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Basement–cover relationships in the Tambo nappe (Central Alps, Switzerland): geometry, structure and kinematics

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Abstract—In the Pennine zone of the Central Alps, the Tambo nappe forms a thin crystalline sliver embedded in the Mesozoic cover. Four Tertiary Alpine deformations are observed. The D_1 ductile deformation is linked to the progressive Eocene stacking of the nappes towards the northwest. During D_1, basement deformation is governed by imbricate tectonics whereas cover is thin-skinned and intensively folded. These different structures reflect the original strong rheological contrast between basement and cover. During the heterogeneous and ductile D_2 deformation, the behaviour of the basement and cover became similar. The strong vertical D_2 shortening, associated with a 'top-to-the-east' shear, led to the folding of the prior SE-dipping structures, developing SE-vergent folds with axes close to the E–W L_2 stretching lineation. D_2 corresponds to post-collisional crustal thinning following D_1 crustal thickening. The D_3 and D_4 deformations occurred under retrograde conditions and can be correlated with uplift and late dextral movement on the Insubric line, respectively.

INTRODUCTION

THE Penninic zone corresponds to the internal parts of the Alpine mountain belt that resulted from the collision between the European plate in the north and the Adriatic plate in the south. This area is constituted overall of imbricate stacks of sedimentary cover and basement slices. The structure of the Penninic basement nappes has been one of the major problems in the geology of the Swiss Alps, and for a long time the subject of numerous controversies (Argand 1909, Milnes & Pfiffner 1980, Trümpy 1980, Frei *et al.* 1989). Based on the geometry of the cover wrapped around crystalline basement, some authors interpret the nappes as huge ductile recumbent folds (Steck 1987, Escher *et al.* 1988), where basement and cover are equally highly deformed. On the other hand, new research on the eastern part of the Penninic zone describes crystalline nappes as huge heterogeneously deformed thrust sheets embedded in the surrounding sedimentary cover (Pfiffner *et al.* 1990b).

The Adula, Tambo and Suretta nappe pile (Gansser 1937, Zurflüh 1961, Blanc 1965, Strobach 1965, Weber 1966) is located in the Central Alps, east of the Lepontine dome (Fig. 1). This paper examines in detail the structure of one of these Penninic nappes: the Tambo nappe. The overall structure of this area was early recognized by Milnes (1974), based on structural observations in the Suretta nappe. On a large scale, the basement slabs were considered as a combination of heterogeneous thrusts and huge recumbent folds (Milnes 1974, Milnes & Schmutz 1978). More recently, new metamorphic and structural investigations have been made in the Tambo and Adula nappes (Heinrich 1986, Löw 1987, Mayerat 1989, Pfiffner *et al.* 1990a,b) benefiting from new geophysical data and reflection seismic profiles from the National Research Programme NFP-20 on the deep structure of Switzerland (Pfiffner *et al.* 1988, 1990a,b, Schmid *et al.* 1990). The bulk tectonics of the Central Alps have been modelled in the laboratory by Merle & Guiller (1989), and Schmid *et al.* (1990) have used the results in their interpretation of the Tambo–Suretta nappe structure and adjacent cover nappes.

The aim of this study is to describe the four Alpine deformations and kinematics of the Tambo nappe, focusing on basement–cover geometrical relationships and the different rheological behaviour of these units, in respect to the successive deformation phases.

Geological setting

The Tambo nappe is located in the southeastern part of Switzerland between the Adula and Suretta nappes (Fig. 1). These three units are mainly composed of an old crystalline basement and small occurrences of Permian rocks. The nappes are separated by different Mesozoic covers (Gansser 1937): (i) the Misox zone, between the Tambo and Adula; and (ii) the Splügen zone, between the Tambo and Suretta. The Misox zone is the southern extremity of the north Penninic Bündnerschiefer and flysch (Tomül unit). It represents the 'suture' resulting from the closing of the Valais trough between the south European margin (s.s.) and the Briançonnais suspect terranes (Tambo and Suretta). The Misox zone does not exceed 800 m in thickness and consists mainly of calcareous schists with some extremely stretched lenses of gneisses (Gadriol gneiss) and basic rocks. The Tambo and Suretta crystalline nappes are surrounded by another cover sequence, common to both. The cover rocks—pinched between the Tambo and Suretta nappes and known as the Splügen zone—show important thickness variations. The Tambo basement consists mainly of polycyclic rocks, intruded in the south by the Truzzo granite, of Permo-Carboniferous age (Gulson 1973).

