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Key Points:
- Central Alpine orogeny driven by mantle llithosphere rollback subduction
- No hard collision between two continents required to build up the Alps
- Deep crustal root compensating loads of relatively low topography and mantle slab

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Rollback Orogeny Model for the Evolution of the Swiss Alps

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Abstract The construction of the European Alps and the Himalayas has been related to the convergence and subsequent collision of two continental plates. Nearly all models of orogeny build on this concept, and all of them relate the stacking of nappes and the buildup of topography to compressional forces at work in response to the collision between two continental plates. For the central European Alps, however, these models fail to explain the first-order observations of a mountain belt, which particularly includes the striking isostatic imbalance between the low surface topography and the thick crust beneath the Alps. Here we review and synthesize data on the geologic architecture of the central Alps, the chronology and pattern of crustal deformation, and information about the deep crustal structure derived from seismic tomography. Furthermore, we discuss the intrinsic and explicit assumptions in the kinematic models of Alpine evolution in the context of plate tectonic considerations. We combine these views with progress in understanding that has been gained through subduction and collision, isostatic mass and force balancing and with information that has been collected on the modern seismic regime. We conclude that a rollback orogeny model for the European plate offers the most suitable concept to explain the ensemble of surface and deep lithosphere observations. In this model gravity forces drive the evolution of the orogen and the construction of surface topography is accomplished without the requirement of a hard collision between two continents.

1. Introduction

The structural and topographic development of orogeny systems has been related to the collision between two continental plates where the mountain belt is constructed through thrusting and shortening mainly of the upper plate, while the continental lithosphere of the lower plate is being subducted (Oncken et al., 2006; Pfiffner & Gonzalez, 2013; Schmid et al., 1996). These mechanisms have been used to explain the accretion of crustal material from the upper and lower plates onto the orogen, the construction of topography, and the erosional recycling of the accreted material (Beaumont et al., 1996; Pfiffner, 2016; Schlunegger & Willett, 1999; Schmid et al., 2017). According to these views, the crustal shortening is primarily driven by the convergence between the two colliding continental plates (Handy et al., 2010; Pope & Willett, 2002; Schmid et al., 1996). Also following these concepts, changes in rates and patterns of surface erosion lead to adjustments of orogen widths through negative feedbacks (Stolar et al., 2006; Wipple, 2009). As a consequence, orogenesis has been explained by a combination of kinematic conditions where the accreted and eroded volumes of masses are being conserved and constraints related to principles of rock mechanics (Koons, 1989). These principles predict that the thickening of orogens, and related to this the surface topography, is limited through the mechanical strength of rock (Willett, 2010). These models are also based on the perception where a rigid indenter, exemplified by a bulldozer (Figure 1), translates the kinematic push into the orogen. These mechanisms have been considered responsible for driving both the crustal accretionary flux and the surface erosional flux, on the proside and the retroside of the mountain belt.

In the past decades, conceptual models on the evolution of various mountain belts have largely been based on these theories. Related concepts have proven useful for the understanding of the collision between, for example, the Brazilian Shield and the South American plate, leading to the construction of the Subandean fold-and-thrust belt on the eastern margin of the Andes (Oncken et al., 2006; Pfiffner & Gonzalez, 2013). The same also concerns our understanding of the evolution of most of the Variscian mountain belts of North America and Europe including the Appalachians and Ural Mountains, where the collision between continental plates has conditioned the buildup of the mountain ranges. However, among the various mountain belts on Earth, the Himalayas and the European Alps have been considered as prime examples (Beaumont et al., 1996) of continent-continent collisional orogens.

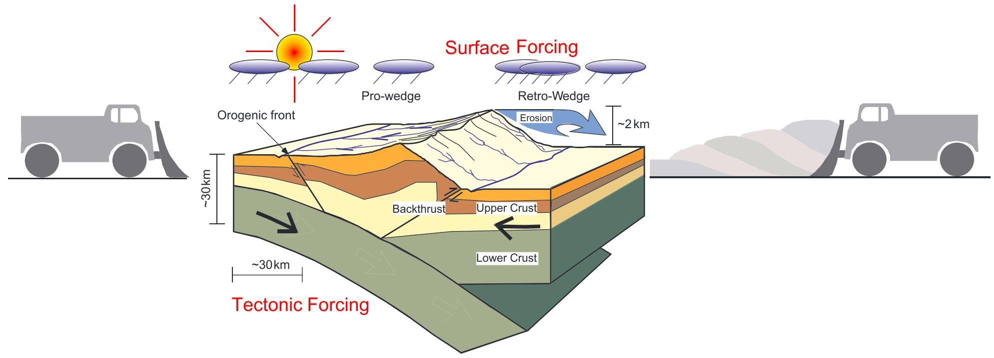

Figure 1. Kinematic model for orogen convergence and collision based on relative motions and extended by critical tapering wedge concepts (e.g., Beaumont et al., 1996; Schlunegger & Willett, 1999; Willett, 2010). Northward migration and bulldozing-type indentation by the Adriatic plate is assumed as primary cause for the subduction of the European plate, for orogen convergence and nappe stacking.

For the case of the central Alps of Switzerland, the application of these theories even resulted in the hypothesis that modifications in constructive growth of the Alps were modulated by changes in global climate (Willett et al., 2006). These models mainly had a kinematic view on orogenesis. In addition, isostatic adjustments to a thickened crust were calculated using solutions where crustal loads are accommodated by a 2-D elastic thin-plate overlying a viscous mantle. However, these models are at odds with strong negative Bouguer anomalies commonly measured in continental orogens (e.g., Lyon-Caen & Molnar, 1989) and related to this, with a thick buoyant crustal root maintaining the orogens' topography. Accordingly, they fail to reproduce two first-order observations at deeper crustal levels and on the surface. In particular, these include (i) a $>$50% underestimate of the depth of the crust-mantle transition, commonly referred to as the Moho, beneath the core of the mountain range, and (ii) an overestimate of the mean surface elevation if principles of isostatic equilibrium were properly considered. This has particularly been the case for the central European Alps, where the crustal root has been seismically determined to be almost 60-km thick seemingly far out of conventional Airy-isostatic equilibrium with a mean surface topography of only about 2 km (Kissling, 1993). Here we review and synthesize data on the geologic architecture of the central Alps, the chronology and pattern of crustal deformation, and information about the deep crustal structure derived from seismic tomography. We will present a revised model on Alpine evolution, which we refer to as slab rollback orogeny model, where the concepts of force balancing (Heuret & Lallemand, 2005) together with the principles of mass conservations, the kinematic history of the orogeny (Malinverno & Ryan, 1986; Royden, 1993a; Schellart, 2008), and the exhumation paths of currently exposed rocks (Schmid et al., 1996) will be considered. The need for such a model together with the principle forces and kinematic conditions of an orogen will be presented in the following chapters.

2. Tectonic Overview of the Central Alps

The present-day tectonic architecture of the central European Alps of Switzerland (Figure 2) has resulted from the subduction of the oceanic part of the European plate beneath the continental part of the Adriatic plate that started in Cretaceous times (Handy et al., 2010; Schmid et al., 1996). Closure of the oceans between the European and Adriatic continents at circa 35 Ma resulted in a phase of continent-continent collision eventually causing the subducted European oceanic lithosphere to break off (von Blanckenburg & Davies, 1995). The latter in terms led to isostatic rebound of the lower plate and to the buildup of the Alpine topography (Schlunegger & Kissling, 2015). At present, the central European Alps form a doubly vergent orogen with a crystalline core of European upper crustal provenance that is exposed in the external massifs such as the Aar massif (Figure 3). On both margins, outwardly verging thrust sheets flank the orogen. These comprise (meta) sedimentary sequences exposed in the Helvetic, Penninic, and Austroalpine thrust sheets on the northern side, where the latter unit forms the structurally highest unit. The Helvetic nappes, representing the lowest unit within this nappe stack, straddle the basal Alpine thrust, which separates the Alpine thrust sheets from the deposits of the peripheral Molasse foreland basin (Figure 3a). This sedimentary trough, situated to the north of the Alpine nappes, consists of an Oligo/Miocene synorogenic clastic sedimentary wedge

