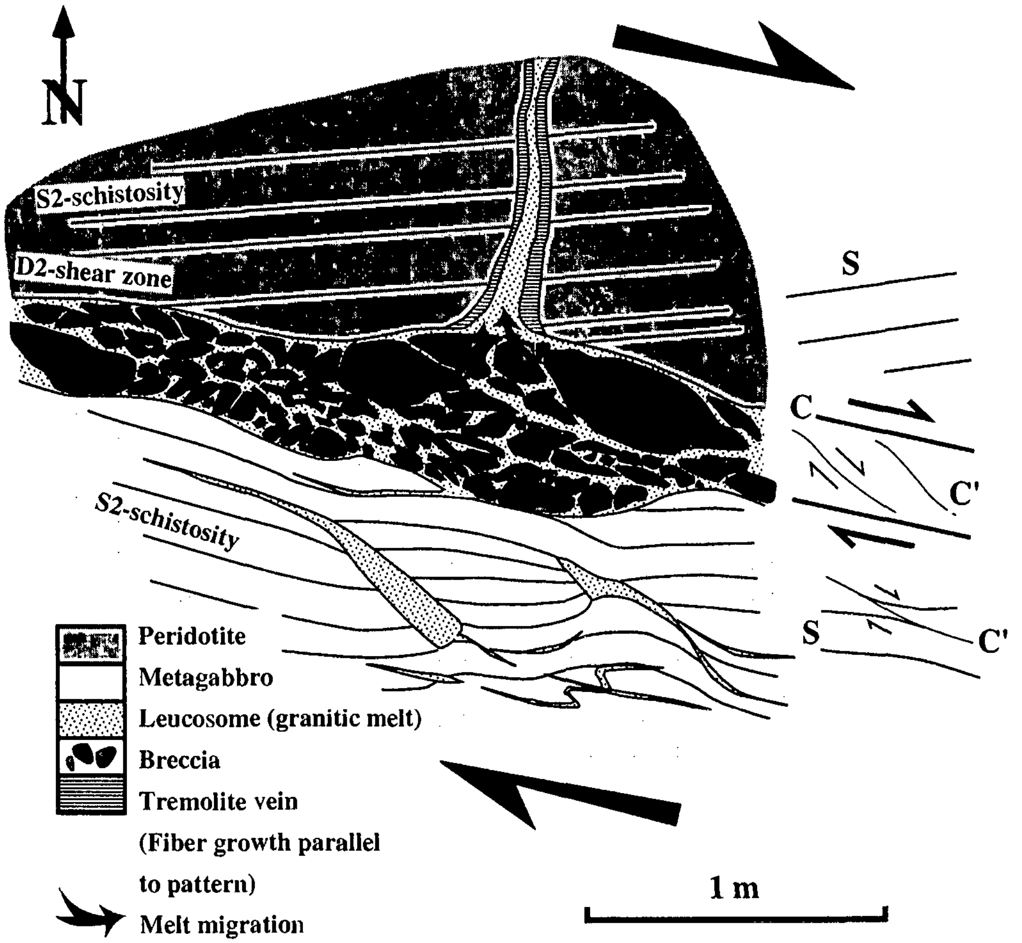

Fig. 6. Schematic map of the outcrop in the lower Val Schiesone (see location in Fig. 4). Melt formation in D2-shear zones (*C'*) in the gabbro and around breccia components (*C/C'*). The melt intrudes in the peridotite along an extension vein. The lithological contacts are rotated by the D3-deformation and subvertical actually.

The fold wavelength decreases while their amplitude increases. An axial planar schistosity with a down dip lineation developed in the strongest deformation zones. Late-D3 brittle–ductile thrusts, still with the same deformation axes, are N-directed and show steeply S-dipping thrust planes. Besides several minor fault zones, there is a major zone in the west which follows the contact of the Chiavenna and Gruf units (Fig. 4; cross-section 2, 3 and 4) and, in the east, cross-cuts the Tambo nappe in the north of the Chiavenna unit (Fig. 4, cross-section 1). All these steep, but not dominant structures are responsible for the steepening of previous structures in this E–W-trending belt north of the Insubric line (Fig. 3, Huber and Marquer, 1996).

The fourth deformation phase is linked to the Oligo–Miocene major faults, the Forcola fault (Marquer, 1991), the Engadine and the Insubric lines (Zingg and Hunziker, 1990) (Fig. 1). They do not affect the preexisting geometry in the N–S cross-sections (Fig. 4), even where the Forcola fault is just underlying the Chiavenna unit and where the brittle Engadine line just ends at its eastern contact.

5. Way-up indicators of partial melting

In the southern part of the Chiavenna unit close to the Gruf contact (Fig. 4) is a zone strongly affected by the D3 deformation. Therefore, all the

