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Syn-orogenic extension along the Forcola fault: Correlation of Alpine deformations in the Tambo and Adula nappes (Eastern Penninic Alps)

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Key words: Normal faulting, kinematics, extension, collision belts, Penninic domain, Alps

ABSTRACT

The Adula and Tambo nappes both experienced the Tertiary tectonics leading to the closure of the Valais ocean, however, their deformation and metamorphic histories show certain differences: the Adula nappe underwent a complex subduction evolution that culminated under eclogite facies conditions (Sorreda-Trescolmen). In contrast, the Tambo nappe recorded lower pressure conditions during nappe stacking (D1). Moreover, E-W syn-orogenic extension took place in the Tambo nappe (D2) while the south-directed subduction was still active in the Adula nappe (Zapport). Since the Eocene, these nappes underwent the same tectonic evolution.

The contact between the Adula nappe and the Tambo nappe is marked by a major Alpine normal fault. This Forcola normal fault consists of mylonites and cataclasites exposed between Mesocco in the Valle Mesolcina (Grisons, Switzerland) and Gordona in the Val Mera (Italy). This ductile-brittle normal fault offsets the two nappes by a vertical amount of approximately 3000 m. In map view the Forcola normal fault cuts out part of the Tambo nappe, the entire Misox zone and parts of the structurally higher the Adula nappe.

The Forcola normal fault reflects Early Miocene NE-SW extension responsible pro-parte for the dome-like structure of the Eastern Penninic domain. This extensional structure could be a conjugate fault with respect to the Simplon fault system. It contributes to the late stages of unroofing of the Lepontine structural dome.

ZUSAMMENFASSUNG

Die Adula-Decke und die Tambo-Decke erfuhren beide die tektonischen Vorgänge im Tertiär, die zur Schliessung des Valais-Ozeans führten, obwohl wesentliche Unterschiede in deren strukturellen und metamorphen Entwicklung festgestellt werden können: Die Adula-Decke durchlief eine komplexe Subduktionsphase, die unter eklogitfaziellen Bedingungen kulminierte (Sorreda-Trescolmen Phase). Im Gegensatz dazu sind in der Tambo-Decke wesentlich tiefere Drucke während der Deckenstapelung (D1) festzustellen. Ausserdem fand eine E-W Extension in der Tambo-Decke statt (D2), während in der Adula-Decke gleichzeitig die süd-gerichtete Subduktion noch immer aktiv war. Seit diesen Ereignissen im Eozän ist die tektonische Entwicklung beider Decken identisch.

Der Kontakt zwischen der Adula-Decke im Liegenden und der Tambo-Decke im Hangenden stellt eine bedeutende Abschiebung (Forcola-Abschiebung) dar. Entlang dieser Abschiebung werden Mylonite sowie Kataklasite beobachtet. Die Forcola-Linie, die zwischen Mesocco im Valle Mesolcina (Graubünden, Schweiz) und Gordona im Val Mera (Italien) aufgeschlossen ist, versetzt die zwei Decken um einen Vertikalbetrag von ca. 3000 m. Im Kartenbild ist ersichtlich, dass die Forcola-Linie Teile der Tambo-Decke, die gesamte Misoxer Zone, sowie geringe Teile der Adula-Decke herausschneidet.

Die Forcola Abschiebung reflektiert eine NE-SW gerichtete frühmiozäne Extension, die mitverantwortlich für die Dom-Struktur der östlichen Penninischen Einheiten ist. Diese Extensions-Struktur stellt möglicherweise ein konjugiertes System zur Simplon Abschiebung dar. Die Forcola Linie trägt einen wesentlichen Teil zur späten Heraushebung des Lepontins bei.

Introduction

The Mesozoic sediments of the Misox zone, situated in the eastern Lepontine dome, separate the Adula nappe from the Tambo nappe. These sediments represent the southern extremity of the North Penninic Bündnerschiefer (Fig. 1). While the Adula nappe paleogeographically belongs to the south European margin, the Tambo nappe represents a part of the Briançonnais domain (Schmid et al. 1990). Hence, the Misox zone represents the suture between the European margin and the Briançonnais paleogeographic domain (Tambo, Suretta and Schams nappes) that resulted from the closure of the Valais trough during Middle to Late Eocene (Stampfli et al. 1998). It was suggested that in the southern part of the area, a normal fault might be responsible for the disappearance of this suture, caused by a major displacement of the Tambo nappe

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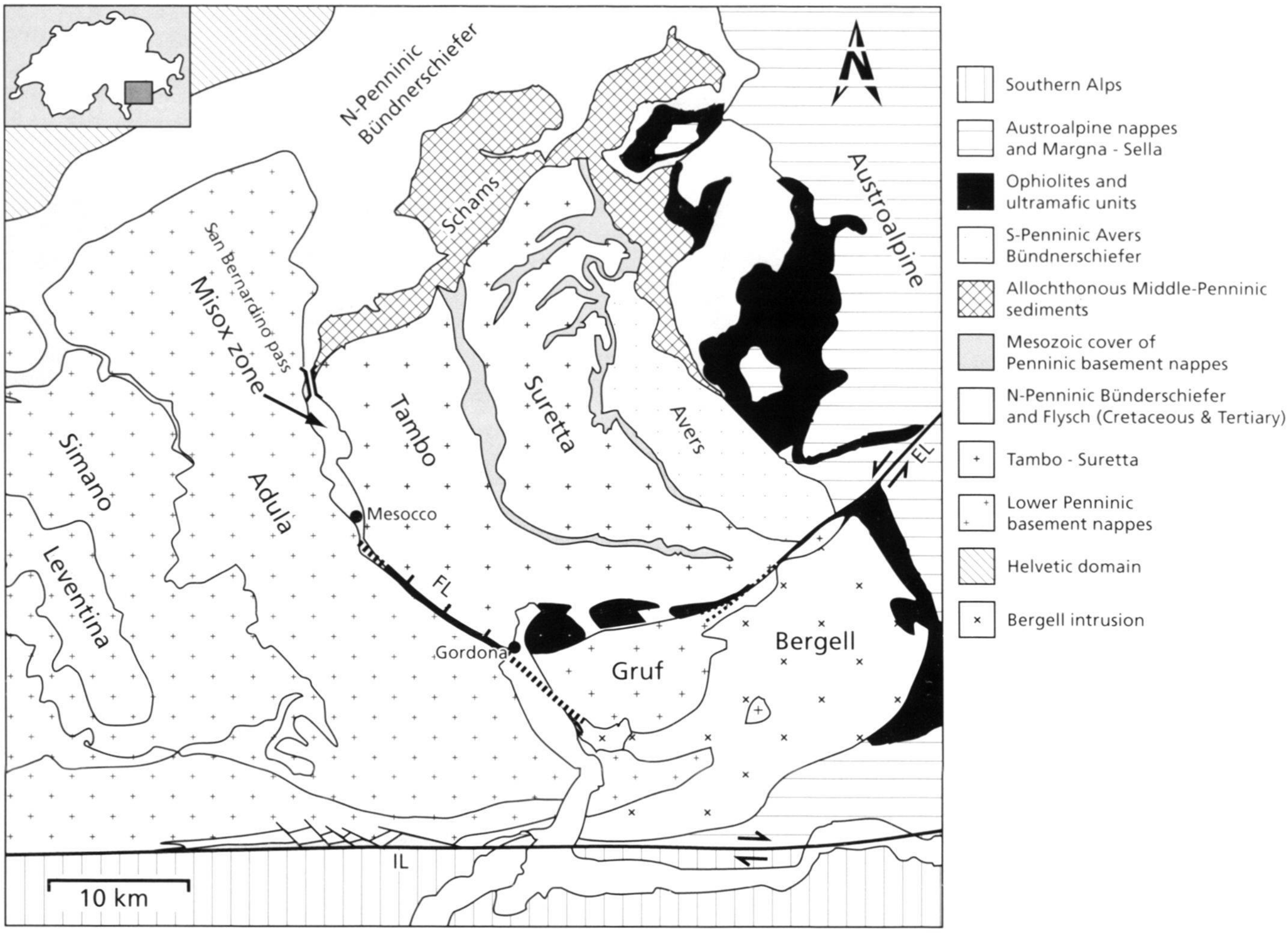

