THE SWISS ALPS: FROM SUBDUCTION TO COLLISION AND EXHUMATION

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Recent geophysical investigations have highlighted the crustal structure of the Swiss Alps: a bivergent orogen, in which upper crustal units were stacked northwards and southwards above an asymmetric subduction geometry involving lithospheric mantle and lower continental crust (Fig. 1). Noth-directed thrusting was essentially responsible for the Penninic and the Helvetic nappes, while south-directed thrusting dominated in the Southalpine nappe stack. Generally speaking all the nappe stacks involve three main types of structures:

1. Nappes consisting essentially of pre-Triassic crystalline basement rocks (continental upper crust);
2. Nappes made up of Mesozoic and Cenozoic sediments, formerly deposited onto thinned continental crust. These nappes were detached from their crystalline substratum in an early stage of their evolution.
3. Nappes containing fragments of oceanic crust (ophiolites including associated sediments).

The internal structure of these nappes includes folded thrust faults and other indications of polyphase deformation suggesting substantial shearing and defomration after emplacement of individual nappes. From stratigraphic and geochronologic data, metamorphic studies and structural analysis the time table of orogenic events as been established (Schmid *et al.* 1997; Escher *et al.* 1997) and has been used to perform palinspastic restorations and to construct retrodeformed cross sections (Schmid *et al.* 1996, 1997,;Pfiffner *et al.* subm.). Based on the type of material entering the S-dipping subduction zone and the evolving subduction geometry, three phases can be distinguished within the kinematic evolution of the Swiss Alps:

1. Subduction of oceanic crust (Cretaceous)
2. Underplating of continental fragments (Paleogene)
3. Collision phase (Neogene), which involved episodes of incipient collision of continental crust, underplating of continental crust, exhumation of the Penninic block with back-thrusting and erosion (Fig. 2), and an episode of shunting/"indentation" with bivergent thrusting propagating out into the N and S forelands of the Alps.

We conducted a number of experiments based on two-dimensional finite element dynamic modeling and compare results from these models with the kinematic evolution of the Swiss Alps during the collision phase. In particular, we investigate the rôle of inherited lateral strength heterogeneities on orogenesis. A number of first order characteristics are directly comparable at crustal scales.
In the models the entry of continental crust into the convergent margin marks the end of near-perfect subduction (Fig. 3). Accretion of material of the subducting plate to the upper plate creates an orogenic wedge on the incoming (pro-)side and initiates a retro-shear zone (or model backthrust). The addition of material to the upper plate builds a bivergent orogen. Heterogeneities in the pro-crust focus shear and lead to the development of 'nappe structures'. The combined action of pro-shear (nappe stacking) and retro-shear (backthrusting) uplifts a plug between the two shear zones. Subsequent focusing of shear along the retro-shear zone results in rotation of the plug and overlying units, leading to crustal scale backfolds as observed in the Swiss Alps.

The model experiments predict features relevant to Alpine dynamics, including:

1. Similar crustal thicknesses and exhumation patterns to those observed in the Swiss Alps today for erosion rates comparable to natural ones [1 mm a^{-1}];
2. Continued accretion and subduction of upper crustal fragments allowing high-pressure metamorphic conditions;
3. Tilting and exhumation of lower crust when a mid-crustal weak zone is present; and
4. 'Shunting' of material across the strong lower crustal wedge of the upper plate.

Numerical dynamic modeling explains how upper crustal material from thinned crustal sections can be subducted to greater depths, whereas in normal crustal sections the upper crust detaches from the lower crust and becomes accreted to the upper plate. The entrance of the European margin into the Alpine subduction zone triggered back-thrusting along the Insubric Line and the adjacent units ultimately leading to the development of a bivergent thrust belt. Underplating and associated N-directed thrusting (pro-shear) produced the Penninic and Helvetic nappe stack, while S-directed thrusting (retro-shear) resulted in the Southalpine nappe pile. Underplating and plug-uplift between pro- and retro-shear accompanied by erosion led to the exhumation of high-grade rocks in the core of the orogen.

