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Artikel: Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden

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Kapitel: 6: Synthesis : structural evolution of the Austroalpine nappes in Graubünden

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intermediate composition and calc-alkaline affinity (Conti et al. 1994). The dykes are about 32 Ma old (Dal Piaz et al. 1988). This age can hence be regarded as a minimum age of the Blaisun phase in this region.

Apart from the Engadine line, active near the Oligocene-Miocene boundary, and other brittle faults kinematically linked to this line (Schmid & Froitzheim 1993), no evidence for younger events is found in the Engadine Dolomites.

In summary, the structural architecture of the Engadine Dolomites is characterized by the strong prevalence of Trupchun-phase structures, including folds and west to northwest directed thrusts. The recumbent "collapse folds" of the Ducan-Ela phase are not observed in the Engadine Dolomites. On first sight, a striking similarity exists between the structural architecture of the Ela nappe and the one of the Ortler nappe: in both units, recumbent folds with north-dipping axial surfaces are the dominant structural elements. This similarity has misled several authors to regard the Ortler nappe as the continuation of the Ela nappe (e. g. Staub 1964, p. 87–88). The similarity, however, is only apparent: the recumbent folds of the Ortler nappe are thrust-related folds of the Trupchun-phase (D_1), whereas the recumbent folds of the Ela nappe are younger "collapse folds" of the Ducan-Ela phase (D_2). A correlation between northeast-striking folds in the S-charl-Sesvenna unit and the Ela "frontal fold", as put forward by Heim (1922, Fig. 227), Eugster (1923, Fig. 32) and Staub (1924, Fig. 34) has to be rejected for the same reason: the first are Trupchun-phase folds, the latter belongs to the Ducan-Ela phase.

6 Synthesis: Structural evolution of the Austroalpine nappes in Graubünden

In the following, we extend our considerations to a larger area within the Austroalpine nappe pile in Graubünden. The sequence of deformation phases developed above applies also to other parts of this nappe pile. A correlation with the sequences established for the western border of the Err-Carungas nappe (Dürr 1992), the Samedan zone (Handy et al. 1993) and for the Margna nappe and surrounding area (Liniger 1992, Hermann & Müntener 1992) is given in Table 1. The correlation with the deformation sequence of the northern Malenco area east of the Bergell pluton (Hermann & Müntener 1992) is partly ambiguous because these authors observed one additional fold generation (D_4) that is not recorded in adjacent areas. It may represent a local phenomenon.

6.1 Cretaceous orogeny

6.1.1 From the Jurassic passive margin to the Late Cretaceous thrust belt

The domains of the Jurassic-age passive continental margin were telescoped by top-northwest to top-west directed thrusting in the Late Cretaceous Trupchun phase. This imbrication of nappes started after 90 Ma in the Ortler zone, as is indicated by the occurrence of Cenomanian to Lower Turonian "Couches rouges" in the core of a Trupchun-phase syncline in Val Trupchun (Caron et al. 1982; see above). The same is true for the Lower Austroalpine (Murtiröl half window and Samedan zone) where "Couches rouges" are overlain by flysch of probably Late Cretaceous age (Rösli 1927, 1946). The onset of flysch sedimentation indicates the beginning of convergence. These biostratigraphic data, together with radiometric ages from the Engadine Dolomites and the Schlinig thrust re-

Silvretta-Ela-Err (this article)	**Western border of Err-Carungas nappe (Dürr 1992)**	**Samedan zone (Handy et al. 1993)**
Domleschg phase	--	F4 (folds)
Turba phase	D3 (top-E normal faults)	steep, E-dipping normal faults
Blaisun phase	D2 (folds)	F3 (folds), N-directed thrusts
Ducan-Ela phase	--	F2 (folds), top-east extensional shear
Trupchun phase	D1 (isoclinal folds, top-west shear)	F1 (folds), W- to SW-directed thrusts

Silvretta-Ela-Err (this article)	**Margna, Sella, Malenco (Hermann & Müntener 1992)**	**Margna, Platta, Avers NW of Engadine line (Liniger & Nievergelt 1990)**	**Schams nappes (Schmid et al. 1990, Schreurs 1993)**
Domleschg phase		D3 (folds)	D3
	D6 ("2nd phase of backfolding")		
Turba phase	D5 (top-east shear zones)	D2 (top-east Turba mylonite zone)	D2
	D4 (folds)		
Blaisun phase	D3 ("First phase of backfolding")	F2 /D1 (folds)	D1
Ducan-Ela phase	D2 (top-east shear zones)	--	--
Trupchun phase	D1 (isoclinal folds)	F1 (isoclinal folds, top-W to top-SW mylonites)	--

Tab. 1. Correlation of deformation sequences.

ported above (chapter 5.3), indicate a westward migration of Trupchun-phase deformation: thrusting along the Schlinig thrust started at about 100 Ma, cleavage in the S-charl nappe was formed around 90 Ma, and the western Ortler nappe was buried under the higher thrust sheets after 90 Ma (Fig. 14).

