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# Deep structure and tectonics of the Valais – and the rest of the Alps

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In principle, the Alps are the product of a classical Wilson cycle that begun with the opening of the Alpine Tethys between Eurasia in the north and Africa and Adria in the south in mesozoic times. In contrast to the wide ocean further east, by mid cretaceous time the western Tethys consisted of a series of relatively small ocean basins of different ages interconnected by even narrower channels but mostly underlain by oceanic lithosphere. Convergence between the two large plates Africa and Europe led to subduction of oceanic lithosphere and subsequent collision of continental lithosphere. A number of peculiarities, however, distinguishes this orogeny from others and they left their specific marks clearly visible in todays deep lithosphere structure and tectonics. By modelling current Alpine orogenic structure with simplified generic plate-tectonic processes we aim to further our understanding of current and past orogenic driving forces.

Presently, the Alps exhibit a significant uplift and erosion rate of about 2 mm/y and in relation to this a very slow convergence rate of only 1-2 mm/y. This slow convergence corresponds with relatively short and small lithosphere mantle slabs that exert only limited pull to the Adriatic micro plate in the south and negligible pull to the large Eurasian plate. Furthermore, geometry of the two slabs (Fig. 1; e. g. Lippitsch et al. 2003) and lower crustal indentation structure in the Central and Western Alps (Fig. 2; Kissling et al. 2006 and references therein) suggest the subduction-collision zone is largely locked.

The European lithosphere slab is obviously denser than asthenosphere and is to weak to elastically support its own weight. Rather it hangs beneath the Central Alpine crustal root adding to the isostatic load of the orogen (Fig. 1c). Recent studies about Alpine isostasy (Deubelbeiss 2005 for western Alps; Ebbing et al. 2006 for eastern Alps) confirmed earlier findings (Kissling 1993 and references therein) that the central Alps have a much to large crustal root compared with the topographic load and in relation to a to positive Bouguer gravity anomaly. As we know today from seismic tomography results, the buoyancy of the large crustal root of up to 28 km is compensated by the topographic load and by the load of the mantle lithosphere slab still attached to European continental lithosphere in the western and central Alps (Fig. 3). The stress field derived from focal mechanism of local earthquakes (Sue et al. 1999) in the western Alps shows compression in the northern foreland and southern hinterland and extension in the axial region of the orogen. This peculiar stress distribution in and alongside the orogen may be interpreted (Fig. 3a) as the result of slow continued convergence of Europe and Adria in combination with isostatic rebound of the axial orogenic region due to erosional unloading of topography and shifting of the load exerted by the man-