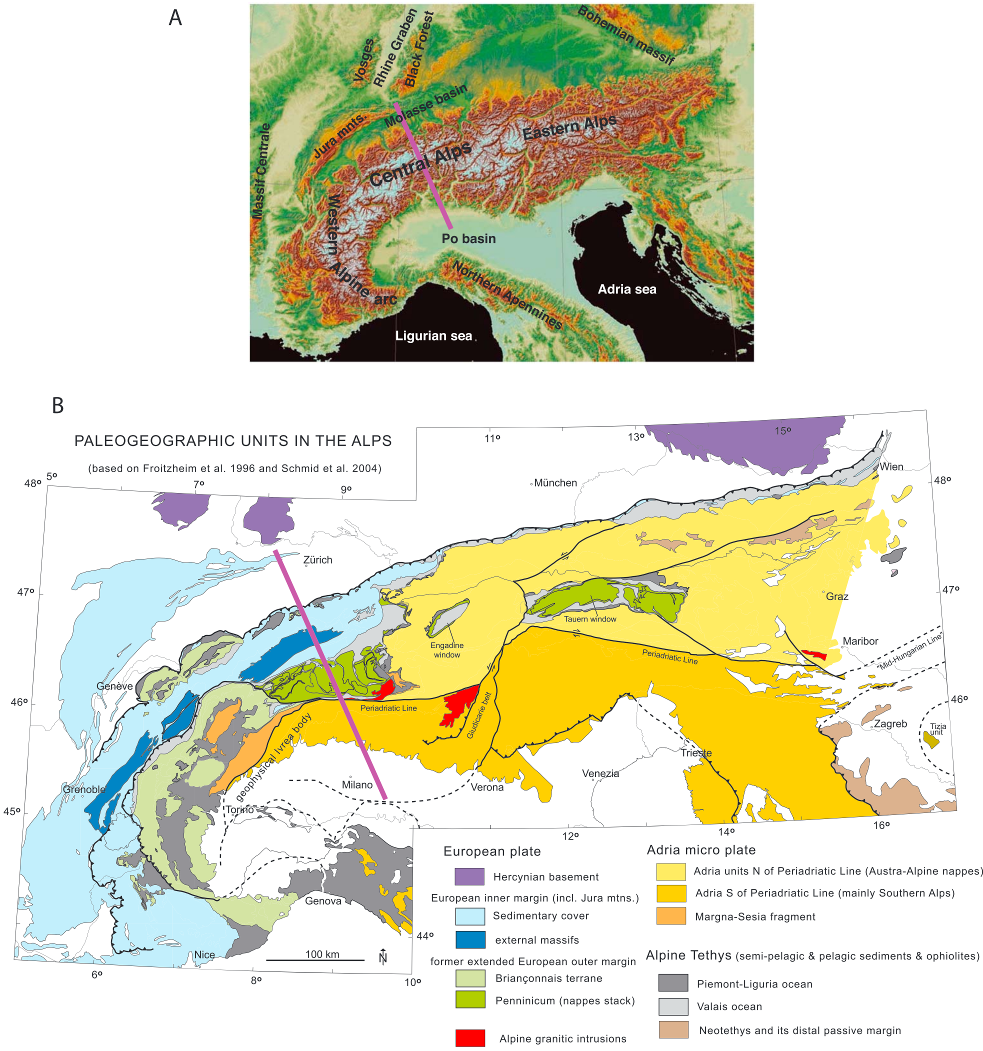

Figure 2. (a) Geographic and (b) geologic overview of Alpine orogen. From SW (Nice) to east (Wien) the European Alps comprise the Western Alpine arc, the central Alps with the Jura mountains north of the Molasse Basin, and the Eastern Alps. The Bohemian massif in the NE and the Vosges and Black Forest bordering the southern Rhinegraben in the NW characterizes the northern Alpine foreland. The tectonic position of the Po Basin is related to the subduction of Adria beneath the northern Apennines. In the Eastern Alps, the Adria-derived Austra-Alpine nappes cover the European-derived units like a blanket with the notable exceptions of the Tauern and the Engadine windows. Originally, this top Alpine nappes system also covered a large part of the central Alps where it was completely eroded during early postcollisional times. The purple line marks the location of the cross section through the central Alps where all major tectonic units of the Alps are represented.

where the detritus was derived from the evolving Alps (Matter et al., 1980). To the north, the distal margin of this basin is delineated by the Jura fold-and-thrust belt that also hosts erosional Molasse remnants in synclines (Spicher, 1980). The southern side of the Alps comprises the Southalpine thrust sheets, which consist of crystalline basement rocks and sedimentary units derived from the Adriatic continental plate (Pfiffner, 2016; Schmid et al., 1996). This fold-and-thrust belt is bordered to the south by the Po Basin where a Pliocene-to-modern suite of shallow marine to fluvial deposits covers the thrust front (Lombardic front), particularly in the vicinity of Milano (Pieri & Groppi, 1981). The north vergent Alpine thrusts are separated from the Southalpine nappes by the steeply north dipping Insubric Line (Schmid et al., 1989). This fault accommodated most of the central Alpine crustal uplift and related exhumation during the Oligocene and the early Miocene (Boston et al., 2017) by back thrusting and right-lateral slip, which resulted in exposure of the high-grade Penninic crystalline core that is referred to as the Lepontine dome in the Alpine literature (Hurford, 1986).

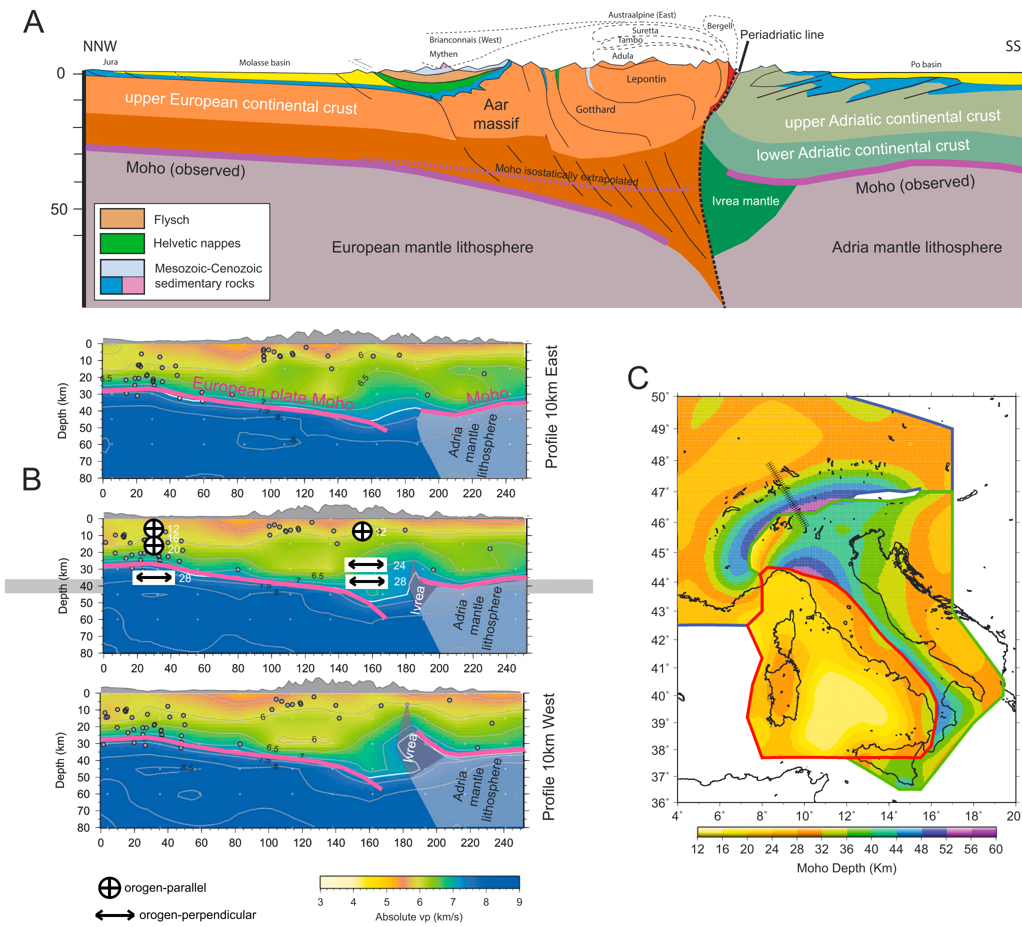

Figure 3. Central Alpine crustal structure and Moho topography in the greater Alpine region. (a) Geologically interpreted crustal cross section representative for the central Alps (see Figure 2 for location), ranging from the Jura mountains in the NNW to the Po Basin in the SSE. The architecture of the crustal root comprises an imbricate stack of lower crustal material derived from the subducting European plate that has been imaged by seismic tomography (Fry et al., 2010; Kissling et al., 2006). Note the significant difference between the seismically determined Moho (solid purple line) and the kinematically modeled Moho (broken purple line) extrapolated for Airy-isostatic compensation of mean surface topography. (b) Three parallel cross sections separated by 10 km each display the *P* velocity structure. These have been obtained by local earthquake tomography (Diehl et al., 2009). They document the strong lateral variation of the deep structure along the central Alps (see Figure 3c for location of central transect). (c) Seismically determined topography of crust-mantle boundary (Moho) in greater Alpine region (Spada et al., 2013).