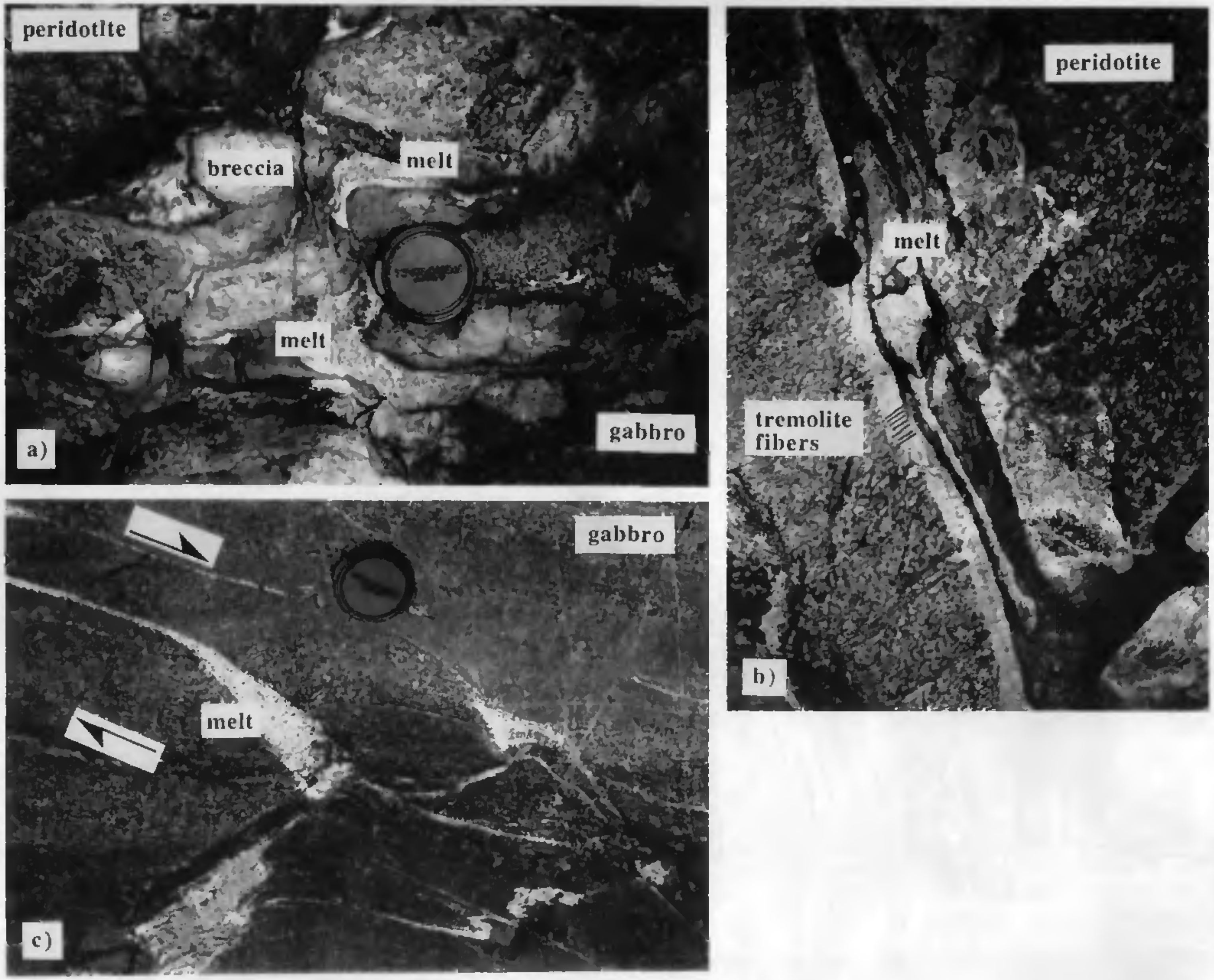

Fig. 7. (a) Melt around the breccia components. (b) Melt intrudes the meta-peridotite in an extension vein. (c) Melt in shear zones in the meta-gabbro.

previously created structures are steeply inclined. How much and with which sense of rotation the steepened pre-D3 structures have to be restored to obtain the D2-geometry? With the following observations it is possible to answer this question and to reconstruct the initial geometry and the orientation of the structures associated with the D2 phase. The present-day geometry of the contact between the ultramafic and mafic rocks belonging to the Chiavenna unit in the lower Val Schiesone (Fig. 4, cross-section 4) is schematically represented in Fig. 6. The contact itself is a sub-vertical dextral shear zone with sub-horizontal E–W-trending stretching lineation (C plane defined after Berthé et al., 1979) occurred during the D2-phase. The D2-mineral lineations trend sub-horizontally E–W on the shear planes and on the schistosity.

The meta-gabbro is composed of amphibole, plagioclase, biotite, epidote, ± quartz–ilmenite–magnetite–titanite. In this meta-gabbro, in-situ granitic melt (30% quartz, 30% K-feldspar, 30% plagioclase and small amounts of biotite and white mica) fills D2 secondary shear zones (C′ plane after Berthé et al., 1979) (Figs. 6 and 7c). The shearing also caused an asymmetric foliation boudinage with melt collected in the interboudin areas (Fig. 6). The melt is an in-situ product, because it fills extension veins and occurs only in narrow zones located in the main shear zones (Fig. 6). This relationships between the structures and the location of melt is an argument against an injected melt coming from deeper levels. The latter would suppose to show cross-cut relationships with respect to pre-existing structures which are not present in the studied out-crops.

The same granitic melt intruded in the meta-peridotite along E–W-opened extension veins in response to the D2 stretching axis which corresponds to the D2 stretching lineation (Fig. 7b). The first stage of the extension vein development is indicated by tremolite fiber growth orientation parallel to the D2 stretching lineations (X axis) (Figs. 6 and 7b). A tectonic breccia made up of components from both lithologies occurs between ultramafic and mafic rocks (Figs. 6 and 7a). The components were rotated in the sense of the shear and form secondary shear zones (Fig. 6; C′). They are surrounded by granitic melt (Fig. 7a). The melt sampled at the immediate contact with the breccia-clasts shows a different composition: almost 100% plagioclase and relic (restitic) biotite and amphibole. In the clasts at the contact with the melt, a poikilitic 'post-kinematic' hornblende overgrowing the S2-schistosity is present.

The melt was formed in structures compatible with deformation D2 in meta-gabbro, but it cuts across the S2-schistosity in the meta-peridotite. This indicates that the melt was formed during the latest stages of D2 high-temperature deformation. This geometric relationship supports a stage of melting prior to the Bergell intrusion, which occurred at the beginning of the D3-deformation (32–30 Ma years after von Blankenburg (1992) and Davidson et al. (1996)).

Assuming it is in situ, the occurrence of granitic melt in high-strain shear zones of biotite bearing meta-gabbro implies high-temperature deformation. The melting temperature of mafic rocks could substantially decrease under water-saturated conditions, creating peraluminous granitic melt and amphibole-rich restite (Beard and Lofgren, 1990; Rushmer, 1991). Different melting curves of wet mafic rocks are summarised in Rushmer (1991), indicating a minimum temperature for the melting around 700°C ± 50°C for pressures between 5 and 10 kbar. This range of pressure–temperature conditions corresponds to the decompression recorded by the Chiavenna unit during D2 (see Section 7 and Fig. 9). Wet conditions may be governed by a fluid supply that was localised in the referenced narrow shear zones. The two-mica leucosome and the poikilitic hornblende could indicate a peraluminous melt and restitic hydrous mineral phase, respectively (Beard and Lofgren, 1990; Rushmer, 1991).