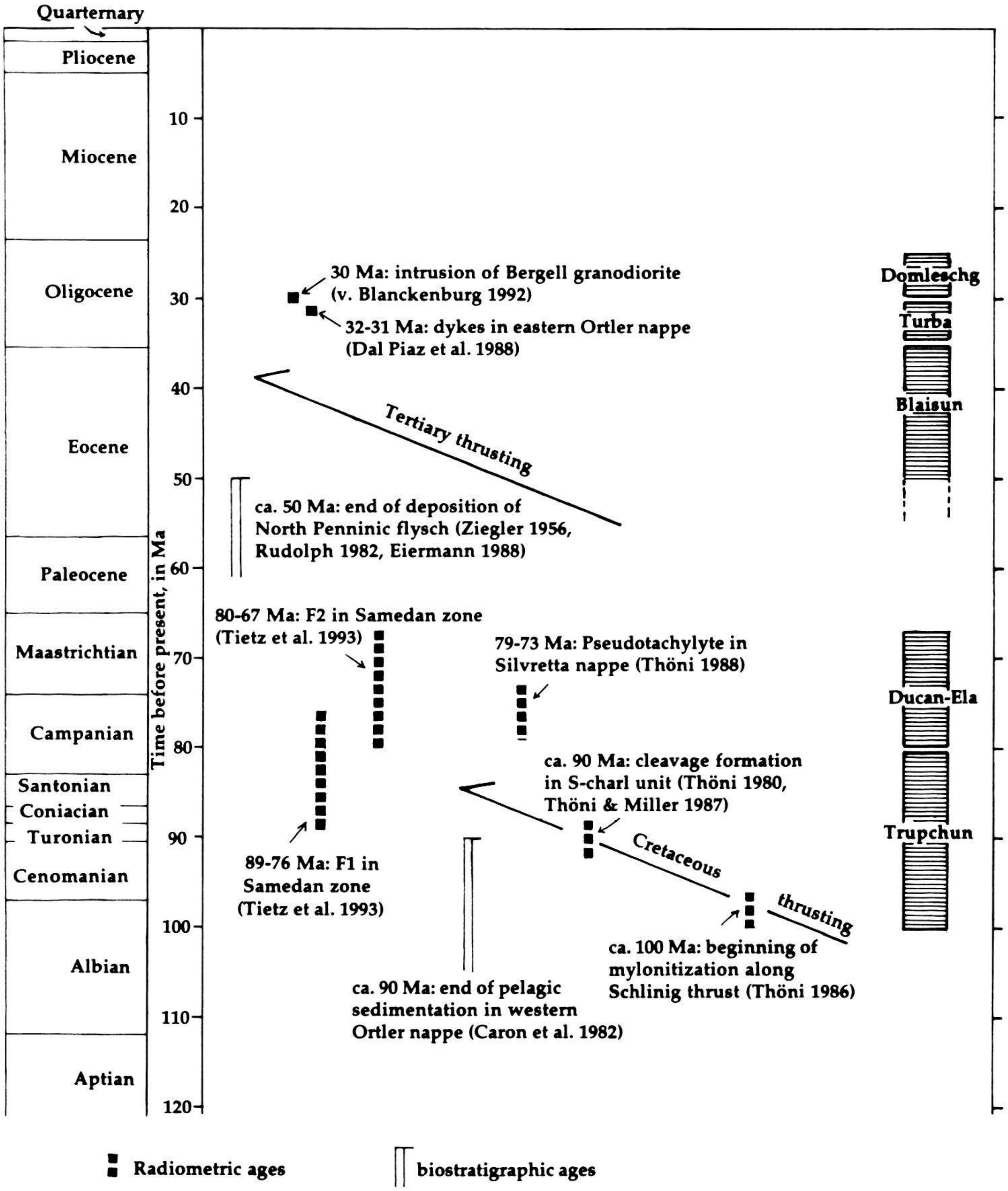
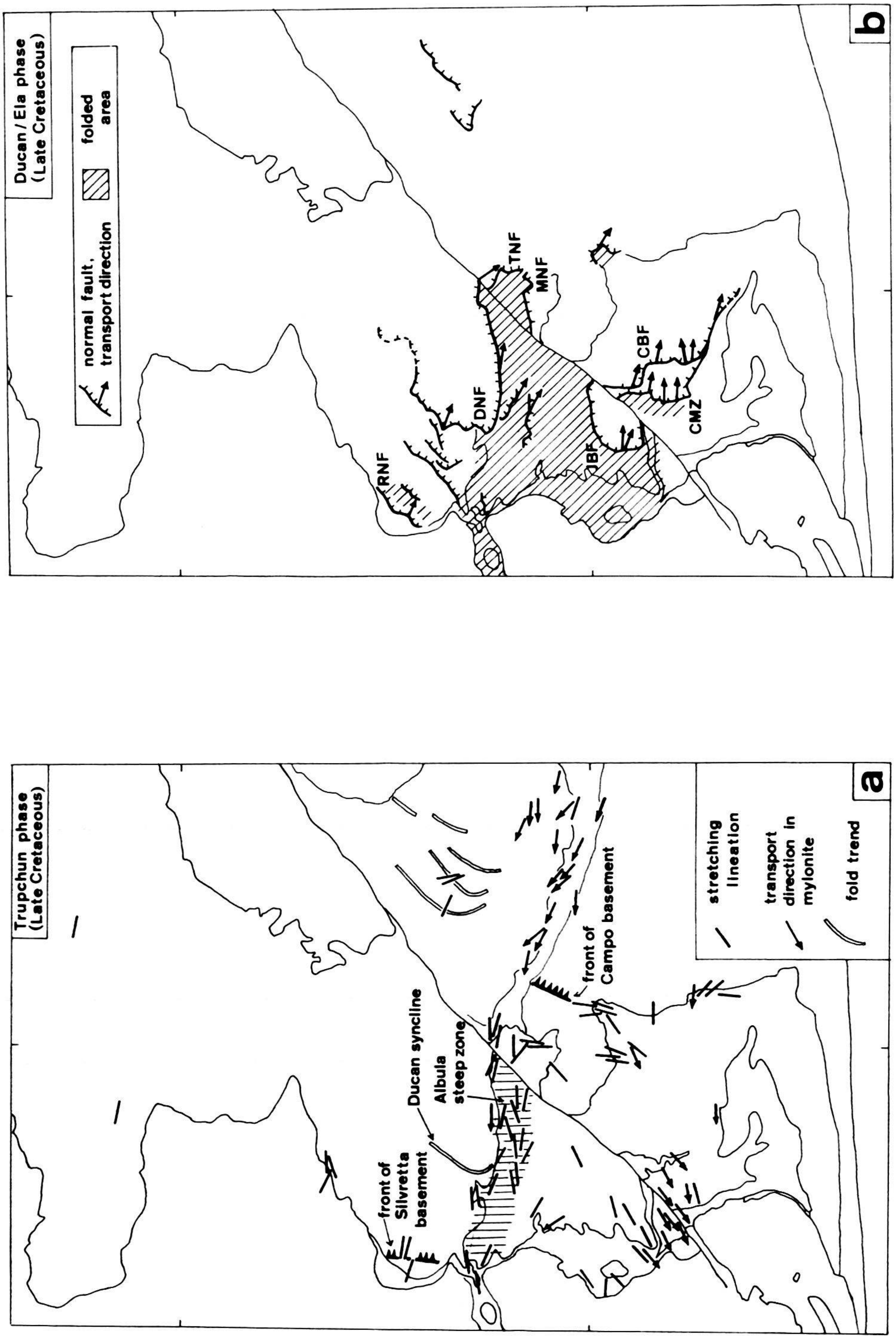
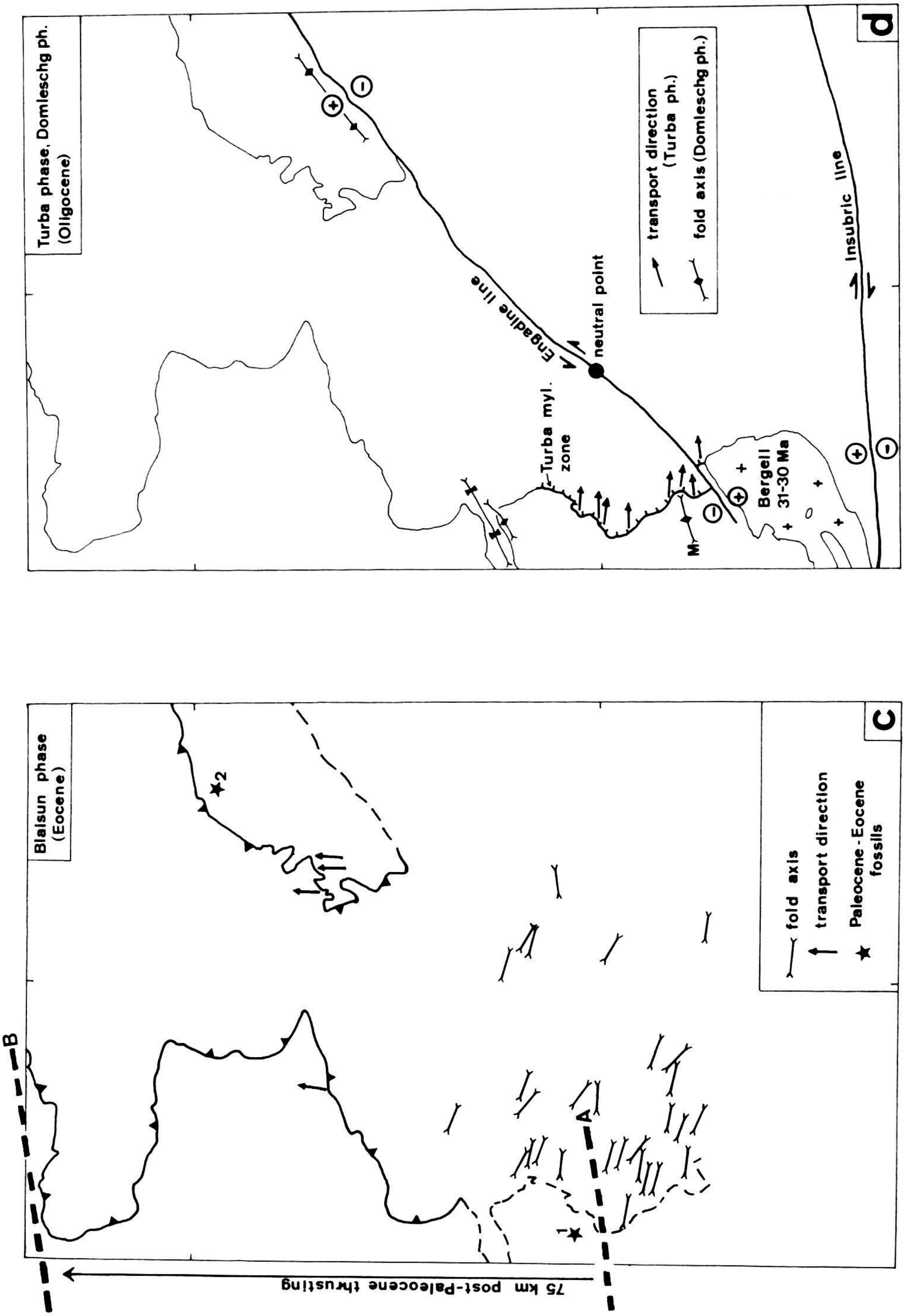


