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

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faulting occurred in the Late Cretaceous and in the Early to Mid-Oligocene. In both episodes, the direction of extension was parallel to the strike of the Alpine chain.

Five stages of the tectonic evolution are recognized: (1) Late Cretaceous nappe imbrication and sinistral transpression (Trupchun phase). The Austroalpine nappe pile was assembled by oblique east-over-west imbrication of the northwest margin of the Apulian microcontinent and was affected by sinistral transpression, localized in the east-west trending Albula steep zone. (2) Late Cretaceous extension (Ducan-Ela phase). The nappe pile was overprinted by top-east to top-southeast directed normal faulting. Recumbent folds developing simultaneously with and in the footwalls of large low-angle normal faults reflect east-west extension and vertical shortening of initially steeply oriented layers. Normal faulting and recumbent folding are therefore viewed as different expressions of the same extension process. (3) Early Tertiary collisional deformation (Blaisun phase). The Late Cretaceous extensional features were overprinted by east- to southeast-striking folds which are probably coeval with Early Tertiary northward thrusting of the entire Austroalpine nappe pile ("orogenic lid") over the deeper Penninic units. (4) Early to Mid-Oligocene extension (Turba phase). This second episode of east-west extension affected the boundary zone between the orogenic lid and the underlying Penninic units, locally leading to an extensional decoupling between these two levels (Turba mylonite zone). (5) Late Oligocene post-collisional shortening (Domleschg phase). The direction of shortening changed to NW-SE at this time.

On the scale of the entire Austroalpine realm, both Cretaceous shortening and following Late Cretaceous extension migrated westward. This first extensional event is therefore interpreted to be caused by instability of a westward advancing orogenic wedge. In contrast, Tertiary east-west extension was contemporaneous with ongoing north-south shortening.

The recognition of two orogenic cycles contradicts the classical view that the Alpine orogeny involves a continuous tectonometamorphic evolution from Cretaceous subduction and high-pressure metamorphism to Tertiary exhumation and Barrow-type metamorphism. Instead, it is postulated that nappe formation related to subduction and exhumation associated with extension occurred twice during the Alpine orogeny.

1 Introduction

Graubünden (SE Switzerland) is a key area for the reconstruction of the Alpine tectonic evolution. In this area, the Austroalpine nappes represent remnants of the southern continental margin of the Alpine Neotethys ocean. They overlie Penninic units, partly derived from oceanic crust, from the northern continental margin, and from continental fragments within the oceanic realm. In other parts of the Alps, the Austroalpine-Penninic contact can only be studied in isolated windows (e. g. Tauern window) or klippen, or has been overprinted by late postcollisional faults such as the Insubric line. The well-exposed, north-south trending Austroalpine-Penninic boundary in Graubünden, however, allows a correlation between the structures and deformational histories of all major units involved in the formation of the Alps. (For a comprehensive introduction into the regional geology and its problems, the reader is referred to Trümpy & Haccard 1969. A short overview is given in Trümpy 1980.)

Although an excellent data set on the regional geology and stratigraphy has been assembled by several generations of geologists, the structural architecture of the Austroalpine units in Graubünden is still poorly understood. This has several reasons. Firstly, Alpine deformation occurred under nonmetamorphic to greenschist facies conditions and affected lithologically heterogeneous units. Therefore the deformation is variable in style and intensity. Competent rock units like the Upper Triassic dolomite remained undeformed or were affected by brittle faults, while shaly formations took up large amounts of strain. As a result, the correlation of structures between different rock units or areas is difficult. Secondly, the Austroalpine nappe pile was formed by imbrication of a passive continental margin of Jurassic age. The crustal structure of this margin had already been strongly disturbed during the rifting phase. The interference of rift-related faults with Alpine thrust faults resulted in a complicated geometry of the nappe pile. Thirdly, this nappe pile was overprinted by several phases of post-nappe refolding and faulting, largely obscuring the original configuration. These complexities have resulted in long-lasting and vigorous controversies about the correlation of nappes, e. g. across the Engadine line (a major post-nappe fault), and about the directions of thrusting.

The direction of thrusting in the Austroalpine became controversial soon after the existence of large-scale thrusting in the Eastern Alps had been revealed by Termier (1903). Termier himself assumed a northwestward transport of the Austroalpine nappes (1903, p. 762). Rothpletz (1905), however, postulated west-directed thrusting (see Oberhauser 1991), which was rejected by most authors (e. g. Heim 1922, p. 867). Spitz & Dyhrenfurth (1913, 1914) also postulated west-directed thrusting based on the observation of westward-convex fold arcs in Graubünden, the "Rhätische Bögen". In contrast, Heim (1922, Fig. 227), Eugster (1923, Fig. 32) and Staub (1924, Fig. 34) arrived at a picture of overall east- to northeast-trending fold arrays by correlating folds in the Ela nappe with folds in the northwestern part of the Engadine Dolomites. They deduced north- to northwest directed thrusting. Recently, the view of Spitz and Dyhrenfurth and their predecessor Rothpletz has won new credit by structural and microstructural work on mylonites from thrust faults in the Eastern Alps in general (Ratschbacher 1986), and along the southwestern border of the Oetztal nappe in particular (Schmid & Haas 1989). These studies have shown that internal thrusting within the Austroalpine complex was in fact predominantly directed towards west. Strain analysis in the Arosa zone at the base of the Austroalpine indicated westward thrusting followed by northward thrusting (Ring et al. 1988, Ring et al. 1989). On the other hand, microstructural work also revealed that some of the faults and shear zones, which had previously been interpreted as thrusts, had the "wrong" sense of shear, i. e. top-east (e. g. Müller 1982), and do in fact represent low-angle extensional faults (Nievergelt et al. 1991 and in press, Werling 1992, Liniger 1992, Handy et al. 1993). Even some spectacular recumbent folds like the Ela "frontal fold" are not related to thrusting and crustal shortening, but to crustal extension (Froitzheim 1992).