Fig. 1. Simplified tectonic map of the eastern Central Alps (after Schmid et al., 1990). – EL = Engadine line, IL = Insubric line, FL = Forcola line.

relative to the Adula nappe (Marquer, 1991; 'Forcola phase' of Schmid et al., 1997a; Fig. 2). Previous field investigations clearly pointed out that the Forcola normal fault, amongst other faults mapped within the Tambo nappe, is associated with substantial omissions of structural levels and that these normal faults formed late during the tectonic history of the Eastern part of the Penninic domain (phase D4 of Marquer, 1991). It is the aim of this study (i) to provide a correlation of Alpine structures between Adula and Tambo nappe, and (ii) to describe the geometry and the kinematics of deformation along this major normal fault in more detail.

Geological setting

The Misox zone includes strongly attenuated units at the southern extremity of the N-Penninic 'Bündnerschiefer', namely the Ucello units and the Gadriol mélange (see Steinmann, 1994, for a correlation with tectonic units further to north). The Misox zone does not exceed a thickness of 800 m in its middle part and consists mainly of calcareous schists with some extremely stretched lenses of gneisses (e.g. Gadriol gneiss of Gansser, 1937) and mafic rocks. Southward, this zone progressively thins out and finally disappears near the Passo della Forcola. This leads to a direct contact between the Tambo and Adula nappes (Fig. 1).

The Adula nappe largely consists of well-foliated quartz-rich ortho- and para-gneisses of pre-Alpine age (Jäger et al. 1967; Hänny et al. 1975). Interlayered with these quartzo-feldspatic rocks are metapelites and mafic lenses of unknown age, occuring as slices of different length (several meters to kilometers). The mafic lenses often show assemblages of Tertiary eclogite facies metamorphism (Heinrich 1986; Meyre et al. 1997). Dolomitic marls and quartzites are rare and are referred to as 'Internal Mesozoic' due to their probable Triassic age (Jenny et al. 1923). In the southern part of the Adula nappe migmatic rocks are abundant, some of them are of Variscan age (Hänny et al. 1975). The Adula nappe is characterized by a well developed main schistosity. Because of this