Fig. 14. Time table, showing radiometric and biostratigraphic age determinations and their relation to the deformation sequence of the Austroalpine units.

Most authors assume that oceanic lithosphere of the South Penninic ocean was subducted under the Austroalpine continental margin in the Cretaceous (Trümpy 1975, Frisch 1979, 1980). The subducted lithosphere carried the Margna-Sella continental fragment which collided with the Austroalpine mainland. The ophiolites of the Platta nappe mark the oceanic suture between Margna-Sella fragment and Austroalpine mainland. Col-


Ducan/Ela phase
(Late Cretaceous)
normal fault, transport direction
folded area
b
RNF
DNF
TNF
MNF
IBF
CBF
CMZ
Trupchun phase
(Late Cretaceous)
stretching lineation
transport direction in mylonite
fold trend
a
front of Silvretta basement
Ducan syncline
Albula steep zone
front of Campo basement


Turba phase, Domleschg ph.
(Oligocene)
d
Engadine line
neutral point
Turba myl. zone
Bergell
31-30 Ma
Insubric line
transport direction
(Turba ph.)
fold axis (Domleschg ph.)
Blaisun phase
(Eocene)
c
B
A
75 km post-Paleocene thrusting
fold axis
transport direction
Paleocene-Eocene fossils

lison and suturing occurred already in the Cretaceous, as indicated by the following facts: (1) The Margna-Platta boundary is truncated by the Corvatsch mylonite zone, a Late Cretaceous extensional fault (Liniger 1992; our Fig. 15b). (2) The Platta-Err boundary is folded around a fold of the Ducan-Ela phase, also Late Cretaceous in age (Fig. 3a).

