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Subduction initiation without magmatism: The case of the missing Alpine magmatic arc

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ABSTRACT

Models of orogens identify subduction of oceanic crust as the key mechanism leading to continental collision. Such models, based *inter alia* on thermobarometric and geochronological evidence preserved in high-pressure metamorphic rocks and subduction-related magmatism, have been used to explain the convergence of Europe and Adria in the Cretaceous–Cenozoic and the subsequent Alpine orogen. Here, we review the metamorphic, igneous, and sedimentary record of the past 300 Ma of the Alpine orogen to show that there is no evidence of igneous activity during subduction initiation and prograde high-pressure metamorphism, leading to an ~50 Ma hiatus in magmatism, or "arc gap." The closure of rift basins forming the Piemont-Liguria ocean did not follow a classical Wadati-Benioff–type subduction. Instead, subduction initiation at passive margins allowed for the accretion of the hydrated portion of the subducting plate within an orogenic wedge as subduction of dry subcontinental lithosphere inhibited magmatism during subduction initiation and ocean closure.

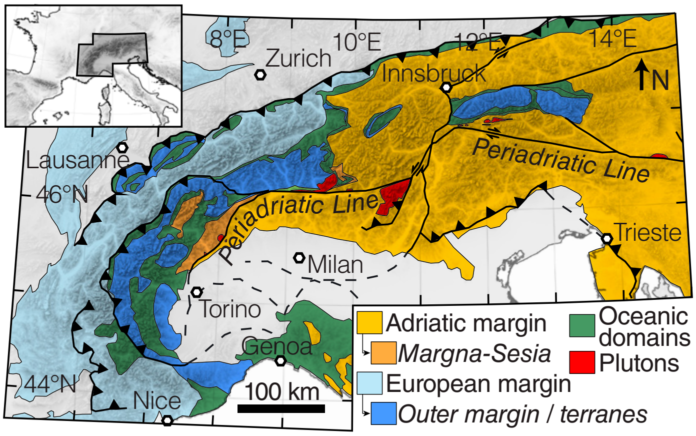

Figure 1. Tectonic map of European Alps showing main paleogeographic units (e.g., Schmid et al., 2004), including Alpine magmatism. Shaded relief is from Jarvis et al. (2008). Note that dikes along the Periadriatic Line are not shown (Bergomi et al., 2015). Oceanic domains include, amongst others, the Valaisan and Piemont-Liguria domains (e.g., Fig. 3D).

INTRODUCTION

Recycling of oceanic lithosphere through subduction is a fundamental process governing plate tectonics, continental collision, and arc magmatism (Cloos, 1993). The mechanisms allowing for the initiation of new subduction zones are related to either spontaneous or induced subduction and are thought to occur predominantly within weaknesses in oceanic lithosphere such as transform faults and oceanic detachments (e.g., Stern and Gerya, 2017). Well-documented examples of subduction initiation in mature oceanic settings (Neotethys supra–subduction zone ophiolites and Izu-Bonin-Mariana arc) have revealed that subduction initiation is characterized by an initial stage of upper-plate extension and tholeiitic to boninitic magmatism (e.g., Shervais, 2001; Maffione et al., 2017). Once initiated, partial eclogitization and densification of the subducting oceanic lithosphere results in a slab-pull mechanism representing a driving force for self-sustaining subduction and ocean closure (e.g., Cloos, 1993). In addition, dehydration of the oceanic crust drives flux melting of the overlying mantle wedge, resulting in predominantly "calc-alkaline" (cf. Arculus, 2003) magmatism (e.g., Grove et al., 2012). Therefore, calc-alkaline magmatism and low-temperature–high-pressure metamorphic rocks are interpreted as strong evidence of paleo–subduction zones (e.g., Stern, 2005).

Evidence of (ultra)high-pressure continental and oceanic fragments in the European Alpine orogen (e.g., Chopin, 1984; Reinecke, 1998) (Fig. 1) has led to models implying the subduction of a 500–1000-km-wide Jurassic Piemont-Liguria ocean during Cretaceous–Cenozoic convergence (e.g., Stampfli et al., 1998; Handy et al., 2010). The Alpine orogen, however, upon subduction initiation at ca. 85–100 Ma (Rosenbaum and Lister, 2005; Handy et al., 2010; Zanchetta et al., 2012), lacks the distinctive characteristics of subduction initiation recorded in Neotethyan ophiolites (Fig. 2). Crucially, unlike Neotethyan ophiolites, preserved alpine ophiolites indicate that the Piemont-Liguria ocean was not floored by mature ocean crust but formed predominantly of basins floored by exhumed subcontinental mantle, similar to magma-poor Iberia-Newfoundland ocean-continent transition zones (OCTs) (e.g., Manatschal and Müntener, 2009; Mohn et al., 2011; Picazo et al., 2016). The complex architectures of these basins are thought to play a major role in the mechanisms controlling the closure of the Piemont-Liguria ocean (e.g., Tugend et al., 2014).

Here we compile igneous, sedimentary, and metamorphic geochronological data of the past 300 Ma encompassing the Alpine orogeny (Fig. 3) and show that there is no magmatic record of subduction initiation and closure of the Piemont-Liguria ocean in the Alps. We discuss potential reasons for subduction without magmatism and propose alternative mechanisms of subduction initiation occurring at passive margins.