References

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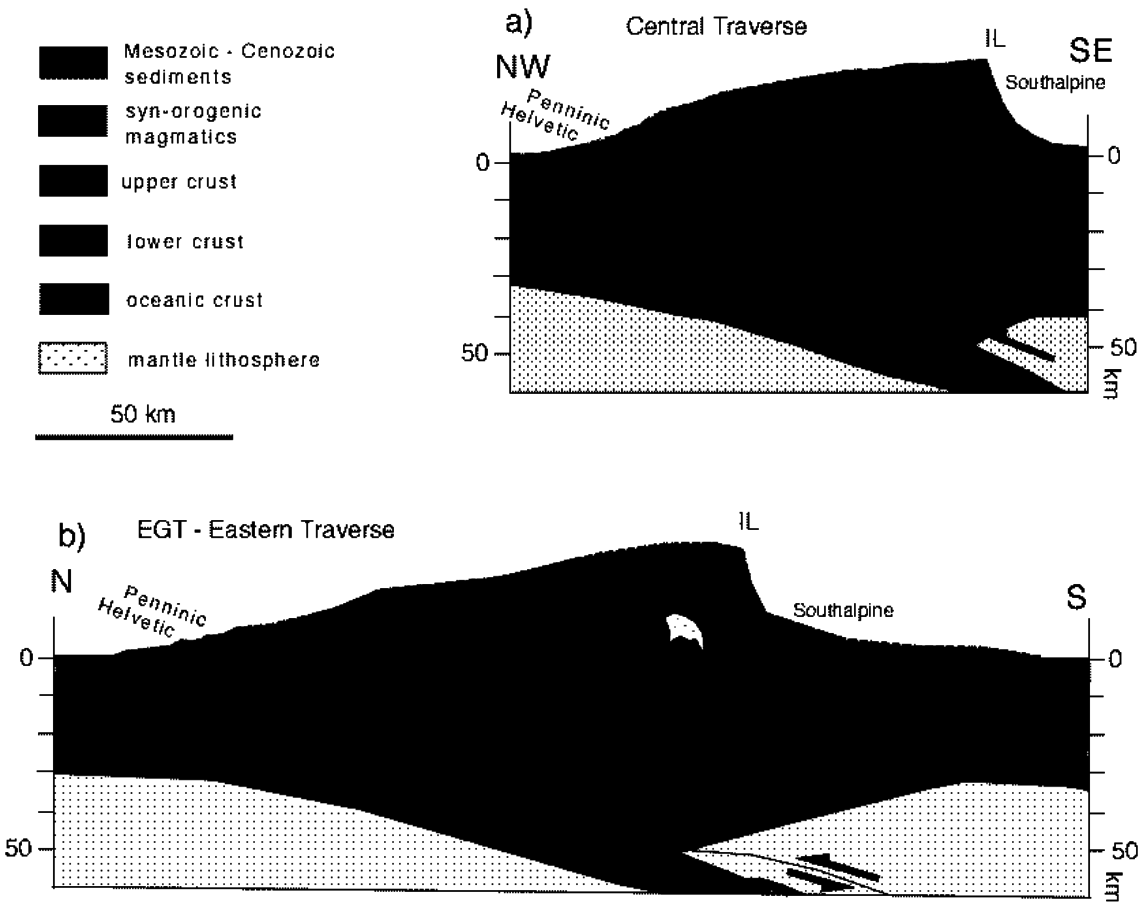

Fig. 1: Cross sections through the Swiss Alps based on seismic and structural data. Lower crust and lithospheric mantle define an asymmetric subduction zone. Upper crustal units are detached from their lower crustal substratum and stacked to a bivergent orogen. The dashed line outlines the approximate volume of material eroded from the orogen.

