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Autor: Froitzheim, Nikolaus / Schmid, Stefan M. / Conti, Paolo

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D_2 normal faults similar to those observed in the Silvretta nappe and also, but to a much lesser extent, in the Ela nappe, have recently been found in the Err-Carungas nappe (Weh 1992, G. Manatschal, pers. comm.). Weh (1992) reported a subhorizontal, top-southeast directed cataclastic shear zone near Murtel Trigd (Fig. 2, coord. 779/161) in the northern part of the Err basement and ascribed it to extensional faulting coeval with D_2 folding. It is possible that more such extensional faults and shear zones, related to D_2 deformation, exist in the northern Err-Carungas nappe.

D_2 and D_1 structures are overprinted by upright, open folds with east- to southeast striking and steeply north- to northeast-dipping axial planes (D_3). D_3 folds in the Err-Carungas nappe are associated with a weak axial plane solution cleavage. The broad antiformal arch described by the D_2 axial surfaces in Figure 3a is a D_3 structure.

The Err-Carungas nappe thus shows a structural evolution very similar to that of the Ela nappe: early thrusting and folding (D_1) were followed by recumbent "collapse folding" (D_2) and by still later, open D_3 folding.

4 Sequence of stages of the orogenic evolution

In the preceding paragraphs, we have described the sequence of deformation phases observed in each of the three nappes, Silvretta, Ela and Err-Carungas. We will now combine these data and propose a reconstruction of the regional tectonic evolution, assuming that the deformation phases are related to distinct stages of the orogenic evolution.

4.1 Trupchun phase (D_1): Cretaceous top-west thrusting and folding

The Trupchun phase includes the D_1 thrusts and folds of the three nappes. It is named after Val Trupchun, situated at the western end of the Ortler nappe (see chapter 5.3), where structures of this phase are particularly well preserved.

We assume that the D_1 folds of the Silvretta nappe, such as the Ducan syncline, were formed during initial detachment and westward transport of the nappe. Their orientation – northeastern strike and northwestward facing – fits well together with the westward to northwestward direction of thrusting, as indicated by the lineation in the older, higher-temperature mylonites at the base of the Silvretta nappe. D_1 folds in the Ela nappe are more complicated. In the Ela nappe, D_1 includes two kinds of folds: first, east-striking, south-facing folds with axial planes subparallel to the basal thrust of the Ela nappe, and second, also east-striking, but upright folds deforming the basal thrust (Fig. 8).

The first "sub-generation" is comparable and probably coeval with the D_1 folds of the Silvretta nappe. The different strike of the fold axes, northeast in the relatively rigid Silvretta nappe and east in the ductile Ela nappe, can be explained with a rotation of fold axes of the Ela nappe into the shear direction. The beginning of such a rotation is noticed in the southwestern part of the Ducan syncline, where fold axes curve around from northeast-striking to north- and northwest-striking. A possible explanation for the anticlockwise rotation of fold axes is a different rate of top-west shearing, higher in the north and lower in the south. This implies that northern parts of the nappe pile advanced towards west relative to more southern parts.

The slightly younger, upright D_1 folds in the Ela nappe have no counterpart in the Silvretta nappe. These upright folds led to a steepening of all rock units in the Albula steep zone, comprising the presently exposed Ela nappe and the northernmost part of the Err-Carungas nappe. D_1 in the Err-Carungas nappe is very similar to D_1 in the Ela nappe, except for a strong decoupling between the basement, remaining undeformed, and the sediments of the Carungas zone, where the occurrence of sheath folds indicates relatively higher strains.

Strictly, it would be possible to split the Trupchun phase in two phases, one for the initial thrusting and one for the formation of the Albula steep zone. Such a distinction, however, is feasible only in a few places. Therefore we prefer to interpret the initial thrusting and the formation of the Albula steep zone as a continuous process that only locally led to geometric overprinting relations.

The age of the Trupchun phase is Late Cretaceous. The youngest biostratigraphically dated sediments in the Carungas zone are Lower Cretaceous (Stöcklin 1949). Good constraints on the age of this phase exist in the Engadine Dolomites (see chapter 5).

4.2 Ducan-Ela phase (D_2): Late Cretaceous east-west extension

Since Eugster (1923) recognized the normal faults of the Silvretta nappe, several authors have tried to explain these faults in the context of crustal shortening (Eugster 1923, Heim 1922, Eichenberger 1986). Eugster (1923) created the new term "Untervorschiebung" ("underfore-thrust") for these faults, implying that they are basically related to thrusting. The drawing by Heim (1922, Fig. 229) suggests a systematic relation between folds – the D_1 folds of the Ducan area – and normal faults, in the way that the normal faults are parallel to the axial planes of the folds. Such a systematic relation, however, does not exist: the Ducan normal fault cuts obliquely through the Ducan syncline.