While the meta-gabbro exhibits ductile structures, the peridotite shows brittle behaviour under the same deformation temperature conditions, emphasised by the tension gash openings and the breccia formation (Fig. 6). During shearing, mylonitisation enhances the fluid circulations along shear zones that can lead to wet melting conditions. The breccia at the interface between the gabbro and the peridotite is interpreted as an hydraulic breccia which, as well as local melting in the gabbro shear zones, occurs because of the presence of a free-fluid phase.

The distribution and geometry of melt, that was formed in the meta-gabbro and was collected in the peridotite, suggest that the peridotite was overlying the gabbro unit at the time of the melt emplacement. The final geometry of this outcrop shows a strong overprint of the D3-phase, reorienting all previous structures (Fig. 6). Therefore, the S2-schistosity and the D2-shear zone are now in a sub-vertical position (Fig. 4, cross-section 4, close to the contact with the Gruf unit). The rotation sense and the amount that occurred during the D3-phase can be estimated by knowing that S2 and SZ2 are gently inclined towards the northeast in regions with little or no D3-overprint (middle and northern Tambo and Suretta nappes in Marquer (1991) and Huber and Marquer (1996)) and the polarity of the D2-phase (Fig. 6). The D3 rotation axes correspond to the D3-fold axes and trend E–W, slightly dipping to the east. Therefore, restoring the D3-phase implies a clockwise rotation around the E–W-trending axes. The final geometry and D3-rotation sense locate the Chiavenna unit on the northern limb of a D3-antiformal structure, which is most probably the Gruf antiform (Fig. 3).

Once restoring the S2, SZ2 and the melt into their original position during D2, it becomes apparent that the mafic–ultramafic contact (Fig. 6) is located on the normal limb of a large-scale D2-antiform (Fig. 5b). In other words, the position of the meta-peridotite, overlying the meta-gabbro, is an inherited geometry, older than the D2-phase.

6. Geometrical restoration

The first step in the reconstruction leading to the possible geometry before Alpine tectonics is to restore the youngest deformation phase. Because the D4-phase does not change the present-day geometry, the D3-structures have been restored as a first step. After unfolding the D3-phase, the geometry of the D2-structures becomes apparent. Four N–S cross-sections point out the D3-deformation in the Chiavenna unit (Fig. 4). The D3 thrust zones lie discordant to the Chiavenna–Gruf contact (Fig. 2). They caused no major offset, leading to a discordance at map or cross-section scale (Figs. 2 and 4). In contrast, the D3-folds with steep south-dipping axial planes are responsible for the steepening of all previous structures. The main thrust zone, with a top-to-the-north shear sense, is located close to the southern contact of the western Chiavenna unit (Fig. 4, cross-sections 1–4).In the eastern Chiavenna unit, the zone is located in the north of the unit (Fig. 4, cross-section 1). Because the D2-axial planes are subparallel to the D3-axial planes in the present-day geometry of the steep zones, they could be misinterpreted (Fig. 4). The recognition of the two phases is based on field observations such as superimposed folding, intersection of schistosities and different directions of stretching lineations.

The large-scale effect of the D3-phase was a differential uplift of the zone north of the Insubric line, which creates an antiform-like structure if the previously flat-lying nappe contacts are regarded as an enveloping surface of the antiform (Fig. 3). The frontal part of the Tambo and Suretta nappes preserved the original flat-lying orientation of the D2-structures and the nappe contacts (Fig. 3). In the Chiavenna unit, restoring the northern limb of the D3-fold involves clockwise rotation around a sub-horizontal E–W-trending axis. This effect was confirmed using the previously described polarity indicator. After this rotation, the northern units (Tambo and Suretta nappes) lie on top of the southern units (Chiavenna and Gruf units) and in that case, large-scale D2-folds (AP2) with a general south-vergence and two major fold planes (AP1) refolded by D2-deformation become apparent. These are represented in two schematic N–S cross-sections of the Chiavenna unit (Fig. 5a,b). The tectonic contacts of all units appear to have been folded by the D2-phase (Fig. 5a,b).

Unfolding the D2-folds leads to the geometry of the D1-phase. The intense D1-folds (AP1) show S-vergence (Fig. 5c). No continuity of the D1-folds could be found in the Tambo and Gruf units (Fig. 4). Therefore, the overlying Tambo nappe and the underlying Gruf unit where separated from the Chiavenna unit by a tectonically active contact during the D1-phase (Fig. 5c).

Finally, unfolding the D1-folds shows the initial geometry of the lithology sequence of the Chiavenna unit (Fig. 5d). At this stage, the peridotite is partially overlain by coarse-grained basic rock, interpreted as gabbro. Several reasons might account for the varying gabbro thicknesses. It might be due to the initial form of an intruded gabbro, or to tectonics, as normal faults or ductile deformation during the D1 and D2 phases (Fig. 5d). Normal faults could have occurred because combined strike-slip and extension events formed the Valais basin and the northern margin of the Briançonnais terrane (Fig. 5d and Fig. 10a) (Stampfli et al., 1998). The high deformation undergone during Alpine tectonics obliterated these previous structures. On the other hand, the gabbro is covered directly by a thin carbonate layer (Fig. 5d). The carbonates could represent sediments, deposited on an exposed sub-continental mantle intruded by gabbros at a thinned continental margin, as is found in other parts of the Alps (Tasna nappe: Florineth and Froitzheim, 1994; Malenco unit: Hermann, 1997; Müntener, 1997) or in the Galicia margin (Boillot et al., 1995). With this reconstruction, fine-grained basic rocks, interpreted as basalts (MORB; Talerico, 1997), lie discordantly on the carbonate and the peridotite (Fig. 5d). A possible interpretation for this unconformable meta-basalt layer on the top of the carbonate rocks is the occurrence of local basic volcanism during the Mesozoic extension leading to an abnormal sequence of oceanic rocks (Fig. 5d).

