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Strain accumulation during basal accretion in continental collision — A case study from the Suretta nappe (eastern Swiss Alps)

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ABSTRACT

Stacked crystalline basement nappes are a typical feature in the core of many orogens. The Suretta nappe, exposed in Eastern Switzerland, consists of Briançon-derived crustal slices which were assembled in a south-dipping subduction zone during the Alpine orogenic cycle. The nappe contains post-Variscan rocks of the Rofna Porphyry Complex (RPC) and Permo-Mesozoic cover sequences, which are ideal to study the strain evolution during Alpine nappe formation. We present new structural cross-sections, finite strain analyses and a retrodeformation for the frontal part of the Suretta nappe. The overall geometry of the Suretta nappe is the result of two main deformation phases: (1) Eocene top-to-the-NNW directed thrusting and folding (Ferrera phase), which is overprinted by (2) backfolding and backshearing (Niemet–Beverin phase). We suspect that this backshearing was caused by the buoyant rise of light continental crust beneath the Suretta nappe and by frictional resistance at the top contact of the Suretta nappe, which had been accreted to the upper plate in the course of nappe stacking. In the lower and interior parts of the Suretta nappe, weakly to undeformed boudins are generally surrounded by L-tectonites indicating WSW–ENE stretching; foliated equivalents reveal a plane strain deformation state. The upper part of the Suretta nappe, which was strongly affected by backshearing, shows flattening strain. Strain data were used to reconstruct the palinspastic evolution of the Suretta nappe at two distinct time slots: Prior to Niemet-Beverin backfolding, the Suretta nappe is characterized by thrust faults and large-scale detachment folds. Before the onset of Ferrera phase nappe stacking, Jurassic normal faults and the RPC intrusion shape trigger the localization of subsequent deformation.
Our structural study confirms a complex, polyphase evolution for the Suretta nappe, which might be characteristic for crystalline basement nappes in continental collision zones elsewhere.

1. Introduction

In continental collision zones the process of basal accretion usually involves stacking of crystalline basement units. The descending plate interacts with the rigid lower part of the upper plate in such a way that the upper layer of the lower plate is offscraped and accreted to the hanging wall. Numerical modeling suggests that basal accretion is accompanied by backthrusting and by cutting a thrust ramp into the future leading edge (or front) of the basement nappe (Beaumont et al., 1996; Carry et al., 2009; Pfiffner, 2006; Selzer et al., 2008). Thrust ramps at nappe fronts are the location of intricate deformation involving both folding and thrusting. However, the original geometry of such nappe stacks is often severely modified by post-nappe folding (Bucher et al., 2003; Milnes, 1974; Milnes et al., 1981; Schmid et al., 1990).

The Suretta nappe of eastern Switzerland is an ideal area to study the complex deformational patterns resulting from nappe stacking and subsequent post-nappe folding during continental collision. It is part of a stack of pre-Triassic crystalline basement and younger sedimentary cover nappes, which were assembled in a S-dipping subduction zone during the Cenozoic Alpine orogenic cycle (Schmid et al., 1997, 2004;). The basement units show complex pre-Alpine polyphase structures and metamorphism, and the Alpine deformation is therefore difficult to track. However, late Paleozoic post-Variscan intrusions as well as Mesozoic sediments intercalated with the basement units allow the study of the deformation and metamorphism that occurred during the Alpine orogenic cycle. In case of the Suretta nappe, spectacular intercalations of Triassic sediments occur deep within the crystalline basement and are well described in the literature (Grünenfelder, 1956; Heim, 1891; Milnes and Schmutz, 1978; Staub, 1958; Streiff, 1939; Wilhelm, 1932). Additionally, a large shallow late Paleozoic intrusion occupies the frontal part of the nappe, namely the Rofna Porphyry Complex (RPC) (Grünenfelder, 1956; Marquer et al., 1998; Rüetschi, 1903; Wilhelm, 1932). Differing tectonic models were proposed for the Alpine deformation history of the Penninic zone of eastern Switzerland. The formation of the Suretta nappe is interpreted as the result of N to NW-directed convergence and nappe stacking during Paleocene/Eocene times (D1 after Marquer et al., 1996; Avers and Ferrera phase after Schmid et al., 1997; D2 after Ring, 1992b). According to Ring

