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

Lukas M. Keller Institut für Mineralogie und Petrologie, Free University Berlin, Malteserstrasse 74-100, 12249 Berlin, Germany
Bernhard Fügenschuh Institut für Geologie und Paläontologie, University Innsbruck, Innrain 52, A-6020 Innsbruck, Austria
Maurus Hess
Bernhard Schneider
Stefan M. Schmid
– Geologisch-Paläontologisches Institut, Basel University, Bernoullistrasse 32, CH-4056 Basel, Switzerland

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 indentation 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. Updoming 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). Keller et al. (2005) traced the fold axial planes of major backfolds south of the Simplon fault zone and along the proposed eastern continuation of the Simplon fault zone, and corroborated earlier propositions (Milnes et al., 1981; Mancktelow, 1992) that regarded backfolding to be coeval with normal faulting. Therefore, orogen-perpendicular shortening and orogen-parallel extension, related to collision and indentation in the western and central Alps, are contemporaneous.

While the northern continuation of the Simplon fault zone into the dextral Rhone line is generally accepted (Hubbard and Mancktelow, 1992; Steck and Hunziker, 1994) (Figs. 1 and 2), any kinematic model of the central and western Alps must answer the question of a southeastern continuation of the Simplon fault zone (Figs. 1B, 1C). Foliation trajectories suggest a continuation of the Simplon fault zone toward the northeast and into the Lepontine dome (e.g., Mancktelow, 1990, 1992). Brittle features, however, suggest a continuation of the Simplon fault zone into the E-W–striking Centovalli fault (Figs. 1B, 1C): the Simplon fault zone would serve as a tensile bridge that transfers dextral strike slip along the Rhone line to the Periadriatic line in an overall dextral transpressive regime (Steck, 1984; Schmid and Kissling, 2000).

Here we present evidence against the existence of such a southeastern continuation of the Simplon fault zone, and we discuss a new kinematic model regarding late-stage faulting and folding in this part of the Alps.

Late-Stage Faulting and Folding along the Simplon Fault Zone

A pair of megafolds (Glishorn-Berisal folds in Fig. 2) formed along the northwest part of the Simplon fault zone. Greenschist facies mylonites, formed during early stages of top-to-the-SW normal faulting, were folded during ongoing faulting and folding and finally offset by a discrete cataclastic fault of the Simplon fault zone (Mancktelow, 1990, 1992; Mancktelow and Pavlis, 1994; Zwingmann and Mancktelow, 2004). A large-amplitude antiform (Toce dome) formed farther south (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