7. Metamorphism

Mineral assemblages for each deformation phase were determined based on textural/microstructural relationships and compared with the T-peak metamorphism in this area (Niggli, 1970; Schmutz, 1976). The main mineral crystallization in all lithologies took place during the D2 deformation phase. Therefore, most often the older mineral assemblages as well as the corresponding structures show relic textures.

In ultramafic rocks, the oldest mineral relic is brown spinel. This indicates a Prealpine mantle origin from the spinel-lherzolite stability field (Fig. 8).

Few relic mineral phases are preserved from the D1-phase. A magnetite corona around the spinel, magnetite relic schistosity in enstatite grown prior to the S2 and antigorite with a static overgrowth of olivine and talc (Schmutz, 1976; C. Talerico, pers. commun., 1997) all indicate stable conditions

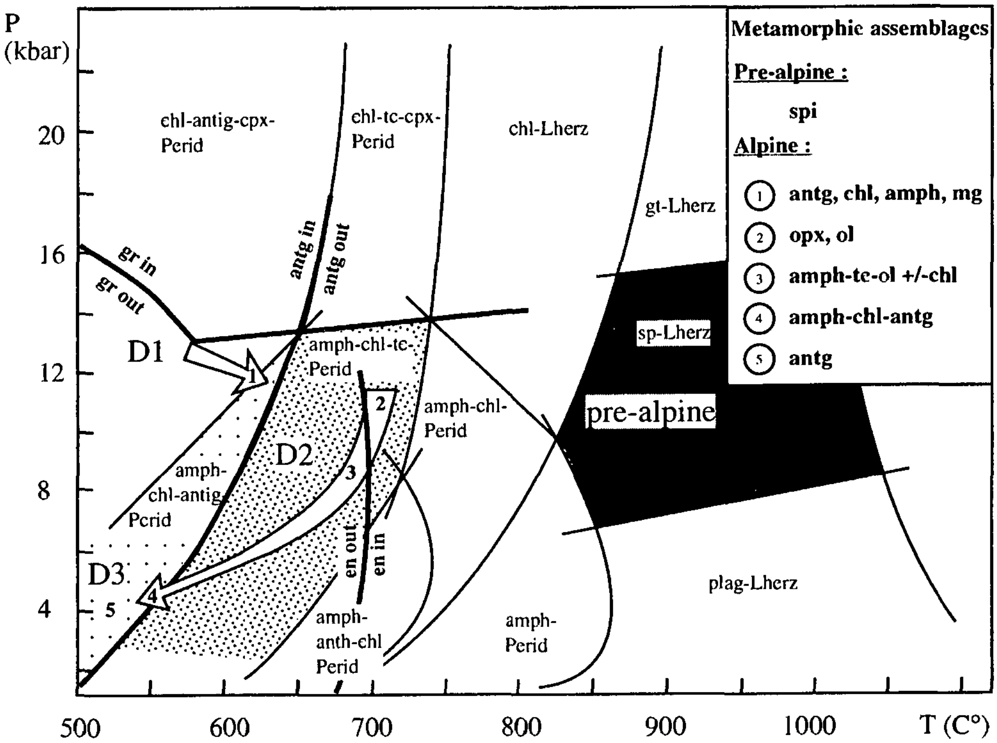

Fig. 8. The metamorphic history of the Chiavenna unit represented in a petrogrid (HCMAS) for meta-peridotites after Jenkins (1980). The garnet stability field for mafic rocks (after Bucher and Frey, 1994) and the enstatite and antigorite stability field for ultramafic rocks (after Raymond, 1995) are shown. Prealpine and Alpine mineral assemblages (*1–5*) are placed in their corresponding stability field and correlated with the Alpine deformation phases (D1–D3).

in the chlorite–antigorite–clinopyroxene peridotite and the chlorite–antigorite–amphibole peridotite stability fields (Fig. 8). The relic schistosity may be interpreted as S1.

The transition between the D1- and the D2-phase is represented by the previously mentioned enstatite and olivine, as well as the first growth of chlorite and amphibole. These minerals are texturally older than the S2, but younger than the D1 described mineral phases.

The D2-schistosity in the ultramafic rocks is manifest by talc, amphibole, sometimes chlorite or/and talc and a second generation of small equigranular olivine. During D2-mylonitization, olivine and amphibole and later antigorite recrystallized. The D2-minerals indicate conditions of the amphibole–chlorite–talc peridotite stability field (Fig. 8).

The dominant mineral of the D3-phase is antigorite, but in early D3-structures some amphibole and chlorite are still abundant. This indicates stable conditions in the amphibole–chlorite–serpentine peridotite field.

In Mg-rich amphibolites, the absence of garnet or garnet pseudomorphs limits the maximum pressure to 14 kbar (Fig. 8; gr-out stability curve; after Bucher and Frey, 1994). Therefore the *PT*-conditions for the Chiavenna unit during D1 are estimated at 550–650°C and 12–14 kbar (Figs. 8 and 9).

The Chiavenna unit came in contact with the overlaying Tambo nappe during the D1-phase. Later, they followed the same tectonometamorphic history. The early Alpine history (D1-phase) of the Chiavenna unit can be related to the tectonometamorphic evolution of the Valais subduction by taking into account the structural restoration (Fig. 5) and the *PT*-path of the Tambo nappe (Fig. 9) (Huber, 1997). Therefore, the *PT*-conditions at the base of the Tambo nappe are a minimum for the Chiavenna unit. This estimate is justified, especially taking into account the small thickness of the Chiavenna unit (Fig. 4). The *PT*-conditions for D1 at the base of the Tambo nappe are about 13 kbar and 500–600°C (Fig. 9) (Baudin and Marquer, 1993).

The growth of enstatite occurred between the development of the S1 and the S2. The estimated minimum temperature is around 700°C (Fig. 8; en-in stability curve; after Raymond, 1995). This growth of enstatite suggests a temperature increase from D1 to D2 and during the early D2 (Figs. 8 and 9). The above-described melt–structure relationships in the mafic rocks, forming melt in locally hydrated shear zones during early D2, indicate melting conditions at about 700–750°C. This observation confirms the temperature estimates based on the enstatite crystallization (Trommsdorff and Evans, 1969). The further *PT*-development during D2, based on recrystallization in successive structures, indicates cooling and decompression in the amphibole–chlorite–talc peridotite stability field (Fig. 8).