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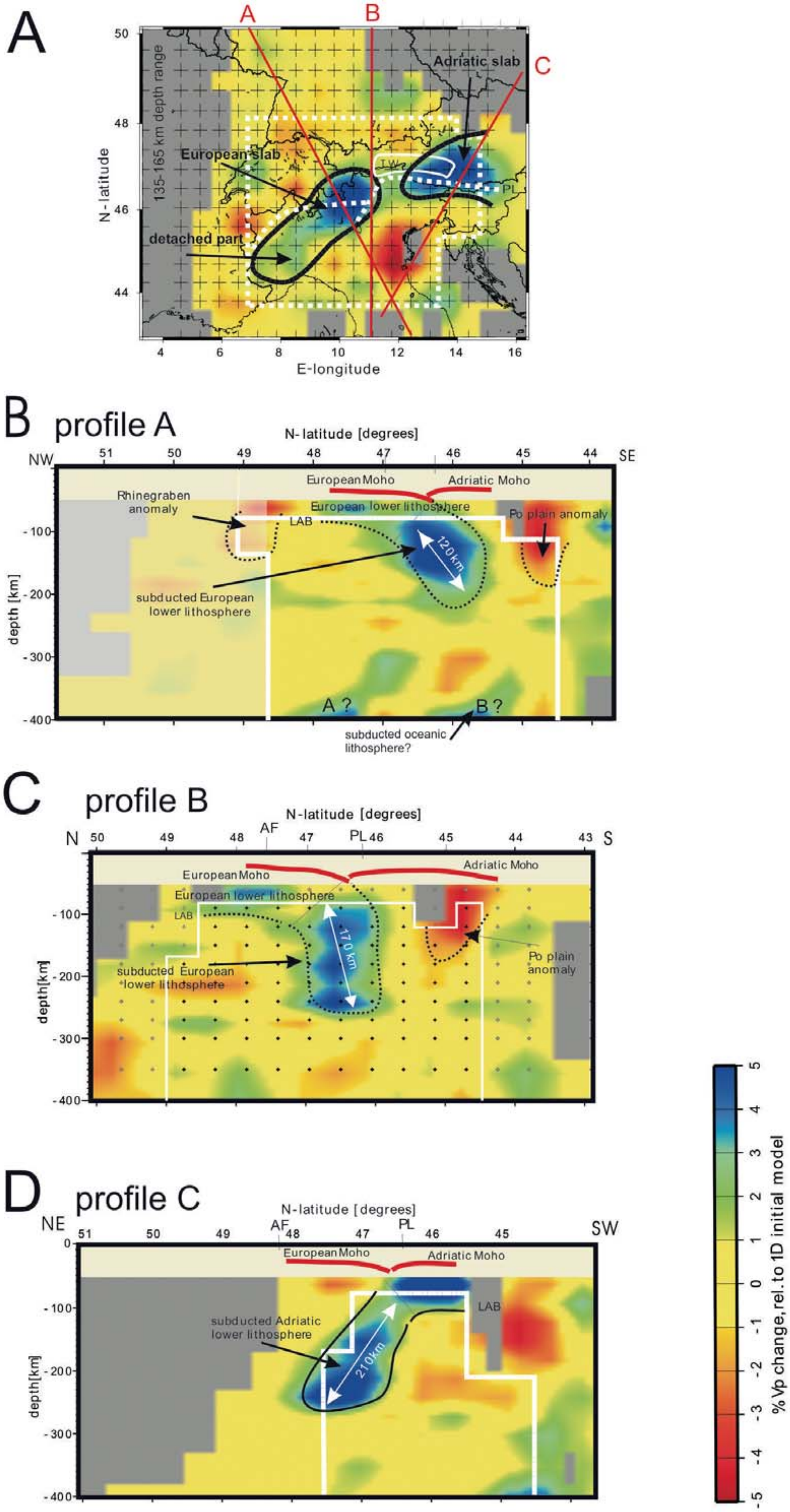

**Fig. 1:** P-velocity structure of lithosphere-asthenosphere system beneath Alps (Lippitsch et al. 2003, Kissling et al. 2006). (A) map view of lateral velocity variation in depth range 135 km to 165 km showing two separated lithosphere slabs beneath the Alpine chain. (B) Profile A from southern Rhine Graben across Central Alps documenting the western slab is attached to European lithosphere. (C) Profile B running N-S through westernmost part of Eastern Alps (European lithosphere slab). D) Profile C through eastern parts of Eastern Alps documenting the eastern slab is attached to Adriatic lithosphere. Scale stands for Vp-velocity variations.

tle lithosphere slab due to northwestward migration of crustal delamination (see below).

The length of the remaining lithospheric slab attached to Europe (160 km, Fig. 1) and estimates of postcollisional crustal shortening coincide well (140 km, Schmid & Kissling 2000) lending further support to the hypothesis of oceanic lithosphere slab break-off upon continent-continent collision (von Blankenburg & Davies 1995). By applying a kind of lithosphere rather than crustal balancing technique, we may also attempt to unravel some earlier stages in the evolution of Alpine orogeny. One of the intriguing peculiarities of Alpine orogeny is the closure of small ocean basins like the Penninic ocean or the even smaller Valais trough by subduction (Fig. 4a, b, c) and the clearly southvergent subduction of Alpine Tethys while the Adriatic micro continent moved north. Based on paleomagnetic record, Europe did not move south significantly during the past 120 million years. Rather, Africa sometimes jointly with the Africa-derived micro plate Adria moved first east, then northeast, and finally north (Lowrie 1986). In addition to the northward migration, for Adria a 30 degree anti clockwise rotation is also documented. Furthermore, during this subduction slivers of upper continental crustal layers now forming the Penninic nappes were exposed to pressures correlating up to 100 km depths followed by excessively fast exhumation rates. A simple solution to explain all these observables in a plate tectonic context is provided by a model of slab roll back (Fig. 4b) affecting the oceanic lithosphere of the Alpine Tethys basins. Very strong buoyancy contrast between the upper crustal slivers like the Brianconnais and the felsic Penninic nappes on one side and the dense oceanic or oceanized mantle lithosphere led to delamination of the thin upper crustal units during subduction and their rapid exhumation within the non-compressive subduction channel.