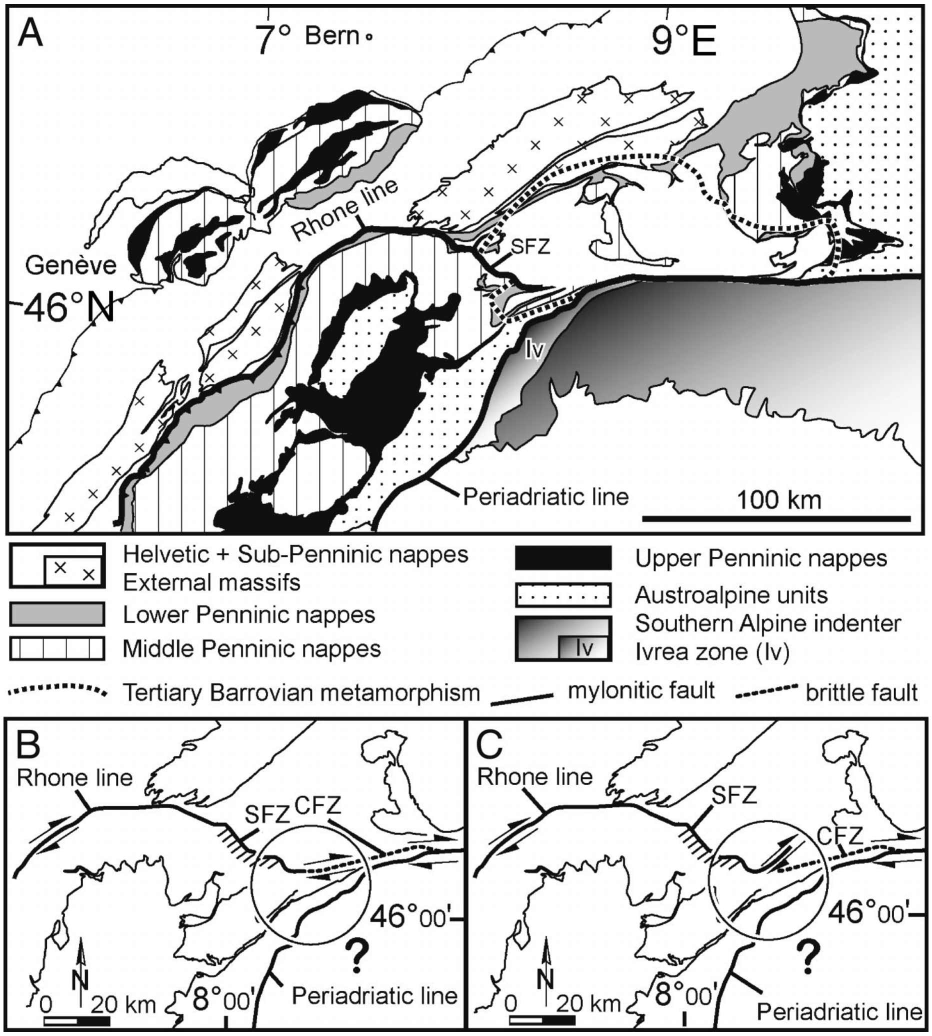

Figure 1. Tectonic map and models and interpretations of late-stage faulting along Simplon fault zone (SFZ; see text for references). A: Map of western and central Alps showing major tectonic units (modified after Schmid et al., 2004). B: Dextral shearing along Rhone line is transferred via normal faulting and dextral shearing along the SFZ-respective Centovalli fault zone (CFZ) to Periadriatic line. C: Ductile normal faulting along Simplon fault zone is transferred into dextral shearing within Lepontine dome.

kinematics of coeval dextral shearing and second-stage backfolding in the south of the Simplon fault zone (Fig. 2). Generally, the pole patterns of the main Alpine foliation south of the Simplon fault zone compose a great-circle distribution that reflects reorientation during backfolding (Fig. 2). While the average foliation trend is NE-SW in the area I of Figure 2, it becomes closer to E-W in the east (area III of Fig. 2). The bulk extension during dextral shearing inferred from the lineations also changes from NE-SW in the southwest to ENE-WSW in the east (Fig. 2). This points toward a change of the stretching direction induced by the curvature of a rigid indenter, as defined by the Ivrea geophysical body (Fig. 1).

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; Oberhänsli 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

