Simplon fault zone in the western and central Alps: Mechanism of Neogene faulting and folding revisited

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ABSTRACT
The Neogene Simplon fault zone is commonly either considered as a transfer zone for dextral strike-slip movements during oblique convergence or as a core complex–type normal fault leading to orogen-parallel extension in the Alps. There is, however, evidence that the Simplon fault zone lacks a southeastward continuation. On the basis of new structural and fission-track data, we propose a model of oblique indention of a bent Adriatic indenter leading to the formation of a curved continuous wedge of backfolds in the south, not including a southern continuation of the Simplon fault zone. Updoling related to backfolding, followed by erosion, assisted exhumation of amphibolite facies rocks. In the north, indentation led to differential shortening in the footwall and hanging wall.

Keywords: Simplon fault zone, indentation tectonics, backfolding, metamorphic domes.

INTRODUCTION
The late stages of the deformation history of collisional orogens commonly involve oblique and/or normal convergence associated with indentation, e.g., as in the Taiwan mountain belt, the Alps, and the Himalaya (e.g., Tapponnier, 1977; Tapponnier et al., 1982; Lu and Malavieille, 1994; Lu et al., 1995; Schmid and Kissling, 2000). Crustal shortening is often associated with concomitant orogen-parallel extension (e.g., Mancktelow, 1992; Steck and Hunziker, 1994; Lu et al., 1995) or block rotations (e.g., Collombet et al., 2002). The amount of extension may be related to local pull-apart structures linked to strike-slip movements. Alternatively, such extension may be an integral part of lateral extrusion (Ratschbacher et al., 1991). In the case of oblique indentation divergent block rotation can also produce a crescent-shaped thrust wedge associated with strike-slip faulting and extensional features due to block rotation around the indentation point (Lu and Malavieille, 1994; Lu et al., 1995). Hence, convergence and indentation tectonics during the final stages of collision may result in different kinematic patterns.

The Neogene Simplon fault zone of the Alps is commonly considered as a textbook example of a major low-angle extensional fault (Mancktelow, 1990, 1992) (Figs. 1 and 2). Mancktelow (1992) demonstrated that normal faulting was coeval to backfolding in the central and northern parts of the Simplon fault zone (Mancktelow and Pavlis, 1994; Fig. 2). As a result, all of these second-generation backfolds are located in the footwall of the Simplon fault zone (Fig. 2), whereas none of them affect the hanging wall in this northwest part of the Simplon fault zone. Recent remapping of the area south of the Simplon fault zone revealed evidence for coeval late-stage backfolding and normal faulting in the hanging wall. The axial traces of major second-generation backfolds show a systematic en echelon arrangement, and their strike changes when approaching the Simplon fault zone (Fig. 2): the NE-SW–striking Vanzone antiform in the west is replaced by the E-W–striking Brevettola and Masera folds farther east (Fig. 2) (Keller et al., 2005). These major changes are located in an area where the surface trace of the Simplon fault zone changes from NW-SE to E-W orientation. In the north the mylonitic foliation of the footwall of the Simplon fault zone is discordant to the main foliation in the hanging wall, but foliation trajectories become parallel to the fault in the south where the Simplon fault zone interferes with these late-stage backfolds. This suggests a genetic link between the location of the marked bend along the southeastern continuation of the Simplon fault zone with this en echelon late-stage backfolding in the hanging wall of the Simplon fault zone (Keller et al., 2005).

Small-scale late-stage backfolds that are associated with the major Vanzone backfold emanate from dextral shear zones, suggesting that they nucleated from such shear zones (Keller et al., 2005). Thus, the formation of Vanzone and adjacent backfolds is associated with a component of dextral shearing, which indicates a kinematic link to normal faulting along the Simplon fault zone. This suggests transformation of the top-to-the-SW movement in the hanging wall of the Simplon fault zone into backfolding, as the trace of the Simplon fault zone abruptly bends into an E-W orientation.

The orientations of foliation poles and stretching lineations give insight into the
Timing of D4 Backfolding and Dextral Strike-Slip Movements

Southwest of the Simplon fault zone, the late-stage Vanzone and Brevettola megabackfolds overprint the mineral zone boundaries related to Barrovian-type metamorphism (Bearth, 1958), associated with an earlier backfolding phase and coeval dextral shearing in deeper structural levels. This early deformation phase was diachronous by ~10 m.y.

In higher structural levels (i.e., at the top of the Monte Rosa nappe), top-to-the-SE backthrusting related to this earlier backfolding phase occurred ca. 40 Ma (Barnicoat et al., 1995).

At deeper structural levels (i.e., in the south of the Simplon fault zone) this earlier backfolding took place at significantly higher pressure-temperature (P-T) conditions by near isothermal decompression from an early high-P metamorphic stage (Keller et al., 2005). According to Schärer et al. (1996), high-T shearing, which predates the formation of the Vanzone antiform, terminated between 29 Ma and 26 Ma. Farther east in the southern part of the central Alps, Barrovian metamorphism reached its thermal peak ca. 28 Ma (Engi et al., 2004). Based on these age data and the fact that the second backfolding phase and associated dextral shearing overprint the Tertiary Barrovian structure, it is evident that this deformation could not have initiated earlier than ca. 27 Ma. However, it was still active after normal faulting along the Simplon fault zone initiated ca. 18 Ma; thermal modeling of Grasemann and Mancktelow (1993) predicted continuously decreasing rates of fault displacement along the Simplon fault zone.