The subduction of the oceanic lithosphere was followed by continent-continent collision when the continental part of the European plate was reached by the retreating trench and was forced to enter subduction beneath the Adriatic plate. As long as the continental crust is attached to mantle lithosphere, continental lithosphere as a whole is buoyant. Hence, subduction of European lithosphere slowed significantly, inevitably causing extreme stress and necking in the long slab near the continent-ocean transi-

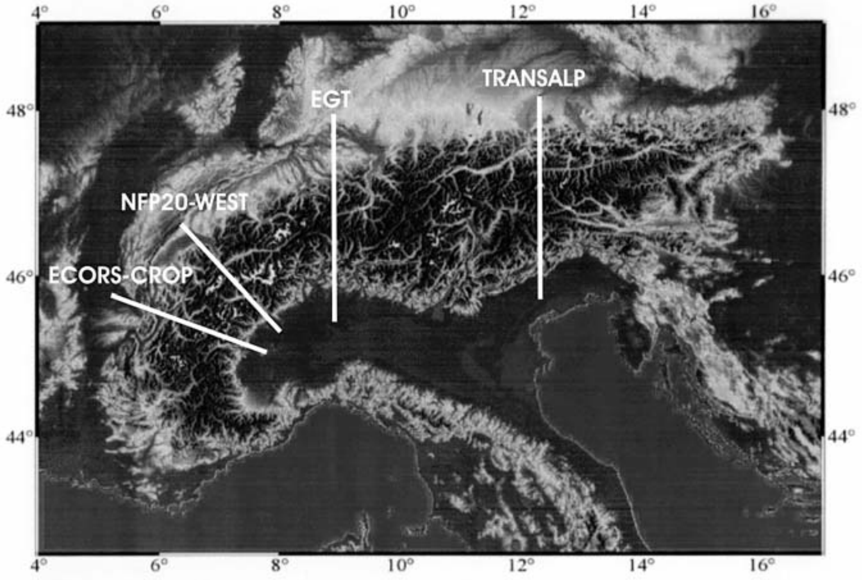

**Fig. 2a:**
Crustal structure of Alps varies strongly along the axis of the orogen and is dominated by wedge tectonics. Map of surface topography of Alpine region with four crustal transects shown in Fig. 2b.