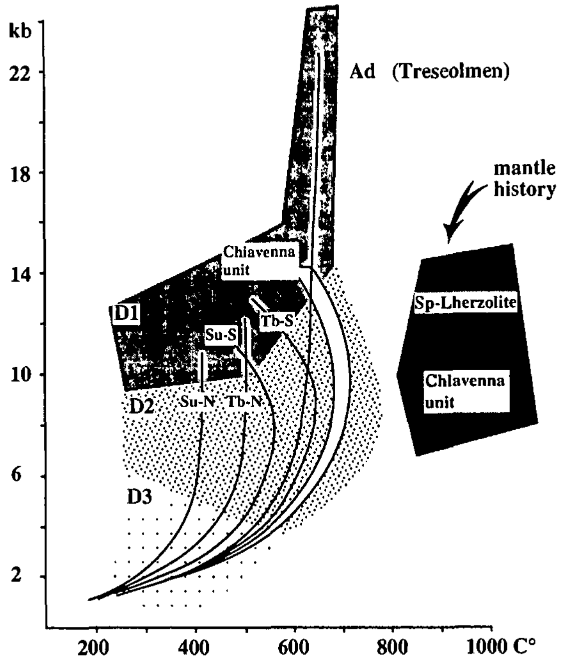

Fig. 9. Compiled *PT*-paths of the northern (*Tb-N*, *Su-N*) and southern (*Tb-S*, *Su-S*) Tambo and Suretta nappes, the Chiavenna unit and the Adula nappe (*Ad*, after Meyre et al., 1997). The deformation phases are indicated with D1, D2 and D3. Note the increase of temperature during the D2-phase in Tb-S, Su-S and the Chiavenna unit, whereas Tb-N and Su-N are submitted to isothermal decompression during D2. Although at higher temperature, the *PT*-path from the Chiavenna unit shows more affinity to the *PT*-paths from the Tambo and Suretta nappes than to the one from the Adula nappe. Prealpine mantle relics of the Chiavenna unit are represented by the spinel-lherzolite stability field.

The dominant mineral of the D3-phase is antigorite, but in early D3-structures some amphibole and chlorite are also abundant (Fig. 8; antg-in stability curve; Raymond, 1995). Because the first occurrence of antigorite is related to the latest D2-

mylonites, the *PT*-path enters into the amphibole–chlorite–serpentine peridotite stability field (Fig. 8) at about 550°C and 5 kbar just before the onset of the D3-deformation phase. The *PT*-path during D3 shows decompression and cooling (Fig. 9).

The *PT*-path for the Chiavenna unit (Fig. 9) has a similar shape to the *PT*-paths of the southern part of the Tambo and the Suretta nappes (Tb-S and Su-S in Fig. 9), although with higher temperature. The temperature increases during the early D2-phase, the same pattern as observed in the southern parts of the Tambo and Suretta nappes. In the Briançonnais and Chiavenna units no high-pressure relics were found like in the Adula nappe (Ad in Fig. 9) (Heinrich, 1986; Meyre et al., 1997; Brenker and Brey, 1997). In that case, the tectonometamorphic history of the Chiavenna unit seems to be related more to the overlying Tambo and Suretta nappes than to the underlying Adula nappe.

8. Palaeogeographic interpretation

Based on the unfolded Prealpine palaeogeometry of the Chiavenna unit (Fig. 5c), the position in the nappe pile (Fig. 3) and the described pressure–temperature-paths (Fig. 9), the following palaeogeographic interpretation is proposed, assuming that the main carbonate layer corresponds to Mesozoic sediments (Fig. 5c). Sediments directly overlying the peridotite and discordant to the peridotite–gabbro contact indicate a common geometry for a thinned continental margin in a lithospheric extension regime, where the subcontinental mantle rocks become exposed due to deep seated normal faults, subsequently covered by sediments (Florineth and Froitzheim, 1994; Boillot et al., 1995; Hermann, 1997; Müntener, 1997). Such a scenario can be imagined at the southern or northern rim of the Valais basin. As the high-pressure metamorphic conditions in the Chiavenna unit are not as high as in the Adula nappe, we attribute the Chiavenna unit to the northern margin of the Briançonnais terranes (Fig. 10a). Therefore, the gabbros may be interpreted as intrusions near the mantle–crust boundary, intruded before the Mesozoic extension. Two explanations are possible for the variable thickness of the gabbros (Fig. 5c): an initial heterogeneity due to the intrusion shape or a change of the thickness due to the effect of normal faulting. The overlying basalts may be explained by local extrusion of basic volcanic rocks in the vicinity of these normal faults during the first stages of the Valais basin opening. These basalt extrusions, cross-cutting the denuded subcontinental mantle at the northern margin of the Briançonnais terranes, could represent an early stage in the development of the formation of Valais oceanic crust (see review of the geological evolution of Briançonnais terranes in Stampfli et al., 1998). During the subduction of the Valais basin, corresponding to the first Alpine deformation phase (D1), in sequence thrusting tectonics leads to the emplacement of the Chiavenna unit into the nappe pile (Fig. 10b).

