Comparison with the Engadine Dolomites

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mylonite, best exposed at Piz Turba between the Oberhalbstein and Bergell valleys (outside the map, Fig. 2), is a calc-mylonite with quartz clasts. Stretching lineation and shear-sense criteria indicate down-to-the-east displacement of the hanging wall comprising Platta nappe and Austroalpine, relative to the Middle Penninic units in the footwall (Liniger 1992). The northern continuation of the Turba mylonite zone is indicated between the Platta nappe and underlying Arblatsch flysch in the southwestern part of the map, Figure 2, and in Figure 3a. Vitrinite reflectance of samples from this area indicates an abrupt decrease of Alpine metamorphic temperatures from the footwall to the hanging wall across the Turba mylonite zone (measurements by R. Ferreiro Mählmann, in Nievergelt et al. in press), compatible with normal fault movement. Still further towards north, the continuation of the Turba mylonite zone is unclear. The extreme thinning of the nappe units east of Tiefencastel (Trümpy 1980, p. 237), where the Ela nappe is represented by only a few metres of Jurassic limestone, overlain by Triassic dolomite of the Silvretta nappe and underlain by a serpentinite-bearing shear zone, strongly suggests that the Turba mylonite zone continues towards the north along the base of the Austroalpine. Late-stage, top-east shearing probably related to the Turba phase was also observed in the Arosa zone near Arosa and along the western border of the Err nappe (Ring et al. 1991, Dürr 1992). The Turba normal fault truncates Blaisun-phase folds in the Margna and Platta nappe near Septimer pass (Liniger & Nievergelt 1990, p. 97; D_2 of these authors corresponds to the Blaisun phase).

Normal faults of the Turba phase have orientations similar to the ones of the Ducan-Ela phase and are therefore easily confounded with these. The two generations of normal faults can only be distinguished by using overprinting relations with folds of the Blaisun phase: Ducan-Ela-phase normal faults are deformed by Blaisun-phase folds (see Fig. 5), whereas the Turba normal fault truncates such folds.

4.5 Domleschg phase (D_5): Late-stage northwest-southeast shortening

The Domleschg phase, originally defined by Pfiffner (1977) in the North Penninic Bündnerschiefer of Graubünden, corresponds to the latest compressional overprint recognized in the Middle Penninic Schams nappes (D_3 of Schmid et al. 1990). Northeast-striking, open folds with constant northwestward vergence and southeast-dipping axial planes only achieve moderate shortening. These folds can be continuously traced from the Schams area towards the east and into the Austroalpine units in the Tiefencastel area. A major Domleschg-phase syncline extends from Piz Toissa northeast into the Silvretta nappe (Fig. 2, coord. 765/168; "Suraver Deckenmulde" of Ott 1925). The preservation of the Toissa klippe, a remnant of the Ela nappe on top of Penninic units west of the Julia valley (Fig. 2), results from its position within this syncline.

The Domleschg phase postdates the Turba phase. South of Piz Turba, the Turba mylonite zone is folded around an east-west striking antiform correlated with the Schams D_3, and thus the Domleschg phase, by Liniger (1992, "M" in Fig. 15d).

5 Comparison with the Engadine Dolomites

In the following, we will compare the structures observed in the Silvretta, Ela, and Err-Carungas nappes with the ones of the Engadine Dolomites. Thereby we will attempt a correlation of deformation phases across the Engadine line (Trümpy 1977, Schmid & Froitzheim 1993), a major discontinuity in the Austroalpine nappe pile of Graubünden. Furthermore, the Engadine Dolomites yield additional information about the geometry and timing of Trupchun-phase thrusting, because of the relatively minor post-nappe overprint as compared to the area described in the preceding chapters.