The paleogeographic situation during Jurassic and Early Cretaceous times largely conditioned the current changes in the lithotectonic architecture along the Alpine arc (Figure 2b). Historically, the Alps have been grouped into the Western, Central, and Eastern Alps. During Mesozoic times, the sedimentary realms of the Western Alps, along their northern domain, were made up of the European continent including its stretched southern margin, marking the transition to the Valais Ocean, a narrow embayment of the Alpine Tethys. Farther south, the Briançonnais swell represented the southeasternmost spur of the Iberian plate (Stampfli et al., 1998). Related Jurassic to Early Cretaceous deposits are found within the entire western Alps. They thin toward the east to form a few isolated Klippen in the Central Alps and finally disappear farther east. The Piedmont-Liguria Ocean, on the southern side of the Briançonnais continental sliver, represented the major spreading zone of the Alpine realm. This was also the region where an oceanic crust was formed during Late Jurassic times and in case of the Valais Ocean arm into Early Cretaceous. The Piedmont Ocean was bordered to the south and east by the northern margin of the continental Adriatic microplate, which hosts the South Alpine sedimentary domain during Mesozoic times. The eastern termination of the Iberian microplate, that is, the Brianconnais, allowed the Valais and Piedmont Oceans to converge in the vicinity of what is now the Central Alps, with the result that the southern margin of continental Europe

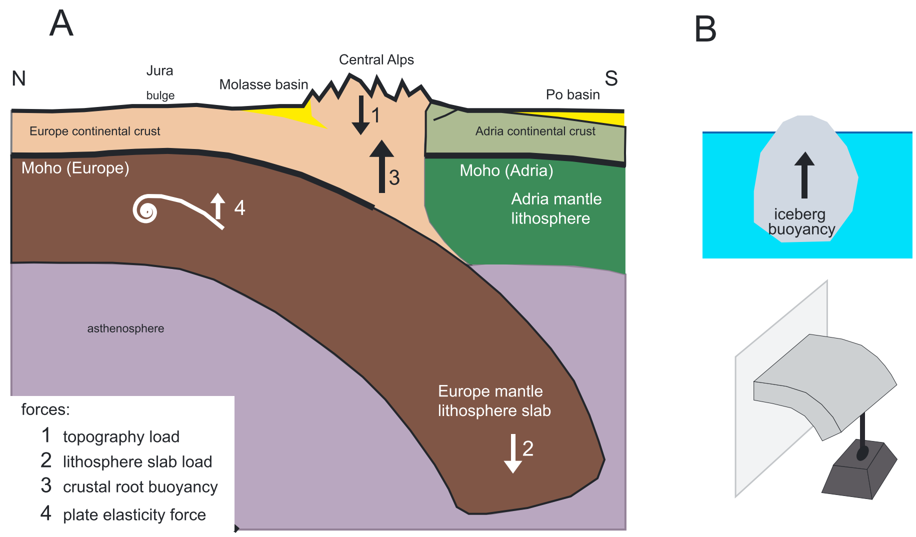

Figure 4. (a) Main forces in dynamic equilibrium driving the central Alpine orogeny since collision times. (b) The main driving forces for mountain building and for subduction are the buoyancy of the crust and the slab pull by the mantle lithosphere, respectively, the latter of which has a higher density than the underlying asthenosphere. Depending on its elasticity, the plate reacts to the bending moment by bulging (Royden, 1993b).

and the northern margin of continental Adria were separated by one single ocean only, which has been referred to as the Alpine Tethys. Farther to the southeast and the east, the sedimentary realms overlying the Adriatic continental plate have been referred to the South Alpine and Eastern Alpine domains, respectively (Figure 2b).

In summary, also from the perspective of the deep structure, there exist three distinctively different parts of the orogen (Figure 2) known as the Western, Eastern, and Central Alps. In this context, the Western Alps are characterized by the following: (i) their arcuate shape, (ii) the Brianconnais unit but no Austra-Alpine nappes, and (iii) the high-density high-velocity Ivrea body along the inner arc. Different from this, the characteristics of the Eastern Alps comprise the following: (i) a distinct linear shape, (ii) a large part of the orogen made up by the Southern Alps south of the suture zone, and (iii) the Austra-Alpine nappes that cover the European Penninic realm with exception of the Tauern window. The Central Alps comprise all major units including both Brianconnais and Austra-Alpine nappes. They record all major orogenic events, and they exhibit a few key elements of the orogen's evolution such as the remaining European mantle lithosphere slab (Lippitsch et al., 2003). Accordingly, the Central Alps are located in a transition domain comprising lithotectonic units of western and eastern provenance. As such, they can be considered as representative for the geodynamic evolution of a large portion of the Alpine arc. Therefore, we choose a transect across the Central Alps to represent and discuss the orogen evolution of the Alps (Figures 3 and 4).

3. Need for a Revised View on the Central Alpine Orogeny

With almost 60-km thickness, the crustal root of the central European Alps (Figure 3) is seemingly far out of conventional Airy-isostatic equilibrium with a mean surface topography of only about 2 km (Kissling, 1993). The surface elevations largely depend on the relative importance of the load forces exerted by the subducted slab versus the buoyancy forces related to the crustal root (Figure 4a). Furthermore, critically tapered wedge models should apply not only to the surface topography but also in analogue form to the crust-mantle boundary (Moho) and the evolution of the crustal root. Under normal temperature and pressure conditions the amalgamation of crustal and mantle material remains intact, thus allowing the continental lithosphere to float on asthenosphere over long geologic times. Increasing pressure and temperature as well as hydration effects in subduction zones, however, may weaken the bond between the crust and the mantle lithosphere (Moho), eventually allowing them to separate (delaminate) (Herwegh et al., 2017; Sokoutis & Willingshofer, 2011). This mechanism then results in the accretion of lower crustal material to the buoyant crustal root. Accordingly, these processes ask for a dynamic model of orogenesis, which requires, per definition, that the concepts of force balancing (Figures 4e and 4b) together with the principles of mass conservations, the kinematic history of the orogeny, and the exhumation paths of currently exposed rocks are considered. The ensemble of these conditions has not yet been considered in previous reconstructions of the evolution of the central European Alps. It is thus the scope of this paper to present such a conceptual model for the evolution of this orogen.

Here we portray the evolution of the central European Alps (Figures 2 and 3) from a historical perspective thereby following two lines of evidence that have been applied during the past decades in geological and geophysical surveys. Geologists have mainly considered the orogen as the result of crustal-scale processes where the accretion of material has been described in a kinematic framework (Pfiffner, 2016; Schmid et al., 1996, 2017). In these concepts, the relative movements between the colliding plates have been considered as the major driver of orogenesis, while vertical load forces exerted by the buoyant crustal root and the subducted slab have generally not been considered (Schlunegger & Willett, 1999; Willett et al., 2006). Supporting evidence for these views has been taken from the results of critically tapered wedge models that have mainly been developed (Dahlen, 1984; Davies et al., 1983; Koons, 1989), and thus applied, for mountain belts in a kinematic framework (Beaumont et al., 1992, 1996; De Celles & Mitra, 1995; Willett et al., 2006; Wipple, 2009).

While these models are balanced in the sense that they consider the forces and stress regimes at work within the orogen (Dahlen, 1984; Koons, 1989), related deep lithosphere structure along with the driving forces has not been expanded back in time. It is the scope of this paper to reconcile both aspects, that is, the kinematic and static views, with the conclusion that a rollback orogeny model best explains the geologic and geodynamic evolution of this mountain belt, at least between the Late Cretaceous and the late Miocene, when the construction of the modern Alps proceeded. In a broader sense, we will argue that a rollback orogeny model explains the construction of an orogen with a pronounced topography and a thick stack of crustal material even in the absence of any convergence and collision between two continental plates, as has been the case for, for example, the Apennines.

4. Geological Surveys Leading to a Kinematic View of the Alps

The view of geologists on the evolution of the Alpine orogen has mainly been influenced by kinematic concepts, where the principles of mass conservation have been considered but where motions of material have been placed in a relative context without explicitly considering the related forces (Handy et al., 2010; Pfiffner, 2016; Schmid et al., 1996). In these views, the stacking of nappes and accretion of crustal material was primarily related to the convergence and collision between the European and Adriatic plates, similar to kinematic concepts of orogenesis (Figure 1). The framework underlying this model is the consequence of a long history of model development prior to and independent of plate tectonics principles, and it has been paired with extensive geologic data collection. One of the first reconstructions of the Alpine evolution in a kinematic framework goes back to Argand (1916), who modeled, from a conceptual point of view, the stacking of the Alpine edifice where the European continental plate was being shifted underneath the Adriatic continental lithosphere. The relative movement between these two plates was then considered as responsible for the shortening of crustal material in both plates, with the result that the Alps started to grow. These kinematic views with a focus on the relative movement of mass also lead to the concept where the European continental plate has been assigned a southward oriented displacement in the related figures (Rosenberg et al., 2015; Schlunegger & Willett, 1999; Schmid et al., 1996; Willett, 2010), although palaeomagnetic evidence clearly documents (Torsvik et al., 2012) that the European continental plate has remained nearly stationary since the latest Cretaceous, or at least it has not shifted southward (Handy et al., 2015; Platt et al., 1989). This kinematic view received most attention when numerical models for the evolution of orogenic systems became available.

