Initiation of subduction in the Alps: Continent or ocean?

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ABSTRACT

The triggering event for the modern evolution of the European Alps was the onset of subduction in the Middle Jurassic. However, there is some debate as to how this onset occurred: as (1) oceanic subduction; (2) the succession of an earlier (Tethys) and a later (Penninic) oceanic subduction; or even (3) intracontinental subduction. Here we show that it is plausible that the continental lithosphere in the center of the Adriatic plate was gravitationally unstable, causing the onset of subduction inside the continent. This gravitational instability was provided by thermal thickening of the mantle lithosphere in the wake of the Permian extensional event, and onset of subduction was facilitated by a strong rheological contrast inside the Adriatic plate.

INTRODUCTION

The cause for the initiation of lithospheric subduction is a subject at the very heart of plate tectonics. Stern (2004) summarized a series of possibilities for this process, but omitted subduction zones that commence inside continents, for good reason: today, among the many subduction zones on Earth, only the Tien Shan forms an intracontinental mountain range, presumably associated with some sort of subduction of the mantle part of the lithosphere inside the Asian plate (e.g., Poupinet et al., 2002). In the Alps, the alpine orogenic cycle was also initiated by a subduction event. A band of high-pressure metamorphic rocks within the Austroalpine nappes (Hoinkes et al., 1999) suggests that this subduction zone was active in the Cretaceous. The onset of this subduction has been the subject of discussion for some time as rock types with oceanic affinities are notably absent from this high-pressure belt. Conversely, suggestions of an intracontinental subduction zone (e.g., Janak et al., 2004) lack a mechanical justification. In this contribution we demonstrate that an intracontinental subduction zone in this region is mechanically plausible.

GEOLOGICAL BACKGROUND

The structural succession of the Alps may be seen in terms of four tectonic units that overlie the European lithosphere (Schmid et al., 2004; Fig. 1): (1) nappes derived from the European continent; (2) Penninic nappes of oceanic origin; (3) the major part of the Austroalpine nappes of continental origin, formerly part of the Adriatic plate but now stripped from their mantle lithosphere; and (4) the upper plate units, also parts of the former Adriatic plate. Today these units of the upper plate include parts of the Austroalpine nappes (e.g., Ötztal area and Drauzug range), but also the entire southern Alps and much of today's Adriatic plate (Fig. 1). Tomographic data show that the lithosphere underneath this pile is currently north dipping (Lippitsch et al., 2003), but in the Cretaceous and Paleogene the European plate dipped to the south and east (e.g., Froitzheim et al., 2008).

Historically, this structural succession was interpreted in terms of a long-lived subduction of the Penninic ocean underneath the Adriatic