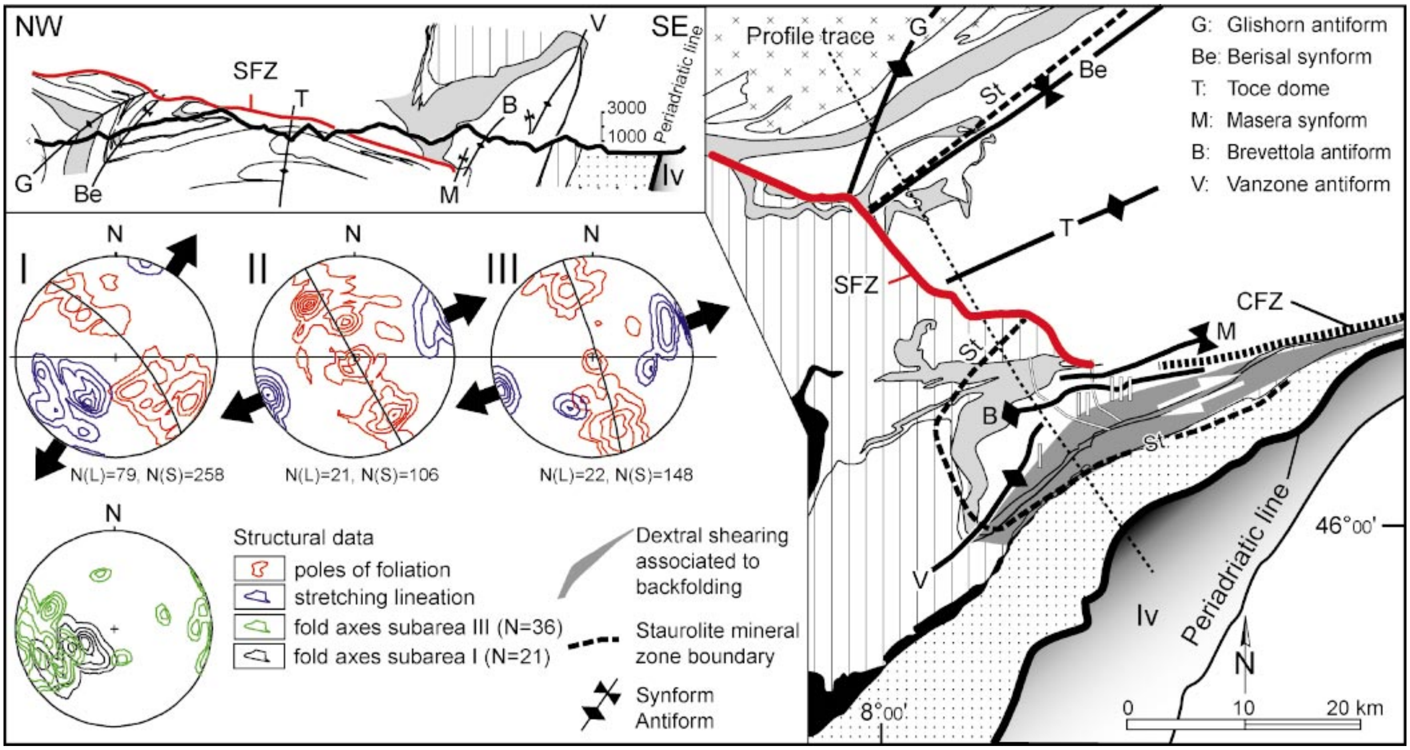

Figure 2. Map showing location of major backfolds, orientation of planar and linear fabric elements divided into subareas (I, II, and III), and staurolite (St) mineral zone boundary adjacent to Simplon fault zone (SFZ; see Fig. 1 for legend of tectonic units). CFZ—Centovalli fault zone. Lower hemisphere 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).