The tectonic evolution of the Tambo and Suretta

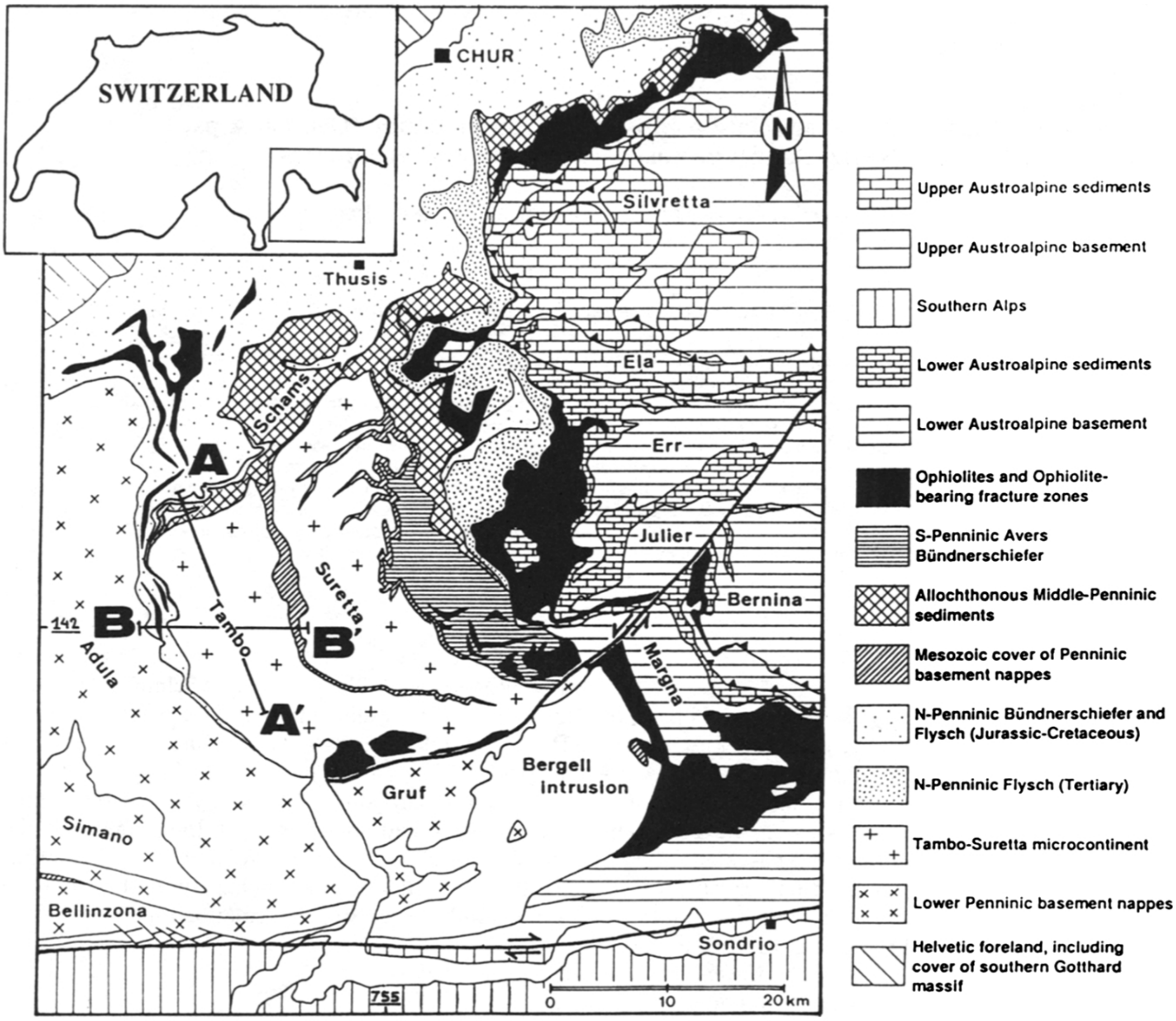

Fig. 1. Geological map of the Central Alps in SE Switzerland and adjacent parts of Italy and Austria (according to Schmid *et al.* 1990). Sections A–A′ and B–B′ correspond to Figs. 2 and 3, respectively. Owing to the regular steep dip of the structures towards the east, the map can be read as a vertical section, with an exaggerated vertical scale.

nappes probably began in early Tertiary times with the stacking of the nappes during the final stages of collision between Europe and Adria (Mayerat 1989, Merle *et al.* 1989, Schmid *et al.* 1990). In the Tambo nappe, the first deformation linked to the stacking, called D_1 (Mayerat 1989, Marquer 1991), occurred under high P–low T (<500°C) conditions (Frey *et al.* 1980, 1983, Pfeifer *et al.* 1991). The entire nappe pile then passed through the Meso-Alpine metamorphic peak (Wenk 1970, 1974, Frey *et al.* 1974) with greenschist facies in the north and amphibolite facies in the southern part of Tambo, simultaneously with the D_2 deformation (Marquer 1991). The following deformations (D_3 and D_4, Marquer 1991) occurred under decreasing P–T conditions with retrograde metamorphism.

Methods

The following interpretation of the tectonic evolution of the Tambo nappe is based on detailed knowledge of: (i) the geometry of the basement–cover interface; (ii) the shear-zone patterns in the basement, especially in the late Variscan Truzzo granite; and (iii) the correlation of deformations between basement and cover. Detailed field work and structural analyses enabled us to distinguish pre-Alpine and Alpine deformational effects in the basement as well as to appreciate the different behaviour of basement and cover units during the same deformational event. More information on the methods used can be found in Mayerat (1989) and Marquer (1991).

GEOLOGICAL UNITS

The Tampo nappe basement

Much of the Tambo basement is 'polycyclic' and characterized by signs of strong pre-Alpine deformations. Most of these polycyclic basement rocks are metapsammites or metagreywackes rich in Na- and K-feldspars. Some metapelites are also present in the nappe, in the form of micaschists with pre-Alpine minerals such as staurolite, kyanite, andalusite, garnet, muscovite and biotite. Some migmatitic rocks are found in the southern part of the nappe. An old orthogneiss (Foppa gneiss) cross-cuts the whole nappe and may have been emplaced during anatectic processes. In the northern part of the nappe, alignment of lenses of mafic and ultramafic rocks are especially well developed. These have become amphibolites, with a few preserved pyroxene–garnet assemblages (pyroxenites or eclogites). In other parts of the nappe, the mafic rocks have suffered a complete retrograde metamorphism which produced prasinites or ovardites. Equivalents of these polycyclic basement rocks are also found in the Suretta basement (Timun complex, Zurflüh 1961, Blanc 1965).

The 'monocyclic' basement in the Tambo nappe is represented by Truzzo granite, well exposed in the southern part of the nappe (Fig. 2). This granitic complex is 293 ± 14 Ma (Rb/Sr whole rock dating, Gulson 1973) and has therefore suffered only Alpine deformation—hence the term 'monocyclic'. Accordingly, it appears as an originally isotropic and homogeneous body of porphyritic granite (with centimetric K-feldspar porphyroclasts), crossed by many Alpine shear-zones (Marquer 1991). Generally, the top of the granite is overlain by polycyclic rocks, except in the southeastern part of the area where it is directly covered by the 'Permo-Triassic' unit (see below).

The Tambo nappe sedimentary cover

Our recent field work has revealed that monocyclic 'Permo-Triassic' rocks are more abundant in the Tambo and Suretta nappes than previously recognized (Baudin *et al.* 1991). The Mesozoic calcareous cover always overlies this volcano-detrital series and is never directly in contact with the basement rocks (Figs. 2 and 3). These two units together are taken to compose the sedimentary cover in the front of the Tambo nappe and are both included in the Splügen zone (Fig. 3). The Splügen zone is considered as a single unit although it shows a complex internal structure composed of several slices. In this new interpretation, the Splügen zone groups together the prior subdivisions of Strobach (1965), i.e. his Bardan and Andossi zones.