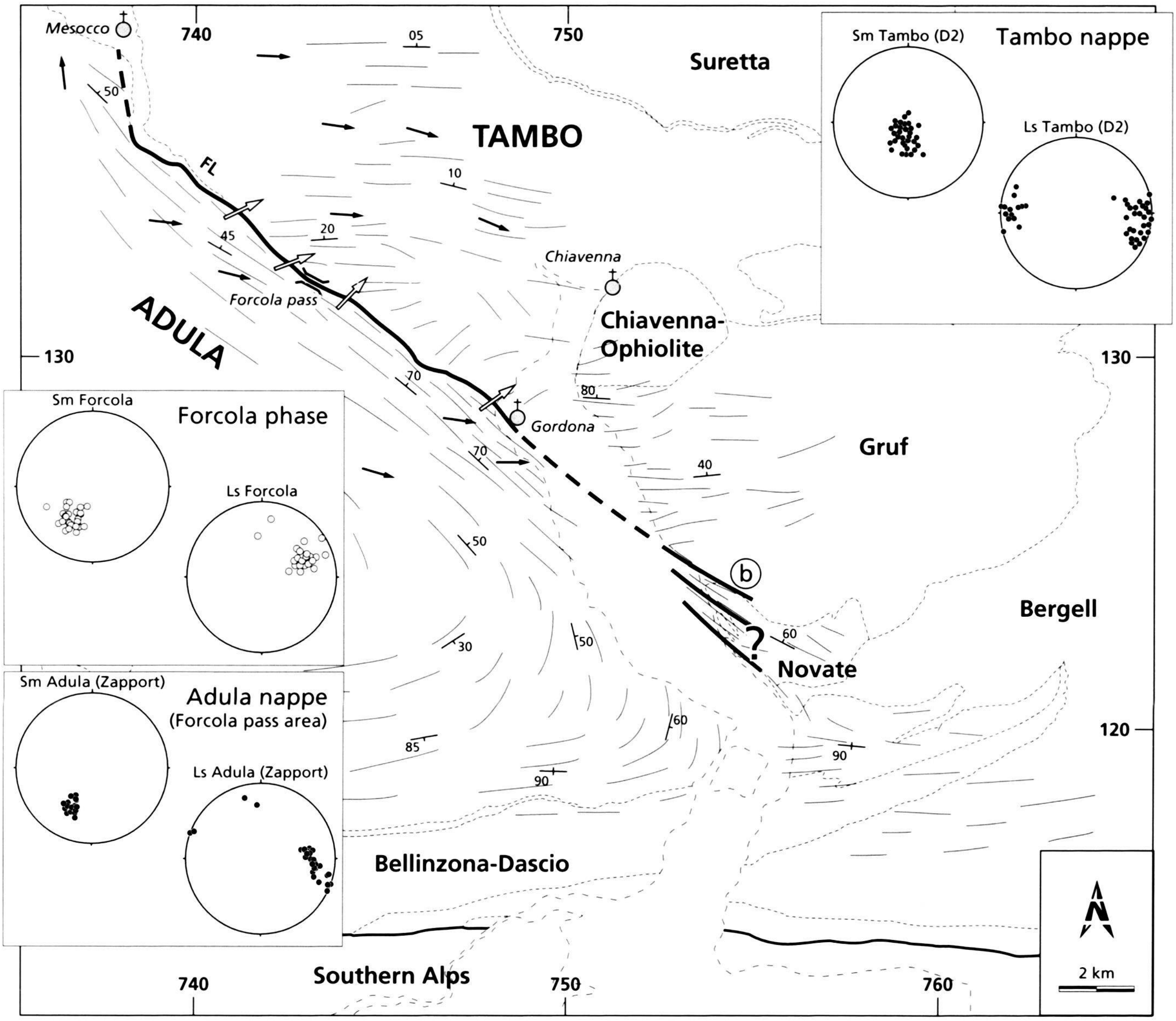

Fig. 2. Foliation trajectory map of the southeastern 'Lepontine'. FL = Forcola Line. Open arrows indicate the direction of faulting (top to NE) according to the Forcola stretching lineation; solid arrows indicate direction of the 'Zapport' stretching lineation. Data are compiled from Wenk (1973), Moticska (1970), Weber (1966), Marquer (1991), Hänny (1972), Rosenberg (1996), A. Berger (pers. comm.), and this study. b = only brittle features. Insets (stereograms): Sm = main foliation, Ls = stretching lineation.

dominant Alpine schistosity, relics of primary contacts of intrusive rocks are only preserved in the less deformed northern part of the nappe (e.g. Zervreila gneiss; Jäger et al. 1967; Löw 1987).

The Tambo basement mainly consists of pre-Alpine ('polycyclic') basement which is intruded by the Truzzo granite in the southern part. The Truzzo granite underwent only Alpine deformation and metamorphism. The 'polycyclic' lithologies are characterized by signs of strong pre-Alpine deformation and metamorphism and mostly consist of metapsammites or metagreywackes. Some metapelites (micaschists) are also present, containing pre-Alpine minerals such as staurolite, kyanite, andalusite, garnet, muscovite and biotite. Some migmatitic rocks are found in the southern part of the nappe. In the northern part of the nappe aligned lenses of mafic and ultramafic rocks are especially well developed. These are amphibolites with few preserved pyroxene-garnet assemblages (pre-Alpine eclogites; Biino et al. 1997). In other parts of the nappe, these mafic rocks underwent a complete Alpine retrograde metamorphism producing amphibolites and prasinites. A pre-Permian orthogneiss crosscuts the entire nappe body and may have been emplaced under anatectic conditions. The 'monocyclic' basement of the Tambo nappe is mainly represented by the Truzzo granite, exposed in the southern part of the nappe (Blanc 1965; Weber 1966; Gulson 1973; Marquer 1991). This early Permian granitic complex (268 ± 0.4 Ma, 206Pb/238U zircons, Marquer et al., in press) experienced only Alpine deformations. Accordingly, it appears as an originally isotropic and homogeneous body of porphyritic granite (with centimetric K-feldspars porphyroclasts), crossed by many Alpine shear zones (Marquer 1991).

Tectonic setting

The stacking of the Adula, Tambo and Suretta nappes results from middle Tertiary accretion of crustal slices (Schmid et al. 1990, 1997a, 1997b; Marquer et al. 1994). By the end of the Eocene, the entire width of the Briançonnais domain had been subducted, together with large parts of the North Penninic 'Bündnerschiefer' (Schmid et al. 1996). The Tambo and Suretta nappes reached peak pressure conditions (10–13 kbar; Baudin & Marquer 1993) by this time. Peak temperatures (500–550 °C) prevailed until 40–35 Ma ago (Hurford et al. 1989; Marquer et al., 1994; Schmid et al., 1996). The subduction of the Adula nappe, representing the southern tip of Europe at that time, is due to the collision of stable Europe with the Briançonnais and the Adriatic plate/microcontinent in late Eocene times, culminating under eclogite facies conditions. Subduction was followed by rapid exhumation and the formation of the Adula nappe, associated with the establishment of the complete nappe pile of the higher Penninic units by the end of the Eocene (35 Ma). In the following we summarize and compare the structural evolution of Adula and Tambo nappes.

Adula nappe

The structural evolution of the Adula nappe has recently been examined in detail (Löw 1987; Meyre & Puschnig 1993; Partzsch et al. 1994; Partzsch 1998). According to these authors, the Adula nappe experienced the following five deformation phases during its Alpine evolution:

Sorreda phase

The Sorreda phase (Löw 1987) represents the imbrication of Mesozoic sediments with basement rocks during subduction of the continental margin of the European plate. However, contacts between these lithologies are totally overprinted by later structures. Although the direction of the Sorreda deformation cannot be reconstructed, a southward directed subduction is most probable, based on the large scale geometry of basement-cover relationships.

Trescolmen phase

The Trescolmen phase operates under eclogite facies conditions, after peak pressure along the retrograde path. Pressure and temperature estimations for this event are in the range of 19–21 kbar and c. 650–700 °C for the middle Adula nappe (Trescolmen locality; Meyre et al. 1997). Elongated garnet aggregates and recrystallized omphacite define a distinct foliation as well as a stretching lineation only apparent in the core of mafic lenses that preserved eclogite facies assemblages. During the following Zapport deformation phase substantial rotations of the mafic lenses do occur. The kinematics of the Trescolmen deformation phase remain therefore unknown. The eclogite facies conditions have no equivalence in the other Penninic units (Simano, Tambo, Suretta).

Zapport phase

Schistosity and lineation formed during the Zapport deformation phase are the dominant fabrics in the Adula nappe (Löw 1987; Meyre & Puschnig 1993; Partzsch et al. 1994; Partzsch 1998). In the central part of the nappe the main foliation dips with about 20° to the ENE and represents the axial plane of isoclinal folds. The fold axes strike subhorizontally N-S to NNW-SSE, the stretching lineation being parallel to the fold axes. Shear sense indicators reveal a top to the North movement during this deformation phase.

In the Forcola pass area the stretching lineations of the Zapport deformation phase progressively curve into an E-W strike while the main foliation constantly dips towards the Northeast.

Leis phase

The Leis phase is characterized by open folds overprinting the Zapport folds and foliation. In sheet-silicate rich lithologies a crenulation develops. The fold axes of the Leis phase strike E-W, the fold axial plane is steeply south dipping, the folds being constantly north-vergent within the entire nappe.