Stretching lineations and shear sense determinations related to the Trupchun phase are represented in Figure 15a. Top-northwest to top-west thrusting prevails, and even top-southwest directed thrusting is documented from the area of the Margna nappe (Liniger 1992). The thrust geometry was largely influenced by the inherited geometry of the Jurassic passive continental margin (Fig. 1b). The latter was characterized by two systems of normal faults, an east-dipping system in the eastern, proximal part and a west-dipping system in the western, distal part (Froitzheim & Eberli 1990). An outer basement high had formed between the west-dipping and the east-dipping fault system, in the area that later became the Bernina nappe. The Jurassic to Lower Cretaceous sedimentary cover of this area is in places extremely thin and reflects erosion and condensed sedimentation on a submarine high (e. g. in the Schlattain-Clavadatsch unit of the Samedan zone, Rösli 1946).

Fig. 15. Maps showing orientation of structures related to different deformation phases in the Austroalpine of Graubünden. For locations compare Fig. 1.

(a) Early, thrusting-related structures of the Trupchun phase. Shear sense of mylonites yields consistently northwest- to west-directed transport. Southwest-directed shearing occurred in the Margna nappe and its vicinity (SW part of map, data from Liniger 1992). The Albula steep zone (vertical ruling) is interpreted as a zone of sinistral shearing also formed in the Trupchun phase. Front of main Upper Austroalpine basement sheets (Campo and Silvretta) is displaced across Albula steep zone.

(b) Late Cretaceous normal faults, mostly low-angle, of the Ducan-Ela phase. Arrows indicate transport direction of respective hanging walls, as derived from kinematic analysis of mylonites and cataclasites (partly data from Liniger 1992, Weh 1992, Spillmann 1993). CBF, Corvatsch-Bernina boundary fault (Fuorcla Surlej – Val Roseg – Fuorcla da la Sella); CMZ, Corvatsch mylonite zone; DNF, Ducan normal fault; JBF, base of the Julier nappe (prolongation of CBF northwest of the Engadine line); MNF, Mezzaun normal fault, between Seja basement below and Mezzaun sediments above; RNF, Rothorn normal fault, between Rothorn nappe below and Arosa Dolomites above; TNF, Trupchun normal fault, between Murtiröl unit below and Ortler nappe above (compare Fig. 5b in Schmid & Froitzheim 1993). Extension-related recumbent folding occurs in the footwall of a system of low-angle normal faults defined by the DNF, TNF, MNF and JBF.

(c) Early Tertiary folding (Blaisun phase) and northward thrusting of the orogenic lid comprising Austroalpine and Platta nappe. Fold axis orientations include data from Liniger (1992) and Handy et al. (1993). Latest Paleocene to Middle Eocene fossils at locality 1 (Parsonz flysch, Ziegler 1956, Eiermann 1988) and Middle Paleocene to Lower Eocene fossils at locality 2 (Tasna flysch, Rudolph 1982) indicate that thrusting of the orogenic lid over these units is post-Paleocene. Transport direction of the basal thrust (arrows) is derived from foliated cataclasites. Dashed parts of the basal thrust are overprinted by later faulting (Engadine line and Turba mylonite zone). A: northernmost possible position of the Austroalpine thrust front in the Late Paleocene to early Eocene; B: present Austroalpine front. These data require 75 km post-Paleocene northward thrusting.

(d) Postcollisional structures of Turba phase and Domleschg phase. The east-dipping Turba mylonite zone records east-directed downfaulting of the orogenic lid before intrusion of the Bergell granodiorite at 30 Ma. Note that the Turba m. z. is truncated by the Bergell intrusion on the southeast side of the Engadine line. East- to northeast-trending Domleschg-phase folds are younger than the Turba mylonite zone. Engadine line and Insubric line are conjugate faults accommodating eastward extrusion of the intervening block. Vertical displacement ("+" and "-" symbols) changes along the Engadine line and is zero at neutral point between St. Moritz and Samedan.

In the proximal part of the margin, especially in the Ortler zone, east-dipping high-angle Jurassic normal faults were transported within thrust sheets and were thus preserved almost in their original configuration (Froitzheim 1988), or were reactivated as thrusts (Manatschal 1991, Conti et al. 1994). The outer basement high was transformed into the Bernina nappe. The basement-dominated character of this nappe, with massive basement sheets and thin cover synclines, is directly inherited from its position in the passive margin. The sediment fill of normal-fault-bounded half grabens immediately east of the basement high partly remained in place, that is, connected to the basement of the Bernina nappe (Piz Alv, Sassalbo, Mezzaun, Pl. 1), partly was sheared off and transported to the west, over the basement culmination, as in the case of the Ela nappe. The pronounced stretching lineation ubiquitous in the Jurassic rocks of the Ela nappe may result from this special situation: These sedimentary rocks were "rolled out" between the obstacle of the Bernina basement below and the Upper Austroalpine basement above (Silvretta, Languard, Campo). In the Err nappe, west of the basement high, Jurassic normal faults were again partly preserved and only weakly overprinted by Alpine deformation (Froitzheim & Eberli 1990). This may be explained by the "pressure shadow" of the Bernina basement high, and by the westward dip of Jurassic normal faults in the Err nappe, unsuitably oriented for reactivation in a framework of top-west thrusting.

6.1.2 Sinistral wrench movement along the Albula steep zone

As stated above, Cretaceous orogeny in the western Austroalpine was dominated by top-west directed nappe imbrication. What is the role of the Albula steep zone in this context? This zone represents a lateral discontinuity of the nappe stack. It formed concomitant with nappe imbrication, or possibly, during a late stage of this imbrication. The significance of this zone may be understood by looking at the position of the crustal segments to the north and to the south of it in terms of Jurassic paleogeography. Across the Albula steep zone, the Upper Austroalpine Silvretta nappe to the north is laterally juxtaposed with the Lower Austroalpine Err-Carungas nappe to the south. The Err-Carungas nappe represents the most oceanward, western part of the Jurassic passive continental margin. In contrast, the Arosa Dolomites, today located at the western rim of the Silvretta nappe, represent a relatively proximal, continentward part of the passive margin (Furrer 1993, Eberli 1988). Therefore we interpret the Albula steep zone as a sinistral wrench zone along which Silvretta nappe and Arosa Dolomites moved from east to west relative to the Err nappe and other units to the south.