The 'Permo-Triassic' cover generally overlies the basement, but it can also be found as thin wedges pinched between slabs of crystalline rocks in the front of or in the roof of the nappe as well as in the base of the overlying Suretta unit. The cover is called 'Permo-Triassic' because of: (i) its stratigraphic position between old basement and Mesozoic carbonate series; and (ii) its facies, similar to that of the Briançonnais zone (Staub 1958). Conglomerates at the bottom of the stratigraphic pile show lithological similarities to the classic 'Verrucano' facies and pass progressively into more and more quartzitic formations. In certain places, the series seems to begin with an augen gneiss a few meters thick and it generally shows strong volcano-clastic tendencies with gneiss-like rocks rich in K- and Na-feldspars. One can observe a clear facies convergence between the latter rocks and the Roffna porphyry, especially when the rocks have been deformed. The Roffna porphyry has a high-level intrusive and volcanic origin (Grünenfelder 1956, Milnes & Schmutz 1978) and forms the frontal part of the Suretta nappe. Until now, its age has been considered as 350 Ma ($^{207}Pb/^{206}Pb$; Hanson *et al.* 1969) but the similarity of most of its volcano-clastic facies with that of the Permo-Triassic cover, directly overlain by Triassic carbonates, could indicate rather a younger age (Permo-Triassic).

The carbonate Mesozoic cover of the Tambo nappe (Splügen zone) has been regarded by most previous authors as only Triassic (with the exception of Staub 1958). Our recent field work has shown the presence of a complete Penninic cover in a normal position, systematically overlying the Permo-Triassic cover. Comparisons with other areas of the Briançonnais cover (Barrhorn series, Sartori 1990; and Vanoise cover, Jaillard 1988) show roughly the same stratigraphic sequence starting with middle Triassic dolomite, followed by the Dogger or Malm breccias, Malm layered marbles and Cretaceous phengite-rich marbles or calcareous schists (perhaps up to the Paleocene). These facies are also those of the Schams nappe, situated in front of the Tambo–Suretta basement units (Mayerat 1989, Schmid *et al.* 1990). Mainly due to the Tertiary Alpine deformation, the thickness of the Mesozoic Splügen zone varies from a few meters up to several hundred meters. It must be pointed out that the 'Permo-Triassic' and the carbonate series of the cover are frequently separated by a cornieule layer which has developed from middle Triassic dolomites and evaporites.

BASEMENT–COVER RELATIONSHIPS

Basement and cover have both undergone a polyphase Alpine deformational history. In the basement, the late Variscan Truzzo granite provides a good lithological marker to separate Alpine deformations from pre-Alpine structures (Marquer 1991). A single deformational event is defined by a group of structures showing the same strain axes, the same bulk kinematics and the same metamorphic evolution. For each deformational event, the principal strain axis X and the X–Y plane of the strain ellipsoid are defined by the stretching lineations (marked by the orientation of minerals, enclaves, pebbles, etc.) and the schistosity plane (Ramsay 1967, p. 177). Using this approach, four successive Alpine deformations, called D_1–D_4, have been recognized. On all scales, the two major phases, D_1 and D_2, are characterized by a heterogeneous ductile deformation (Marquer 1991). Therefore, relics of pre-Alpine and/or D_1 stretching lineations are well preserved in weakly deformed domains surrounded by strongly deformed D_2 zones. These D_1 and D_2 deformation phases have led to the present nappe structure. D_3 and D_4 did not have a significant effect on the overall geometry of