The D_2 normal faults of the Silvretta postdate Trupchun-phase crustal shortening and are related to subsequent east-southeast directed crustal extension, for the following reasons: (1) The faults clearly overprint the dominant D_1 folds and the basal thrust of the Silvretta, so that their formation cannot be related to folding and thrusting as envisaged by Heim (1922) and Eichenberger (1986). (2) The normal faults are not restricted to deformation within the Silvretta nappe. The Ducan normal fault additionally reactivated the Silvretta basal thrust, a process that transported the Silvretta nappe back towards east-southeast relative to deeper units.

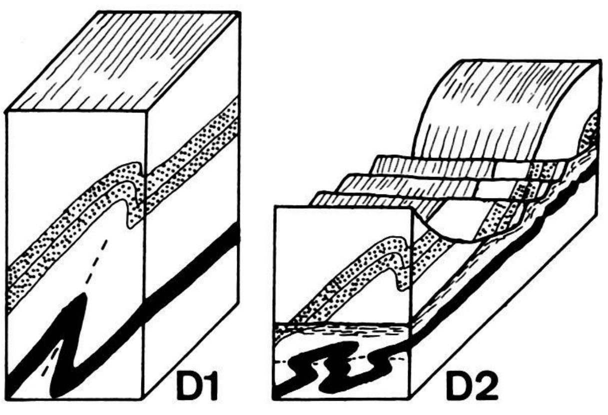

Fig. 12. Model for contemporaneous development of normal faults and second-generation folds during crustal extension. Left: earlier, upright folds of the Trupchun phase; right: extension and thinning of the crust in the Ducan-Ela phase, leading to normal faulting in an upper layer and to formation of recumbent second-generation folds below. The contact between the two layers is a low-angle extensional shear zone (cf. Silvretta base east of Bergün).

D_2 structures in the Ela and Err-Carungas nappe are recumbent folds and, to a minor extent, top-east-southeast directed low-angle normal faults. It was shown above that the recumbent folds developed together with the normal faults, and reflect horizontal extension and vertical shortening of steeply inclined layers. We assume that D_2 folding of the Ela and Err-Carungas nappes and normal faulting within the Silvretta nappe resulted from the same event of crustal extension. The different style of deformation can be explained in the following way: normal faulting in the Silvretta unit reflects brittle extension in a higher crustal level, whereas D_2 folding within the Ela and Err-Carungas nappes documents ductile extension in a deeper crustal level. The low-angle part of the Ducan normal fault acted as a décollement horizon separating the two levels (Fig. 12). Apart from the depth of burial, the style of extension also depends on the lithological composition of the nappes (Weh 1992): The Ela and Err-Carungas nappes, comprising sedimentary rocks with extreme competence contrasts (dolomite versus shale) and lacking a pre-Mesozoic basement, are more likely to develop folds than the basement-dominated Silvretta nappe. In addition, rock units had been steepened during D_1 in the Ela and Err-Carungas nappes, but not in the Silvretta nappe. Such steepening is a pre-requisite for "collapse folding" (Froitzheim 1992).

The ductile thinning in the Ela and Err-Carungas nappes was not coaxial, but had a component of top-east-southeast directed shearing, as indicated by the generally eastward transport direction of the minor normal faults associated with the D_2 folds. This offers an explanation for the eastward facing direction of north-south striking D_2 folds in the Ela nappe (Fig. 7b).

The extensional event responsible for normal faulting in the Silvretta and D_2 folding in the Ela and Err-Carungas nappes, the Ducan-Ela phase, is probably Late Cretaceous in age. Evidence for this age will be provided below (chapter 6.1.3). At this stage it is important to note that the Ducan-Ela phase predates renewed noth-south shortening during the Blaisun phase.

4.3 Blaisun phase (D_3): Early Tertiary north-south shortening

This phase produced the east- to southeast-striking D_3 folds observed in all three nappes. This folding is particularly intense and beautifully exposed at Piz Blaisun and is therefore referred to as "Blaisun phase". Within the Ela nappe the intensity of Blaisun-phase folding decreases towards west (compare Figs. 3a and b). Blaisun-phase folding resulted in the present synformal shape of the Ducan normal fault. The age of the Blaisun phase is Early Tertiary (see below, chapter 6.2).

4.4 Turba phase (D_4): Renewed east-west extension

Above we have discussed the three most important stages of deformation in the area of the Silvretta, Ela and Err-Carungas nappes. The following phases have only weakly modified the internal geometry of the Austroalpine, but have strongly affected the Austroalpine-Penninic boundary zone.

A second phase of top-east-directed extensional faulting is documented by the Turba mylonite zone, an east-dipping normal fault between the Platta nappe above and the Arblatsch flysch below (Fig. 1, Nievergelt et al. 1991 and in press, Liniger 1992). The Turba 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