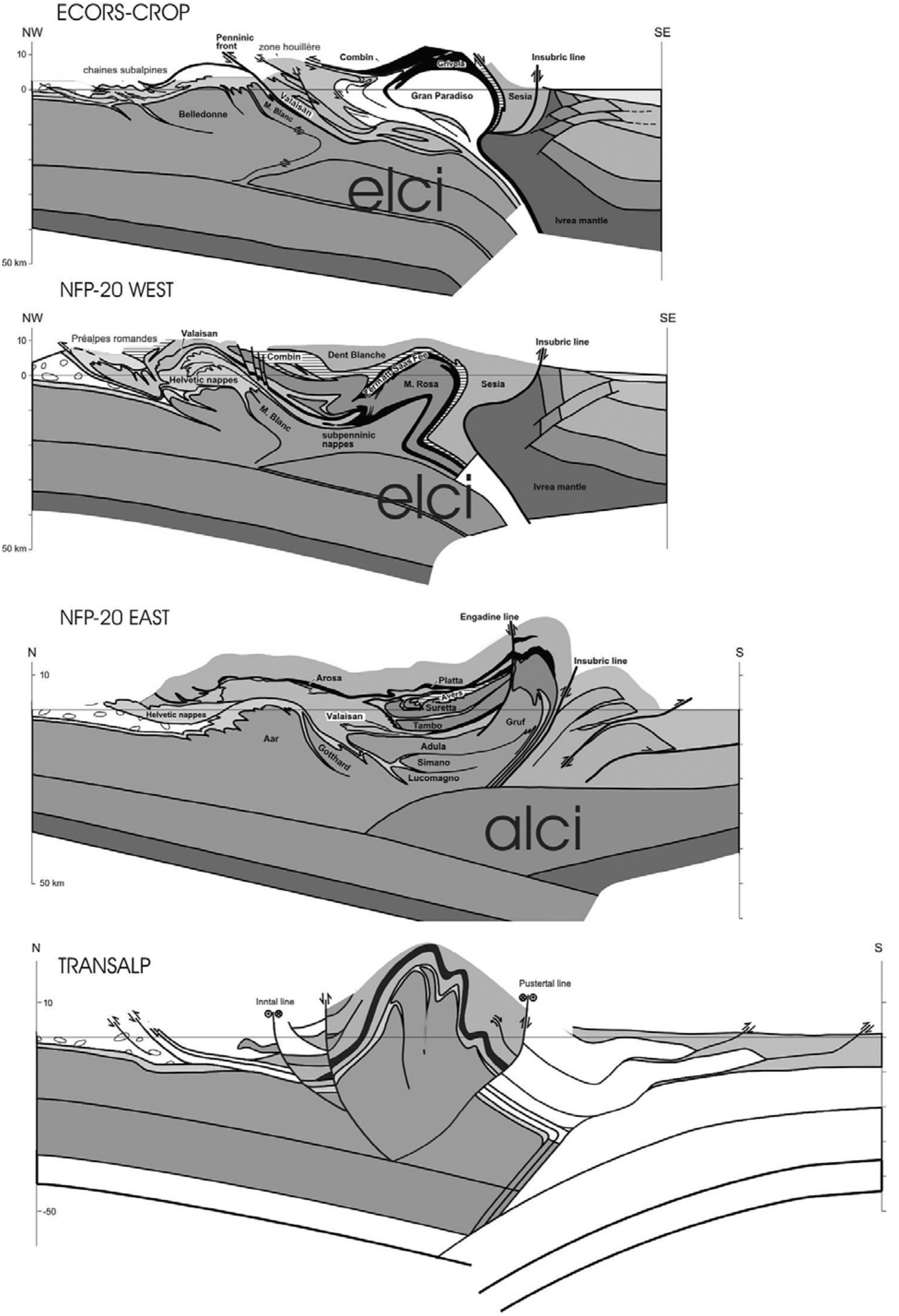

**Fig. 2b:** Crustal transects as shown in Fig. 2a (elci: european lower crustal indenter, alci: adriatic lower crustal indenter). Adapted from Schmid et al. 2004.

tion (Fig. 4c). The weight of the subducted oceanic lithosphere – of Alpine Tethys basins – forced the European lithosphere below the Adriatic plate that continued to move slowly toward NNW. Eventually, the long oceanic slab broke off (Fig. 5) and the collision continued further by delaminating the European mantle lithosphere and wedging of the continental crust (Figs. 2, 3 and 4c). Once the continental crust has been sheared off, the denser mantle lithosphere sank in the asthenosphere again starting to roll back (Figs. 4c and 5) since it remains attached to the European plate. This roll back delamination process is very slow since most of the original slab weight has been lost due to break off and since it is controlled by the delamination process near Moho level (Figs. 3 and 5).