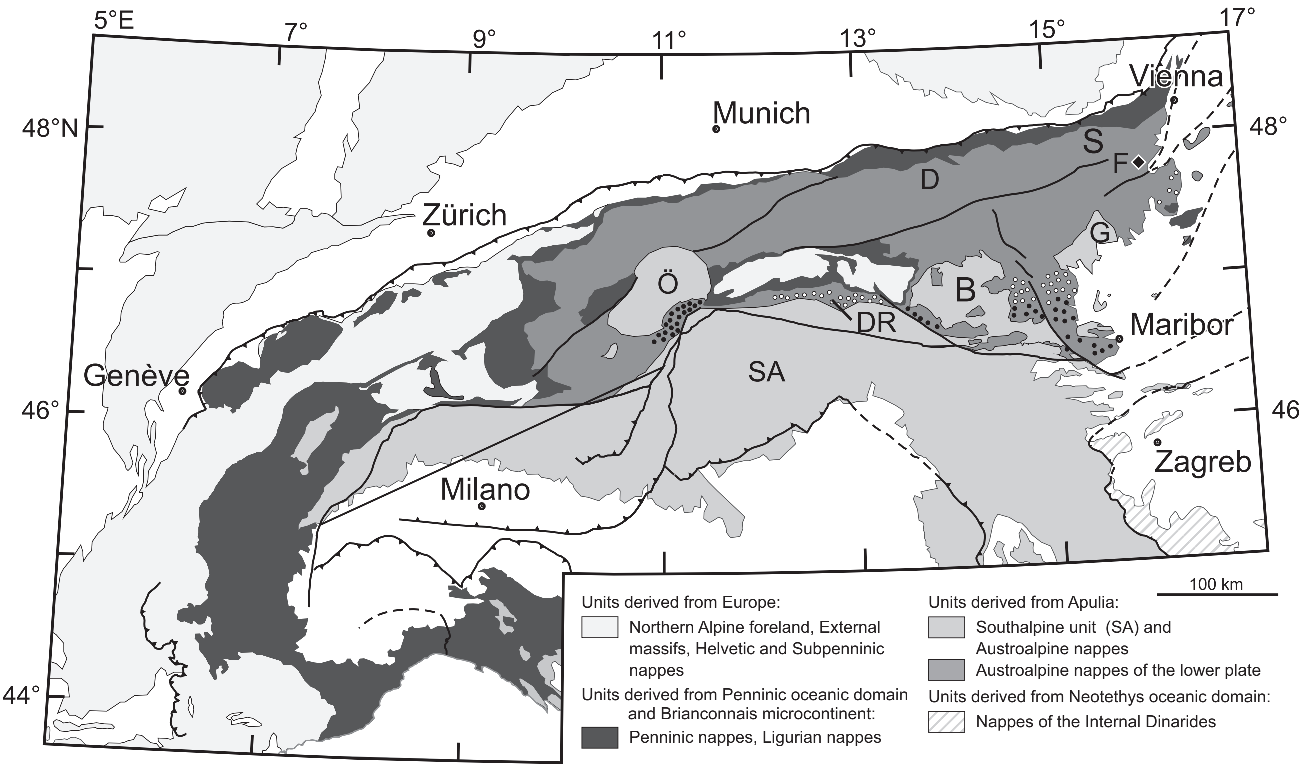

Figure 1. Tectonic map of Alps showing structural position of four major units (modified after Schmid et al., 2004). F—Florianikogel. Parts of Northern Calcareous Alps: D—Dachstein massif, S—Schneeberg. Parts of upper plate: Ö—Ötztal complex, G—Paleozoic of Graz, B—Bundschuh complex, DR—Drauzug range. Locations of high-pressure metamorphic rocks are shown with dots (black—structurally upright; white—structurally inverse).

plate (Tollmann, 1977). This subduction was presumed to have commenced ca. 135 Ma (documented by the Rossfeld event in the northern Calcareous Alps; Faupl and Tollmann, 1979). The stacking of the Austroalpine nappes was considered to have occurred in the hanging wall of this subduction zone and both the Cretaceous and mid-Cenozoic geochronological ages documented throughout the Alps were related to this long-lived event (Frank et al., 1987). However, the discovery of Cretaceous (Eoalpine) peak metamorphic ages for eclogites (Thöni and Jagoutz, 1993) in a west-east–striking band within the Austroalpine nappes (e.g., Hoinkes et al., 1999) suggested that a second subduction zone was active. Subduction of an oceanic embayment of the Neotethys Ocean (called the Meliata-Hallstatt or Vardar ocean) was considered responsible for this event (Thöni and Jagoutz, 1993; Froitzheim et al., 1996; Gawlick et al., 1999). This ocean is well known as important for the evolution of the Dinarides southeast of the Alps (Schmid et al., 2008; Stampfli and Borel, 2004).

Within this model two separate subduction zones of entire lithospheric slabs control the tectonic evolution of the Alps (Froitzheim et al., 1996; Neubauer et al., 2000): (1) an older subduction zone in the Neotethys realm (Meliata-Hallstatt ocean) southeast of the Alps that dipped toward the south or southeast and commenced ca. 170 Ma and caused much of the stacking of the Austroalpine nappe stack as well as the formation of the Eoalpine eclogites since 135 Ma; and (2) a younger subduction zone that caused southeast-directed subduction of the Penninic domain and the emplacement of the Austroalpine nappe stack on the Penninic rocks. The trace of the older subduction zone is presumably given by the line of high-pressure metamorphic rocks in the eastern part of the Alps and it ends somewhere to the south of the Ötztal mountains (Fig. 1). As it is missing in the western Alps, reconstructions of the geodynamic evolution are different for the two parts of the orogen. Nevertheless, the model of two oceanic subduction zones is very appealing as it explains the two important discrete structural and metamorphic events recognized in the Alps, the Alpine (Cenozoic) and the Eoalpine (Cretaceous) events, in terms of their respective subduction zones.