Figure 16 is a schematic reconstruction of the nappe geometry after the Trupchun phase. Platta-, Err-Carungas-, Ela-Bernina and Silvretta-Campo nappes had been imbricated along east-dipping thrusts. The Albula steep zone acted as a sinistral wrench zone within the nappe stack, accommodating different amounts of westward thrusting of Austroalpine units situated north and south of it. A northern block, including the Silvretta nappe, differentially advanced towards the west in respect to a southern block, including the Err nappe. This explains the counterclockwise rotation of D_1 folds in the Ela nappe and at the southwestern termination of the Ducan syncline. Slightly younger, upright D_1 folds in the Albula steep zone indicate a component of north-south shortening acting contemporaneously with sinistral wrench movement.

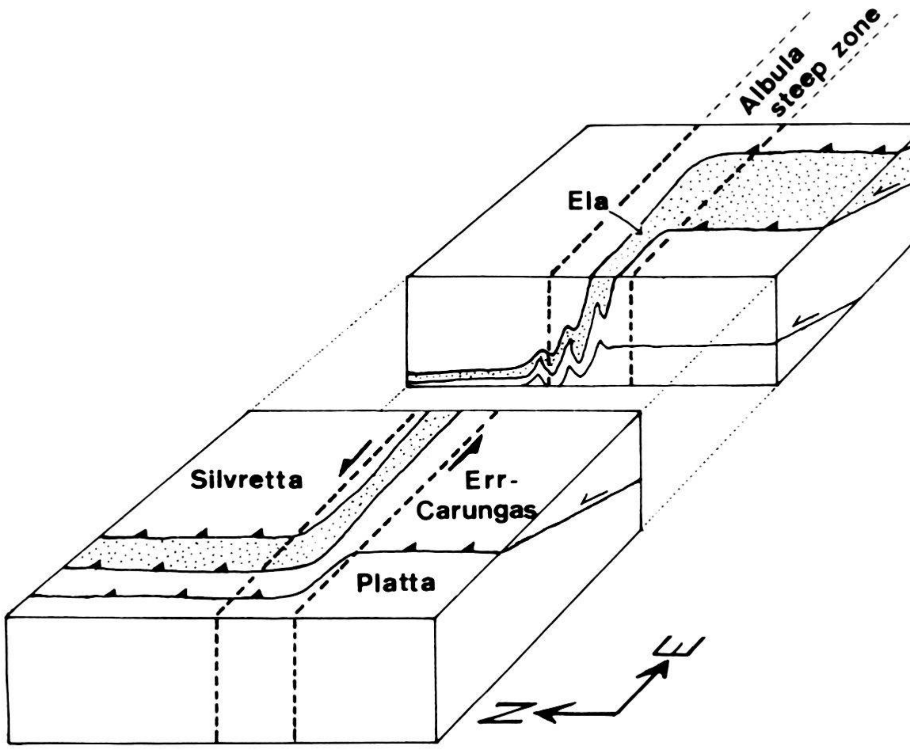


Fig. 16. Reconstruction of the "Albula steep zone". The Silvretta nappe advanced towards west relative to the Lower Austroalpine nappes (Ela, Err-Carungas) along an east-west trending, sinistral shear zone. Already existing thrusts were folded due to a component of north-south shortening concomitant with sinistral shearing in a late stage of the Trupchun phase (Late Cretaceous), leading to the steep orientation of the nappe boundaries.

The location of the eastern continuation of the Albula steep zone across the Engadine line remains uncertain, partly because of a severe extensional overprint in the Murtiröl-Mezzaun half window (Figs. 1, 15b). Retro-deformation of movements along the Engadine line (Schmid & Froitzheim 1993) constrains this continuation to be situated between the Campo basement to the south and the Sesvenna basement to the north. This can be used for an estimate of the displacement along the Albula steep zone. As discussed above, the Campo nappe and the Silvretta nappe occupy the same structural level in the original nappe pile. We assume that Campo and Silvretta were parts of one continuous basement complex before the displacement along the Albula steep zone. Today, the western boundary of the Silvretta basement and the wetern boundary of the Campo basement are offset in a sinistral sense by 40 to 45 km (Fig. 15a). Both boundaries are not erosional, in which case they could not be used for an estimation of the offset, but represent the primary front of the basement: the western front of the Campo basement is defined by the wedging-out of this unit between the underlying Languard nappe and the overlying Ortler nappe (Fig. 1), and the western front of the Silvretta basement is represented by a fold core enveloped by Permo-Triassic cover rocks. Therefore, this offset of 40 to 45 km constrains the displacement across the Albula steep zone. An independent estimate is provided by pronounced facies analogies in the Late Triassic and Early Jurassic of the Arosa Dolomites and the central Ortler nappe (Furrer 1993, Eberli 1988), indicating that these units are derived from closely neighbouring areas. The sinistral displacement beween these areas amounts to about 50 kilometres. This second estimate depends, of course, on a simple and possibly unrealistic arrangement of facies zones.

Late Cretaceous, east- to northeast-striking sinistral wrench faults in the Austroalpine realm were inferred on the grounds of paleogeographic considerations by Trümpy (1976). The Albula steep zone might well represent one of these. Another sinistral wrench zone was inferred between the Northern Calcareous Alps and the Central Austroalpine (Bechstädt 1978, Trümpy 1992), in order to account for the different facies of the Triassic in these two areas. In our study area, this other wrench zone would be situated between the Silvretta nappe to the south and the Northern Calcareous Alps to the north. This proposition is in good accordance with our observations. The Late Cretaceous to Eocene dextral movement in the Albula-Ortler zone proposed by Laubscher (1991), however, is in contradiction to the field evidence and has to be rejected. In our study area, we did not find any indication for dextral wrenching along east-striking faults or shear zones during the Cretaceous. The absence of such structures is remarkable, because dextral transpression was inferred as the general mechanism of Cretaceous deformation in the Austroalpine by many authors (Ratschbacher 1986, Ring et al. 1989, Ratschbacher et al. 1989, etc.).