9. Conclusions

Assuming that the carbonates are of Mesozoic age, the unravelling of the geometry of the Chiavenna unit shows peridotites originating from a subcontinental mantle. Peridotites were intruded by gabbros located at the crust–mantle boundary at pre-Mesozoic time. During the Mesozoic extension, mantle denudation led to development of the Valais basin between the north of the Briançonnais terranes and the south European margin. This extension is responsible for the characteristic geometry of a denuded subcontinental mantle in the vicinity of a thinned continental margin, as well as its exposure at the seafloor resulting in the deposit of an unconformable carbonate cover. The position of the Chiavenna unit in the nappe pile and the similar shape of its pressure–temperature-path, compared to those of the Tambo and the Suretta nappes, favour the origin of the Chiavenna unit at the northern thinned margin of the Briançonnais terranes. During the subduction of the Valais basin, thrusts at mid-crustal level initiated the nappe geometry of the Tambo and Suretta nappes, whereas the lower parts of the crust disappeared in the subduction zone (Fig. 10). The initial geometry and location of the Chiavenna unit and movement along the mantle–crust décollement led to the emplacement of the Chiavenna unit in the nappe pile (Fig. 5c, Fig. 10b). During this deformation phase (D1), the first isoclinal folds were formed. The second isoclinal folds (D2) affecting the contacts

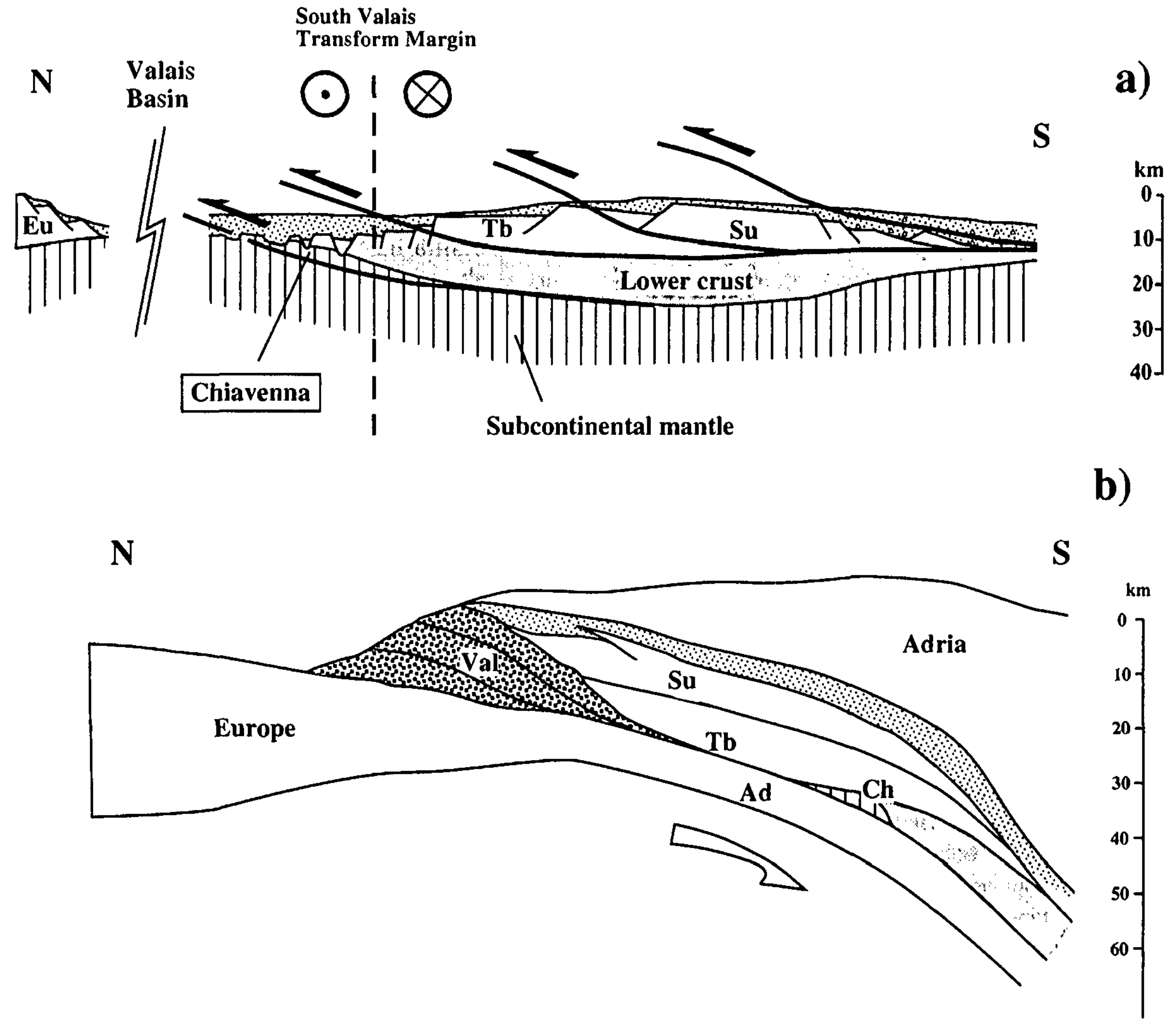

Fig. 10. (a) A model for the palaeogeographic reconstruction of the Chiavenna unit interpreted as denuded subcontinental mantle at the thinned northern margin of the Briançonnais terranes (*Tb*: Tambo nappe; *Su*: Suretta nappe; *Eu*: European margin). Late Mesozoic sinistral transtension in the Valais basin (*Val*) forms the geometry of the northern Briançonnais margin with steep normal faults and assists to the exhumation of the Chiavenna unit. Tertiary thrusts (D1) in the Briançonnais nappes are indicated with black arrows. (b) Nappe stacking during the subduction event (D1). Most of the lower crust (grey pattern) gets subducted, while the Briançonnais domain is overriding the Valais basin (*Val*) and the European margin (*Eu*) and Adula nappe (*Ad*).

of the stacked tectonic units were formed during syn-collisional extension. Associated thermal equilibration led to the thermal peak during the D2 Alpine metamorphism locally creating a melt that intruded into the overlying peridotite. Late Alpine uplift along the Insubric mylonites led to the final geometry of the Chiavenna unit, shown by the steepening of the nappe pile and N-directed local thrust.

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Résumés étendus

1. EUG 1995

THE RELATIONSHIP BETWEEN EXTENSION AND UPLIFT-EROSION PROCESSES IN THE ROOT ZONE OF THE EASTERN PENNINE NAPPES (VAL BREGAGLIA)

R.K. HUBER, T. BAUDIN
(Institut de Géologie, rue E.-Argand 11, 2007 Neuchâtel, Suisse)

Exhumation can be caused by two main processes, either by normal faulting or by uplift-erosion processes. A distinction can be made by taking into account structural and metamorphic data, which is the aim of this work.