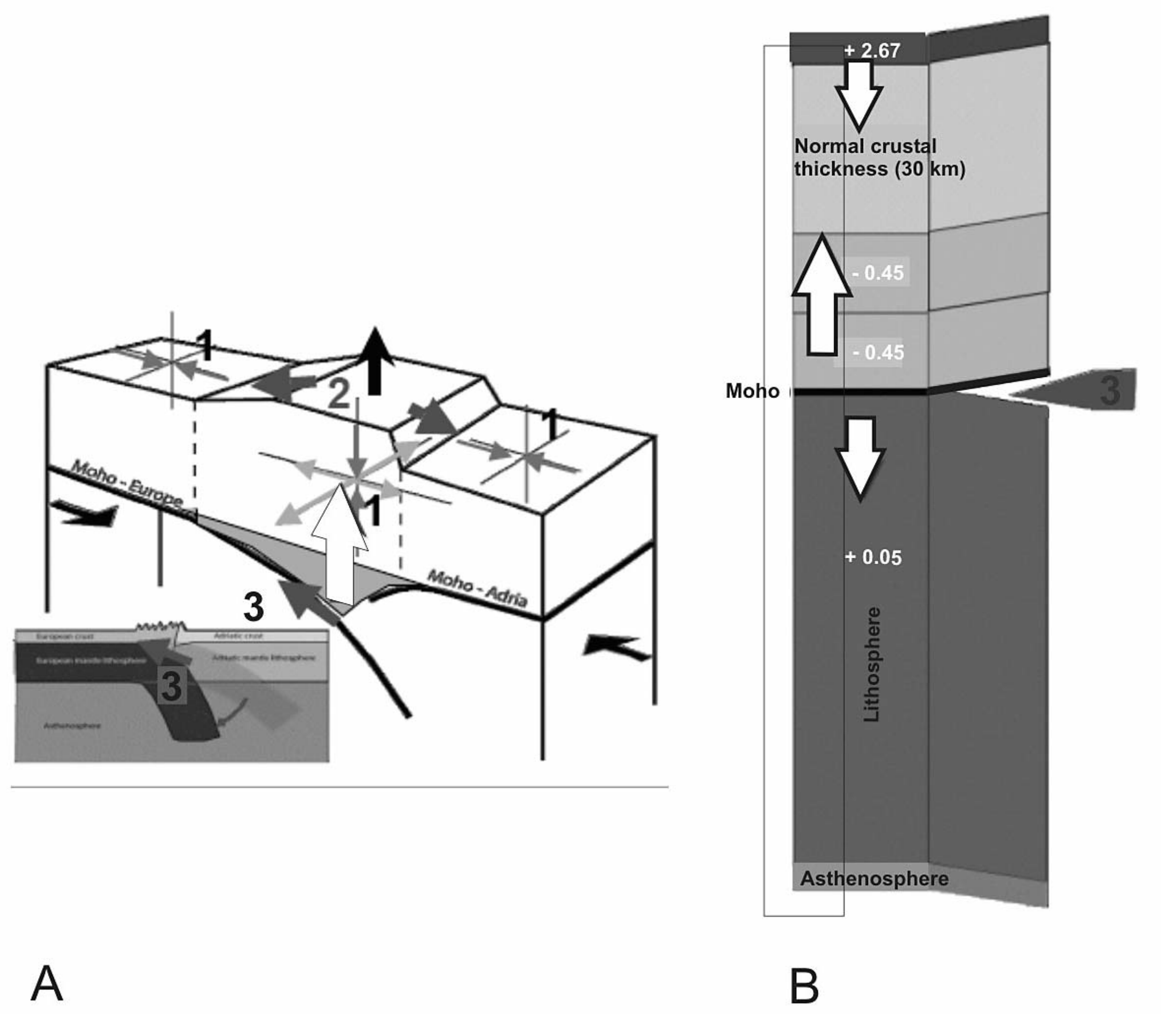

**Fig. 3:** Simplified Alpine lithosphere isostasy. (A) schematic crustal cross section of Central Alps showing strongly buoyant (white arrow) asymmetric deep crustal root that causes topographic uplift of the Alps; 1: stress field in foreland, backarc, and axial regions (Sue et al. 1999) under plate convergence between Europe and Adria; 2: erosional unloading of topography; 3: slab weight unloading by delamination along Moho (see text). (B) Airy isostatic model exemplifying balance between weights by surface topography and lithosphere slab and buoyancy of crustal root (Moho depth reaching 58 km, Waldhauser et al. 1998).