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that parts of the intrusion remained unaffected by Alpine deformation, rendering the annotation "Rofnagneiss" (Schmidt, 1891; Wilhelm, 1929) and "Roffna gneiss" (Hanson et al., 1969), respectively, inappropriate. Marquer et al. (1998) switched to "Roffna rhyolite" separating the effusive-type rocks ("Roffna rhyolite") from "older orthogneisses". We propose to use the more general term "*Rofna Porphyry Complex*" (RPC). The magmatic event emplacing the RPC is dated at 268.3 ± 0.6 Ma ($^{206}Pb/^{238}U$ zircon age) (Marquer et al., 1998). However, a distinct lithological variation of the RPC (the augengneisses on Fig. 2) was interpreted to be of Ordovician age by various authors (Marquer et al., 1996; Nussbaum et al., 1998; Spicher, 1980). Preliminary results of LA-ICP-MS measurements on zircons indicate that all members of the RPC most likely represent Permian magmatic rocks as already proposed by Hanson et al. (1969). Detailed petrographical descriptions of the RPC can be found in Schmidt (1891), Rüetschi (1903), Grünenfelder (1956), Hanson et al. (1969) and Streiff et al. (1976). (3) Permo-Mesozoic autochthonous sediments overlie both the Timun complex and the RPC throughout the study area (Fig. 2). They consist from bottom to top of conglomerates, quartzites and carbonates. No fossils are recorded from these sediments. However, they have to be younger than the RPC and further age constraints can be gathered from similar and dated stratigraphic sequences elsewhere in the Alps (Baud and Septfontaine, 1980; Ellenberger, 1953; Lemoine, 1960; Rück, 1995).

Mineralogical and structural investigations of mafic lenses embedded within the Timun complex led to the distinction of two events in the metamorphic history of the Suretta nappe: a pre-Alpine high-P, high-T subduction-collision event and an Alpine high-P, low-T event of 380-450 °C at about 1 GPa (Biino et al., 1997; Nussbaum et al., 1998; Ring, 1992a; Steinitz and Jäger, 1981). In the N-Penninic Bündnerschiefer units (Tomül, Grava nappes) Wiederkehr et al. (2008) recognized two heating pulses during the Alpine metamorphic history.

The Suretta nappe is separated from the underlying Tambo nappe by the Splügen zone, a unit comprising Permo-Mesozoic strata (Fig. 2). Basal conglomerates, quartzites and dolomitic marbles on top of the Tambo basement are considered as its autochthonous cover, but are overlain by strongly sheared and imbricated allochthonous Triassic carbonatic sequences (Baudin et al., 1993; Blanc, 1965; Mayerat Demarne, 1994; Zurflüh, 1961). The Suretta and Tambo nappes are wrapped in their frontal parts by an assemblage of carbonate-rich platform sediments, known as Schams nappes (Schreurs, 1993, 1995). These nappes are in tectonic contact with the S-Penninic Avers nappe and the N-Penninic Tomül nappe, respectively (Fig. 2). The tectonic contact of the Schams nappes is in many places accompanied by a tectonic mélange. Sedimentological and structural investigations of the rootless Schams nappes by Kruysse (1967) and Rück (1995) state a Carnian to Upper Cretaceous age of the strata. Their substratum corresponds at least partially to an external (NNW) part of the Briançon continental crust (Schmid et al., 1990). The Suretta nappe is in its southern part overlain by the Avers nappe (Fig. 1), a unit mainly composed of dark calcareous schists with intercalations of radiolarian cherts and mafic to ultramafic rocks suggesting a S-Penninic origin (Oberhänsli, 1978; Wiederkehr et al., 2008). Remnants of the Piemont–Liguria oceanic crust within the even higher Platta nappe define the suture between the continental Briançon swell and the Apulian (Austroalpine) margin (Fig. 1).