Most of the models that have particularly been applied to the Alps are based on the theory of critically tapered mechanical wedges, where the vertical growth of mountain belts is limited by the mechanical strength of the accreted rock units and the detachment horizons (Dahlen, 1984; Davies et al., 1983). These models predict that critically tapered orogens adapt a wedge-shaped geometry with a low-tapered proside facing the subducting plate and a high-tapered retroside that marks the opposite flank of the orogen (Koons, 1989; Willett et al., 1993). The driver for the evolution of these mountain belts was illustrated in the form of a bulldozer with a rigid back stop, in front of which material is being accreted as the bulldozer moves forward (Figure 1). Related analytical solutions with applications to accretionary wedges were first presented by Davies et al. (1983) and by Dahlen (1984). According to these authors, the geometries of critically tapered orogens depend on material strengths, shear strengths, and dip angles of the detachment horizons. Among available numerical solutions for related problems, the models developed by Beaumont et al. (1992), Willett et al. (1993), and Beaumont et al. (1996) presumably have received most attention when applied to the Alps (Pfiffner et al., 2002; Schlunegger & Willett, 1999; Willett, 2010) but have continuously been contested (e.g., Rosenberg et al., 2015). The deformation component of this model uses a finite element technique to solve for large-strain, Coulomb plastic and temperature-dependent viscous deformation (Beaumont et al., 1992; Fullsack, 1995; Willett et al., 1993). The domain for which strain is being calculated considers a single layer that represents the deformable crust. A relative convergence velocity between two nondeformable mantle plates induces shear forces within the crust, which are responsible for the deformation. At a particular point referred to as the singularity, the mantle plate detaches from the crust and descends beneath the overriding mantle plate on the other side of the collision zone. Progressive deformation leads then to the formation of a doubly vergent orogenic wedge that is capable of growing outward in both directions (Figure 1). In these models, isostatic accommodation of the thickened crust was based on solutions for a continuous viscoelastic beam overlying a fluid substratum (e.g., Schlunegger & Willett, 1999). However, related calculations yielded unrealistically shallow depths for the crust-mantle boundary and thus for the Moho. Accordingly, neither of these models was capable of explaining the large negative Bouguer gravity anomalies surrounding the center of the Alps (Holliger & Kissling, 1992; Lyon-Caen & Molnar, 1989). Even more compelling, the obvious mismatches between the modeled Moho and the seismically determined Moho map (e.g., Kissling et al., 2006) were not discussed and simply ignored in these studies. Nevertheless, the concepts underlying critically tapered wedge solutions for the evolution of orogens have offered an avenue for exploring possible feedbacks between erosional unloading and crustal deformation in the Alps (e.g., Schlunegger et al., 2007; Willett, 2010; Willett et al., 2006). The search for possible controls of erosion on crustal deformation became a frequently addressed topic (Wipple, 2009) and was mainly stimulated through the legendary article by Molnar and England (1990) where the chicken or egg problem for our understanding of the relationships between the Late Cenozoic uplift of mountain ranges and global climate change was brought forward.

A second line of evidence leading to orogen models for the Alps on the basis of kinematic principles was guided by the results of the Swiss National Research Program 20 disclosing the deep structure of the Swiss Alps (Pfiffner et al., 1997; Schmid et al., 1996). The preferred geological interpretation of seismic reflectors was that of a rigid indenter beneath the core of the Alps. This material of Adriatic origin was considered to have been pushed between the interface of the subducting European lower crust and upper crustal material, which in turn became accreted into the orogen through nappe stacking (Pfiffner, 2016; Schmid et al., 1996). The inferred occurrence of an indenter, whose tip was directly linked with the origin of the Insubric Line at deep crustal levels (Schmid & Kissling, 2000), was considered as strong support for the application of critical taper wedge models to the Alps, because a potential bulldozer has been identified.

5. Geophysical Surveys of Deep Crustal Levels Resulting in a Static View of the Alps

While the early plate tectonic concepts failed to convince the Alpine geology community (Trümpy, 2001), Laubscher's (1970) speculative plate tectonic models for Alpine orogeny greatly influenced the geophysical exploration of the deep structure of the Alps. Prior to the 1990s, the available seismic methods comprised surface wave analysis for regional structure and 2-D profiling with refraction and reflection seismics (so-called controlled-source seismology, CSS). CSS profiling were the methods of choice, and during half a century of CSS exploration (e.g., Behm et al., 2007; Blundell et al., 1992; Closs & Labrouste, 1963; Gebrande et al., 2006; Mueller, 1977; Pfiffner et al., 1997; Roure et al., 1990) a wealth of crustal-structure information, unprecedented for any other orogen, was assembled (e.g., Kissling et al., 2006). The main targets of geophysical exploration were the Moho (Figures 3b and 3c) and the Conrad topography, the top basement topography, the mountain crustal roots, and the geophysical Ivrea body dominating the magnetic and the gravity fields along the inner parts of the Western Alpine arc (Coron & Guillaume, 1966). To accommodate the arcuate shape in the western half of the orogen, information on the deep crustal structure was usually compiled and interpreted along transects in terms of gravity field and tectonic structures.

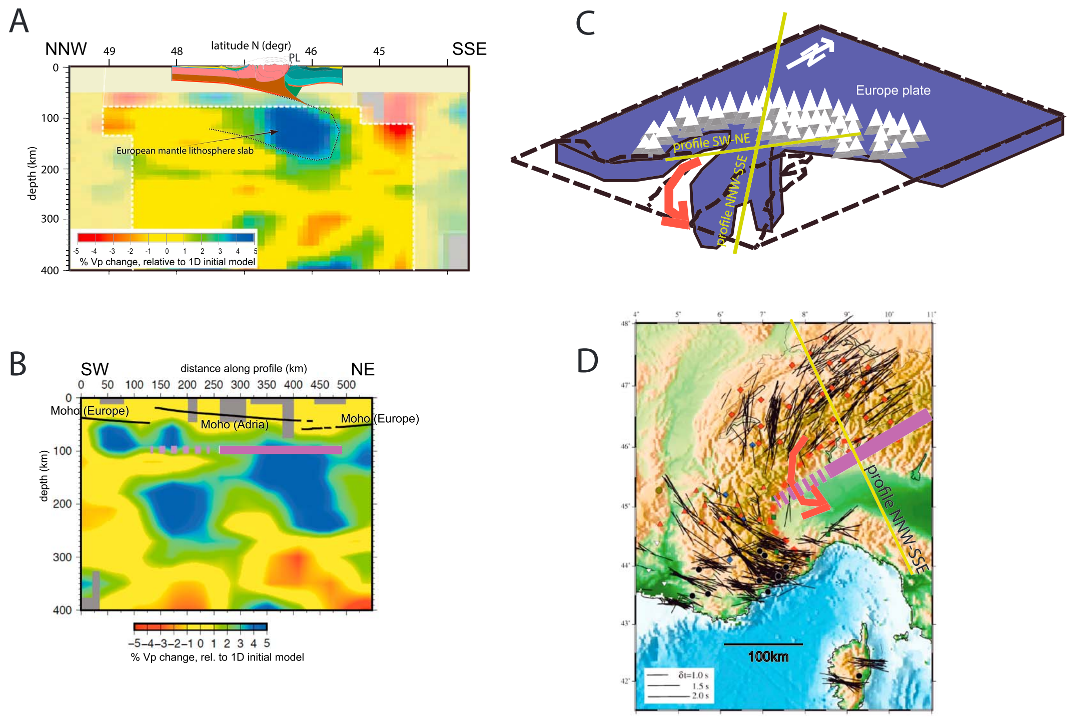

Figure 5. The lithosphere-asthenosphere system beneath the Alpine orogen with mantle slabs and asthenosphere flow. (a) High-resolution teleseismic tomography image (Lippitsch et al., 2003) of todays European mantle lithosphere slab along a cross section through the central Alps superimposed with the crustal structure (see Figure 4a). (b) Tomographic image (Lippitsch et al., 2003) along strike the orogen documenting the European mantle lithosphere slab being detached beneath the Western Alps and still attached beneath the central Alps. Purple line corresponds with bottom of lithosphere (solid: slab attached; broken: slab detached). Note that profiles shown in a and b are approximately perpendicular. (c) Cartoon illustrating 3-D geometry of the European plate and the mantle lithosphere slab (in blue) beneath the Alps. Yellow lines document the locations of the two profiles shown in a and b. Red arrow denotes probable mantle flow in asthenosphere around the slab. (d) *S* wave velocity anisotropy obtained from SKS wave splitting interpreted to document the flow pattern in the mantle (Barroul et al., 2011). Solid yellow line denotes profile location of Figure 5a. Purple line corresponds with Figure 5b, documenting the bottom of the European plate (solid: slab attached; broken: slab detached).

In accordance with modern assessments (Rosenberg & Kissling, 2013; Schmid et al., 2017; Schmid & Kissling, 2000) these models document the deep crustal structure of the Alps to be noncylindrical at all scales and apparently out of Airy-isostatic balance along the entire orogen (Kissling, 1993). The depth of the crust-mantle boundary (Moho), compiled (Spada et al., 2013; Wagner et al., 2012) from the results of many seismic surveys (Figure 3c), and the corresponding 3-D *P* velocity field of the crust (Figure 3b) (Diehl et al., 2009) provide important constraints for the construction of the cross-section illustrated in Figure 3a.

Early CSS Moho mapping (e.g., Ansorge, 1968; Hirn et al., 1989; Miller et al., 1977) revealed a striking asymmetry of the crustal root and an apparent pronounced imbalance among topographic load, Moho depth, and Bouguer gravity in the Central and Western Alps (Kissling, 1993; Lyon-Caen & Molnar, 1989), leading to the proposal of a lithosphere mantle slab load to achieve isostatic equilibrium (Holliger & Kissling, 1992; Zanolla et al., 2006). The presence of such a deep-seated load has recently been confirmed through advances in seismic tomography technologies (Figure 5). Progress in the field of teleseismic tomography has mainly been achieved in response to advances in computer technology, paired with improvements of the quality of seismic data acquisition and the availability of an a priori 3-D crustal model (Arlitt et al., 1999). Modern high-resolution teleseismic tomography disclosed further details of the lithosphere structure of the central Alps beneath the Moho (Figure 5), where a southward dipping mantle lithosphere slab of 160-km length is attached to the European plate (Lippitsch et al., 2003). Beneath the Western Alps, however, the downward directed slab has already been broken off from the European plate, resulting in a tear within the subducted European slab (Figure 5c). The tip of this tear is currently located beneath the eastern margin of the Western Alps. We note here that Zhao et al. (2015) proposed a geological interpretation based on a receiver function

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profile and on teleseismic imaging (Zhao et al., 2016) where the European slab is still attached beneath the southern Western Alps. However, we consider the seismic evidence for this interpretation as ambiguous because it is mainly based on 2-D information and data with very low signal-to-noise ratio. Contrariwise, the Lippitsch et al. (2003) interpretation is based on 3-D high-resolution teleseismic tomography imaging, which includes a priori correction for 3-D crustal structure encompassing also the Ivrea body.