The region of interest is the pennine nappes of the Briançonnais zone located in the eastern Central Swiss Alps. It has been chosen because of its structures of the late alpine orogenic evolution.

This work is based on detailed structural and microstructural mapping. The evaluation of field data gives the following sequence of structural phases: A first gently N dipping schistosity and stretching lineation has been overprinted by a second schistosity whitch dips moderately to the NE. Its associated stretching lineation dips to the E and is linked to shear zones showing a top-to-E movement. They are responsible for the offset of lithological units in normal faults. The third schistosity and lineation are both steeply S dipping. They are contemporaneous with steeply inclined N dipping and S thrusting shear zones. In very limited zones, a fourth phase is formed by E dipping normal faults with a NE dipping lineation. Late lithological and structural offsets can be linked to it.

The first phase is due to nappe stacking during the subduction of the Briançonnais basement. The second phase is due to syn-orogenic ductile extension in the nappe pile. This extension is due to a buoyancy desequilibrium caused by the abnormal thickness of the crust. The third phase formed during late continental collision which caused a major uplift accompanied by erosional exhumation. The fourth phase involves late orogenic normal faulting due to the movements along the Engadine and Insubric Lines.

2. TMIDSR 1995

ALPINE TECTONIC AND METAMORPHIC EVOLUTION OF THE ROOT ZONE OF THE EASTERN PENNINE NAPPES (VAL BREGAGLIA, CENTRAL SWISS ALPS)

RACHEL K. HUBER, THIERRY BAUDIN & DIDIER MARQUER
Institut de géologie, Université Neuchâtel, Switzerland

Tertiary deformation and kinematics, as well as the associated metamorphic assemblages were defined in the root zone of the eastern pennine nappes. This data base allows to propose an interpretation about the tectonic evolution during Tertiary collision of the studied area and a correlation with the regional tectono-metamorphic history. The region of interest is formed by the southern parts of the Tambo and Suretta nappes, located in the Val Bregaglia, Central Swiss Alps. Those are in the position of the two upper most eastern pennine units in the nappe pile and are derived paleogeographically from to the Briançonnais zone. These heterogeneously deformed nappes are mainly build up by a polycyclic and polymetamorphic basement consisting in metasediments, amphibolites and metagranitoids. They are crosscut by late Variscan intrusives and overlain by a thin autochthoneous Permio-Mesozoic cover. The upper part of the Mesozoic cover is formed by an allochthoneous unit, the Starlera nappe. The Tambo and Suretta nappe are underlain by the "Ophiolites of Chiavenna" and the Adula nappe and overlain by the Avers schistes lustrés. This structural data, acquired by structural and microstructural fieldwork, allow to draw schistosity and lineation trajectory maps and to define the kinematics of each
deformation phase. Finally, microprobe and microscope analysis permit to determinate the
metamorphic evolution. Based on this survey the following phases can be distinguished:

The first phase shows a ductile heterogeneous deformation with localized top to the N moving shear zones. Its schistosity and adjacent lineation are gently NNW dipping. The corresponding mineral phases recrystallized under HP conditions (eg. Tambo nappe: ~13-10 kb, ~500°C). This first phase is overprinted by a ductile second phase, which creates the main gently NNE dipping schistosity. Its adjacent sub horizontal lineation trends EW. Contemporaneous shear zones with a top to the E movement can be observed at all scale. They are responsible for the offset of the lithological contacts and the thinning of the nappes in the southeast. The second phase was set under decompressional but constant thermal conditions (eg. Tambo nappe: ~11-6 kb, ~500°C). The third phase is observable only in restricted areas. Its schistosity and lineation are both steeply S dipping and are associated to E-W striking open folds. They are contemporaneous with a set of steeply inclined S dipping N thrusting shear zones and its conjugated N dipping and S thrusting minor set. This phase is responsible for the steepening and reorientation of the second schistosity in the root zone and the pop up of the Bergell area. It took place under lower greenschist facies conditions close to the brittle-ductile transitions. The forth phase is formed by major NE dipping normal faults.

The first phase is interpreted as the main nappe stacking towards NW during the Eocene subduction of the Briançonnais basement during the closure of the Valais trough. The second phase is due to syn-orogenic ductile extension in the nappe pile parallel to the orogenic belt axe. This Eocene to Oligocene extension is due to the relaxation of a buoyancy desequilibrium caused by the abnormal thickness of the crust and led to the observed isothermal decompression. The third phase formed during late continental collision implied a differential uplift with the major elevation in the southern most parts. The uplift forces erosional exhumation and induces the starting of the cooling. This Oligocene phase is syn-post Bergell intrusion. The fourth phase involves late orogenic normal faulting contemporaneous to the movements along the Engadine and Insubric Lines (Ss. Tonale Line) and is a symmetric equivalent of the brittle Simplon phase in the western part of the Pennine zone.

3. EUG 1997

The Tectonometamorfic Evolution of the Continental Crust and the Upper Mantle during the Alpine Tertiary Continental Collision shown at the example of the Eastern Penninic Nappes (Val Bregaglia, Switzerland)

Rachel K. Huber1
(huber@geol.unine.ch)

1 Institute of Geology, Neuchâtel University, Neuchâtel, Switzerland

The tectonometamorphic evolution during alpine Tertiary continental collision of several adjacent tectonic units from the upper crust to the upper mantle has been established taking into account metamorphic and structural data. Different processes are proposed to explain the diverging, respectively converging PT-paths of the units.

The worked out area is situated in Southeastern Switzerland and contains the eastern penninic nappes. Today the units are stacked from the bottom to the top as following: Gruf unit (lower crust, no sediment cover) and Chiavenna

unit (ultramafic and mafic rocks, no sediments), Tambo and Suretta nappes (upper crust up to sediment cover). They are overridden by the Austroalpine units and crosscut by the Tertiary Bergell intrusion.