6.1.3 Late Cretaceous extension: Collapse behind a migrating orogenic wedge

As demonstrated above for the Ducan normal fault and its continuation along the base of the Silvretta nappe, kinematic analysis of mylonitic and cataclastic fault rocks along shallowly dipping tectonic contacts has revealed important top-to-the-east extensional faulting in the Austroalpine units of Graubünden. Indicated in Figure 15b are normal faults that are ascribed to the Late Cretaceous extension, and shear direction and sense of associated fault rocks. Because the extensional faulting overprinted an earlier stack of nappes, normal faults do not always emplace younger rocks on older rocks, but the opposite is also observed.

The Trupchun normal fault (TNF) is interpreted as the continuation of the Ducan normal fault east of the Engadine line. Along this fault, the Upper Austroalpine Ortler nappe is directly emplaced on Cretaceous flysch of the Err system, and substantial parts of the nappe pile are omitted (Bernina nappe and Languard nappe). We have no fault rock data from this poorly exposed fault. The Mezzaun normal fault (MNF) forms the boundary between the Mezzaun sediments (Bernina system) above and the Seja basement and Murtiröl sediments (Err system) below. It represents a marked discontinuity crosscutting older structures. Scarce kinematic indicators from the main fault plane and its immediate vicinity (fibre-growth slickensides, grooves and ridges) indicate top-southeast directed movement. In contrast, paleostress analysis using minor faults in sedimentary rocks above the fault indicates top-southwest directed normal faulting (Schmid & Froitzheim 1993). In spite of this ambiguity concerning the exact movement direction, the normal-fault character of the MNF is clear because higher thrust sheets are emplaced on lower ones along this post-nappe discontinuity.

The Corvatsch-Bernina boundary fault (CBF) is a low-temperature quartz mylonite zone with top-east shear sense (Spillmann 1993). It partly coincides with an extremely thinned sediment syncline between two basement sheets, the Bernina nappe s. s. above and the Corvatsch nappe below. The Julier base fault (JBF) is the continuation of the

CBF north of the Engadine line. It represents an original thrust that was reactivated as a normal fault (Handy et al. 1993). The Corvatsch mylonite zone (CMZ) is a broad zone of basement- and sediment-derived mylonites between the Covatsch nappe above and the Platta nappe below. The shear sense is top-to-the-east (Müller 1982, Liniger 1992).

Another low-angle normal fault, the Peio line, is found outside our study area at the southeastern border of the Campo nappe (Werling 1992). This is an oblique-slip, top-east normal fault between two basement units of the Austroalpine, the Campo nappe below and the Tonale series above. The fault was active while greenschist facies conditions prevailed in the footwall (Werling 1992). The same author assumed a Late Cretaceous age for the activity of this normal fault.

Ducan-Ela-phase folds are most pronounced in the Lower Austroalpine west of and below a belt of normal faults defined by the DNF, TNF, MNF, CBF, CMZ and JBF (folded area indicated by oblique hatching in Fig. 15b). These folds reflect ductile stretching and vertical shortening of initially non-horizontal layers. Therefore the belt of normal faults is interpreted as a decoupling horizon between ductilely extended crust below and brittlely extended crust above (Fig. 12).

The age of the Ducan-Ela phase was determined radiometrically by Tietz et al. (1993) on rocks from the Samedan zone: K-Ar dating on white mica grown along S_2 (Ducan-Ela phase) cleavage surfaces yielded ages of 67.5+-2.0 Ma, 79.7+-2.4 Ma, and 70.3+-0.3 Ma (Fig. 14). Late Cretaceous extension was also observed farther east in the Austroalpine (Ratschbacher et al. 1989). According to these authors, the formation of the Gosau sedimentary basins with 90 to 60 Ma old sediments was related to this extension. The rapid deepening of the basins at about 80 Ma is interpreted as marking the main extensional phase. Consequently, the extension began at 90 Ma east of the Tauern window. At this time, west-directed thrusting and folding of the Trupchun phase just began in the Austroalpine of Graubünden (see above). This indicates a westward migration of both crustal shortening and immediately following east-west extension, as already assumed by Ratschbacher et al. (1989). Such a scenario is compatible with the westward progradation of the orogenic wedge system. In this case, Gosau and Ducan-Ela extension could be caused by an overthickened wedge according to the model of Platt (1986), migrating towards the west.

The westward migration of the orogenic wedge has an important implication: It becomes unlikely that the subduction of South Penninic oceanic lithosphere under the Apulian plate represents the "motor" for Cretaceous orogeny in the Austroalpine. If Cretaceous orogeny had been caused by this subduction, thrusting should have occurred first in the distal continental margin, that is, in the Lower Austroalpine. This is not the case. Instead, the thrusting started in the internal parts of the Austroalpine and reached the ocean-continent transition only at a late stage. Consequently, the formation of the Austroalpine orogenic wedge is better explained by a continental collision east or southeast of the Austroalpine realm, i. e. along the Vardar-Hallstatt ocean, as proposed by Thöni & Jagoutz (1993).

6.2 Tertiary orogeny

6.2.1 Early Tertiary collisional deformation

After the Late Cretaceous extensional phase, the Austroalpine – Upper Penninic nappe edifice was thrust as a "traîneau écraseur" (Termier 1903) or "orogenic lid" (Laubscher 1983) towards north over the Middle and North Penninic units. The basal thrust of the orogenic lid is exposed at the western border of the Engadine window, between basement rocks of the Silvretta nappe above and Mesozoic sediments of the Arosa zone below (Laubscher 1983). This thrust is of Tertiary age, because it truncates pseudotachylyte veins which yielded Late Cretaceous ages (78.5+-4.6 Ma and 73.2+-3.2 Ma, Rb-Sr thin slab isochrons, Thöni 1988) and are in our opinion related to crustal extension during the Ducan-Ela phase (Fig. 14). Shear-sense indicators in a thin mylonite layer along the thrust give top-north-directed movement (arrows in Fig. 15c). Late, top-north directed movement following earlier, west-directed shearing was also demonstrated for the Arosa zone along the western margin of the Austroalpine and in the Engadine window by Ring et al. (1988, 1989). The north- to slightly north-northeastward transport direction (Fig. 15c, see also Ring et al. 1988, 1989) differs from the northwest to north-northwest directed transport inferred for the same time interval in the Penninic Schams nappes (F_1 of Schmid et al. 1990). The Schams nappes, however, are severely overprinted by later deformation. Hence we regard the kinematic data presented in Figure 15c to be more reliable.