5.1 General description

The Engadine Dolomites (Fig. 13, Plate 1) represent a triangular-shaped area of Upper Austroalpine sedimentary rocks bounded to the northwest by the Engadine line, to the south and southeast by the basement of the Campo nappe, and to the northeast by the overlying Oetztal thrust mass, also formed by pre-Permian basement (Spitz & Dyhrenfurth 1914). Several thrust sheets are exposed in this area: from south to north, the Ortler, Quattervals and Sesvenna – S-charl nappe. The Zebru thrust separates the lowermost thrust sheet, the Ortler nappe (predominantly Mesozoic rocks), from the underlying Languard and Campo basement nappes. The Trupchun-Braulio thrust defines the top of the Ortler zone and the base of higher thrust sheets, referred to as Quattervals nappe and Terza unit, sedimentary units of predominantly Late Triassic age. Towards east, the Quattervals nappe is interleaved with the Umbrail-Chavalatsch zone (Schmid 1973), a pile of often extremely thin thrust sheets or slivers in which the proportion of basement rocks derived from the Oetztal nappe increases from west to east. The largest basement sheet in this imbricate zone is the Braulio crystalline unit. North of the Quattervals nappe and the Umbrail-Chavalatsch zone follows the S-charl-Sesvenna nappe, divided from the former units by the Gallo line. Although the exact nature of the Gallo line is still dubious, it is well established that the Quattervals nappe and Umbrail-Chavalatsch zone are in a structurally higher position in respect to the S-charl-Sesvenna nappe (Schmid 1973). Hence, the Gallo line represents the basal thrust of the Quattervals and Umbrail-Chavalatsch units above the S-charl-Sesvenna nappe. Sesvenna and Campo basement thus occupy the lowermost structural position in the nappe pile of the Engadine Dolomites. An uncertainty exists about the importance of later extensional reactivation or overprint of the Gallo line, already assumed by Schmid (1973).

All subunits of the Engadine Dolomites can be traced into the footwall of the Schlinig thrust, forming the base of a higher Upper Austroalpine unit: The Oetztal nappe. The Zebru thrust, the Trupchun-Braulio thrust, and the Gallo line merge into a mylonitic belt associated with the Schlinig thrust ("intra-basement shear zone", Schmid & Haas 1989).

5.2 Correlation across the Engadine line

The geometric relations between Engadine Dolomites and the units northwest of the Engadine line have been subject to longstanding controversies (see discussion in Schmid & Haas 1989). A recent kinematic analysis of the Engadine line (Schmid & Froitzheim 1993) yielded movement vectors consistent with a sinistral strike-slip motion associated with a block rotation. This results in a component of downthrow of the Engadine Dolomites with respect to the Silvretta nappe. Retro-deformation of movements along the Engadine line yields the following nappe correlations: (1) The Ela nappe occupies a structur-