Carassino phase

The Carassino phase mainly affected the frontal part of the Adula nappe and is responsible for an undulation and kinking of the leucocratic lithologies of the Adula nappe. Possibly, the Carassino phase is a time-equivalent to the Forcola phase (Schmid et al. 1996), but no direct correlations exist.

Tambo nappe

D1 deformation

The D1 ductile Alpine deformation (Marquer 1991) is linked to the progressive Eocene stacking of the Suretta, Tambo and Adula nappes towards the NNW (Ferrera phase of Schmid et al. 1997a). D1 is associated with a strong SSE-NNW oriented stretching lineation and a top to the NNW shearing (Baudin et

Table 1: Correlation of Alpine deformation phases of the Adula nappe and the Tambo nappe

Time interval	Deformation phases Adula nappe *Ref.	Tambo nappe *Ref.	Tectonic events (Central Alps)
Middle to Late Eocene (c. 45–40 Ma)	Sorreda (1) subduction (S-directed) imbrication	D1 (Ferrera) (2, 3, 4) nappe stacking; thrusting and isoclinal folding LS: SSE–NNW; S: subhorizontal	subduction of and peak-P in Briançonnais domain, followed by subduction of European margin (Adula), leading to eclogite facies conditions
	Trescolmen (5) eclogite facies conditions after peak-pressure		
Late Eocene – Early Oligocene (c. 40–30 Ma)	Zapport (1, 6, 7) top-N shearing, isoclinal folds LS/FA: NNW–SSE; S: dipping 40° to ENE	D2 (Niemet-Beverin)(2, 3, 4) E–W Extension LS: E–W; S: subhorizontal	ongoing N-S compression in Central Alps, combined with E-W stretching in the Tambo and Suretta nappes intrusion of Bergell granodiorite (30 Ma)
Middle Oligocene (c. 30–25 Ma)	Leis (1, 6, 7) crenulation; open folds ENE dipping fold axes (dipping 35°), north vergent fold axes	D3 (Domleschg) (2, 3, 4) staircase geometry folds E–W fold axis, north vergence fold axial plane: steeply south dipping	back-thrusting along the Insubric Line
Oligocene–Miocene (c. 25–21 Ma)	Forcola (Carassino?) (1, 8) top-NNE normal fault kinking and undulation in frontal part of Adula nappe brittle-ductile deformation	D4 (Forcola) (2, 3, 4, 8) NNW–SSE normal faults brittle-ductile deformation	dextral brittle slip along Insubric Line block rotation along sinistral Engadine Line

*References:
(1) Löw (1987), (2) Marquer (1991), (3) Baudin et al. (1993), (4) Schmid et al. (1996), (5) Meyre et al. (1997), (6) Meyre & Puschnig (1993), (7)Partzsch et al. (1994), (8) this study.
LS = stretching lineation, FA = fold axe, S = foliation

al., 1993). Estimates of the P-T conditions are based on phengitic substitution (Massonne & Schreyer 1987) in D1 mylonitic foliations and systematically show HP-LT metamorphic conditions (Baudin & Marquer 1993). For example, metamorphic conditions of about 12 kbar and 500 °C are attained at the bottom of the Tambo nappe. Ahead of the Tambo and Suretta basement, the pile of crystalline and sedimentary slabs (Ucello, Areua, Schams, Vignone) represents an accretionnary wedge particularly well-developed in the northern Penninic 'Bünderschiefer' and flysch (Steinmann 1994). The overall geometry of the frontal slices is related to the closure of the Valais trough.

D2 deformation

Deformation D2 is a ductile and heterogeneous deformation linked with a gentle east-dipping schistosity and an E-W stretching lineation. Most of the D2 mylonitic zones cross-cut previous contacts and indicate top to the East shearing. D2 is responsible for large scale structure on the top of the Suretta nappe, developing recumbent SE vergent folds F2 with very low angles between fold axes and mainly N70 to E-W oriented stretching lineations (Marquer et al., 1996). The phengitic substitution values measured in the D2 mylonites or in the D2 shear bands indicate pressures, which progressively decrease with time, associated with a slight decrease in temperature. For example, a progressive decrease of pressure and temperature from 11 down to 5 kbar and 550 down to 500 °C is recorded at the bottom of the Tambo nappe (Baudin & Marquer 1993) and from 10–5 kbar at 400–450 °C in the Roffna granite (Challandes, 1996). This tectono-metamorphic evolution of the D2 deformation is interpreted in terms of strong vertical shortening associated with preferentially top to the East shearing, which occurred synchronously with substantial decompression (Baudin & Marquer 1993). This progressive deformation induces crustal thinning with a stretch parallel to the Alpine chain during Late Eocene to Early Oligocene (Marquer et al. 1994), simultaneous with refolding of the Schams nappes (Niemet-Beverin phase of Schmid et al., 1996) and ongoing N-S convergence in the Adula nappe.

D3 deformation

This deformation event occurred under lower greenschist facies conditions and became much more localized. D3 deformation results in local staircase shaped folding, with steeply south dipping axial planes and E-W fold axes, preferentially developed in the southern part of the nappes (Baudin et al. 1993). This D3 deformation was generated by differential uplift of the southern part of the nappe and could be associ-

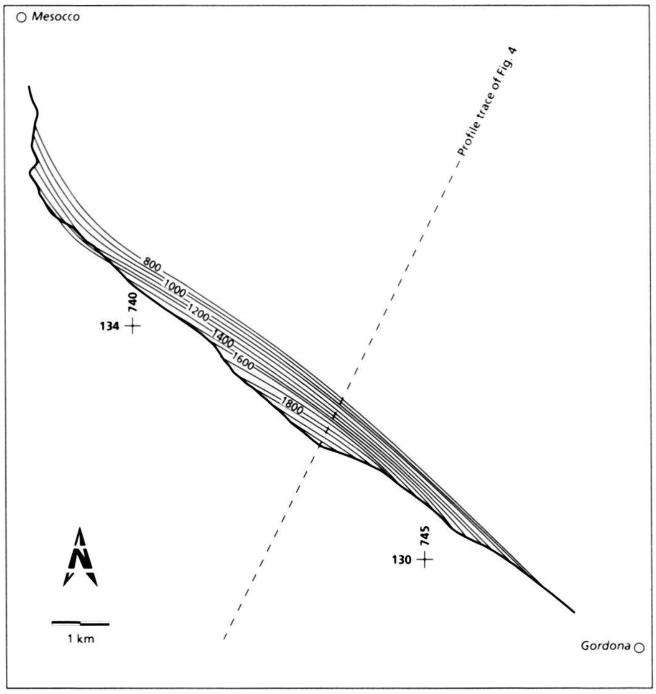

Fig. 3. Contour map of the fault plane of the Forcola normal fault. The contours are mainly constrained by data from Weber (1966) and our own field observations. Contour lines are given in 100 m interval. Profile trace refers to the cross-section in Figure 4.

ated with the Oligo-Miocene vertical movements along the Insubric Line (Hurford 1986; Heitzmann 1987; Schmid et al., 1989).