Teleseismic imaging techniques thus illuminated a complex and highly noncylindrical architecture of the deepest Alpine structure, where the subducted European lithospheric mantle is attached to the European continental plate beneath the Swiss and thus the central parts of the Alps only (Figure 5d). The subducted but still attached slab exerts a downward directed pull force and keeps the Alpine topography at relatively low elevations. The resulting vertical slab load force and the bending moment (Figure 4a) has been used (Singer et al., 2014) to explain the peculiar seismicity at middle to lower crustal levels in the Alps and the foreland (Deichmann et al., 2000), where focal mechanism solutions of earthquakes point to the occurrence of a predominantly extensional stress normal to the strike of the orogen at work within the crust. Recently, seismic anisotropy tomography studies also revealed the details of the architecture of the crustal root (Fry et al., 2010), which comprises an imbricate stack of lower crustal material derived from the subducting European plate (Figure 3a). Much progress has been achieved based on seismological data and particularly by mapping the pattern of seismic anisotropy through the analysis of vertically propagating SKS waves' splitting. It was claimed (Barroul et al., 2011) that these shear waves record strain-induced preferred orientations of rock-forming minerals within the upper mantle, thus documenting flow-induced anisotropy in the asthenosphere beneath the Central and Western Alps around the European lithospheric mantle slab (Figure 5d). The related pattern is characterized by a combination of fast split directions that closely follow the trend of the belt and by the occurrence of a maximum in anisotropy magnitude beneath the external units. This has been used to propose the occurrence of sublithosphere mantle deformation, which was accomplished through recent or active mantle flow around the European slab beneath the Central Alps (Figure 5). Accordingly, the combination of (i) a relatively low mean surface topography and moderately negative Bouguer gravity anomalies with respect to the large crustal root in the Central Alps, (ii) focal mechanism solutions of earthquakes at lower and upper crustal levels, and of (iii) tomographic images and information about possible mantle flow patterns around the European mantle lithosphere slab calls for an extensional plate tectonic regime. As outlined below, we relate this to the vertical load forces generated through rollback mechanisms of the subducted lithospheric mantle (Schlunegger & Kissling, 2015). Such a mechanism is indeed characterized by an extensional rather than a compressional orogenic driving force.

6. A Dynamic Model of Alpine Orogen Evolution Encompassing the Kinematic Views of Alpine Orogeny

The above summarized kinematic-based view about the evolution of the European Alps is consistent neither with the current seismic regime nor with first-order isodynamic mass and force balancing approximations, which call for a different geodynamic model. Likewise, static views on the Alps that are based on the results of geophysical surveys may be correct in the way in which the relevant forces are being considered (i.e., vertical-directed slab load forces and upward directed forces exerted by the buoyant crustal root), but they fail to explain the evolution of the Alps through time since they do not consider any time components.

Based on a review about the architecture of the Alps, on the chronology and pattern of crustal deformation, and on recently published seismic tomography, we came to the conclusion that a rollback orogeny model for the European Alps is more suitable to explain the following: (i) Europe remaining stable during the precollisional phase of southward subduction of the Alpine oceanic lithosphere and also during the postcollisional evolution of topographic growth; (ii) the fast exhumation of ultrahigh-pressure rocks along the subduction channel prior to 35 Ma; (iii) the occurrence of oceanic lithosphere slab breakoff beneath the central Alps at circa 30–35 Ma; (iv) the stacking of nappes; (v) the growth of the buoyant crustal root, thereby continuously balancing the surface topography and the slab loads; (vi) the evolution of the Molasse foreland basin; and (vii) the current extensional seismicity pattern. This is what we refer to as slab rollback model and it contrasts with the previously published view on the collisional development of the Alps mainly because in our refined model, crustal uplift, nappe stacking, and the buildup of topography are solely driven by ongoing rollback and conditioned by the mechanical strength of the subducting slab. Note that our model consists of postcollisional

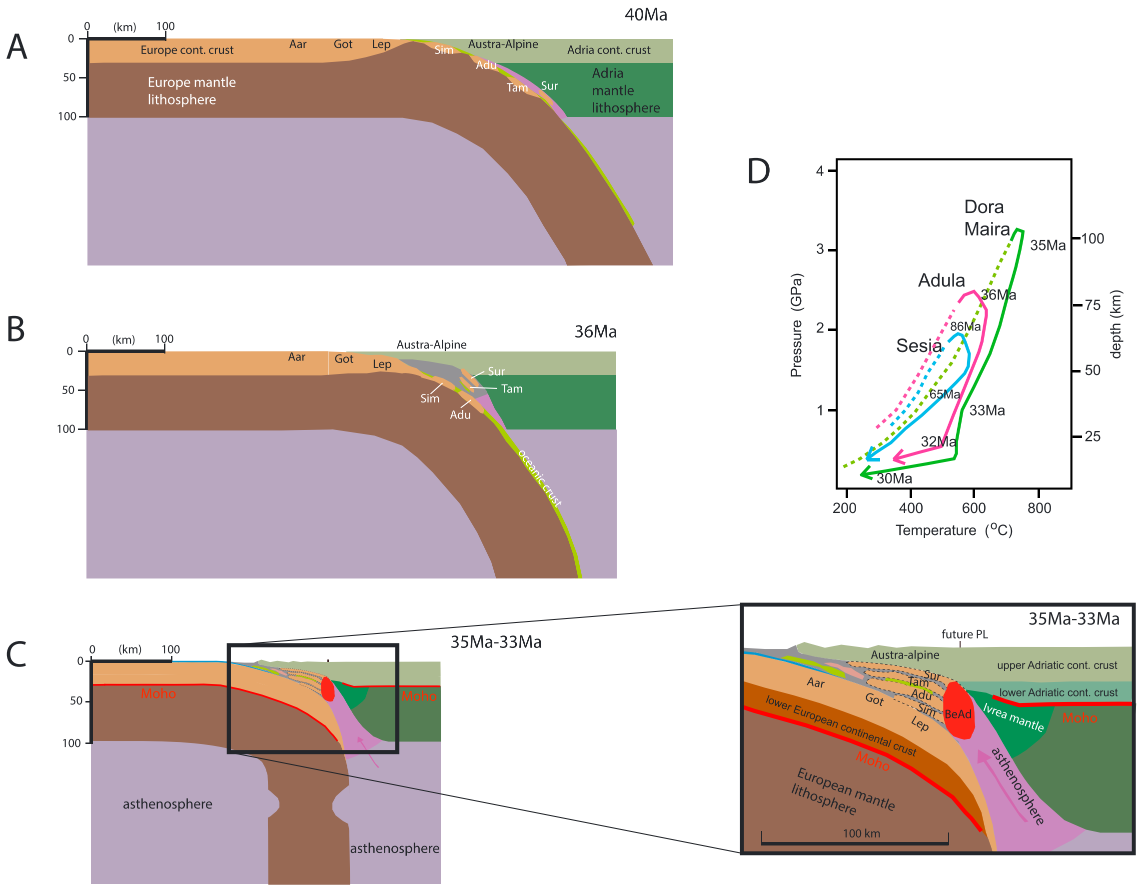

Figure 6. Rollback subduction and evolution of Penninic nappe stack in the central Alps until shortly before slab breakoff. (a) Situation envisioned for 40 Ma when the formerly extended European margin with slivers of upper crust had entered the subduction zone. These slivers became later the following Penninic nappes: Suretta (Sur), Tambo (Tam), Adula (Adu), and Simano (Sim). (b) Situation at circa 36 Ma when the buoyant continental margin with Lepontine (Lep), Gotthard (Got), and Aar massif (Aar) units was forced into the subduction zone eventually bringing the subduction of oceanic lithosphere to stop and the slab to turn subvertical. Note that the topography remained low and typical Flysch sedimentation continued. (c) Combination of buoyancy of continental lithosphere and slab pull of subducted oceanic lithosphere leads to necking and eventually slab breakoff and to the opening of the subduction channel. As a result, the asthenosphere entered the channel (von Blanckenburg & Davies, 1995), thereby causing intrusion of Alpine granitic magma (Bergell-Adamello BeAd) beneath the future Periadriatic Line (PL). This suture will later mark the plate boundary at the surface. (d) Pressure-temperature path for selected nappes in the central Alps (see Froitzheim et al., 2003; Carry et al., 2011 for Adula) and for comparison in the Western Alps (see Rubatto et al., 2011 for Sesia and Carry et al., 2011 for Dora Maira). They document the characteristic cycle of subduction-delamination-rapid exhumation (Malusa et al., 2011) for many units in this realm and from the beginning (Sesia) to the end (Adula-Simano) of subduction of the Alpine Tethyan Ocean.

slab rollback of the European mantle lithosphere, which continued to sink into the mantle after the breakoff of the main part of the subducted oceanic lithosphere at circa 30–35 Ma. This mechanism also results in extensional rather than compressional forces within the subducting plate and thus in a different view on the principal driver of Alpine orogenesis. The slab rollback model is described in the next paragraph.