However, within our modern understanding of the tectonic subdivision of the Alps (Schmid et al., 2004), the position of the supposed older (Meliata-Hallstatt) subduction zone is highly problematic. The only material derived from the Neotethys oceanic realm within the Austroalpine unit is detrital input in Jurassic and Cretaceous sediments and small slivers of serpentinite and Jurassic flysch at Florianikogel (Mandl and Ondrejickova, 1993) (Fig. 1). Although Kozur (1991) and Neubauer et al. (2000) suggested that Florianikogel forms part of a west-east–trending trace of the Meliata suture zone, these slivers are substantially north of the high-pressure belt and are squeezed between nappes composed of low-grade metamorphic Permian–Triassic successions. Conversely, the area of the more likely position of the subduction zone, in the high-pressure metamorphic belt, lacks any ophiolites or other subduction-related rocks. The eclogite facies suture zone consists largely of metapelites with high-pressure parageneses and minor intercalation of eclogites derived from pre-Permian or Permian precursor rocks (Thöni and Jagoutz, 1993). Moreover, there are geometric problems with the removal of the mantle part of the lithosphere from the Austroalpine nappes in a scenario with two independent subduction zones of entire lithospheric slabs (as suggested by Neubauer et al., 2000).

An oceanic nature of the southern of the two subduction zones long believed to control the evolution of the Alps is highly questionable. As an alternative, Janak et al. (2004) suggested that an intracontinental subduction in the center of the high-pressure metamorphic belt may have initiated the Eoalpine orogenic cycle. While this model explains many features of the tectonic evolution of the Alps, Janak et al. (2004) did not explore the mechanical feasibility of this model or discuss its orogen-wide implications for the later evolution of the Alps throughout the Cenozoic.

CAUSES OF INTRACONTINENTAL SUBDUCTION

It is widely accepted that subduction is triggered by gravitational instability. Therefore, the most likely place for subduction to commence is inside the oceans. Oceanic lithosphere is negatively buoyant beyond an age of ~30 m.y. (Turcotte and Schubert, 2002; Stüwe, 2007) and much of its presence on the ocean floors is only due to its extreme strength. Akin to the sinking of a metal sheet on the surface of a lake, oceanic subduction requires a trigger (Stern, 2004). In contrast, thermally stabilized continental lithosphere is much more buoyant due to the presence of ~30 km of crust of granitic material and the much higher mean temperature of the mantle part of the lithosphere. However, regions of thin continental crust and thick mantle lithosphere may be negatively buoyant as a whole.

Here we suggest that the thickness ratio of the crust and mantle part of the lithosphere in the continental Adriatic (also called Apulian) plate just prior to the onset of subduction provided such a scenario. In the Permian, this Adriatic lithosphere was substantially thinned until the Meliata-Hallstatt ocean (an embayment of the Neotethys) opened to the southeast (Schuster and Stüwe, 2008). Subsequently (from ca. 240 Ma onward), the bulk of the extensional strain was partitioned in the oceanic domain and the continental crust of the Adriatic plate commenced to cool. Passive thermal equilibration (i.e., thickening) of the heavy mantle part of the lithosphere caused sag stage subsidence. Today this sag stage is well documented in the Triassic carbonate platforms of the Northern Calcareous Alps and the Dolomites and in the prolonged cooling history of the Permian metamorphic rocks (Schuster and Stüwe, 2008). Toward the end of this evolution (in the Early Jurassic), the Neothethys margin of the Adriatic lithosphere was left with an unusually thinned crust overlain by thick carbonate sequences and underlain by a massive mantle part of the lithosphere (white arrow in Fig. 2B). Such a continental lithosphere is negatively buoyant (Fig. 3, central part). We suggest that it is the negative buoyancy of the continental Adriatic plate rather than that of the Meliata-Hallstatt ocean that caused the onset of Eoalpine subduction in the Early Cretaceous. The wake of the Permian event therefore provided ultimately the driving force for the onset of the Eoalpine orogenic cycle.