D4 deformation

The last extensional D4 deformation consists of several NNW-SSE brittle-ductile normal faults, steeply dipping towards the ENE and systematically lowering the eastern compartments with hectometric fault throws. The geometry and the kinematics of this deformation is contemporaneous with activity along the Forcola normal fault.

Tectono-metamorphic evolution

The tectono-metamorphic evolution of the Adula and the Tambo nappe is described in detail in Löw (1987), Meyre & Puschnig (1993), Partzsch et al. (1994), Partzsch (1998), Meyre et al. (1997) concerning the Adula nappe and in Baudin & Marquer (1993), Marquer et al. (1994) concerning the Tambo nappe. A comprehensive description of the tectonic evolution of the entire Penninic domain can be found in Schmid et al. (1996; 1997a; 1997b). The structurally higher part of the Adula nappe experienced a clockwise Alpine PT-loop culminating under eclogite facies conditions. The temperatures and pressures of this event range from 450–550 °C and 11–13 kbar in the northern part (locality Vals) to 750–900 °C and 18–35 kbar in the southern part (localities Alpe Arami, Cima di Gagnone) (Heinrich 1983; Heinrich 1986; Risold et al. 1996). The retrograde path is characterized by isothermal decompression during the Zapport phase. The tectono-metamorphic Alpine evolution of the Tambo nappe is characterized by peak metamorphic conditions at c. 500 °C and 13 kbar in its southern part. Like in the Adula nappe it is also followed by isothermal decompression. For the further retrograde evolution the pressure- and the temperature-path coincide (cf. Marquer et al. 1994).

Correlation of deformation phases in the Adula and Tambo nappes

Concluding from the above sections, we can correlate the deformation phases in the footwall (Adula nappe) and in the hangingwall (Tambo nappe) of the Forcola fault (Tab. 1). The 'Trescolmen' deformation phase, associated with eclogite facies conditions in the Adula nappe (Meyre & Puschnig 1993, Meyre et al. 1997), corresponds to the early stages of the Zapport phase of Löw (1987) and Schmid (1996).

The subsequent decompression of the Penninic units is accompanied by E-W extension restricted to the hangingwall (D2 in Tambo nappe) and N-S compression in the footwall ('Zapport' deformation phase in the Adula nappe).This D2 deformation is correlated with the Niemet-Beverin phase described in the Suretta and the Schams nappes by previous authors (Milnes & Schmutz 1978; Schmid et al. 1990; Schreurs 1993) and the Zapport phase in the Adula nappe. This correlation is based on the observation of a continuous transition of the Zapport foliation into the Niemet-Beverin axial planar foliation in the San Bernardino pass area. In the same area the stretching lineation continuously turns from a N-S direction ('Zapport') into an E-W direction (D2). The latest stages of the 'Zapport' phase were contemporaneous with the Niemet-Beverin phase in the Schams nappes and in parts of the North Penninic 'Bündnerschiefer' (Schmid et al. 1996). This equivalence gives an important time constraint for this deformation event because structures related to the Niemet-Beverin phase are cut by the Turba normal fault (Nievergelt et al. 1996), which is itself truncated by the intrusion of the Bergell granodiorite (30 Ma, after von Blanckenburg, 1992). It is important to note that D2 E-W stretching was active in the upper Penninic nappes (i.e. the Tambo and Suretta nappes) while the lower Penninic nappes (i.e. the Adula nappe) were progressively stacked towards the north ('Zapport'). Moreover D2 thinning could also explain part of the exhumation of the eastern part of the high grade Ticino dome (Bradbury & Nolen-Hoeksema 1985; Hurford 1986; Hurford et al. 1989; Merle 1994).

The Leis phase can be correlated with the Domleschg phase that has been described in the N-Penninic Bündnerschiefer and flysch by Pfiffner (1977). The Domleschg phase is equivalent with the D3 deformation phase in the Tambo nappe (Steinmann 1994; Schmid et al. 1996).