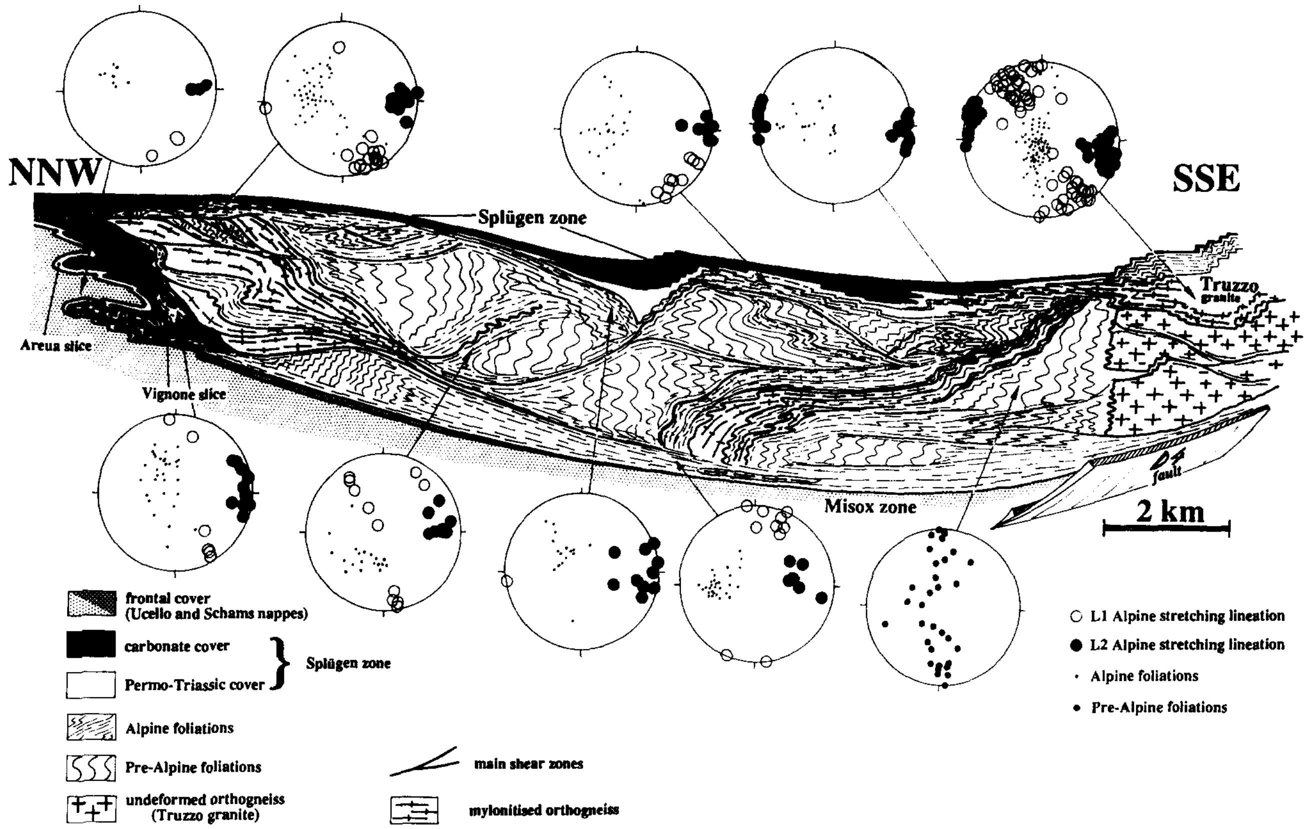

Fig. 2. NNW–SSE cross-section of the Tambo nappe (for location see line A–A′ on Fig. 1). Equal-area lower-hemisphere stereoplots show stretching lineations on Alpine foliation planes. The southern part of the nappe is cut by a NNW–SSE-striking D_4 normal fault with downthrow to the NE (see text for explanation).

the nappe pile. A possible correlation of these events with those recognized in adjacent areas is shown in Table 1. For every deformational event: (i) the orientation of deformation axes and interpretation of kinematics based on various asymmetric shear criteria (Simpson & Schmid 1983) and shear-zone patterns (Gapais *et al.* 1987) are summarized (further descriptions in Marquer 1991); and (ii) basement and cover deformations are described and discussed.

D_1 *deformation and kinematics*

This first clearly distinguishable Alpine deformation is defined by a strong NW–SE to N–S L_1 stretching lineation inscribed on generally subhorizontal S_1 foliation planes (Fig. 2). D_1 is a ductile and heterogeneous deformation associated with coeval occurrences of thrusting and folding. On a large scale, these major thrusts reflect the emplacement of the Tambo

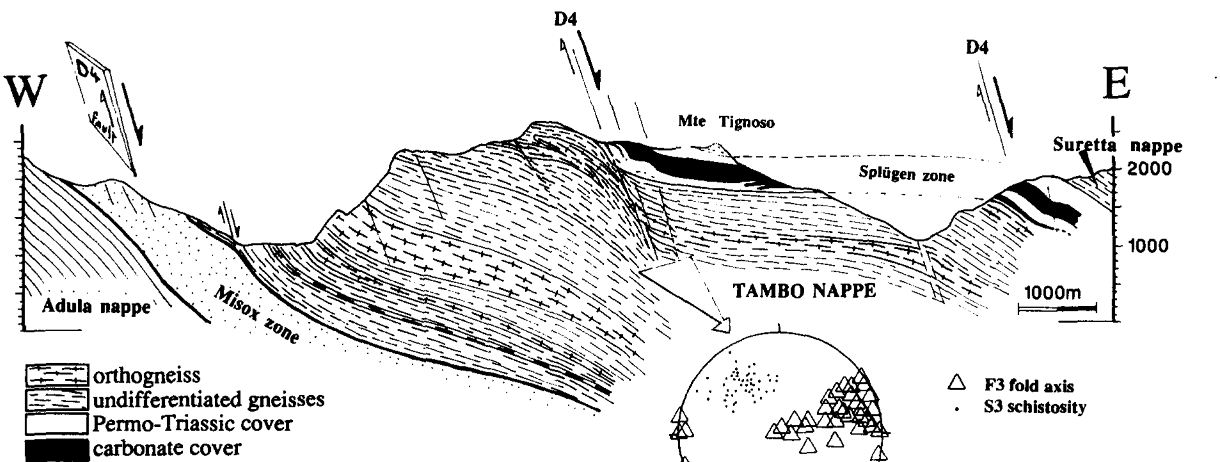

Fig. 3. E–W cross-section of the Tambo nappe (for location see line B–B′ on Fig. 1). The NNW–SSE D_4 normal faults show downthrow to the ENE. The equal-area lower-hemisphere stereoplot shows D_3 fold axes and schistosity scattered by D_4 deformation.

Table 1. Correlation of deformations in the Central Penninic Alps, east of the Ticino dome (location on Fig. 1)

Milnes & Schmutz (1978) Suretta	Löw (1987) Adula	Mayerat (1989) Front of Tambo	Schmid *et al.* (1990), Schreurs (1990) Schams Nappes + adjacent cover nappes	Marquer (1991) and this work Tambo
				D_4: NNW–SSE normal faults. Downthrow of the northeast block. Brittle–ductile deformation.
'D_5': Open folds. E–W axis. Subvertical axial plane.	Carrassino: North-vergent flexure.	D_4: Open folds. E–W axis. Subvertical S_4.	D_3: NNW-vergent folds. WSW–ENE axis. Steeply SSE-dipping axial plane.	D_3: Staircase geometry folds. E–W axis, north fold vergence. Steeply southwards dipping S_3.
Niemet: Recumbent fold. North closure. ENE–WSW fold axis. Schams: Late thrusting.	Leis: Regional folding. E–W axis.	D_3: E–W L_3 stretching lineation. 'Top-to-the-east' shearing. D_2: Subhorizontal S_2. South-vergent folds. E–W to ENE–WSW fold axis.	D_2: Niemet-Beverin 'backfolding'. Large-scale north closure. 'Top-to-the-southeast' shearing.	D_2: Subhorizontal S_2. E–W L_2 stretching lineation 'Top-to-the-east' shearing. SSE-vergent folds.
Ferrera: Isoclinal folds.	Zapport: N–S stretching lineation. N–S fold axis. High pressure.	D_1: Subhorizontal S_1. NW–SE L_1 stretching lineation. Thrusting and folding.	D_1: Subhorizontal S_1. NW–SE L_1 stretching lineation. Thrusting and folding.	D_1: S_1 subhorizontal (10–15 kb). NW–SE L_1 stretching lineation. Thrusting and folding.
Avers: Early thrusting.	Sorreda: Misox imbricating.			

nappe on the Misox zone, and of the Suretta nappe on the Splügen zone. Associated with these major zones, small-scale structures such as shear bands, asymmetric boudinage, asymmetric porphyroclasts, etc. (Berthé *et al.* 1979, Simpson & Schmid 1983) indicate an overall 'top-to-the-northwest' shearing. On this basis, D_1 is interpreted as a progressive deformation resulting in the stacking of the main nappes during Paleocene to Eocene times (Schmid *et al.* 1990).