Unraveling the suite of structural deformation phases allows indications about the kinematic evolution of the tectonic units, whereas the mineral assemblages linked to each particular deformation phase describe a time relative PT-path. The PT-paths of the Suretta and Tambo nappes shows a similar path from HP to isothermal decompression and Barrovian cooling (Suretta: Pmax. 9-12 kb, Tmax. 500-560°; Tambo: Pmax. >12 kb, Tmax. 580-650°). The Chiavenna unit shows constant cooling and decompression from subcontinental mantle depth to exhumation (Pmax. >10 kb, Tmax. 700-800°). So only the second part of the PT-path for the Tambo and Surtta nappe is similar to the path for the Chiavenna unit. The PT-path for the Gruf unit indicates isothermal decompression and later Barrovian cooling from HP-HT conditions to exhumation. The highest condition's mineral assemblage is related to prealpineroxene, Garnet, Sillimanite: Pmax. >10 kb, Tmax. 750-800°). It represents a mixed PT-path, which shows only a similar form to the paths from Tambo and Suretta during the cooling/decompression history.

The Tambo and the overlaying Suretta nappe had the same tectonic history through the Tertiary orogenesis; they passed through subduction, and after the continent-continent collision, to exhumation. No LP-LT relicts of an oceanic stage can be found in the Chiavenna unit. They show only an exhumation, but no subduction history. This fact is interpreted as a deeply situated origin of the ultramafic and mafic rocks, joining the general PT-path trend after the continental collision. A possible subduction event does not modify the original P-indicators. The Gruf units inherited dray HP-HT mineral assemblage may be responsible for the lack of registration of an HP-LT assemblage during the alpine subduction event. But it shows distinctly the general PT-path trend after the continental collision during exhumation. The long lasting HT condition could be maintained by the near melt formation close to the Bergell intrusion. Extension in the crust and the upper mantle, preceding subduction, may explain the emplacement of the originally deep seated Gruf and Chiavenna units at upper crustal level.

4. Padova 1998

TECTONOMETAMORPHIC EVOLUTION OF THE EASTERN PENNINE ALPS DURING TERTIARY CONTINENTAL COLLISION: STRUCTURAL AND PETROLOGICAL RELATIONSHIPS BETWEEN SURETTA-, TAMBO-, CHIAVENNA AND GRUF UNITS (SWITZERLAND/ITALY).

Rachel K. Huber & D. Marquer
Institut de Géologie, Université de Neuchâtel, E.-Argand 11, 2009 Neuchâtel, Suisse

The Suretta and Tambo nappes, as well as the Chiavenna and Gruf units belong to the Eastern Pennine nappe pile. The region of interest is formed by the southern parts of the Tambo and Suretta nappes, located in the Val Bregaglia, Eastern Swiss Alps. Those are in the position of the two upper most eastern pennine units in the nappe pile and are derived paleogeographically from to the Briançonnais zone. These heterogeneously deformed nappes are mainly build up by a polycyclic and polymetamorphic basement consisting in metasediments, amphibolites and metagranitoids. They are crosscut by late Variscan intrusives and overlain by a thin autochthonous Permo-Mesozoic cover. The Tambo and Suretta nappe are underlain by the Chiavenna and Gruf units. The Chiavenna unit is built up mostly by ultramafic and mafic rocks with a subcontinental to oceanic origin. The Gruf unit consists of metagranitoids and granulites of presumably pre-alpine age and migmatites of alpine and pre-alpine age.

Tertiary deformation and kinematics, as well as the associated metamorphic assemblages were defined in the four tectonic units. This data base allows to propose an interpretation about the tectonic evolution during Tertiary collision of the studied area and a correlation with the regional tectono-metamorphic history. Based on this survey the following phases can be distinguished:

The first phase shows a ductile heterogeneous deformation with localized top to the N-moving shear zones. Its schistosity and adjacent lineation are gently NNW dipping. The corresponding mineral phases recrystallized under HP-conditions (eg. Tambo nappe: ~13-10 kb, ~500°C). This first phase is overprinted by a ductile second phase, which creates the main gently NNE-dipping schistosity. Its adjacent sub-horizontal lineation trends EW. Contemporaneous shear zones with a top to the E-movement can be observed at all scale. They are responsible for the offset of the lithological contacts and the thinning of the nappes in the southeast. The second phase underwent decompression with a thermal maximum at the beginning of D2 (eg. Tambo nappe: ~11-6 kb, ~610°C), whereas in the northern Tambo and Suretta nappes almost isothermal decompression took place. The PT-conditions during the D2-phase increase through the nappe pile from top to bottom (Suretta nappe: ~10-5 kb, ~550°C and Gruf unit: ~10-4 kb, ~730°C). In the north, the third phase is observable only in restricted areas, whereas in the south, the whole area is isoclinally folded. Its schistosity and lineation are both steeply S-dipping and are associated to folds with E-W striking fold axes. They are contemporaneous with a set of steeply inclined S-dipping N-thrusting shear zones and their conjugated N-dipping and S-thrusting minor set. This phase is responsible for the steepening and reorientation of the second schistosity in the root zone and the pop up of the Bergell area. In the north, this deformation took place under lower greenschist facies conditions close to the brittle-ductile transition and in the south in the Gruf unit, it started at ~4 kb, ~550°C. The forth phase is formed by major NE-dipping normal faults sub-parallel to the Forcola fault.

The first phase is interpreted as the main nappe stacking towards NW during the Eocene subduction of the Briançonnais basement during the closure of the Valais trough. The second phase is due to syn-orogenic ductile E-W extension in the nappe pile parallel to the orogenic belt axes. This Eocene to Oligocene extension is due to the relaxation of a buoyancy desequilibrium caused by the abnormal thickness of the crust and led to the observed isothermal decompression. The third phase formed during late continental collision implied a differential uplift with the major elevation in the southern most parts. The uplift forces erosional exhumation and induces the starting of the cooling. This Oligocene phase is syn-post Bergell intrusion. The fourth phase involves late orogenic normal faulting contemporaneous to the movements along the Engadine, Insubric Lines (Ss. Tonale Line) and the Forcola fault and is a symmetric equivalent of the brittle Simplon phase in the western part of the Pennine zone.