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

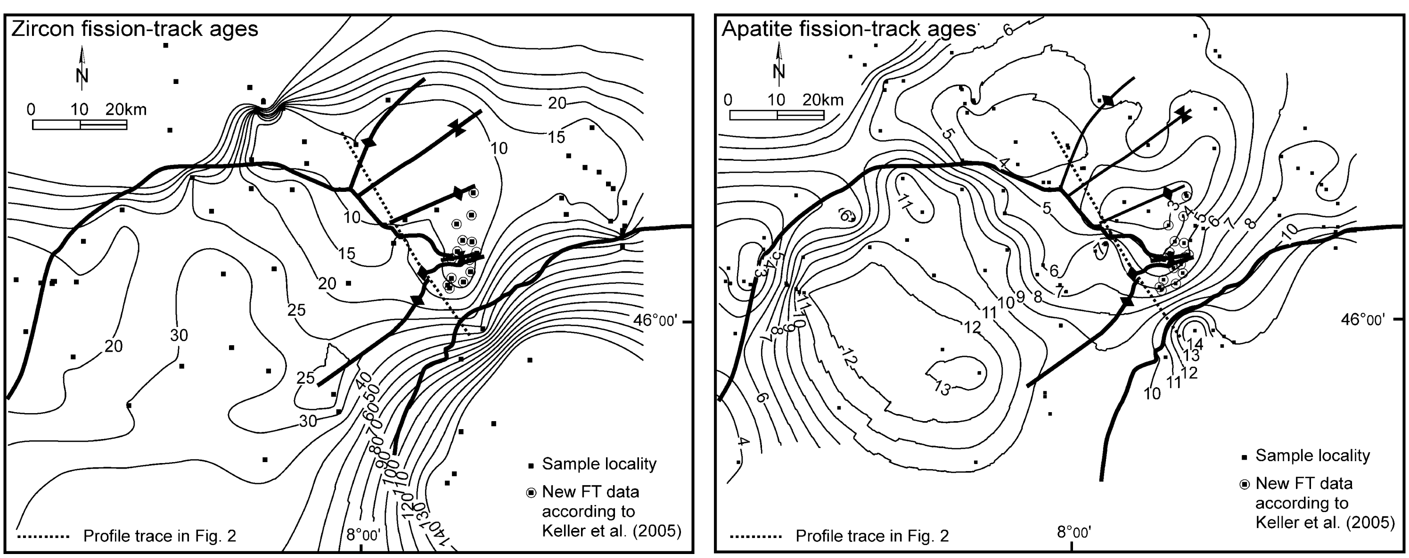

Figure 3. Contours of published zircon and apatite fission-track (FT) age data. (Data are from Hurford, 1986; Hurford et al., 1991; Seward and Mancktelow, 1994; Soom, 1990; Wagner et al., 1977; Vance, 1999; Keller et al., 2005.)

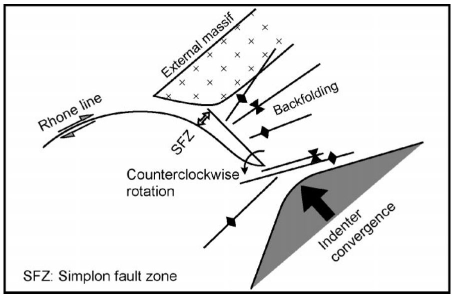

Figure 4. Tectonic model illustrating Neogene faulting and folding in area of western and central Alps. Eastern area, located between the indenter of the southern Alps and the external massifs, is characterized by backfolding and dextrally transpressive faulting in footwall of Simplon fault zone (SFZ). Indentation in the central area leads to extension and shortening along Simplon fault zone. Based on strike change of main Alpine foliation around the bent indenter, counterclockwise rotation of hanging-wall block of Simplon fault zone is proposed.

(Collombet et al., 2002), in support of a differential rotation of the western Alps with respect to the central Alps. Although the Taiwan model of differentially rotating blocks may be nicely applied to the southern part of the Simplon fault zone, the predicted continuous increase in the amount of extension toward the north (i.e., the Rhone area) is not supported.

Based on our data and observations as well as the paleomagnetic results of Collombet et al. (2002), we propose a model of oblique indentation (Fig. 4) that leads to counterclockwise rotation of the SW block, i.e., the hanging wall. The expected clockwise rotation of the footwall block, i.e., the Lepontine dome, is hindered because this part of the Alps is strongly pinched between the rigid indenter (i.e., the southern Alps) and the external massifs (Fig. 4). Pinching is directly evidenced by numerous late-stage folds (Fig. 2), a feature essentially missing in the hanging wall. Neogene exhumation of the Lepontine dome is partly related to updoming during the formation of antiformal fold structures and thus controlled by erosion. However, the Neogene Simplon fault zone, linking the differentially shortened blocks, allows for rather fast exhumation by tectonic unroofing. Contoured zircon and apatite fission-track data (Rahn and Seward, 2004; Fig. 3) roughly match the axial traces of late-stage folds and thus indicate coeval cooling and formation of those folds.