D_1 *deformation within the basement*

The structural and kinematic data of the Truzzo granite testify to the D_1 NNW overthrusting (Marquer 1991). The Truzzo granite reacted as an isotropic body during D_1 ductile deformation. Conjugate shear bands therefore appear more clearly in the granite than elsewhere. At the present time, the geometry of the Truzzo granite, with its vertical magmatic contacts (Fig. 2), enables an estimation of D_1 strain intensity on the nappe scale: overall D_1 shearing deformation is quite weak in the center of the granite but it increases dramatically towards the top of the Tambo nappe. On the nappe scale, D_1 is actually expressed by low-angle shear zones (with respect to horizontal) cross-cutting pre-Alpine foliations. Both northward-dipping normal faults and southward-dipping thrust faults are present, suggesting a unique sense of movement, 'top-to-the-north'. These opposite dips create an undulating structure on the roof of the nappe causing a great variation of sediment thickness (Fig. 2, see also Fig. 5a). The mylonites generated within these shear zones are enriched in quartz and, more rarely, in small lenses of calcite or dolomite. The frequency of these shear zones is higher at the top of the crystalline nappe than in its core. Consequently, there is a deformation gradient from the nappe core where pre-Alpine structures have been better preserved, up to the overlying cover where only Alpine foliations are observed (Fig. 4a). The topmost part of the nappe is intensively mylonitized (50 m width, for the Truzzo granite) and shows a conspicuous interlayering of basement with pinched 'Permo-Triassic' cover that indicates a kilometric-scale northward displacement (Fig. 2). The planar anisotropy increases in these narrow deformation zones and enables development of curviplanar asymmetric folds (Fig. 4a). Within the basement core itself, conjugate shear planes intersect and delimit large, weakly deformed lenses (Fig. 5a). These protected zones are not only frequent in the vicinity of the Truzzo granite but are also found elsewhere in the basement (Fig. 2). Surviving pre-Alpine foliations are still often subvertical but nevertheless affected by folding, with a E–W to ENE–WSW axis (Fig. 2). These folds are symmetrical or with northward vergence, and have S_1 as subhorizontal axial-planar schistosity.

D_1 *deformation within the cover*

The contact between the 'Permo-Triassic' cover and the basement is always strongly sheared (Fig. 4a). Although the sedimentary strata had suffered intense ductile folding, several minor D_1 thrusts that formed are obviously controlled by thrusts in the basement. These shear planes are distinguishable either by duplication of lithological units, or by cornieule and, exceptionally, gypsum layers. Just above the top of the basement, the 'Permo-Triassic' quartzites and gneisses very often show an asymmetric foliation boudinage (Fig. 5a, cf. Platt & Vissers 1980). Within the highly deformed quartzitic gneisses, shear zones are often made up of anastomosing phengitic layers which probably resulted from deformation processes. The basement–cover contact is frequently marked out by secondary quartz layers or lenses, a few metres thick, and associated with C–S and C' microstructures in the strongly deformed rocks (Berthé *et al.* 1979). D_1 not only formed shearing structures but also produced pervasive isoclinal and intrafolial folding (Figs. 4a and 5a). Fold axes are completely scattered and thus sometimes parallel to the NNW–SSE stretching lineation. Generally, the folds have a westward or northward vergence and are also the cause of multiple repetitions of layers. In the Splügen zone, D_1 folding is restricted to a small scale, while in front of the nappe, kilometre-size folds (wavelength) are present (Fig. 6). These have affected the frontal stack of slivers which could also have resulted from the same, progressive D_1 (under-)thrusting. In other words, both shearing and folding are interpreted here as the contribution of the same, progressive D_1 deformational event.

Because the strain suffered by the cover was more intense and homogeneous than the one recorded by the basement, an apparent excess of bed length within the sedimentary strata is compensated by intense thrusting and folding in front of the crystalline basement slabs. These types of structures may be observed on all scales, from mesoscopic to nappe dimensions (Fig. 4a).

D_2 *deformation and kinematics*

D_2 is a pervasive and heterogeneous deformation associated with an E–W stretching lineation L_2 on the subhorizontal S_2 cleavage planes. This schistosity represents the axial planes of folds with ENE–WSW axes and SSE fold vergence. These folds have been, up to now, interpreted as the lower limb of the large Niemet-Beverin fold (see Milnes 1974, Milnes & Schmutz 1978). Small-scale shear criteria in basement zones of intense deformation and asymmetric shear-zone patterns (Marquer 1991) argue for a bulk 'top-to-the-east' shearing. D_2 deformation might be contemporaneous with the peak of Lepontine metamorphism, dated earlier at 29–23 Ma (Deutsch & Steiger 1985) or 38 ± 2 Ma (Jäger *et al.* 1967, Jäger 1973, Steinitz & Jäger 1981). This deformation, linked to the strong E–W stretching linea-