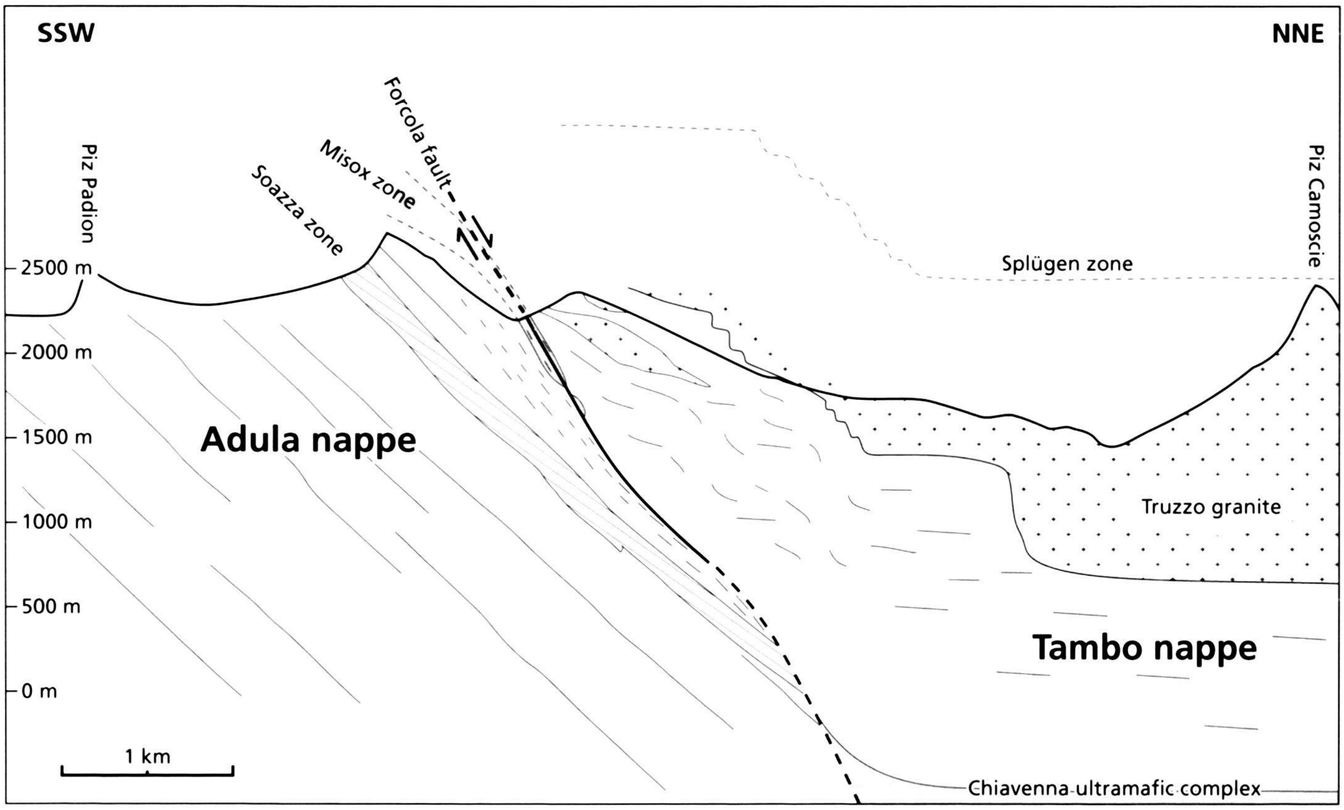

Fig. 4. Tectonic cross-section at the Forcola pass area, perpendicular to the fault orientation. Minor relics of the Misox zone can be observed at the Forcola pass area. The Soazza zone is truncated by the Forcola Line because of a high angle between the main foliation in the footwall and the fault.

Forcola phase

Field geometry

In map view the trace of the Forcola Line forms a slight arc concave towards the northeast. The construction of a contour map of the fault surface reveals a more or less constant inclination of the fault between 40° and 50° towards northeast (Fig. 3).

The flat lying foliation of the hangingwall is clearly discordant to the fault zone, whereas in the footwall a discrimination between the pre-existing 'Zapport' foliation and the subparallel Forcola mylonitic schistosity is not always clear because of the small angle between the two foliations. Towards the southeast, the Forcola normal fault cuts off the 'Soazza' zone (Weber 1966), which is a zone of metasedimentary rocks (paragneisses and metapelites) within the leucocratic gneisses of the structurally higher Adula nappe. The Misox zone is entirely thinned out due to Forcola phase movements. The last small slices of the Misox zone are preserved in the Forcola pass area.

The vertical component of displacement, induced by normal faulting may be estimated from a cross section in the Forcola pass area (Fig. 4) and amounts to 3000m at least.

The continuation of the Forcola line towards the southeast, as well as towards the northwest is still unclear. In the northwest (the Valle Mesolcina) the fault possibly continues at the base of the Misox zone, although north of Mesocco no relics of this normal fault could be detected so far. In the southeast the trace of the normal fault is covered by the alluvial plain of the Valle Mera, the last outcrop being found near the village of Gordona. However, inspection of the foliation trajectory map of the southeastern part of the Lepontine area (Fig. 2), reveals a significant change in the orientation of the foliation across Valle Mera: The E-W striking foliation on the east side of Valle Mera (Gruf unit) contrasts with the NW-SE strike of the west side (Adula nappe). This prominent change could indicate a continuation of this line across the alluvial plain of Valle Mera, as indicated in Figure 2. This hypothesis is supported by the occurrence of brittle fractures and faults in the region north of Novate (work in progress, L. Ciancaleoni). However, the exact localization of the major fault zone in the Novate intrusion is still unknown. Furthermore, mylonites clearly related to the Forcola phase are not apparent on the east side of the Valle Mera. The continuation of the Forcola normal fault across the Valle della Mera south of Gordona, such as suggested by Fig. 2 has two important consequences:

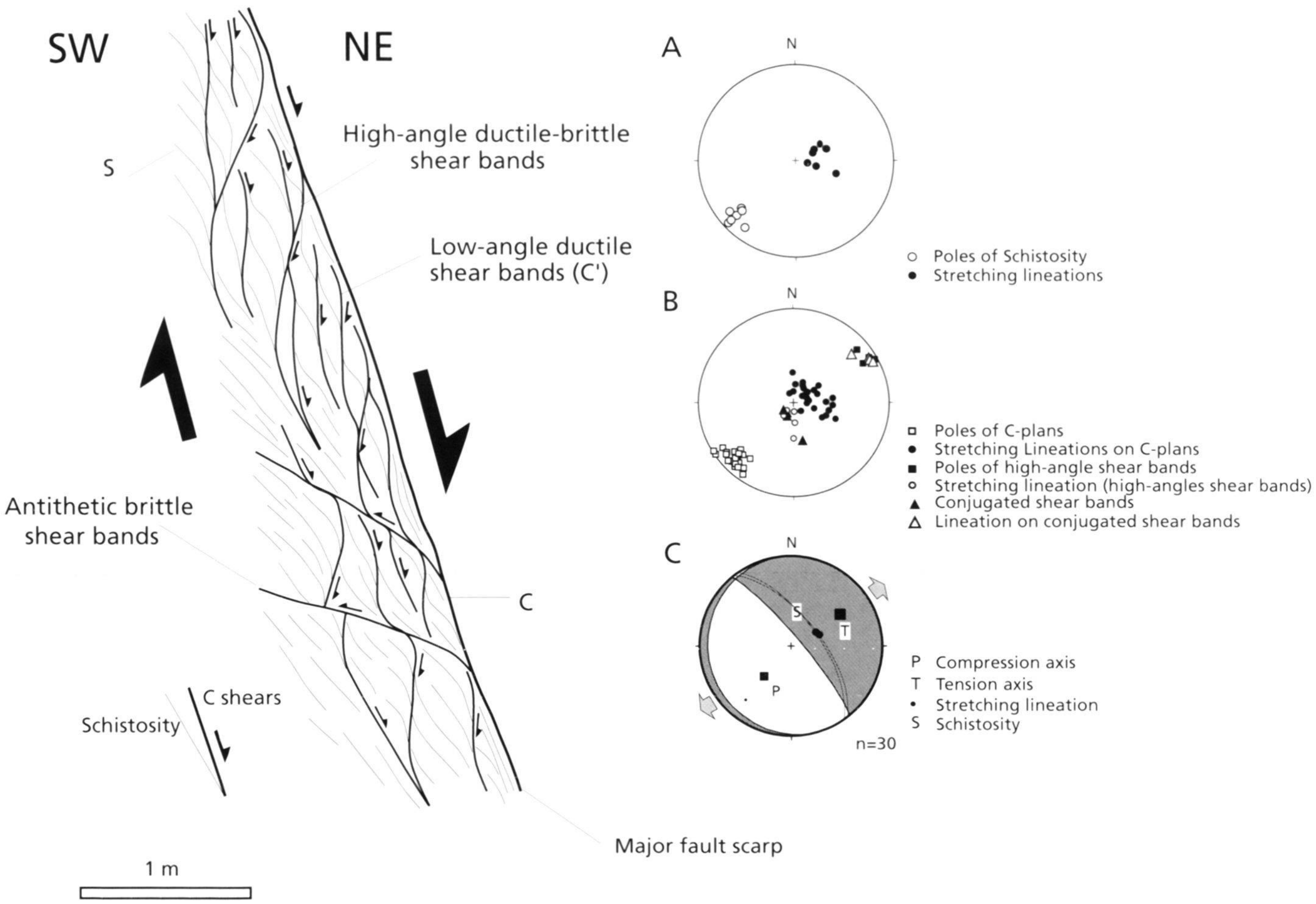

Fig. 5. Kinematic analysis in the footwall of the Forcola fault. (location: west of village of Gordona). Lower hemisphere stereograms. S: schistosity, C: shear plane after Berthé et al. (1979).

(i) the Chiavenna ultramafic complex appears as the lateral equivalent of the Misox zone, both units being situated in the hangingwall of the Forcola normal fault and structurally below the Tambo nappe, and

(ii) the Gruf unit is separated from the Adula nappe by the Forcola normal fault, causing the same angular difference between the foliation trajectories east and west of the normal fault also observed north of Gordona (NW-SE vs. EW). This supports the view that the Gruf unit represents the lateral equivalent of the Adula nappe as proposed by Berger et al. (1996).

Deformation

The Forcola phase is characterized by three dominant structures: a schistosity S_F, a lineation L_F and shearbands, which are especially well established in the hangingwall (Tambo nappe). The Forcola phase overprints the Zapport and Leis structures in the Adula nappe with increasing intensity towards the Forcola Line. In the footwall, the strain due to the Forcola deformation is restricted to a zone that is at most 200 m wide. Within the Tambo nappe, however, shear bands and small normal faults related to the Forcola phase can be observed within the entire nappe. Brittle features are abundant in the hangingwall but can also be observed in the footwall.

Schistosity S_F

In average the Forcola schistosity S_F is dipping with about 42° towards NNE (032/42; cf. inset in Fig. 2). Within the Tambo nappe, the Forcola schistosity is oblique with respect to the older flat-lying predominant schistosities. In the Adula nappe, however, the Forcola schistosity is subparallel to the older 'Zapport' foliation. Here, it is therefore difficult to differentiate between the two schistosities or even between two parageneses. No folds related to the Forcola phase can be observed.

First isoclinal folds in the footwall clearly belong to the Zapport deformation phase and occur about 150 meters below the normal fault zone. Only a few open folds of the Leis phase have been detected in the footwall of the Forcola pass area.

Lineation L_F

The Forcola lineation L_F dips with about 40° to the ENE (067/39). This stretching lineation is mainly built up by chlorite and elongated quartz aggregates. The orientation of the lineation L_F is interpreted to be oriented subparallel to the displacement vector on the normal fault. The Forcola lineation makes a small angle with respect to the pre-existing lineation in the footwall (Zapport lineation of the Adula nappe) as well as in the hangingwall (D2 lineation in the Tambo nappe; Fig. 2).

Shear bands

Shear bands related to the Forcola phase are very abundant and sporadically develop within the non-mylonitic rocks of the hangingwall (Tambo nappe). Deformation is much more pervasive and homogenous in the footwall (Adula nappe) than in the hangingwall. These shearbands are prominent within the first 50 m of Adula-derived mylonites. Further below, shear bands die out as the Forcola phase deformation becomes less intense. A strong deformation gradient within the top 200 m of the Adula nappe is also apparent with respect to fold geometry: Older 'Zapport'-phase folds are not present within the mylonites of the fault zone, while dismembered folds can be observed in the structurally lower 200m. In the Soazza zone isoclinal folds, clearly related to the Zapport phase, are apparent.

Although no quantitative determinations of pressure and temperature are possible, a qualitative statement with respect to the difference between hangingwall and footwall of the fault zone can be deduced. The observed microstructures imply colder temperatures in the hangingwall and warmer conditions in the footwall: Brown biotite has grown within shear bands in the mylonites of the Adula nappe and green biotite and chlorite found in comparable lithologies from the Tambo nappe support this assumption. Therefore, shearbands as well as the other structural elements clearly developed under greenschist facies conditions. Although brittle as well as ductile features can be observed, it is not possible to map out a systematic distribution of brittle and ductile phenomenas due to insufficient displacement across the Forcola normal fault.

Kinematics

In the footwall of the Forcola fault (300m west of Gordona), extensional structures developed under gradually decreasing temperatures (Fig. 5). On the outcrop, C/S relationships, asymmetric clasts, foliation boudinage, and shear bands are the typical structures of the ductile deformation (Hanmer and Passchier, 1991). Low-angle ductile shear bands (C' of Berthé at al. 1979) are better expressed in phyllosilicate-rich lithologies and have shallow angles to the main mylonitic schistosity. In more competent layers, like gneisses, brittle-ductile shear bands develop at higher angles (up to about 60°) to the main mylonitic schistosity (high-angle ductile-brittle shear bands of Fig. 5). These high-angle shear bands gradually evolved into brittle faults, bearing quartz-chlorite striae. They are in the orientation of synthetic Riedel shears with respect to the C-surfaces (Fig. 5). The down-dip chlorite stretching lineation on the major fault scarp, parallel to the C-planes is associated with sense of shear criteria indicating a consistent top-down to the NE-directed relative offset. Antithetic brittle shear bands developed during the last increments of the progressive deformation, conjugate to the main C-surfaces and cross-cutting earlier formed high-angle ductile-brittle shear bands (Fig. 5). All these ductile-brittle shear bands did not offset the main C-planes. On the basis of these field relationships, these microstructures are interpreted as coeval progressive sets of shear bands associated with ongoing Forcola deformation under cooling conditions and across the ductile-brittle transition.

In ductile shear zones, the shear plane and stretching lineation may be considered in first approximation to reflect the displacement-plane and vector, respectively. The inversion programs, often used to deduce stress axes in brittle deformation, can give indications about the incremental strain axes and the bulk kinematics of ductile deformation (Marquer et al., 1996). The program 'Fault kinematics' (Allmendinger et al., 1989), which is based on the P-T axes and the right dihedral graphical methods, was used to determine principal strain axes from striated faults and brittle-ductile shear zones. Fault-slip data from these brittle-ductile normal faults indicate NE-SW oriented extension (Fig. 5C) which is compatible with the extension direction deduced from schistosity-stretching lineations pairs of the ductile deformation (Fig. 5A). The bulk asymmetry between the resolved T axis comprise in the T-intermediate axes plane and the average of schistosity-stretching lineation couple give an indication for a normal faulting with a lowering of the north-eastern block (Fig. 5C).