The southward continuation of the Tertiary-age basal thrust at the western margin of the Austroalpine units must be assumed beneath the Platta nappe, because Platta and Margna nappes were welded to the Austroalpine already in the Cretaceous (see above). Both Platta nappe and Margna nappe were part of the orogenic lid in the Tertiary (Liniger & Nievergelt 1990). This implies that the tectonic position of the Platta nappe is fundamentally different from that of the Arosa zone, although both units comprise ophiolites of the South Penninic ocean: the Arosa zone is a mélange between ophiolites and Austroalpine units that formed during Cretaceous subduction and was reworked in Tertiary time as a top-north directed shear zone below the orogenic lid. The Platta nappe, however, represents ophiolites which were accreted to the Austroalpine continental margin in the Cretaceous and became part of the orogenic lid in the Tertiary. The base of the Platta nappe was overprinted by the Turba mylonite zone later on during the Early Oligocene. Therefore, the basal thrust of the Tertiary-age orogenic lid is not preserved in the Oberhalbstein area and south of it (dashed continuation of the thrust in SW part of Fig. 15c).

The grade of the Late Cretaceous metamorphism in the units overlying the basal thrust of the Tertiary-age orogenic lid decreases from south to north, from the higher greenschist facies in the Margna nappe (Guntli & Liniger 1989) to the diagenesis/anchizone boundary at the western border of the Silvretta nappe (Dunoyer de Segonzac & Bernoulli 1976). Consequently, the southernmost units forming the orogenic lid were detached from deeper parts of the crust in the Early Tertiary. This geometry explains the strong reduction or total lack of Lower Austroalpine units in the north, that is, in the Engadine window and in the Prättigau half-window (Fig. 1). The basal thrust of the Tertiary orogenic lid must have climbed into increasingly higher previously emplaced, i. e. Cretaceous, nappe units from south to north.

Tertiary fossils were found in flysch sediments below the orogenic lid in the Oberhalbstein area (Ziegler 1956) and in the Engadine window (Rudolph 1982), indicating that Tertiary thrusting is post-Paleocene (Fig. 14). The foraminifera in the Oberhalbstein are Latest Paleocene to Middle Eocene (Eiermann 1988) corresponding to about 57 Ma to 38.6 Ma (Harland et al. 1990). The ones in the Tasna flysch of the Engadine window are Middle Paleocene to Early Eocene (Rudolph 1982), corresponding to 60.5 to 50 Ma. These findings allow an estimate for the amount of thrusting during the Tertiary. To allow for the sedimentation of the Tertiary flysch in the Oberhalbstein area, the front of the Austroalpine must still have been south of this area in the Early Eocene. Today, this front is at the northern border of the Alps. These constraints indicate a Tertiary northward displacement of the orogenic lid of at least 75 km, measured parallel to the movement direction (north).

The orogenic lid was not an absolutely rigid block, but suffered some internal deformation: it was affected by east- to southeast-trending folds of the Blaisun phase (Fig. 15c). The exact relative timing of northward thrusting and Blaisun-phase folding in the Austroalpine is not known. We assume, however, that both phenomena were closely related, if not coeval. The strike of Blaisun-phase folds is relatively uniform, southeast to east and thus roughly perpendicular to the transport direction of the basal thrust of the orogenic lid (Fig. 15c). The dip of axial planes, however, is variable: At the southern border of the Silvretta nappe, axial planes are subvertical, steeply north-dipping, or steeply south-dipping (e. g. Fig. 3b). In the Ortler nappe, axial surfaces dip south (Conti et al. 1994). In the southern part of the Austroalpine, e. g. in the Malenco area, the axial surfaces of the Blaisun phase are generally N-dipping ("First phase of backfolding", Hermann & Müntener 1992). This is also the case at the western border of the Err-Carungas nappe (Dürr 1992). This variability and the lack of a predominant vergence indicate that Blaisun-phase folding reflects inhomogeneous internal shortening of the orogenic lid. On a very large scale, this internal shortening was near-coaxial.

Northward thrusting of the orogenic lid and Blaisun-phase folding are probably related to the continental collision that occurred after subduction of the last remaining oceanic lithosphere, the Valais ocean, at about 40 Ma (Frisch 1979). The change from Cretaceous westward thrusting to Early Tertiary northward thrusting is not a gradual one. Instead, Cretaceous and Tertiary thrusting are clearly separated by the Late Cretaceous extensional event. After the extensional event, renewed thrusting began with a N-directed transport direction, almost perpendicular to the Cretaceous shortening.

6.2.2 Postcollisional deformation of the Austroalpine nappes

Tertiary northward thrusting and folding during the Blaisun phase were followed by renewed east-west extension during the Turba phase. Liniger (1992) showed that the Turba mylonite zone is intruded by the Bergell granodiorite (30 Ma, von Blanckenburg 1992). On the other hand, the mylonite zone affects the Arblatsch flysch, deposited until about 50 Ma (Early to Middle Eocene, Ziegler 1956). Thus, the Turba mylonite zone must have formed between about 50 and 30 Ma. Because the northward thrusting of the orogenic lid over the Lower and Middle Penninic units predates the Turba extension, we place the Turba phase towards the end of this time span, that is, in the Early Oligocene (Fig. 14).

Extensional faulting along the Turba mylonite zone is intimately linked to recumbent folding in the footwall of this zone, i. e. in the Suretta and Schams nappes and surrounding units (Niemet-Beverin phase, D_2 of Schmid et al. 1990 and Schreurs 1993). Folding of the Niemet-Beverin phase is viewed in the context of vertical extrusion from an east-west-striking zone immediately north of the Insubric Line (Schmid et al. 1990, Merle & Guillier 1989). According to new data, this Niemet-Beverin-phase folding was accompanied by east-west extension and vertical shortening (Baudin et al. 1993, Nievergelt et al. in press). The Turba mylonite zone marks a final stage of this extension. These relations indicate that the east-west directed Turba extension was roughly contemporaneous with north-south shortening. Therefore the Turba extension is not regarded as a postorogenic collapse leading to crustal thinning.