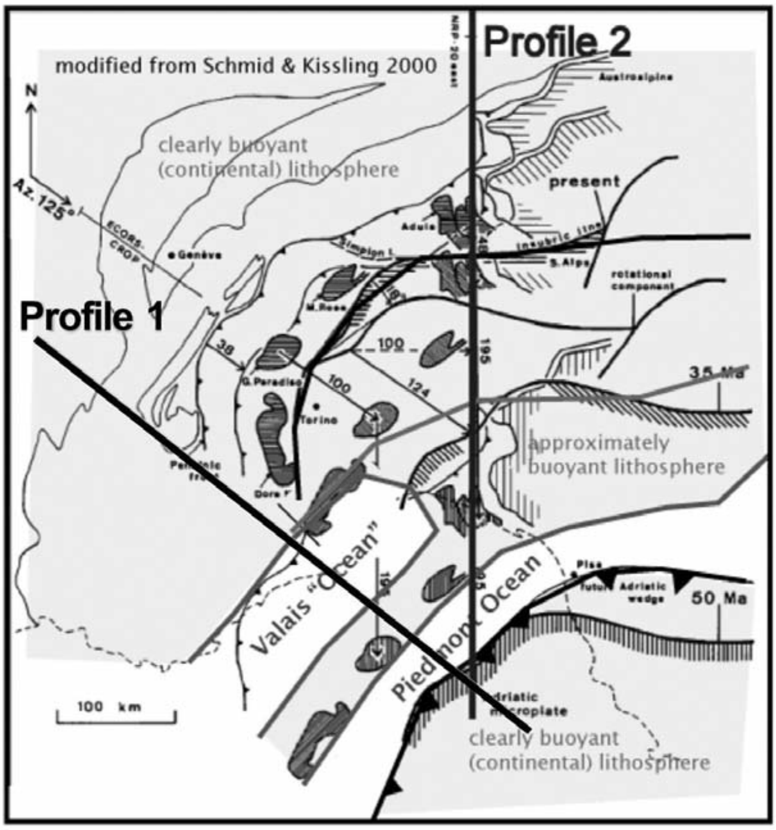

**Fig. 4a:**
Evolution of the western and central Alps from near end of subduction through collision. Cartoon showing paleogeographic evolution of the western Alps after 50 million years including characterisation of lithosphere type (modified from Schmid & Kissling 2000).