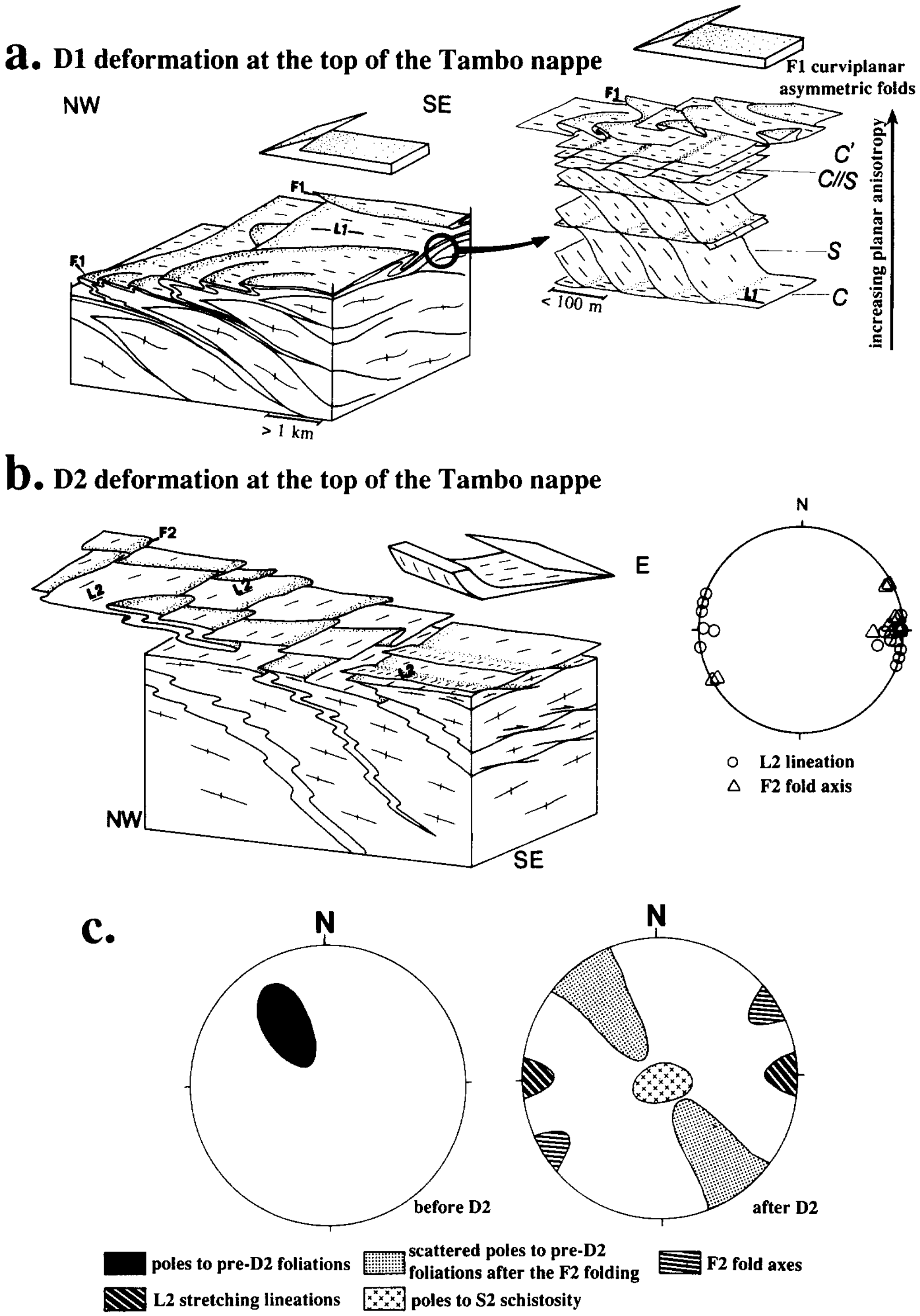

Fig. 4. Illustration of basement–cover relationships at the top of the Tambo nappe during D_1 and D_2 deformations. (a) D_1 deformation produced thrusting in the basement and curviplanar asymmetric folding in the cover. L_1 is the stretching lineation. The planar anisotropy, with schistosity (S) becoming parallel to the shear band (C), increases from the basement core towards the cover. In the strongly deformed zones, C' shear bands can occur. (b) D_2 deformation, associated with a 'top-to-the-east' shearing component, affects the whole structure in the same way. The strong, vertical shortening produced minor folding with D_2 axes close to the stretching L_2 lineation (see equal-area lower-hemisphere stereoplot). (c) Schematic stereogram showing the effects of D_2 folding on previous foliations dipping to the southeast.

tion and leading to overall vertical shortening, affects the whole nappe pile (Adula, Löw 1987; Tambo and Suretta, Schmid *et al.* 1990). This deformation is related to Oligocene crustal thinning (Bradbury & Nolen-Hoeksema 1985). During D_2 deformation, the direction of the extensional axis was subparallel to the strike of the Alpine mountain belt.

D_2 deformation within the basement and cover

In the basement, the style of ductile D_2 deformation is heterogeneous and quite similar to D_1. In the southern part of the Truzzo granite, the stretching of K-feldspars and the associated microstructures (myrmekites, intra-crystalline mechanisms) seems to indicate a higher temperature for D_2 deformation (Marquer 1991). A number of D_1 shear planes were probably reactivated by the 'top-to-the-east' D_2 shearing, while new D_2 shear planes were developed (Fig. 5a). However, D_2 shear planes are randomly located within the nappe pile and are not systematically confined to major D_1 thrust contacts. The folding associated with D_2 is always of minor amplitude and is present almost everywhere. This folding occurred between highly deformed D_2 zones and has an axial trend of NE–SW to E–W, close to the E–W L_2 stretching lineation (Fig. 4b). The fold vergence is always towards the southeast (Fig. 5a). This particular geometry, with fold axes subparallel to the stretching lineation, can be explained by the D_2 folding of older foliations dipping towards the southeast as a consequence of D_1 thrusting. On a N–S cross-section, D_2 folding shows a backfold-like geometry linked to the L_2 E–W stretching. Some of the minor D_1 folds, originally with NE–SW or E–W axes and a northward vergence, were also sheared towards the east during D_2 shearing. It must be specified that it is not always easy to distinguish a real E–W stretching lineation on the S_2 foliation from a D_1 fold–hinge intersection, especially in refolded quartz veins. Accordingly, in the absence of a stretching lineation on an axial-plane schistosity, distinction between the D_1 and D_2 generations of folds becomes uncertain. Because deformation was more ductile and homogeneous in the cover than in the basement, D_2 shearing planes there are not clearly perceptible. With respect to the basement, D_2 folding appears to be less widespread. It seems to be located only where structural planes had a previous dip orientation towards the southeast and does not appear where subhorizontal or gently N-dipping structures are present (Fig. 5a).