The results of the kinematic analysis of the brittle and brittle-ductile deformations in the Forcola area are coherent in the footwall and the hangingwall. In the latter, particularly well-developed shear bands are found in the Truzzo granite, north of the Forcola pass (Fig. 6). Brittle faults with the same direction and sense of shear occur further northeast in the Tambo nappe, far away from the main Forcola fault. These results are consistent with an NE-SW directed extension affecting the entire area. This extension was active during decreasing temperatures conditions, as shown by the ductile to brittle transition.

This latter observation indicates that the Forcola normal fault must have been active at a time when the southern Tambo nappe cooled down to below about 300 °C, that is between about 18 and 25 Ma according to biotite Rb-Sr and K-Ar ages (Jäger et al. 1967; Purdy and Jäger 1976; Marquer et

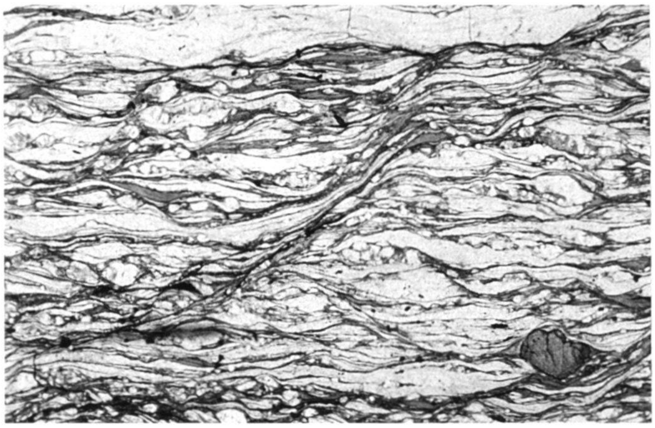

Fig. 6. Micrograph of shear band in deformed 'Truzzo' granite (sample T34, southern Tambo nappe). Sinistral sense of shear indicates top to NE shearing. Field of view is 2.7 mm.

al., 1994). The beginning of the Forcola fault activity cannot be placed before 25Ma because the 25Ma old Novate granite was also deformed by this normal faulting phase. During its last stage (i.e. at around 18Ma), the Forcola phase seems to be coeval with the beginning of displacement on the Simplon normal fault, its symmetrical equivalent structure starting around 20Ma at the western part of the structural Lepontine dome (Steck 1984, Mancktelow 1985; Steck 1990). From its age and kinematics the Forcola normal fault has to be seen in the context of Late Oligocene-Early Miocene transpression, associated with an orogen-parallel stretch and coeval with conjugate dextral and sinistral strike slip along the Insubric and Engadine Lines (Periadriatic fault system), respectively (Schmid & Froitzheim 1993).

Hence, this normal faulting substantially post-dates normal faulting along another prominent E-dipping normal fault in a higher tectonic level, the Turba mylonite (Zapport-D2) (Nievergelt et al. 1996), which predates the intrusion of the Bergell granodiorite (30 Ma; von Blanckenburg 1992). The Early Miocene NE-SW directed extension, well-expressed by the Forcola fault, could be interpreted as the continuation of the Oligocene ductile deformation phase in the Upper Penninic nappes (E-W extension during D2 within the Tambo nappe and Turba normal fault), but with a slightly different stretching direction. It appears that normal faulting on the eastern side of the Lepontine dome corresponds to a main process of stretching oriented parallel to the orogen belt from Late Eocene to Early Miocene time. While the late Eocene-Oligocene E-W extension (D2) is associated with a large isothermal decompression and Oligo-Miocene extension (D4) acts during typical Barrovian cooling, this last event does not necessarily imply a strong crustal thinning or extensional collapse. Hence E-W to NE-SW extensions are not incompatible with the simultaneous N-S to NW-SE bulk compression which is documented in the northern and southern foreland of the Alps for the same interval of time. These two events of stretching parallel to the Alpine belt correspond to different deformation processes during the tectonic evolution of the internal domain of the Alpine belt. These different tectono-metamorphic evolutions reflect a strong exhumation during the main European subduction and lateral extrusion during the evolution of the Periadriatic system, respectively.

Conclusions

Being both due to the Tertiary closure of the Valais ocean, the deformation phases of the Adula and the Tambo nappes can be correlated. However, there are some differences in their tectonic and metamorphic histories: the Adula nappe underwent a complex subduction process that culminated under eclogite facies conditions (Sorreda-Trescolmen), in contrast the Tambo nappe reached lower pressure conditions (D1). Furthermore, deformation related to the south-directed subduction was recorded in the Adula nappe (Zapport), while E-W syn-orogenic extension D2 took place in the Tambo nappe during Eocene time. After these early deformations, the two nappes followed the same Oligo-Miocene tectonic history.

From the observations discussed in the previous chapter, it is evident that the Forcola normal fault greatly contributes to the late stages of unroofing in the Central Alps and plays an important role for the dome-like structure in the SE-Lepontine zone. The main tectonic implications concerning the Forcola deformation are the followings:

(1) The Forcola normal fault offsets the Tambo nappe in the hangingwall relative to the Adula nappe in the footwall with an amount of approximately 3000 m. The direction of faulting is top to ENE.
(2) Due to the observation of ductile and brittle structures, the Forcola fault was active under progressive retrograde conditions. 'Cold' structures are apparent in the hangingwall, 'warmer' structures are apparent in the footwall. An offset of the mineral isograds cannot be determined because of the lack of critical assemblages in the different lithologies as well as a insufficient resolution of the petrologic data.
(3) The continuation of the fault towards the southeast is not clear. However, from trajectory maps of the southeastern 'Lepontine', from contour maps of the fault surface and from recent field work we can suggest that the fault continues into the northern end of the Novate intrusion.
(4) Timing constraints of the Forcola Line are given indirectly by cooling ages from this well-studied part of Central Alps. A realistic age interval is between 25 and 18 Ma.
(5) The Forcola fault might be an equivalent structure to the Simplon fault in the western Central Alps. The Forcola fault was active before the normal faulting in the Simplon area. This time-discrepency could be related to the time-space evolution of the Periadriatic fault system during the late Oligocene-early Miocene transpressive displacement of the Adria plate.

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