Today's geometry of the Penninic units in eastern Switzerland is interpreted as the result of five superimposed deformation phases (terminology after Pfiffner, 1977; Milnes and Schmutz, 1978; Schmid et al., 1997; Wiederkehr et al., 2008):

(1) The *Avers phase* is considered as an early detachment and thrusting stage, which marks the beginning of a continuous thrusting history during the Paleocene and Eocene. During this phase, the Avers nappe (Piemont-Liguria affinity) is emplaced on top of the Suretta nappe and the Schams nappes are detached from their crystalline substratum (Briançon basement). In the N-Penninic Bündnerschiefer (Fig. 1) the equivalent Safien phase is held responsible for the stacking of different cover nappes (Grava and Tomül).
(2) The *Ferrera phase* represents the major stage of nappe imbrication affecting crystalline basement and, furthermore, the main phase of ductile penetrative deformation. The transport direction is inferred to be to the NNW.
(3) The *Niemet-Beverin phase* is associated with large scale backfolding and backshearing of the nappe stack around an ENE-WSW striking fold axis. During the final stages of the Niemet–Beverin phase, vertical shortening of the entire nappe pile was accompanied by localized E-W extension (e.g. Turba mylonite zone, shown in Fig. 1b, described by Nievergelt et al., 1996).
(4) The *Domleschg phase* is mainly associated with a crenulation cleavage in the N-Penninic units and asymmetric NNW-verging folds at various scales in the Schams nappes. Both structures are related to SSE-NNW directed shortening of the nappe pile.
(5) The *Forcola phase* encompasses E-W extension along distinct normal faults, accompanied by the uplift of the Lepontine dome.

3. Field results

In the following, we summarize the results of fieldwork in the northern part of the Suretta nappe (Figs. 1 and 2). We present a geological and structural map (Fig. 2), a structural profile (Fig. 3), field photographs (Fig. 4) and structural data (Figs. 5 and 6) for this region.

3.1. Lithological observations

The northern part of the Suretta nappe is mainly made up of different lithologies related to the RPC. According to our observations, the RPC consists mainly of two types of igneous rocks: porphyritic rock types and augengneisses (Figs. 2 and 3). Porphyritic rocks of the RPC with typical rounded quartz and feldspar phenocrysts (up to 1 cm in diameter) in an aphanitic matrix cut through the Stella-Timun mass and also intrude augengneiss bodies of the RPC. Because of the presence of gray gneiss horizons in the Timun complex that look very similar to the foliated Rofna porphyry, intrusive contacts are often hard to recognize in the field. Locally preserved magmatic structures in the RPC include colored layering, xenoliths and slight variations in grain sizes of feldspars and quartz phenocrysts. RPC augengneisses have the same mineralogical composition as porphyritic rock types but contain much larger original magmatic feldspar phenocrysts (up to 5 cm long). Comprehensive mapping divulges a clear cross-cutting relationship between RPC augengneisses and RPC porphyritic rock types and reveals that bodies composed of augengneiss are in many cases directly underlying autochthonous Triassic sediments, but are never in contact with rocks of the Stella-Timun mass. Furthermore, augengneisses of the RPC are always foliated, while porphyritic rock types reveal variable degrees of Alpine deformation (see below). The Stella-Timun mass embeds various augengneiss horizons, but none can be directly connected to the body of the RPC in the studied area.