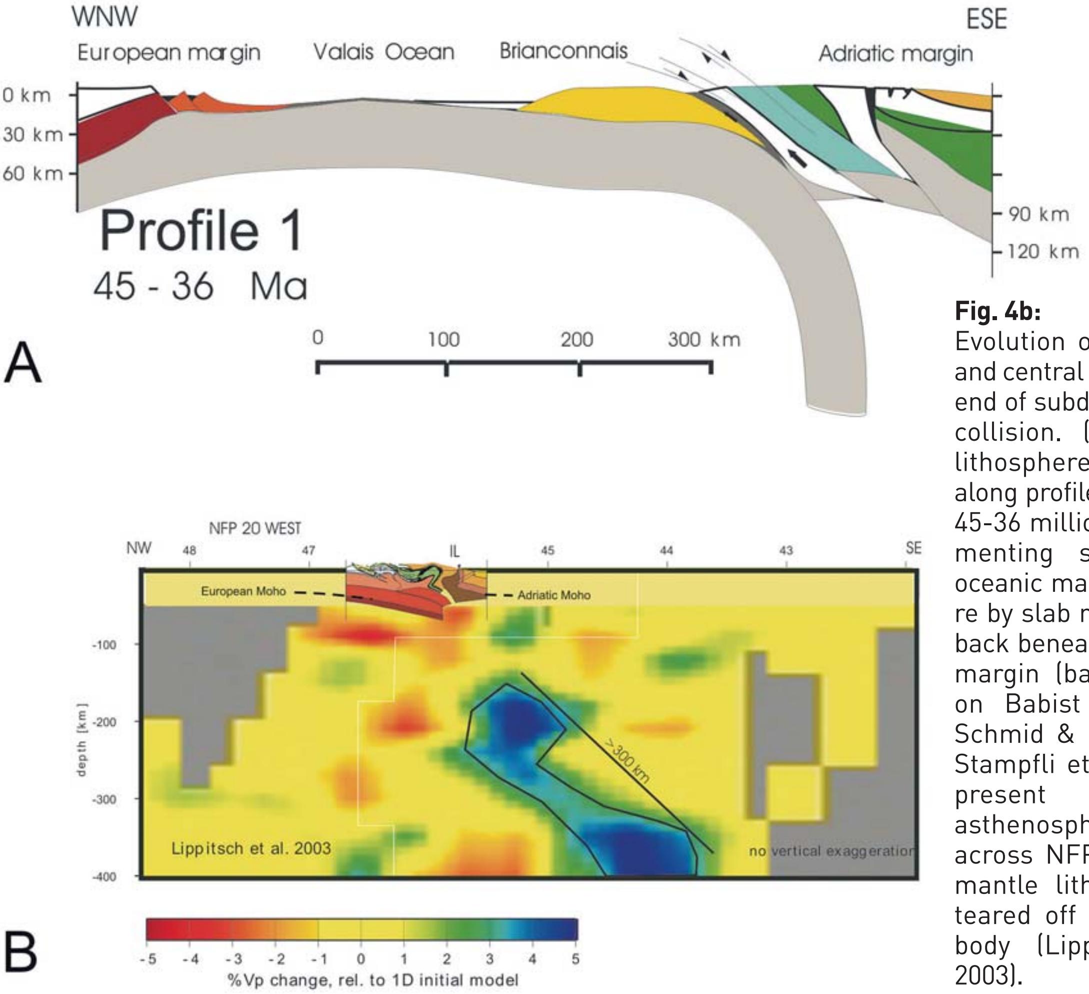

**Fig. 4b:**
Evolution of the western and central Alps from near end of subduction through collision. (A) schematic lithosphere cross section along profile 1 (Fig. 4a) for 45-36 million years documenting subduction of oceanic mantle lithosphere by slab retreat and roll back beneath Adriatic NW margin (based primarily on Babist et al. 2006, Schmid & Kissling 2000, Stampfli et al. 2002). (B) present lithosphere-asthenosphere structure across NFP20 West with mantle lithosphere slab teared off beneath Ivrea body (Lippitsch et al. 2003).