Ongoing subduction stacked rocks in the upper plate and successively consumed more parts of the lower plate until the Penninic ocean to the north was subducted (Fig. 2C). The model is very appealing as it explains the entire alpine orogenic cycle by the continuous subduction of a single lithospheric slab. Within this model the discrete Cretaceous and mid-Cenozoic metamorphic events simply reflect the peak of activity of the earlier continental subduction within the Austroalpine nappes and the later continental collision following the consumption of the oceanic Penninic domain along the same suture. The removal of the mantle part of the lithosphere from the Austroalpine crust is also elegantly explained by this model without the need for a delamination event.

DISCUSSION

The suggestion that the continental lithosphere became negatively buoyant in the wake of the Permian evolution may be tested quantitatively: the vertical buoyancy force of the lithosphere on top of a supporting asthenosphere may be easily calculated if the density structure of the lithosphere is known (Turcotte and Schubert, 2002). In general, this buoyancy force is directly proportional to the isostatically supported surface elevation, but water loading and negative buoyancy of the oceanic lithosphere cause differences between continent and oceans. Here we have calculated the buoyancy force that supports surface elevation above the asthenosphere using equation 4.31 of Stüwe (2007) for surface elevation of the continent multiplied by a mantle density of $\rho_m = 3100$ kg m^{-3} and the gravitational acceleration to obtain