The convergence between the European and Adriatic plates followed the Jurassic to Early Cretaceous phase of spreading. It started with the Late Cretaceous to Eocene subduction of the oceanic lithosphere and the stretched continental margin of the European plate beneath the Adriatic continental plate resulting in the closure of the Alpine Tethys (Figure 6). Subduction to greater depths resulted in high-pressure conditions recorded by mineral assemblages that are characteristic for blueschist metamorphic conditions with pressures up to 10 kbar (Babist et al., 2006; Carry et al., 2011; Engi et al., 1995; Ring, 1992; Rubatto et al., 2011). Minerals detected in the Dora Maira and Zermatt-Saas zones (Chopin, 1984; Frezzotti et al., 2011; Reinecke, 1991) and thermo barometric analyses of mineral compositions in tectonic slivers within the Adula nappe (Carry et al., 2011; Froitzheim et al., 2003) indicate UHP conditions and eclogite facies in the Sesia zone (Figure 6). These units belong to the belt of Penninic crystalline rocks along the inner arc of the Western and Central Alps (Figure 2). Ongoing subduction resulted in the delamination of the tectonic slivers

(Simano, Adula, Tambo, and Surretta nappes, Figure 6) made up of extended upper crustal rocks of the European plate. These slivers were accreted to form the nappe stack of Penninic crystalline rocks beneath the Adriatic continental lithosphere (Schmid et al., 1996) that represented the hanging wall plate.

Also, during this time of European oceanic lithosphere subduction, the foreland basin in the north was underfilled, and Flysch sedimentation under deep marine conditions prevailed. As the European plate did not shift southward, the only way by which subduction could have been accomplished was through a rollback mechanism where the plate sinks down and rolls back into the mantle, driven by an increasing relative importance of slab load forces upon subduction (Figure 4). During this subduction process, referred to as rollback subduction (Heuret & Lallemand, 2005), the hinge of the subducting plate and also the flexural fore bulge (Royden, 1993b) on the European continent shifted farther northward (Lihou & Allen, 1996), while the European oceanic lithosphere was continuously sinking to greater mantle depths (Figure 6).

At 33 Ma, a remarkable change occurred in the subduction mechanisms. This was characterized by the closure of the Alpine Tethys and the first subduction of buoyant continental lithosphere with a lower flexural rigidity than the previously consumed oceanic lithosphere. These circumstances created extensional forces within the slab (Figure 6c), driven by differences in flexural strengths and buoyancy forces between the subducted, dense, and relatively stiff oceanic lithosphere and the buoyant continental lithosphere. The differential forces at work resulted in slab breakoff, the heating of the overriding lithosphere by the upwelling asthenosphere, and the generation of magmas, which intruded into the Alpine nappe stack between 30 and 32 Ma (von Blanckenburg & Davies, 1995). In addition, the advection of heat resulted in a Barrovian-type metamorphism with temperature conditions up to 650°C particularly in the southern limb of the Penninic nappe stack (Frey, Bucher, et al., 1980; Hurford, 1986). Furthermore, the removal of the oceanic lithosphere slab load increased the relative importance of the buoyancy forces, thereby lifting the Alpine topography to the modern elevations within 2–3 Ma (Figure 7). The result was an increase in the sediment discharge to the foreland basin during the Late Oligocene paired with a decrease in the basin's accommodation space, which terminated the underfilled Flysch stage at 30 Ma (Schlunegger & Kissling, 2015; Sinclair, 1997).

The Barrovian metamorphism also affected the Alps farther north surrounding the area of the Aar massif including the Helvetic domain. At 30 Ma, the Penninic and Austroalpine nappes had already been emplaced (Burkhard, 1988). These units overlay the Helvetic thrust nappes, which underwent low-grade metamorphism sometime between 30 and 35 Ma (Frey et al., 1973; Frey, Teichmueller, et al., 1980; Groshong et al., 1984; Hunziker et al., 1992). Thrusting of the Helvetic thrust nappes above the Aar massif and its sedimentary cover resulted in low-grade metamorphism in the latter units between 20 and 25 Ma (Frey, Teichmueller, et al., 1980; Niggli & Niggli, 1965; Rahn et al., 1994, 1995). A subsequent forward thrusting event along the basal Alpine thrust was identified by a discontinuity in the metamorphic gradient within the Helvetic units (Frey, 1988), which resulted in a 5–10 km out-of-sequence offset of the 20–35-Ma isotherms (Frey, Teichmueller, et al., 1980; Rahn et al., 1995; Wang et al., 1995). In addition, post-25-Ma deformation mechanisms (Figure 7) affected the proximal foreland basin deposits, resulting in initial thrusting and imbrication of coarse-grained Molasse units and the formation of the Subalpine Molasse. Likewise, this was also the time when the deformation front on the southern margin of the Alps started to propagate toward more distal sites, reaching the vicinity of Milano at 20 Ma at the latest. These processes were contemporaneous with the uplift and exhumation of the Gotthard nappe and the Aar Massif, which started at circa 25 Ma, accelerated between 20 and 10 Ma, and continued to up to circa 5 Ma (Fügenschuh & Schmid, 2003; Michalski & Soom, 1990; Vernon et al., 2008).

Miocene and Early Pliocene imbrication and uplift of the External Massifs was accompanied by detachment and NW translation of the Molasse Basin above a Triassic detachment horizon, which resulted in thin-skinned deformation of the Jura fold-and-thrust belt some 50–80 km north of the front of the Alpine nappes (Affolter & Gratier, 2004; Buxtorf, 1916; Dezes et al., 2004; Laubscher, 1961, 1992; Sommaruga, 1997, 1999). During Pliocene time, ongoing Alpine deformation involved thick-skinned deformation in the region north of the Jura (Guellec et al., 1990; Ustaszewski & Schmid, 2007). At circa 5 Ma, the Alps including the Molasse Basin started to experience a long-wavelength phase of uplift and accelerated erosion (Cederbom et al., 2011), while subsidence continued in the Po Basin on the southern margin (Baran et al., 2014).

Since circa 30 Ma, erosion resulted in the removal of more than 12 km of upper crustal material in the Central Alps (Schlunegger & Willett, 1999), while the dynamic force balance requires the Moho to be "isostatically" maintained at a depth of ~50 km during most of the time. This invokes a mechanism where crustal