CONCLUSIONS

The Neogene Simplon fault zone is genetically linked to late-stage backfolding caused by oblique indentation. This causes the formation of an en echelon arrangement of backfolds in the south, which led to a young and common cooling history for the southern areas of the Simplon fault zone, the exhumation of which is triggered by the formation of the antiformal megafold wedge. Toward the north, the Neogene Simplon 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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REFERENCES CITED

Barnicoat, A.C., Rex, D.C., Guise, P.G., and Cliff, R.A., 1995, The timing of and nature of greenschist facies deformation and metamorphism in the upper Pennine Alps: Tectonics, v. 14, p. 279–293.

Bearth, P., 1958, Ueber den Wechsel der Mineralfazies in der Wurzelzone des Penninikums: Swiss Bulletin of Mineralogy and Petrology, v. 38, p. 363–373.

Collombet, M., Thomas, J.C., Chauvin, A., Tricart, P., Bouillin, J.P., and Gratier, J.P., 2002, Counterclockwise rotation of the western Alps since the Oligocene: New insights from paleomagnetic data: Tectonics, v. 21, p. 1–15.

Engi, M., Bousquet, R., and Berger, A., 2004, Explanatory notes to the map: Metamorphic structure of the central Alps: Mitteilung der Oestreichischen Mineralogischen Gesellschaft, v. 149, p. 157–173.

Grasemann, B., and Mancktelow, N.S., 1993, Two-dimensional thermal modelling of normal faulting: The Simplon fault zone, central Alps, Switzerland: Tectonophysics, v. 225, p. 155–165.

Handy, M.R., Babist, J., Wagner, R., Rosenberg, C., and Konrad, M., 2005, Decoupling and its relation to strain partitioning in the continental lithosphere: Insight from the Periadriatic fault system (European Alps), *in* Gapais, D., et al., eds., Deformation mechanism, rheology and tectonics: From minerals to the lithosphere: Geological Society [London] Special Publication 243, p. 249–276.

Heller, F., 1980, Paleomagnetic evidences for late Alpine rotations in the Lepontine area: Eclogae Geologicae Helvetiae, v. 73, p. 607–618.

Hubbard, M., and Mancktelow, N.S., 1992, Lateral displacement during Neogene convergence in the western Alps and central Alps: Geology, v. 20, p. 943–946.

Hurford, A.J., 1986, Cooling and uplift in the Lepontine Alps south central Switzerland and an age of vertical movements on the Insubric fault line: Contributions to Mineralogy and Petrology, v. 92, p. 413–427.

Hurford, A.J., Hunziker, J.C., and Stöckert, B., 1991, Constraints on the late tectonic evolution of the western Alps: Evidence for episodic rapid uplift: Tectonics, v. 10, p. 758–769.

Keller, L.M., Hess, M., Fügenschuh, B., and Schmid, S.M., 2005, Structural and metamorphic evolution of the Camughera-Moncucco, Antrona and Monte Rosa units southwest of the Simplon line, western Alps: Eclogae Geologicae Helvetiae, v. 98, p. 19–49.

Lu, C.Y., and Malavieille, J., 1994, Oblique convergence, indentation and rotation tectonics in the Taiwan mountain belt: Insights from experimental modelling: Earth and Planetary Science Letters, v. 121, p. 477–494.

Lu, C.Y., Angelier, J., Chu, H.T., and Lee, J.C., 1995, Contractional, transcurrent, rotational and extensional tectonics: examples from northern Taiwan: Tectonophysics, v. 246, p. 129–146.

Mancktelow, N.S., 1990, The Simplon fault zone: Beiträge zur Geologischen Karte der Schweiz, Lieferung 163, 74 pp.

Mancktelow, N.S., 1992, Neogene lateral extension during convergence in the Central Alps: Evidence from interrelated faulting and backfolding around the Simplonpass (Switzerland): Tectonophysics, v. 215, p. 295–317.