Although these recent structural observations have largely improved the knowledge about the tectonic evolution of the Austroalpine, they have not yet been integrated into a general picture. The purpose of the present paper is therefore to define the temporal and spatial relations between the deformational structures of the Austroalpine units, and propose a structural evolution scheme that is not only locally valid, but applies to the whole area of the Austroalpine in Graubünden. Of course, the proposed scheme is only a first attempt towards a final synthesis. It will have to be tested and certainly modified in the future.

After a short overview of the Austroalpine nappes (chapter 2), the paper focuses on the area of the southwestern Silvretta, Ela and Err-Carungas nappes, serving as a "type area". There, structures of and overprinting relationships between different deformation phases are especially well preserved (chapter 3). As a base of our analysis of this area, we used the excellent regional studies and geological maps of earlier authors, in the Silvretta-Ela-Err area mainly those of Brauchli (1921), Brauchli & Glaser (1922), Eugster (1923, 1924), Ott (1925), Frei (1925), Frei & Ott (1926), Eggenberger (1926), Eugster & Frei (1927), Eugster & Leupold (1930), Cornelius (1932, 1935, 1950), Bearth et al. (1935), Stöcklin (1949) and Heierli (1955). The results of these authors had been complemented and in part corrected by stratigraphic-sedimentologic work of a research group led by

R. Trümpy (Furrer 1993, Eichenberger 1986, Naef 1987, Eberli 1985, 1988, and numerous diploma theses). All these studies provide a very detailed data set concerning the general geology of the area. Within this framework, we studied and mapped outcrop-scale deformation structures with an emphasis on structural overprinting. Direction and sense of displacement of major fault structures were determined by microstructural examination of mylonites and cataclasites.

Based on the structural analysis of the southwestern Silvretta, Ela and Err-Carungas nappes, a sequence of deformational phases will be developed and regional names will be introduced for these phases (chapter 4). In a next step the results from the Silvretta-Ela-Err region will be compared to and complemented with structural observations in the Engadine Dolomites (chapter 5). Finally, we will attempt a synthesis of the tectonic evolution of the Austroalpine units in Graubünden (chapter 6).

2 Austroalpine tectonic units in Graubünden and their position in the Jurassic passive continental margin

In this paragraph we give an overview of the Austroalpine nappe pile. Because the quantity of nappes and minor tectonic units must be confusing to readers not familiar with the area, a block diagram (P1.1) is attached, showing all the mentioned units and their mutual relations in a simplified way. The term "nappe", as used in this paper, simply means a tectonic unit that is internally (more or less) coherent but completely separated from overlying, underlying and adjacent units by major Alpine (Cretaceous or Tertiary) faults.

The Austroalpine nappes resulted from tectonic imbrication of a passive margin of Jurassic to Early Cretaceous age, and the major tectonic units roughly correspond to paleogeographic domains of this margin (Fig. 1b; Froitzheim & Eberli 1990). The following major units or "nappe systems" can be distinguished in this way (Fig. 1, Pl. 1): (1) The Upper Austroalpine nappe system, also called Central Austroalpine (Trümpy 1980), represented by the Ötztal, Silvretta, Campo and Languard basement nappes, the Sesvenna – S-charl nappe (Sesvenna basement and its partly detached sedimentary cover in the S-charl unit of the northern Engadine dolomites), and completely detached sedimentary cover units like the Quattervals nappe, Ortler nappe and the Arosa Dolomites. These nappes were derived from the proximal, continentward part of the passive margin, characterized by east-dipping normal faults active in the Liassic (Furrer 1993, Eberli 1988, Froitzheim 1988, Conti et al. 1994). (2) The Bernina system, comprising the Bernina nappe s.l. with the exception of the Corvatsch and Sella units, further comprising the Mezzaun unit and the Corn slice, the Julier nappe and klippen of the Samedan zone (e. g. Piz Padella), most of the Albula zone, the Ela nappe and the Rothorn nappe (Rothorn basement and sedimentary cover). These units were derived from the "outer basement high" of the passive margin and from a number of basins east of this high which were bounded by east-dipping normal faults, active in the Liassic and a second time in the Middle Jurassic (Furrer 1993, Eberli 1988). (3) The Err system, comprising the Err-Carungas nappe, the Samedan zone with the exception of the klippen of Bernina nappe, the Corvatsch nappe, most of the Murtiröl unit and the Tschirpen nappe. This paleogeographic domain is characterized by one or more top-west directed extensional detachment faults (Froitzheim & Eberli 1990), overlain by tilt blocks, active in the Middle