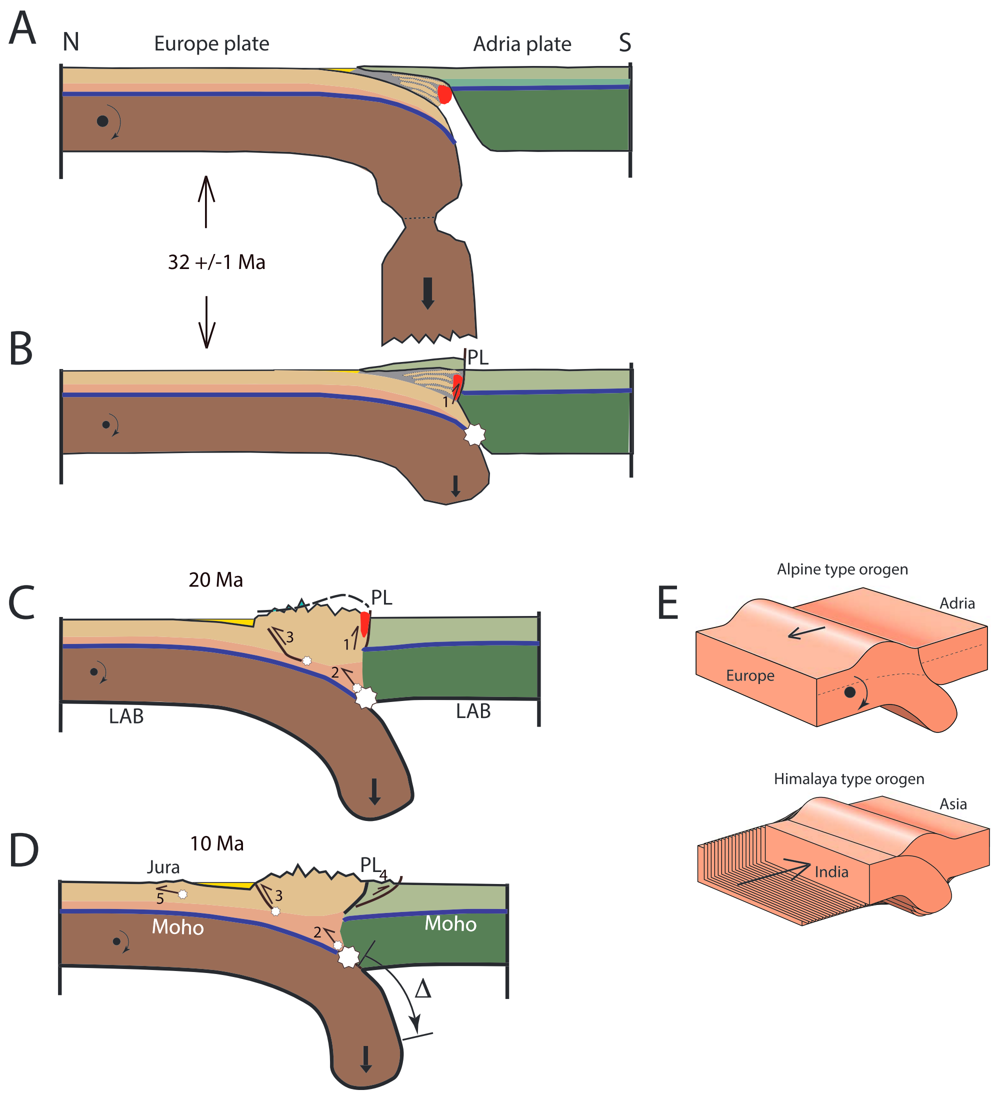

Figure 7. Postcollisional evolution of central Alps driven by crust-mantle lithosphere delamination and slab rollback. (a and b) Situation shortly before (a) oceanic lithosphere slab breakoff (see also Figure 6c) and shortly thereafter (b). Elastic rebound of European plate after breakoff caused the subduction channel to close and subduction wedge to be thrusted upward (faulting 1) along the new plate boundary fault system (PL = Periadriatic Line). The delamination of continental crustal material from its mantle lithosphere (marked by white star) continued, though at a much slower rate compared to the time before breakoff. (c) Delamination processes played a pivotal role in the postcollisional evolution of the central Alps (Willingshofer et al., 2013). Delaminated lower crustal material continuously replenished the crustal root (faulting 2), while the Alps have been uplifted and eroded by up to 20 km since the last 30 Ma. Delamination of the European mantle lithosphere continued in response to slow rollback, thus forcing the Molasse Basin and the whole Alpine mountain range to migrate northward (Burkhard, 1988; Schlunegger & Kissling, 2015). Within the Alps, significant deep crustal delamination culminated with the detachment of the Aar massif around 20 Ma ago (faulting 3) (Herwegh et al., 2017), and it terminated shortly after 10 Ma. (d) Northward migration of Alpine thrusting, caused by European slab rollback, ended with the formation of the Jura mountains (faulting 5) between 12 Ma and 5 Ma. Along the central Alpine transect discussed in this paper, south directed back thrusting within the Adriatic upper crust (faulting 4) between 18 Ma and 10 Ma (Schönborn, 1992) documents a short phase where the Adriatic plate was actively indenting into the Alpine orogen. (e) Cartoons illustrating the differences between a rollback subduction-collision Alpine type orogen and a normal subduction-collision Himalaya type orogen. Note that in the case of the Alps, the orogen resides on the lower plate that is subducting yet not moving toward the trench. Rollback causes the migration of the orogen in opposite direction of the subduction and the retreating slab exerts a suction force to the overriding plate. If the overriding plate migrates in the direction of suction forces, as is the case for the Alpine orogeny, an overall convergence is observed between the two plates, yet no compressional forcing is required. Back-arc extension is observed in the overriding plate if it does not migrate toward the trench, as is, for example, the case in the Aegean.

accretion in the crustal root must have continued. We envisage a process where decoupling, or delamination (Willingshofer et al., 2013), of buoyant lower crustal material along the Moho resulted in the accretion of material into the crustal root during postcollisional time of slab rollback, similar to the buildup of the Penninic nappes in precollisional times.

7. Alpine Rollback Subduction in the Context of Subduction Models

For the case of the Alps, the generally accepted model of orogenic evolution is characterized by three phases denoting the subduction of the oceanic lithosphere of the Alpine Tethys, the collision between the two continents at about 35 Ma, and the subsequent postcollisional convergence (see above). The subduction of the Alpine Tethys as part of the European plate occurred toward the south beneath the continental lithosphere of the Adriatic microplate (e.g., Butler, 2013; Carry et al., 2011; Froitzheim et al., 1997; Schmid et al., 1996; Vignaroli et al., 2008). Various evolutionary models have been proposed, and discussions in these articles mainly focused on how the buildup of orogens can be related to the different subduction mechanisms (e.g., Dewey, 1980; Royden, 1993a; Schellart, 2008). Here we have focused on a subduction model that is characterized by trench retreat. Also, in this model, the subduction of the European plate has been accomplished through a slab rollback mechanism at the boundary between the European and Adriatic plates. As outlined above, we thus refer to the related subduction processes as rollback subduction. Consequently, the built up of an orogen in relation to rollback subduction is referred to as a rollback orogeny.

We note here that rollback subduction models for the Alps have previously been suggested by Froitzheim et al. (1997) for the subduction of the Alpine Tethys. Related processes, sketched in Figures 6a and 6b, have indeed been considered as a likely plate tectonics setting for explaining the exhumation of UHP rocks (e.g., Babist et al., 2006; Husson et al., 2009). Following Malinverno and Ryan (1986), where the sinking velocity of the oceanic lithosphere slab exceeds the convergence velocity between overriding and underthrusting plates (Figure 8a), we observe trench retreat, slab rollback, and—in case of fixed upper plate—back-arc extension (Figure 8b). For all possible combinations of these key parameters Schellart (2008) and Stegman et al. (2010) evaluated the tectonic features that would correspond to the respective subduction model. Heuret and Lallemand (2005) documented the forces acting on the slab and driving the subduction system (Figure 8b). For the case of the Central Alps, the presently preserved boundary between the European and the Adriatic plates is represented by the Periadriatic line (Figure 2) along the southern margin of the Alps. The former trench, however, follows the northern margin of the Alps as documented by the Flysch sediments originating from the subduction period and by the Molasse sediments during postcollisional times. Furthermore, during subduction and postcollisional convergence, Europe remained stable (Torsvik et al., 2012) and the Adriatic plate migrated northward (e.g., Handy et al., 2010). Hence, in our model the underthrusting plate (Europe) remains fixed, and the upper plate (Adria) migrates at a rate that is equal to the trench migration rate. As a consequence, there is no back-arc extension in the upper plate (Figures 8c and 8d). Finally, we extend the dynamic force balance (Heuret & Lallemand, 2005) from the subduction to the postcollisional states of the Alpine evolution. The three main components of this force balance driving Alpine tectonics are the two loads related to the surface topography and the mantle lithosphere slab and, as counterpart, the buoyant crustal root (Figure 4).

8. "Normal" Versus Rollback Subduction and Collision

At the crustal scale, the commonly preferred model for Central Alpine postcollisional orogeny was based on the assumption where the Adriatic microcontinent was indenting into the interface between the lower and upper crust of the European lithosphere. These mechanisms have been used to explain the bending and subduction of the European plate, and the migration of the Alps toward the NW and north, driven by the push of the Adriatic plate. By pure kinematical perspectives, this model describes the Alps as the product of two converging continental blocks, that is, Adria in the south and Europe in the north, which were originally separated by the Tethyian Ocean. Such geologic models have been suggested even before the development of plate tectonic concepts (e.g., Argand, 1916). Because kinematic models are relative in nature, it seems to make no difference if Europe as lower plate is moving and subducting south (e.g., Willett, 2010) or remains stationary, as long as Adria moves northward relative to Europe, which it reportedly did (e.g., Handy et al., 2010). From a plate tectonic point of view, however, there is a significant difference between normal and

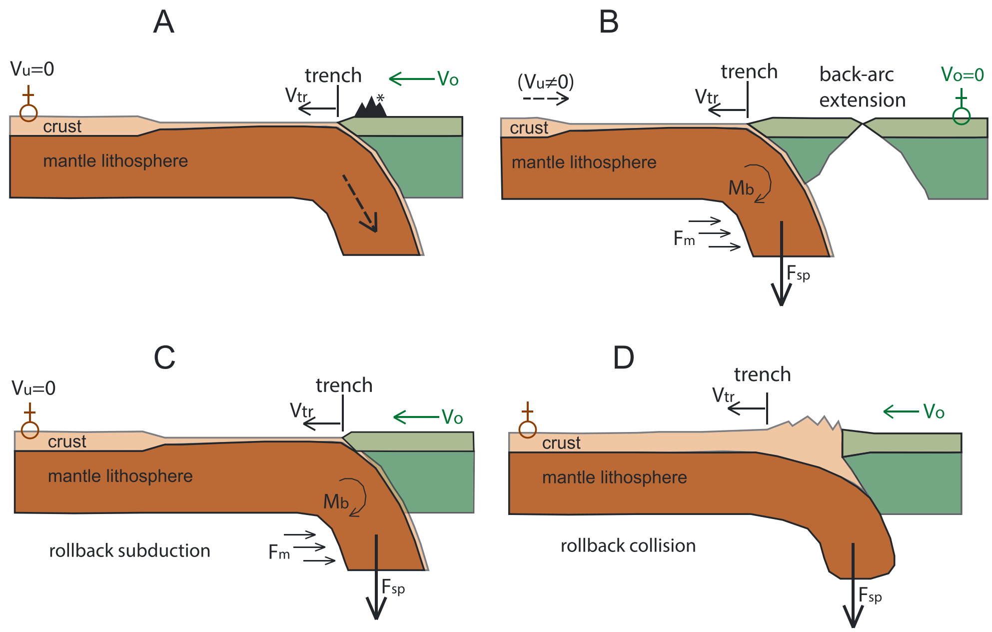

Figure 8. Cartoons illustrating slab rollback concepts and mechanics of Alpine rollback collision. (a) Original rollback subduction model based on kinematic principles (e.g., Dewey, 1980; Malinverno & Ryan, 1986; Royden, 1993a; Carminati et al., 2003; Schellart, 2008). In a reference frame fixed with respect to the underthrusting (subducting) plate, the kinematic balance between trench migration Vtr and trench-perpendicular convergence between the two plates Vo defines the tectonic style (Malinverno & Ryan, 1986). This results in either arc compression for Vo > Vtr, neutral for Vo = Vtr, or trench retreat, rollback subduction, and back-arc extension for Vo < Vtr. Note that this model does not provide any implication about the true motion of the underthrusting plate that is actually exposed to strong slab pull. (b) The slab rollback model by Heuret and Lallemand (2005) that combines kinematics with a slab pull force Fsp and a bending moment Mb that acts on the plate. If the upper plate is fixed, then slab pull forces, bending moment, and pressure forces generated by mantle flows on the back side of the slab define the trench motion Vt and this in term defines the tectonic style in the overriding plate, either neutral (Vtr = 0), compressional (Vtr < 0), or back-arc extension (Vtr > 0). Here motions >0 are toward the left. (c) Rollback subduction model proposed for the Alps. Europe as lower plate remains fixed, while Adria as upper plate migrates northward (e.g., Handy et al., 2010; Vignaroli et al., 2008). (d) Rollback postcollisional model proposed for the central Alps. Note that the Alps reside on lower plate (Europe): the trench is situated on the northern side, while the plate boundary is located on the southern side of the Alps.