Mancktelow, N.S., and Pavlis, T.L., 1994, Fold-fault relationships in low-angle detachment systems: Tectonics, v. 13, p. 668–685.

Milnes, A.G., Greller, M., and Müller, R., 1981, Sequence and style of major post-nappe structures, Simplon-Pennine Alps: Journal of Structural Geology, v. 3, p. 411–420.

Oberhänsli, R., Bousquet, R., Engi, M., Goffeé, B., Gosso, G., Handy, M., Höck, V., Koller, F., Lardeaux, J.-M., Polino, R., Rossi, P., Schuster, R., Schwarz, S., and Spalla, M., 2004, Metamorphic structure of the Alps: Paris, UNESCO, Commission for the Geological Map of the World, scale 1:1,000,000.

Rahn, M., and Seward, D., 2004, Fission track age contour maps for the Central Alps: Late-stage doming, normal faulting and thrusting: Swiss Geoscience meeting, 2nd, Lausanne, Switzerland, abstract volume, p. 272–273.

Ratschbacher, L., Merle, O., Davy, P., and Cobbold, P., 1991, Lateral extrusion in the Eastern Alps, Part 1: Boundary conditions and experiments scaled for gravity: Tectonics, v. 10, p. 245–256.

Schärer, U., Cosca, M., Steck, A., and Hunziker, J., 1996, Termination of major ductile strike-slip shear and differential cooling along the Insubric line (Central Alps): U-Pb, Rb-Sr and $^{40}Ar/^{39}Ar$ ages of cross-cutting pegmatites: Earth and Planetary Science Letters, v. 141, p. 331–351.

Schmid, S.M., and Kissling, E., 2000, The arc of the western Alps in the light of geophysical data on deep crustal structure: Tectonics, v. 19, p. 62–85.

Schmid, S.M., Fügenschuh, B., Kissling, E., and Schuster, R., 2004, Tectonic map and overall architecture of the Alpine orogen: Eclogae Geologicae Helvetiae, v. 97, p. 93–117.

Seward, D., and Mancktelow, N.S., 1994, Neogene kinematics of the central and western Alps: Evidence from fission-track dating: Geology, v. 22, p. 803–806.

Soom, M.A., 1990, Abkühlungs- und Hebungsgeschichte der Externmassive und der penninischen Decken beidseits der Simplon-Rhone-Linie seit dem Oligozän: Spaltspurdatierungen an Apatit/Zirkon und K-Ar Datierungen and Biotit/Muskowit (westliche Zentralalpen) [Ph.D. thesis]: Bern, Switzerland, University of Bern, 64 p.

Steck, A., 1984, Structures de déformation tertiaires dans les Alpes centrales: Eclogae Geologicae Helvetiae, v. 77, p. 55–100.

Steck, A., and Hunziker, J.C., 1994, The Tertiary structural and thermal evolution of the Central Alps—Compressional and extensional structures in an orogenic belt: Tectonophysics, v. 238, p. 229–254.

Tapponnier, P., 1977, Evolution tectonique du système alpin en Méditerranée: poinconnement et écrasement rigid-plastique: Bulletin de la Société Géologique de France, v. 19, p. 437–460.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., and Cobbold, P., 1982, Propagation extrusion tectonics in Asia: New insights from simple experiments with plasticine: Geology, v. 10, p. 611–616.

Wagner, G.A., Reimer, G.M., and Jäger, E., 1977, Cooling ages derived by apatite fission-track, mica Rb-Sr and K-Ar dating: The uplift and cooling history of the Central Alps: Memorie degli Istituti di Geologia e Mineralogia dell' Università di Padova, v. 30, p. 1–28.

Vance, J., 1999, Zircon fission track evidence for a Jurassic (Tethyan) thermal event in the Western Alps: Memorie di Scienze Geologiche, v. 51, p. 473–476.

Zwingmann, H., and Mancktelow, N., 2004, Timing of Alpine fault gouges: Earth and Planetary Science Letters, v. 223, p. 415–425.

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