Normal faulting along the central part of the Simplon fault zone caused a jump in metamorphic grade and fission-track cooling ages (Figs. 2 and 3) (Wagner et al., 1977; Soom, 1990; Steck and Hunziker, 1994; Grasemann and Mancktelow, 1993; Oberhansli et al., 2004). New zircon and apatite fission-track data from the southern part of the Simplon fault zone revealed no discrete age jump across any of the proposed faults in this area (Fig. 3) (Keller et al., 2005). Instead, the same young cooling ages characteristic of the footwall of the Simplon fault zone farther north were found, as well as a moderate increase of ages toward the south (zircon fission track, 6–10 Ma; apatite fission track, 2–6 Ma) (Fig. 3). The entire region south of the bend in the Simplon fault zone is characterized by young cooling ages, and no differential cooling (and exhumation) pattern may be inferred for the area southeast and east of the classic area of the Simplon fault zone. The area that displays such young footwall-type cooling ages (Fig. 3) largely overlaps with the area that exposes high-grade metamorphic rocks (Fig. 2). All this suggests that there is no continuation of the Simplon fault zone toward the east. Instead there is ample evidence that the rather discrete Simplon fault zone ends in a broad E-W–trending belt of backfolds (Fig. 2).

Kinematic Model

In the Alps, NW-directed convergence of the southern Alpine indenter (Fig. 1) led to variable lateral displacement directions, which are linked to an isolation of crustal blocks around a complexly shaped southern Alpine indenter (Handy et al., 2005).

Foliation pole patterns corresponding to the region south of the Simplon fault zone (Fig. 2) indicate a change of the lateral displacement direction around the asymmetric edge of the southern Alpine indenter, defined by the Ivrea zone (Figs. 1 and 4). The en echelon arrangement of the backfolds can then be explained by different shortening directions around a bent southern Alpine indenter during ongoing convergence. In addition, the changing stretching directions and associated coeval shortening around the bent indenter surface reoriented the bulk strike of the main Alpine foliation to the south of the Simplon fault zone. The angle between the foliation poles of...
subareas I and III in Figure 2 indicates a relative rotation of ~25° of the bulk strike of the main Alpine foliation. This suggests that the NW convergence of the bent indenter was accommodated by block rotation around the indentation point at least in the area south of the Simplon fault zone. Such a scenario was, for example, shown for the Taiwan mountain belt, where oblique indentation caused divergent block rotation around an indentation point (Lu and Malavieille, 1994; Lu et al., 1995). By assuming a similar scenario for our working area, differential rotations are expected in the central and western Alps. Thus, the two oppositely rotating blocks would be separated by an extensional zone, the Simplon fault zone. Note that, according to this scenario, the displacements along the Simplon fault zone would cease toward the south, i.e., toward the tip of the indenter. While paleomagnetic data from the central Alps do not indicate such dextral rotation relative to stable Europe (Heller, 1980), data suggest very large counterclockwise rotations of the western Alps.

Figure 2. Map showing location of major backfolds, orientation of planar and linear fabric elements divided into subareas (I, II, and III), and staurolite (St) mineral zone boundary adjacent to Simplon fault zone (SFZ; see Fig. 1 for legend of tectonic units). CFZ—Centovalli fault zone. Lower hemisphere equal-area projections show contoured poles of main Alpine foliation, stretching lineations, and fold axes; contour intervals are multiples of uniform distribution depending on number of measurements (N). Structural data are from Keller et al. (2005, their subareas V–IX); data of stretching lineations and fold axes correspond to second stage of backfolding and coeval dextral shearing. Gray area marks location of dextral shearing during late-stage backfolding. Black arrows indicate inferred bulk extension. Inset shows interpretative profile along indicated trace (redrawn and modified after Mancktelow, 1990; Keller et al., 2005).

Figure 3. Contours of published zircon and apatite fission-track (FT) age data. (Data are from Hurford, 1986; Hurford et al., 1991; Seward and Mancktelow, 1994; Soom, 1990; Wagner et al., 1977; Vance, 1999; Keller et al., 2005.)
which is triggered by the formation of the an-
of the Simplon fault zone, the exhumation of
common cooling history for the southern areas
folds in the south, which led to a young and
shortened blocks, allows for rather fast exhu-
tioned parts of the Alps is
partly related to updoming during the forma-
tion of the Lepontine dome.

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CONCLUSIONS

The Neogene Simpion fault zone is genet-
cally linked to late-stage backfolding caused by
oblique indentation. This causes the for-
mation of the Neogene Simpion fault zone marks
the boundary between differentially rotated and
shortened blocks, allowing for combined
erosion-controlled and tectonic exhumation of
the Lepontine dome.

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(Rahn and Seward, 2004; Fig. 3) roughly match the axial

deformation and metamorphism in the upper


In Fig. 2), a feature

essentially missing in the hanging wall. Neoe-
genue exhumation of the Lepontine dome is

partly related to updoming during the forma-
tion of antiform fold structures and thus con-
trolled by erosion. However, the Neogene
Simpion fault zone, linking the differentially
shortened blocks, allows for rather fast exhu-

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