rollback subduction (e.g., Elsasser, 1971; Heuret & Lallemand, 2005; Malinverno & Ryan, 1986; Platt et al., 1989; Schlunegger & Kissling, 2015). Kinematic models (Beaumont et al., 1992; Willett et al., 2006) are capable of reproducing the uppermost crustal architecture and surface features with sufficient detail, but they are in obvious conflict with some of the most significant characteristic features of the deep lithosphere structure of the Alps (e.g., Kissling et al., 2006), and they may not account for the precollisional evolution where rollback subduction dominated (e.g., Vignaroli et al., 2008).

Though retreating subduction boundaries (Froitzheim et al., 1997; Lallemand et al., 2008; Royden, 1993a, 1993b) are common features of today's active subduction zones in the Mediterranean (Faccenna et al., 2004; Jolivet et al., 2013), the related source mechanism of slab rollback has conventionally been discarded as the main driving mechanism for the Alpine orogeny (e.g., Schmid et al., 1996; Carry et al., 2011; Butler, 2013). One of the main reasons for this is the obvious lack of regional extension in the overriding Adriatic microplate, a key element in the originally purely kinematic definition of surface features (Heuret & Lallemand, 2005; Malinverno & Ryan, 1986) for slab rollback (see Figure 8). During Alpine Tethys subduction times, however, the Adriatic microplate migrated north to NNW in accordance with European slab rollback, that is, the retreating subduction boundary, and it continued doing so during collisional times (e.g., Handy et al., 2010) leaving no physical reason for internal extension. Note that an analogue process occurred when Corsica and Sardinia separated from Europe following the Adria slab rollback and leading to the opening of the Gulf of Lyon and the Liguria Sea behind them (e.g., Handy et al., 2010; Jolivet et al., 2015). We propose, therefore, that the suction forces resulting from slab rollback might have been large enough so that the

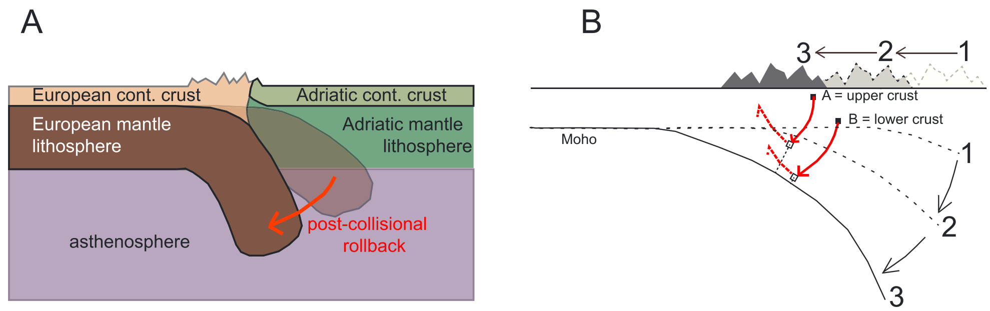

Figure 9. Postcollisional rollback and crustal material path to exhumation. (a) Model of postcollisional rollback of European mantle lithosphere delaminated from its crust as primary cause for Alpine orogeny proposed in this study. (b) Time steps 1 to 3 documenting northward migration of Alpine orogen and subduction-metamorphosis (solid red arrows) to delamination-exhumation (broken red arrows) paths for European continental upper and lower crustal material building the Alpine orogen.

overriding continental plate either—if it was small enough—migrated in accordance to subduction boundary retreat or was ripped apart if it did resist migration, as it is currently the case in the Aegean (e.g., Jolivet et al., 2013).

For the surface scale (Sinclair & Allen, 1992), the evolution of the Alpine topography is closely related not only to surface processes (e.g., Willett, 2010) but also to long-term uplift in relation to the evolution of the buoyant crustal root that provides the isostatic balance. In a plate tectonic context where plates float on the asthenosphere mantle, however, an isostatic balance, or alternatively dynamic vertical force equilibrium, is maintained among the three body forces. These include topographic and slab loads and buoyancy forces exerted by the crustal root with some additional contribution by plate elasticity (Figure 4). In this context, critical tapering of the surface must be correlated with analogue structures at depth, that is, with a corresponding geometry of the crustal root. Note that with isostatic concepts where mantle slab loads are neglected, this correlation is even more pronounced to the point where integrated surface and Moho topography are analogously symmetrical. For their kinematic models, various authors (Beaumont et al., 1992; Willett et al., 1993) applied a factor of 1:6 between the mean height of the surface topography and the thickness of the crustal root. These authors additionally defined, and also fixed, a so-called singularity point where crustal material of the incoming plate separates into downgoing and upgoing flows, the latter forming the orogen. For the greater Alpine region, however, the present Moho topography has been known far better than for any other orogen (Spada et al., 2013, and references therein), as this surface has been mapped during decades through seismic investigations. The results of these surveys document a crustal root twice as thick as needed for compensating the current mean surface topography through Airy-isostasy. This well-known apparent imbalance (Braitenberg et al., 1997; Kissling, 1993) combined with the results of high-resolution teleseismic tomography (Lippitsch et al., 2003) requires the additional load exerted by the current European mantle lithosphere slab to be taken into account (Schlunegger & Kissling, 2015). Thus, the most significant differences between previous kinematic models and our preferred geodynamic model regard (i) the transport processes of crustal material, which has resulted in the accretion and the buildup of the crustal root and (ii) the rollback of the subducted mantle lithosphere (Figure 9). Accordingly, in a rollback orogeny model (Stampfli & Hochard, 2009), the subducting mantle lithosphere takes the role of the main driving force for the convergence across the Alpine orogen. This contrasts to the previous views where the European lithosphere was assigned a rather passive role, in which the crust was peeled off and the slab warped downward by the indenting Adriatic plate (e.g., Pfiffner, 2016; Schlunegger & Willett, 1999). Note, however, that we do not suggest though that postcollisional indentation by Adria did not occur, but this processes was confined to the post-18-Ma period at least in the Western and Central Alps, when the southern Alpine nappes were formed (Schönborn, 1992).

9. Conclusions: A Rollback Orogeny Model for the Evolution of the Alps

First of all, a rollback process is needed to allow the subduction of the European oceanic lithosphere because the European continent has not shifted southward (Torsvik et al., 2012). Second, although rollback subduction is well known from ocean-ocean environment and understood to exert strong suction forces on the overriding plate (e.g., Sternai et al., 2014) causing back-arc extension, a rollback mechanism, also applied to a continent-continent collisional stage such as the Alps, allows for a reconciliation of previous obvious conflicts. These mainly concern the >50% mismatch between the results of kinematic models and the seismically exceptionally well-determined depth of the Moho (e.g., Spada et al., 2013) and the dominantly extensional seismicity that is an expression of the bending of the lower plate. In a broader context, a rollback orogeny model is capable of explaining the stacking of crustal material. This mass of accreted crust, in turn, is capable of forming, and also sustaining, topography through its buoyancy. Accordingly, a rollback orogeny model allows to explain the construction of an orogen with a pronounced topography and a thick stack of crustal material even in absence of any convergence and collision between two continental plates, as has been the case for, for example, the Apennines (Carminati et al., 2003) and possibly most of the circum-Mediterranean arc (Brun & Faccenna, 2008; Faccenna et al., 2004; Jolivet et al., 2013; Royden, 1993b). Contrariwise, the mountain belt stretching from the Zagros to the Himalayas (Hodges, 2000), and possibly also the Andes and most of the Variscian mountain belts of North America and Europe, serve as much better examples where crustal stacking and the evolution of the topography were related to the horizontal push of the continental plates. As such, we propose that while these latter mountain ranges could be considered as suitable representatives of an orogen in the classical sense, the understanding of the geologic history of Alps does require an alternative view (Figure 7). However, it is probably because the Alps have been the prime example for studying the structural fabric within a kinematic framework, they have hindered an alternative view on this orogen where dynamic forces are paired with motions of rocks. Thus, the dominant process of rollback subduction in Alpine orogeny, as suggested in this paper, was possibly one of the reasons "Why plate tectonics was not invented in the Alps" (Trümpy, 2001).

Acknowledgments
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