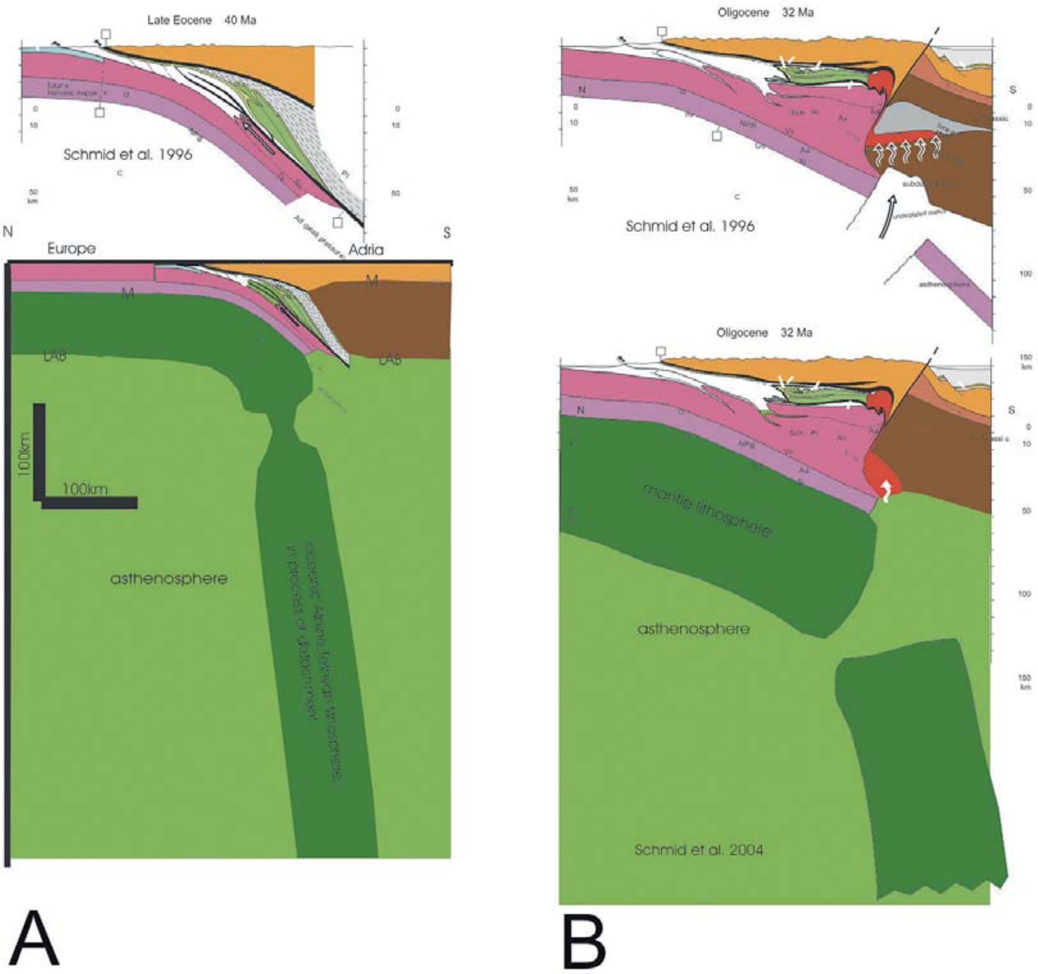

**Fig. 4c:** Evolution of the western and central Alps from end of subduction through collision. (A) schematic lithosphere cross section along profile 2 (Fig. 4a) in late eocene time: crustal structure by Schmid et al. 1996 (top part) with corresponding lithosphere structure (bottom part) documenting necking of slab near ocean-continent transition zone of European plate (see text); (B) schematic lithosphere cross section along profile 2 (Fig. 4a) in oligocene times showing slab breakoff postulated by von Blankenburg & Davies 1995.

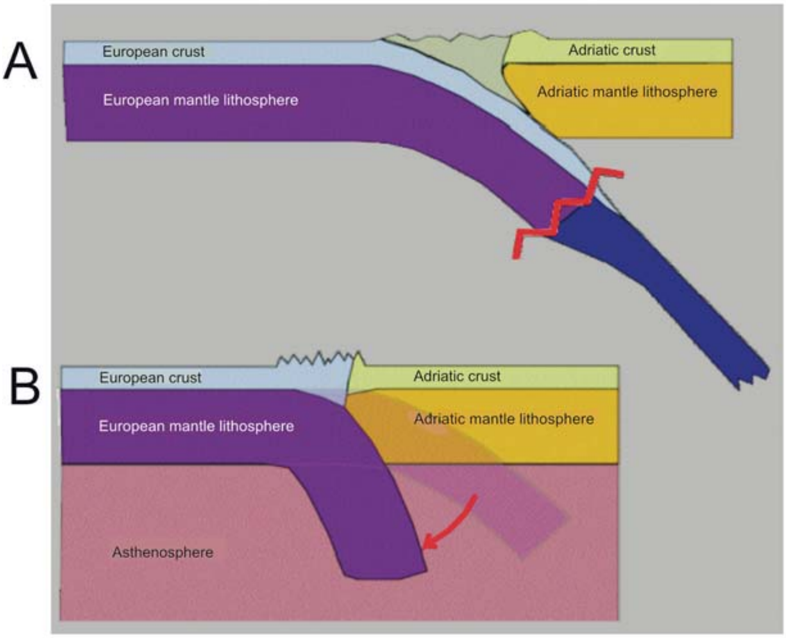

**Fig. 5:**
Simplified evolution of lithosphere-asthenosphere system in the Central Alps from subduction to collision by European slab roll back. (A) subduction of dense oceanic lithosphere beneath Adria comes to a stop when buoyant normal continental European lithosphere enters trench and consequently oceanic slab breaks off. (B) Delamination of continental crust from European mantle lithosphere in subduction channel results in further thickening of crustal root and in sinking of denser mantle into the asthenosphere. Since mantle lithosphere slab is still attached to European plate, slab exhibits again slow roll back.

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I thank the VSP/ASP for the opportunity to present this study at their 2008-meeting in Sion. The conference and field excursions have been a memorable experience with many interesting and stimulating scientific discussions. I was particularly touched by the active participation of Prof. Rudolf Trümpy, who introduced me to Alpine geology some 30 years ago. I dedicate this article to his memory.

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