Permo-Mesozoic sediments occur throughout the study area (Fig. 4a). In the southern part of the study area, quartz-rich basal conglomerates (Verrucano-type, upper Permian?) reach thicknesses up to 150 m on top of the Stella-Timun mass, whereas the RPC is overlain by a thin cover of conglomerates with a maximal thickness of 20 m and

Fig. 2. Tectonic map of the studied area based on maps of Staub (1926), Wilhelm (1929), Grünenfelder (1956), Kruysse (1967), Streiff et al. (1971), Milnes and Schmutz (1978), Schmid et al. (1990), Mayerat Demarne (1994), Marquer et al. (1996) and own observations. The geological situation of the frontal part of the Suretta nappe is highlighted. For rocks of the RPC a subdivision based on deformation intensity is provided. Note that fold axes and stretching lineations are undifferentiated with respect to distinct phases.

a lower normal limb and an upper overturned one (Niemet fold after Milnes and Schmutz, 1978). This huge fold has a complex shape. Tracing one axial surface or defining a major hinge zone in the Suretta basement, as attempted by Milnes and Schmutz (1978), is not possible owing to the existence of several hinges, which cannot be connected (Fig. 3). Small-scale structures related to this fold are patchy in appearance. In the interior of the RPC, parasitic folds and crenulations are mainly restricted to hinge zones and to the lower part of the nappe. The folds hardly ever developed an axial planar cleavage and show inconsistent vergence. Measured fold axes scatter around the mean value of this huge fold (062–25), which was constructed from Ferrera phase foliation poles (Fig. 5h). In the polymetamorphic basement of the Stella-Timun mass, fold amplitudes tend to be higher, ranging from meter to decameter scale and fold axes show a stronger scatter. Poles of associated axial planes show a girdle distribution similar to those of the Ferrera phase foliation (Fig. 5) and display an axial planar fan in cross-sectional view (Fig. 3). The orientation of these small scale folds is in accordance with large-scale Niemet–Beverin phase structures and they clearly overprint the Ferrera phase foliation. Therefore we assign them to the Niemet–Beverin phase.

The widespread ENE–WSW stretching lineation in the interior of the nappe discussed above is parallel to the plunge of Niemet-Beverin phase fold axes (Fig. 5). However, in contrast to previous works (Marquer et al., 1996; Ring, 1992b) we did not observe ubiquitous shear sense criteria linked to this stretching lineation. Our observations and strain analysis suggests that this stretching lineation is not the result of only one deformation phase, as previously thought, but rather the result of both Ferrera and Niemet-Beverin phase, which both took place under metamorphic conditions where quartz deformed in a ductile manner. As fold overprinting relationships are often lacking, structures that could not be unambiguously attributed to either Ferrera or Niemet-Beverin phase, or structures that resulted from both phases, are gray-colored in the stereoplots in Fig. 5.

The traces of the Ferrera phase foliation and the trace of the large-scale sediment intercalations are non-parallel in cross-sectional view at first sight (Fig. 3). This is best seen in the upper parts of the Suretta nappe at the Gruoba, Nursera and Muttala intercalations (Fig. 3). Closer inspection, however, reveals that the Ferrera phase foliation curves progressively into parallelism with the mylonitic foliation in the Triassic sediments. Such geometries are therefore interpreted as large scale shear zones with a north-side-down shear sense for the Gruoba and Nursera intercalations and a top-to-the-NW shear sense in case of the Muttala intercalation. At Gruoba, the situation is quite chaotic because sediments are disrupted and completely thinned out. In the westerly part of the Muttala intercalation, an asymmetric configuration can be observed. A meta-sedimentary sequence with basal quartzite and carbonates overlies porphyritic rock types of the RPC and is in turn directly overlain by augengneisses of the RPC (Fig. 3). The Muttala intercalation continues laterally as an intra-crystalline shear zone with augengneisses in the hanging wall and porphyritic rocks in the footwall (Fig. 4d). Shear planes successively grade into the Ferrera phase foliation and vanish. Prior to the Niemet-Beverin phase, the relatively small augengneiss body of Muttala was most probably connected to the larger block farther up (cf. cross-section of Fig. 3). The Piz Miez intercalation is characterized by a symmetric succession with carbonates in its core, bound by a thick band of quartzite overlying basement rocks. This Ferrera phase fold is itself deformed by a Niemet–Beverin fold. These large-scale Ferrera phase synclines strongly affected deformation and strain localization during the Niemet–Beverin phase.