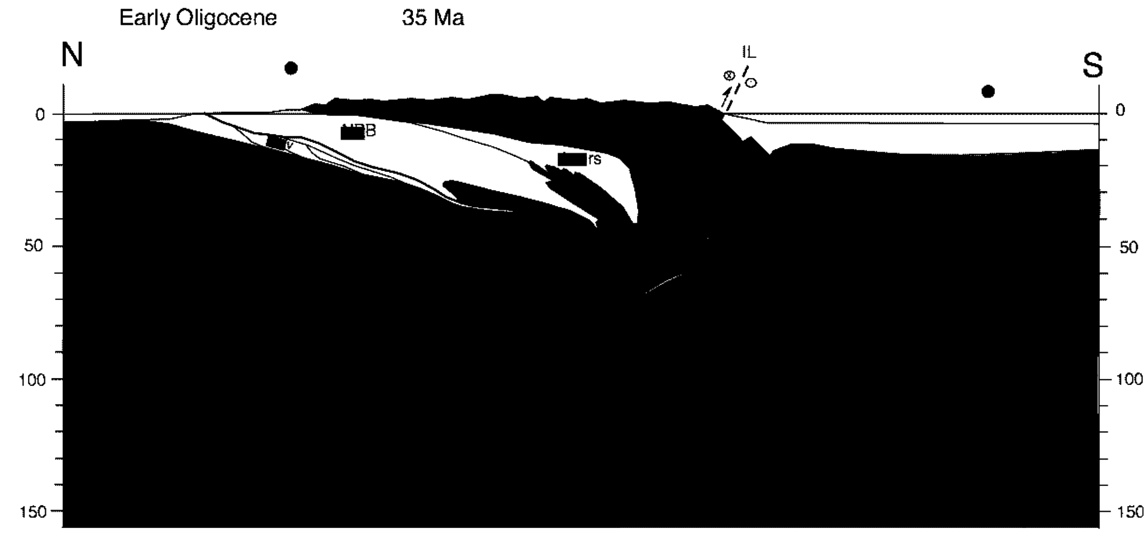

Fig. 2: Retrodeformed cross section through the Swiss Alps after 45 km of post-collisional convergence. Upper crustal units (Su=Suretta nappe, Ta=Tambo nappe, Adula nappe) are detached from the lower crust and underplated beneath the Austroalpine nappes. Back thrusting along Insubric Line (IL) is active and shear associated with it deforms the base of the Austroalpine nappes. Lower crust (dark gray) of the European margin is subducted beneath the Adriatic plate.

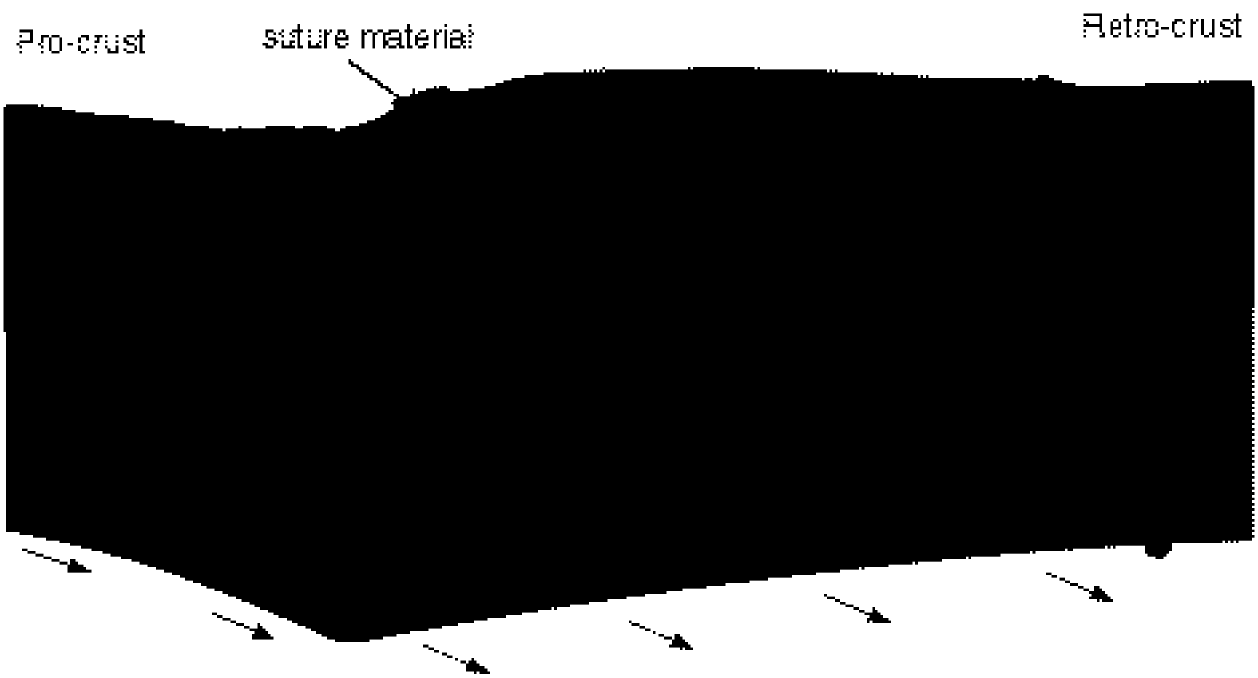

Fig. 3 Model experiment after 150 km post-collisional convergence. Weak inclusions in pro-crust develop into nappe-like structures. Retro-crust experiences retro-shearing. Suture material is sheared and rotated in the hanging wall of underplated model-nappes and undergoing exhumation.