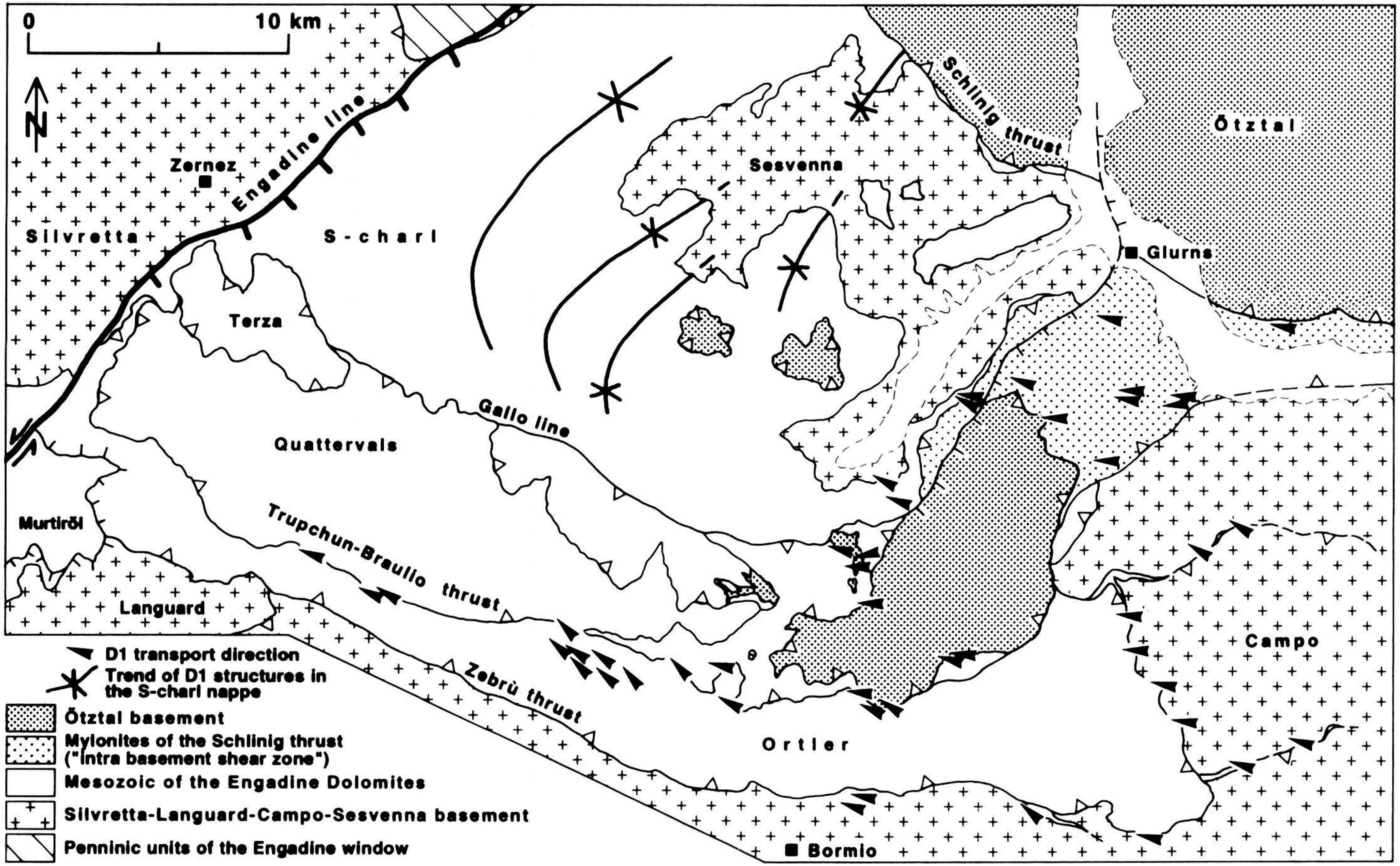

Fig. 13. Tectonic map of the Engadine Dolomites. Arrows indicate D_1 transport directions as determined by microfabric analysis of mylonites and cataclasites.

ally lower position in respect to the Engadine Dolomites and the basement thrust sheets of Languard and Campo, and has to be considered part of the Lower Austroalpine Bernina system (Fig. 1). This interpretation is contrary to the classical one, assigning the Ela nappe to the Upper Austroalpine (e. g. Spicher 1972: Tectonic map of Switzerland). Southeast of the Engadine line, the Triassic and Jurassic sedimentary rocks of the Corn unit represent a direct equivalent of the Ela nappe (Pl. 1). The Corn sediments are the uppermost element of the Bernina system, directly underlying the Languard basement. (2) The Sesvenna, Languard and Campo basement units are comparable to the Silvretta nappe regarding their tectonic position in the original nappe pile. (3) Equivalents of the Engadine Dolomites on the western side of the Engadine line were situated above the Silvretta basement and have been eroded away, with the exception of the Silvretta cover in the Ducan and Landwasser areas.

5.3 Trupchun-phase folding and thrusting in the Engadine Dolomites

Thrusting towards northwest to west and associated folding are particularly well exposed in the Ortler nappe. At the western end of this unit, in Val Trupchun, the local D_1 (Trupchun-phase) folds are open to isoclinal and associated with an axial plane cleavage. In contrast to the D_1 folds in the Silvretta cover, Trupchun-phase fold axes in the Ortler nappe have rotated towards parallelism with the transport direction by variable amounts. In stereographic representation the fold axes cover almost a complete great circle (Froitzheim 1988). Northwest-directed transport was deduced from an analysis of fold axis orientations (Froitzheim 1988). The different style of deformation during the Trupchun phase, when compared to the Silvretta nappe, is at least partly due to the different lithological composition: Lower to Middle Jurassic marls and limestones of the Allgäu Formation, predominant in Val Trupchun, contrast with the dolomite-dominated Triassic cover of the Silvretta nappe. A maximum age for the Trupchun phase in this area is given by the youngest sediments affected by these folds: Upper Cretaceous sediments occur in the core of a Trupchun-phase syncline in Val Trupchun. These are Cenomanian and possibly Middle Turonian foraminiferal marls (about 90 Ma, Caron et al. 1982), first described and termed "Couches Rouges" by Zoeppritz (1906). Therefore, thrusting and folding in the Ortler nappe began after 90 Ma.