In parautochthonous carbonates of the Suretta nappe recumbent Niemet–Beverin folds are often associated with an axial-planar cleavage dipping gently towards the E to NE. Shear sense criteria such as shear band foliations and asymmetric porphyroclasts that developed during Niemet-Beverin deformation show SE to SSE-directed movement (Fig. 6). In adjacent units (Schams nappes, Avers nappe, Arblatsch flysch) shear bands indicate top-to-the-SE shearing as well (Schmid et al., 1990; Schreurs, 1993). Approaching the Turba mylonite fault zone in the hanging wall of the Arblatsch flysch (Fig. 1b) the transport direction changes into the more easterly direction characteristic of the Turba mylonite zone, which formed during the closing stages of the Niemet-Beverin phase (Liniger, 1992; Nievergelt et al., 1996).

3.3. Piz Grisch area

The Piz Grisch area in the easternmost part of the Suretta nappe (Fig. 2) represents a particularly complex structure. It corresponds to the backfolded frontal part of the hanging wall of the Nursera thrust (Fig. 6). Masses of cargneule north of Piz Grisch mark the trace of this thrust. Compared to the other domains within the RPC, the Piz Grisch area has a particular feature:

A large-scale fold north of Piz Grisch affects the Nursera thrust; its hinge line plunges to the east (065–10, Fig. 6). A second large-scale fold affects the basement-cover contact in the summit area of Piz Grisch, but with a hinge line plunging to the NNE (010–10, Fig. 6). Small-scale fold axes in this area (Fig. 5e) scatter on a great circle. Stretching lineations are parallel to the small-scale folds and thus also scatter on a great circle (Fig. 6). This scatter is in contrast with the elsewhere observed dominant easterly trend of minor folds and stretching lineations.

North of the trace of the Nursera thrust, a thin and strongly sheared basement sliver with an upright autochthonous sedimentary cover is surrounded by cargneules (Fig. 2). Most likely, it represents a frontal crystalline fragment of the Nursera hanging wall. This slice can be linked to augengneisses farther to the east (N of Alp Mos), also showing normal lying stratigraphy on it. There the basement-cover contact steepens and runs into a narrow hinge zone that follows up the NNW ridge of Piz Grisch. W and NW of the summit of Piz Grisch (Fig. 2), the basement-cover contact is inverted. Therefore the crystalline of the Piz Grisch represents an isoclinal fold with an upper, normal limb thinning out northwestward.

This basement-cover contact is accompanied by a range of parasitic folds, which can be best studied in the area NW of Alp Mos. There a stretching lineation in quartzite is folded around a NNE-SSW striking fold axis.

Normal faulting along the Turba mylonite zone affected the Piz Grisch crystalline unit in its footwall which reoriented stretching lineations and fold axes around a subvertical axis. Locally new folds developed and folded pre-existing stretching lineations.

3.4. Younger deformation features

Deformation during the Domleschg phase, which is prominent farther north in the Bündnerschiefer (Tomül nappe) and Schams nappes, left only minor imprints on the Suretta nappe's configuration. Structures related to the Domleschg phase are expressed by a steeply SE-dipping crenulation cleavage (Pfiffner, 1977) or by NE- to ENE-plunging fold axes with a NW to NNW vergence and steeply inclined SE-dipping axial planes (Schmid et al., 1997; Schreurs, 1995). Since Niemet-Beverin parasitic folds in the Suretta basement locally include

Fig. 5. Stereoplots (equal area, lower hemisphere) showing the variable orientation of structural elements in domains (a–g) of the RPC. Composite stereoplots are provided (h). Structures that could not be unambiguously restricted to one deformation phase are gray-shaded in the plots. Abbreviations are: n = number of measurements, npl = number of planar structures measured; nfa = number of fold axis measured.