The most noteworthy effect of D_2 folding is that it turns D_1 structures upright in front of the basement (Fig. 6). As opposed to the kilometre-scale D_1 folds, D_2 folds are always on a mesoscopic scale. Furthermore, D_2 structures have the same style, geometry and scale in both basement and cover.

D_3 *deformation*

D_3 is a discontinuous deformation, and much less pervasive than D_1 and D_2. Minor F_3 folding with fold-axis trends varying from NE–SW to E–W and a systematic northward fold vergence creates the appearance of a staircase geometry (Fig. 2, southern part). The axial-plane cleavage is mostly steep and in some places supports a NNW–SSE to N–S stretching lineation (Fig. 5b). D_3 is located within narrow deformation zones oriented in a W–E direction. These zones appear more frequently distributed towards the south.

At this stage in the tectonic evolution, behaviour of both basement and cover becomes absolutely identical. The geometry of the overprinting D_3 folds, with NE–SW to E–W axes and subvertical axial planes, is controlled by the orientation of pre-existing structures (Fig. 5b). Where enveloping surfaces had northward dips (generally with a northern D_1 fold-vergence), D_3 folding strongly accentuated these dips, creating staircase-shape D_3 folds (Fig. 2). Where the pre-existing planar structures had southward dips (generally with southeast D_2 fold-vergence) or were horizontal, D_3 folding generated asymmetric chevron folds—folds with very short, subvertical north limbs. This latter geometry is especially well visible at the basement–cover contact, which is still subhorizontal at the top of the northern part of the nappe (Fig. 2). At nappe scale, the systematic northward vergence of D_3 folds and S_3 cleavages suggests a 'top-to-the-north' (subvertical) shearing. In the south, D_3 folding is much better developed and induces a bulk northwards-tilting of the first Alpine foliations (Fig. 2). This differential D_3 uplift between north and south probably produced a slight northwards reactivation of the Adula–Tambo and Tambo–Suretta thrust contacts (Fig. 5b). The reactivated contact, within the Splügen zone (Tambo cover), is marked by extensional crenulation cleavages (Platt & Vissers 1980) which locally define horizontal shear zones with a 'top-to-the-north' motion. The overall D_3 fold geometry, with its northern fold and cleavage vergence, suggests a subvertical northward shearing (Fig. 5b), which could be regarded as conjugate to the main Insubric fault zone during the late Oligocene to early Miocene uplift (Hurford 1986, Hurford *et al.* 1989).

D_4 *deformation*

D_4 structures are predominantly ductile–brittle normal faults cross-cutting the entire nappe pile. They strike NNW–SSE with downthrow to the northeast (Fig. 3). The D_4 stretching lineation plunges steeply towards the east-northeast. These later shear zones cut obliquely through the contacts between Adula–Tambo and Tambo–Suretta nappes and also affect the middle of the Tambo nappe and its frontal sedimentary units (Fig. 3). On the nappe scale, this fault system looks like large-scale extensional crenulation cleavage (Platt & Vissers 1980) whereby Alpine foliation is curved at the contact of the shear planes, indicating downthrow to the east. On a small scale, extensional crenulation cleavages are well developed only in basement and cover rocks which have a strong planar anisotropy. Isotropic rocks, such as in zones preserved in the Truzzo granite, show undulatory and localized fault zones. In the subhorizontal carbonate layers, D_4 extensional deformation produced a high density of vertical brittle faults parallel to the major NNW–SSE D_4 strike, which could be interpreted as a large-scale fracture cleavage. With respect to the Lepontine dome, the extensional D_4 deformation would appear to be symmetrical to the last Miocene structures linked to the Simplon normal fault (Mancktelow 1985, 1987); it could thus be coeval with the bulk dextral transpressional regime along the Insubric line (Heitzmann 1987a,b, Schmid *et al.* 1987).

CONCLUSION

During progressive D_1 deformation, the rheological contrast between basement and cover was considerable:

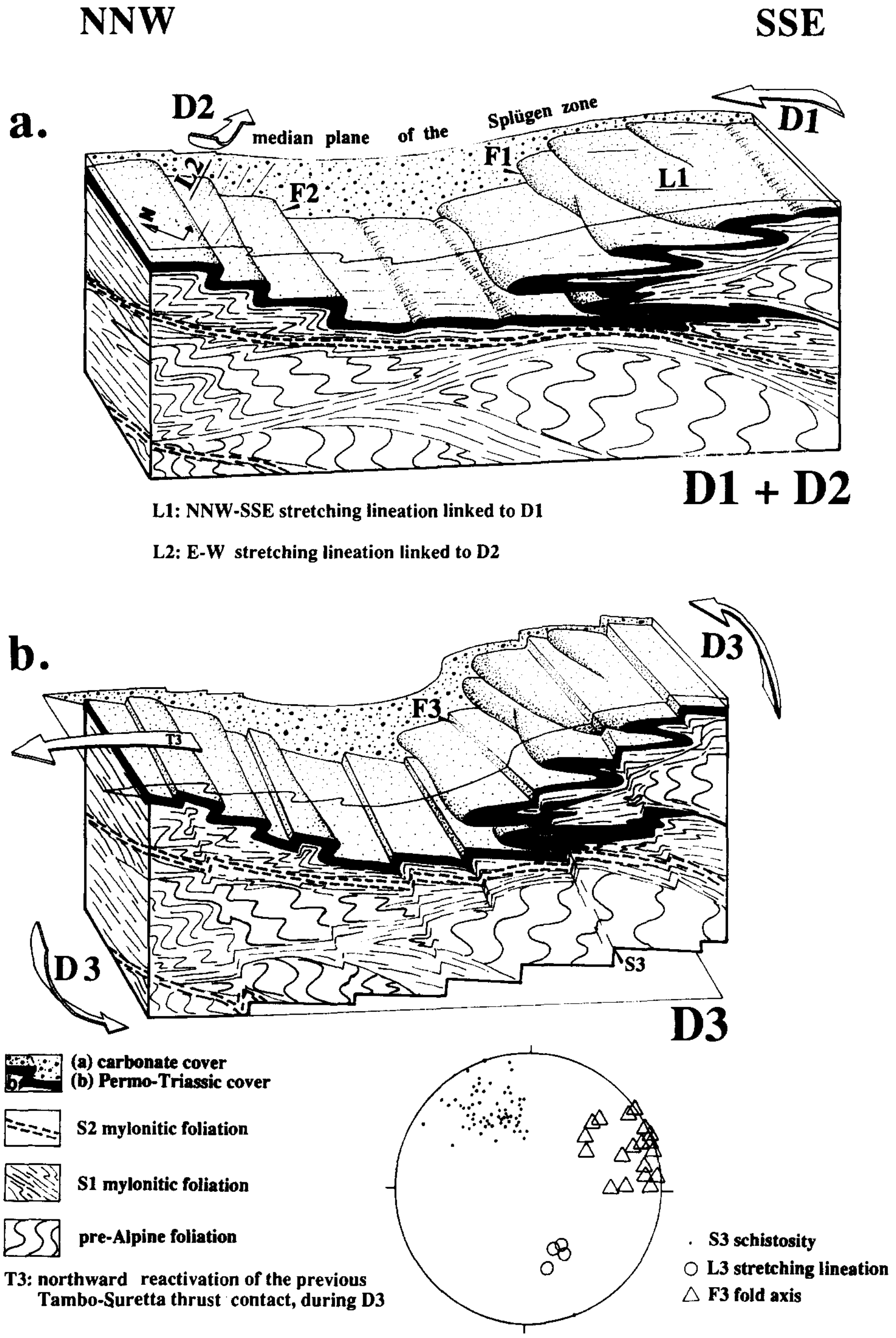

Fig. 5. Kinematic sequence showing the effects of D_3 folding (b) on the older structures (a). The top of the basement, highlighted by the Permo-Triassic cover, forms an undulating structure whose troughs are filled with thick cover carbonate strata. The equal-area lower-hemisphere stereogram shows S_3 schistosity, L_3 stretching lineations and F_3 fold axes. D_3 produced a differencial uplift which slightly reactivated the Splügen zone (T3 on the sketch).

(i) the geometry of basement structures was governed by a strongly heterogeneous deformation related to thrust tectonics (Figs. 2 and 4a); (ii) by contrast, the cover underwent a much more homogeneous and ductile deformation, characterized by thin-skinned thrusting and refolding (Figs. 4a and 6). The first D_1 deformational event corresponds to the stacking of the nappes towards the north-northwest, which could have started as early as the Eocene (Steinitz & Jäger 1981, Schmid *et al.* 1990, Schreurs 1990). At the end of the progressive D_1 deformation, the stacking of the nappes was completed and the whole of the Penninic nappes was buried under high-pressure conditions, below the Austro-Alpine lid (Heinrich 1986, Frey *et al.* 1980, Hurford *et al.* 1989, Pfeifer *et al.* 1991).

During D_2 deformation, the rheological contrast between basement and cover became very weak: (i) a similar style of heterogeneous deformation affected both basement and cover (Fig. 4b); and (ii) the Splügen zone was not reactivated as much as it should have been if it had been a plane of weakness at that time. D_2 deformation was synchronous with the Lepontine metamorphic peak (Deutsch & Steiger 1985). This late Oligocene deformation induced the thinning of the previously

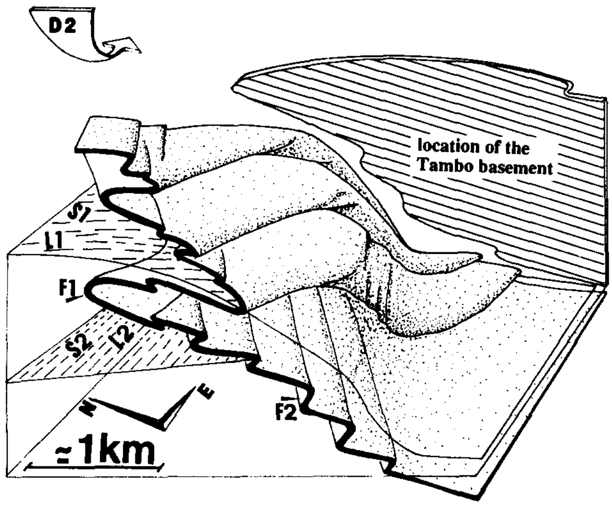

Fig. 6. Illustration of the structure in the cover as shown by the Areua slice at the northern front of the Tambo nappe (for location see Fig. 2). The older D_1 folds (with S_1 axial plane and L_1 lineation) are refolded southeastwards by D_2 folding (S_2 axial plane and L_2 stretching lineation).

emplaced stack of nappes with an E–W ductile stretching. The strong, vertical shortening, associated with a 'top-to-the-east' shearing, folded the previously SE-dipping foliations with axes close to the E–W stretching lineation (Figs. 4b and 5a) creating folds with systematic southeast vergence (Fig. 6).

D_3 and D_4 deformations occurred under greenschist facies retrograde conditions in a more superficial crustal domain. These deformations gradually became much more localized. The staircase geometry of D_3 folds was generated by the differential uplift of the southern part of the nappe which slightly reactivated the contact between the Adula and Tambo nappes (Fig. 5b). D_3 folding could be associated with the Oligocene–Miocene movements on the Insubric line (Hurford 1986, Heitzmann 1987b, Schmid *et al.* 1987). The late extensional D_4 deformation consisted of NNW–SSE brittle–ductile normal faulting. D_4 probably dates to the Miocene (Jäger *et al.* 1967, Wagner *et al.* 1977, Bradbury & Nolen-Hoeksema 1985) and could be associated with the last dextral transpressional movements on the Insubric line during the Miocene. This late eastern D_4 deformation therefore appears to be a symmetric equivalent of the Simplon normal fault (Mancktelow 1985, 1987, Heitzmann 1987a).

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