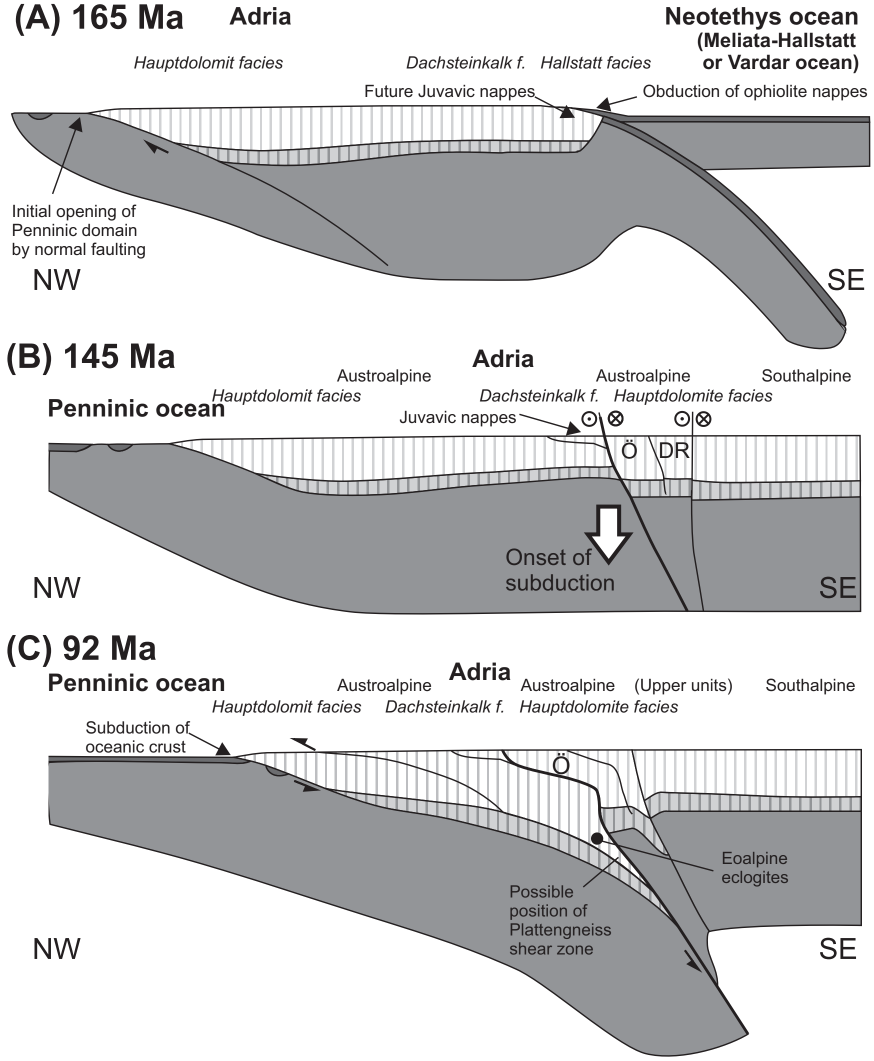

Figure 2. Geological profiles showing evolution of eastern Alps, as discussed in text. Abbreviations as in Fig. 1.

the buoyancy force. For the oceans, we use Stüwe's equation 4.45, neglecting the water loading in order to be able to quantify negative buoyancies of subducting slabs. Figure 3 shows this buoyancy force (in N m^{-2}) in a simplified profile across Figure 2 for standard ranges of the physical and thermal parameters as described in Stüwe (2007). It may be seen that a 20-km-thick continental crust atop a 130-km-thick mantle lithosphere has a negative vertical buoyancy of $\sim -2 \times 10^7$ N m^{-2}. The transition from positive to negative vertical buoyancy occurs for a crustal thickness of ~25 km (for a total lithospheric thickness of 150 km). In the oceanic part of the profile, the transition from positive to negative vertical buoyancy occurs at an oceanic lithosphere age of ~30 m.y.

Paleogeography Provides a Strength Contrast

Our proposition that intracontinental subduction inside the Adriatic plate initiated the alpine orogenic cycle poses the question as to the exact location of this onset and the role of the Meliata-Hallstatt ocean in this scenario. As for the location, we suggest that the west-east–trending band of Eoalpine high-pressure metamorphic rocks just below the upper plate units is the trace of the intracontinental subduction zone described here (Fig. 1). In the eastern part, the band of high-pressure metamorphic rocks may be divided into structurally inverse and structurally upright parts (Fig. 1), suggesting that the subduction zone suture may be located between. Some evidence for this zone may be given by the Plattengneiss shear zone in the Koralpe. This shear zone has an exposure of ~1000 km^2, the largest of its kind in the eastern Alps, and may form the trace of a downward-extracted crustal sections in the subduction channel (Fig. 2C).

The position of the Meliata-Hallstatt ocean during this subduction event is not trivial; the existence of an oceanic domain southeast of the Adriatic plate is well documented (Haas et al., 1994). In the Alps, the lagoonal facies of the Triassic sediments of the upper plate units indicates that these units were situated more toward the west in a distal position with respect to the Meliata-Hallstatt ocean. Frank and Schlager (2006) suggested that this facies distribution is best explained by substantial sinistral strike-slip motion between the central-upper nappes and the upper plate units. The strike-slip motion has to be later than the obduction of the Dinaric ophiolite nappes (170–160 Ma; Fig. 2A) and earlier than the onset of the Eoalpine compression in the Early Cretaceous (135 Ma). Frank and Schlager (2006) argued that Late Jurassic tectonics described by Gawlick et al. (1999) are related to this sinistral strike-slip event.

Here we argue that this paleogeographic model of Frank and Schlager (2006) not only provides a welcome explanation for the absence of Meliata-Hallstatt fragments from the Cretaceous high-pressure belt, but also provides a cause for the onset of intracontinental subduction, as suggested here. The sinistral strike-slip motion would have been responsible for the juxtaposition of the two pieces of Adriatic continental lithosphere with widely different rheological properties: to the north there is the Permian highly attenuated crust underlain by thermally thickened (and negatively buoyant) mantle lithosphere and overlain by the outer shelf sediments, whereas to the south there is a thicker continental crust with lagoonal sediments in the largely undisrupted southern Alps (Fig. 2B). These two pieces of Adriatic continental lithosphere would have had widely different rheological properties (see black stress envelopes in Fig. 3A): to the north of this strike-slip zone the lithosphere is very strong due to the substantial thickness of the mantle part of the lithosphere ($\sim 2 \times 10^7$ Nm), while its strength to the south is normal. Figure 3C illustrates that this juxtaposition causes a dramatic strength contrast of $\sim 1.5 \times 10^7$ Nm within the Adriatic plate.