A second step of postcollisional deformation is represented by the folds of the Domleschg phase and by the movements along the Engadine line (Fig. 15d). The Domleschg phase is probably pre-Miocene: cooling through 300 °C near the Oligocene-Miocene boundary is reported for the southern Tambo nappe (Jäger et al. 1967, Purdy & Jäger 1976), a region affected by Domleschg-phase folding (F_3 of Baudin et al. 1993). The ductile style of Domleschg-phase folding in this area requires temperatures above 300 °C. This suggests that Domleschg-phase folding occurred before or near the Oligocene-Miocene boundary.

In the Suretta and Tambo nappes and surrounding units, west and northwest of the Bergell intrusion, the Domleschg-phase folds exhibit a general vergence towards north, with steeply southeast- to south-dipping axial surfaces (F_3 of Schmid et al. 1990, Baudin et al. 1993). The northeastward trend of fold axes, indicating southeast-northwest directed shortening, is in accordance with a framework of dextral transpression along the Insubric line. In fact, the timing of the Domleschg phase coincides with the beginning of the "Insubric phase" of dextral transpression in the Late Oligocene (Schmid et al. 1987). Hence the kinematic framework of NW-SE directed shortening, typical for the external zones of the Alps, was not established until the Late Oligocene.

Field relations in the upper Val Bregaglia suggest that the Engadine line postdates the Domleschg phase: the style of Domleschg-phase folds is ductile in this area, whereas deformation along the Engadine line is brittle. According to the kinematic analysis of Schmid & Froitzheim (1993), movement along the Engadine line was a combination of sinistral strike-slip and block rotation. Along the southwestern part of the line, the block rotation resulted in relative uplift of the southeastern block. To the northeast, the vertical component was reversed and the northwestern block was upliftet relatively. A neutral point with no vertical displacement exists between St. Moritz and Samedan. There, the displacement is sinistral strike-slip on the order of 3 km.

In the area of Maloja pass, near the northern end of the Bergell intrusion, the Engadine line truncates the contact metamorphic aureole of the intrusion (Fig. 4 in Trommsdorff & Nievergelt 1983). The relative uplift of the Bergell intrusion caused by movements along the Engadine line is very substantial and amounts to 7 km along the profile on the front of the block diagram in Plate 1. The counterpart of the relative uplift of the Bergell intrusion and its countryrocks along the southwestern Engadine line, is the exhumation of the Engadine window in the Lower Engadine, situated along the northeastern part of this line (Pl. 1). In the vicinity of the Engadine window, the Engadine line dips southeast and acted as a major oblique-slip normal fault with a vertical displacement component of at least 3 kilometres, downthrowing the southeastern block relative to the northwestern block (Schmid & Haas 1989, Schmid & Froitzheim 1993). The Engadine window is situated on the uplifted shoulder of the northwestern block. Additionally, the window is accentuated by a major northeast-striking antiform which we correlate with the Domleschg phase. The hinge of this antiform is near the southeastern border of the window (Fig. 15d; Gürler 1982).

According to a fault plane analysis along the Engadine line (Schmid & Froitzheim 1993), the least compressive principal stress (σ_3) was constantly oriented E-W all along the Engadine line, suggesting that an east-west stretch was accommodated by a combination of normal faulting and sinistral strike-slip movement. The sinistral movement along the Engadine line and the dextral movement along the Insubric line accommodated eastward extrusion (in the sense of Ratschbacher et al. 1991) of the triangular block bounded by these two lines (Fig. 15d), leading to local east-west directed extension also during this stage. Late Miocene deformation in the Southern Alps and along the Giudicarie line postdates this east-west stretch (Schmid & Froitzheim 1993). Therefore a Latest Oligocene to Early Miocene age is inferred for the movements along the Engadine line.

7 Conclusions

Two orogenic cycles, of Cretaceous and Tertiary age, have been demonstrated by the structural analysis of the Austroalpine nappes in Graubünden. The first cycle included west- to northwestward imbrication of upper crustal thrust sheets and sinistral transpression along the east-striking Albula steep zone (Trupchun phase), followed by east-southeast directed extensional overprint of the nappe edifice, involving low-angle normal faults and recumbent "collapse folds" (Ducan-Ela phase). In the second cycle, of Tertiary age, the Austroalpine and previously accreted Upper Penninic units were thrust northward and emplaced as an orogenic lid on the deeper Penninic units. Internal folding of the orogenic lid was associated with this northward thrusting (Blaisun phase, Eocene). Thrusting and folding were followed by a second phase of east-west extension, roughly contemporaneous with ongoing north-south compression (Turba phase, Early Oligocene). This second extensional event was followed by NW-SE shortening (Domleschg phase, Late Oligocene), and by sinistral slip and block rotation along the Engadine line near the Oligocene-Miocene boundary.

Regarding the Cretaceous orogeny in the Austroalpine realm, the following inferences can be drawn: (1) Cretaceous crustal shortening was accommodated by top-west to top-northwest thrusting. On the scale of the entire Austroalpine realm, this shortening propagated from east to west and was followed by an extensional collapse, also propagating from east to west. The westward migration of the orogenic wedge implies that Cretaceous orogeny did not result from the subduction of South Penninic oceanic lithosphere under the Austroalpine realm, but rather from a collision event east or southeast of the Austroalpine realm. (2) In the study area, we found no indications for Cretaceous dextral wrench movements as expected from broadly accepted models which assume a dextrally transpressive framework for the Cretaceous orogeny (Ratschbacher 1986, Ring et al. 1989, Ratschbacher et al. 1989). On the contrary, a sinistrally transpressive shear zone is observed (Albula steep zone), in accordance with models of Trümpy (1976) and Bechstädt (1978).

The recognition of two orogenic cycles contradicts the classical view of the Alpine orogeny as a continuous tectonometamorphic evolution. This view regarded all high-pressure metamorphism, even in the Penninic units, to be of Cretaceous age. Since our