The Trupchun-Braulio thrust at the top of the Ortler nappe and the Zebru thrust at the base of this nappe are both top-west to -northwest directed (Fig. 13), as is unambiguously demonstrated by kinematic analysis of calc-mylonites from the Trupchun-Braulio thrust and quartz mylonites from the Zebru thrust (P. Conti, work in prep.). Schmid (1973) and Froitzheim (1988) erroneously interpreted the Trupchun-Braulio thrust as a top-southwest backthrust, because Trupchun-phase folds are truncated by this thrust. At the eastern end of the Ortler nappe, Conti (1992) found a two-stage evolution of thrusting during the Trupchun phase: the Trupchun-Braulio thrust overprints earlier, also west- to northwest-directed thrusting along the Zebru thrust. Such a two-stage evolution of thrusting may account for the overprinting relation observed in Val Trupchun. Both the Trupchun-Braulio and the Zebru thrust can be continuously traced further towards east where the synkinematic metamorphic grade systematically increases and reaches the greenschist facies near the eastern margin of Figure 13 (Schmid & Haas 1989). They finally both merge with the eastern continuation of the Schlinig thrust, for which a Late

Cretaceous age of thrusting, between 100 and 80 Ma, is well constrained (e. g. Thöni 1986, review of radiometric ages in Schmid & Haas 1989).

Northeast-striking folds are dominant in the S-charl-Sesvenna nappe (Spitz & Dyhrenfurth 1914, Stutz & Walter 1983, Schmid & Haas 1989, see Fig. 13). These folds are the oldest Alpine structures in this area and can be attributed to the Trupchun phase. They are about perpendicular to the transport direction which was west-northwest to northwest as indicated by stretching lineations. The general style of the folds is very reminiscent of the Trupchun-phase folds in the Silvretta cover. In the area of the southern Sesvenna – S-charl nappe, a gradual change in the orientation of the Trupchun-phase folds is observed (Fig. 13): towards southwest, the folds curve from northeast-striking over north-striking to northwest-striking (Spitz & Dyhrenfurth 1914). This fold arc resembles the one observed at the southwestern termination of the Ducan syncline (Spitz & Dyhrenfurth 1913).

Locally within Permian to Lower Triassic pelites of the S-charl-Sesvenna nappe, a cleavage has developed under conditions of the lowermost greenschist facies. The formation of this cleavage is dated at 89+-5 Ma by K-Ar determinations on white micas (Thöni 1980), confirmed by ^{40}Ar-^{39}Ar work (Thöni & Miller 1987).

5.4 Post-nappe deformation of the Engadine Dolomites

Unambiguous evidence for an extensional overprint during the Ducan-Ela phase has not been found yet within the Engadine Dolomites. Northwest-southeast-directed Alpine extension is observed in Upper Triassic dolomites of the S-charl unit (Schmid & Haas 1989) and the Ortler nappe (Froitzheim 1988). These authors attributed extension of the Upper Triassic dolomite layer to bookshelf- or domino-type antithetic faulting, related to Trupchun-phase thrusting. As discussed in Ratschbacher et al. (1989), local extension can be associated with non-plane-strain shearing, coupled with vertical thinning, in a large-scale overthrust shear zone. However, in the light of our recent discovery of crustal extension affecting a previously stacked pile of thrust sheets along the Ducan normal fault, such crustal extension during the Ducan-Ela phase cannot be ruled out as an explanation for some of the extensional structures in the Engadine Dolomites. We tentatively assume that both processes, thrust-related, local extension in the sense of Schmid & Haas (1989), and crustal-scale extension during the Ducan-Ela phase, left their traces in the Engadine Dolomites. Many of the southeast-dipping Alpine normal faults in the S-charl unit and in the Ortler nappe are restricted to the Hauptdolomit layer and do not continue in the over- and underlying strata. These faults probably formed during thrusting as proposed by Schmid & Haas (1989) and Froitzheim (1988). Some normal faults in the S-charl unit, however, cut down into the basement (see Fig. 5 in Schmid & Haas 1989) and may reflect crustal extension during the Ducan-Ela phase.

The local D_2 folds of the western Ortler nappe (Froitzheim 1988) are characterized by east- to southeast-trending axes and steeply south- to southwest-dipping axial planes. Very much analogous to the Blaisun-phase folds in the Ela nappe, these folds are responsible for tilting of previously flat-lying structural elements (in the Ela nappe, the axial planes of recumbent Ducan-Ela-phase folds) towards the north. Therefore this local D_2 can confidently be correlated with the Blaisun phase (D_3) defined in the Ela nappe. In the eastern part of the Ortler zone, Blaisun-phase folds are crosscut by dykes of mafic to 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-