We conclude that it is mechanically plausible that the onset of subduction in the Alps is due to a gravitational instability provided by a prolonged cooling phase following Permian tectonic events (Schuster and Stüwe, 2008). Subduction commenced at a locus of extreme strength contrast inside the Adriatic plate, which was caused by substantial sinistral strike-slip motion juxtaposing parts of the Adriatic plate that were and were not affected by Permian extension.

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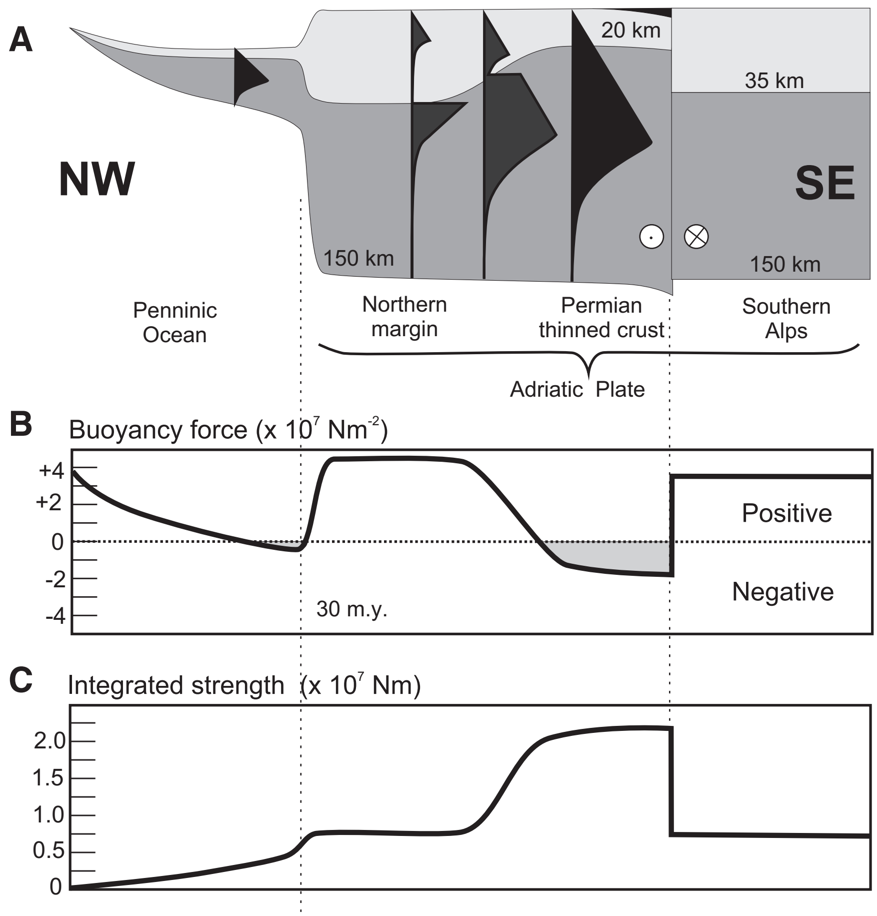

Figure 3. A: North-south profile through Penninic domain, Adriatic plate, and southern Alps (asymmetric extension at north end of Adriatic plate is omitted for simplicity). Crust is shown with vertical ruling. Mantle part of lithosphere is shaded dark. Note that southern half of Adriatic plate is characterized by Permian thinned crust and thick mantle lithosphere. B: Curve for vertical buoyancy force. C: Curve for integrated strength. See discussion in text.

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