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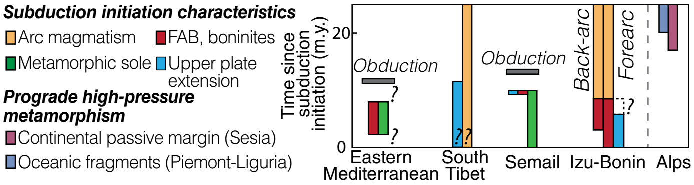

Figure 2. Timeline of initial 25 Ma following subduction initiation and showing subduction-related magmatism and metamorphism for subduction of mature oceanic lithosphere in the Neotethys (Eastern Mediterranean, Tibet, and Semail [Oman and U.A.E.] ophiolites) and Izu-Bonin arc, as well as Alpine-type subduction along the western and central Alps. Subduction initiation for Alps is estimated at 100 Ma (Zanchetta et al., 2012). References used for figure compilation can be found in the Data Repository (see footnote 1). FAB—forearc basalts.

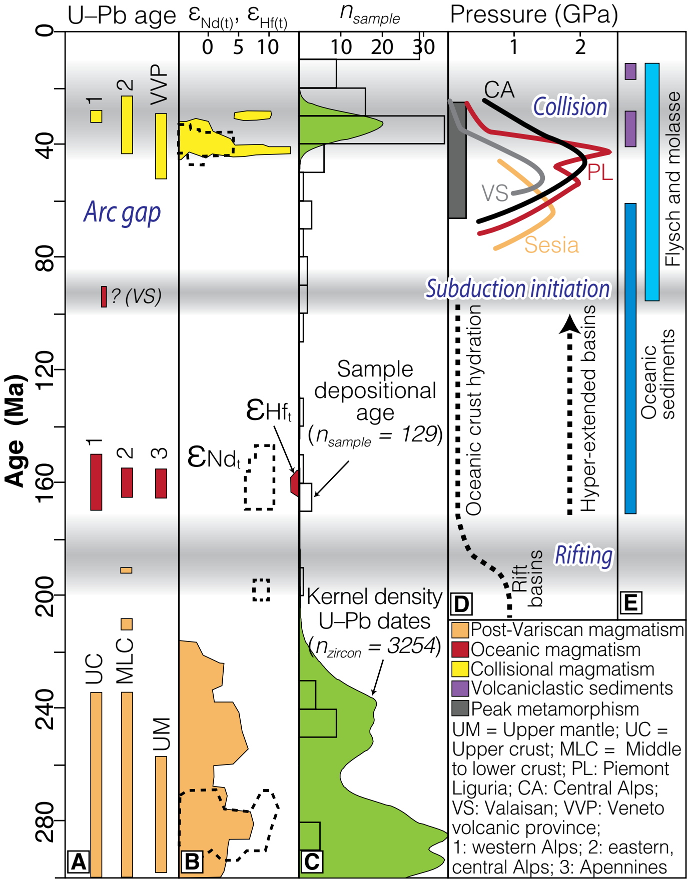

Figure 3. A: Compiled U-Pb crystallization ages from central European magmatism. B: Time-corrected $\varepsilon_{Nd(t)}$ (bulk rock, mineral separates; black dashed polygons) and $\varepsilon_{Hf(t)}$ (zircon; colored polygons) of magmatic products. C: Distribution of U-Pb dates of detrital zircons. D: Schematic metamorphic pressure-time (*P-t*) paths of Alpine units. E. Sedimentary deposition, including oceanic sediments, flyschs and molasse as well as volcaniclastic deposits. Three distinct Alpine magmatic phases can be distinguished: (1) (post-)Variscan magmatism (ca. 300–240 Ma); (2) oceanic magmatism (ca. 170–145 Ma); and (3) syn-collisional magmatism (ca. 50–28 Ma). In D, double *P-t* peak for Piemont-Liguria is related to different paths of distinct tectonic units. Note that Veneto volcanic province consists of sporadic alkaline magmatism in northeast Italy. See the Data Repository (see footnote 1) for more information.

MAGMATISM IN THE ALPS

Major tectonic events in the European Alps are recorded in the magmatic, sedimentary, and metamorphic record extending back to 300 Ma, and are summarized in Figure 3. Pre-rift magmatism is related to the formation of (post-)Variscan volcano-sedimentary basins during a prolonged period of post-collisional extension in Europe. The formation of Jurassic OCTs is manifested by exhumed subcontinental mantle, thinned continental crust, and sparse mid-ocean-ridge basalts and gabbros (e.g., Mohn et al., 2011; McCarthy and Müntener, 2015). Convergence-related high-pressure metamorphism is widespread and starts with continental fragments within the southern passive margin of the Piemont-Liguria ocean, reaching peak metamorphism at ca. 75 Ma, with the age of peak metamorphism younging northwards to the European margin (e.g., Berger and Bousquet, 2008) (Figs. 2 and 3). However, upon prograde high-pressure metamorphism and ocean closure, no record exists of island-arc magmatism (Fig. 2), while collisional calc-alkaline magmatism is found mostly as small intrusive bodies along the Periadriatic Line (Fig. 1) at ca. 42–28 Ma (e.g., Del Moro et al., 1983; Hürlimann et al., 2016) and as andesitic clasts in sediments shed from the nascent Alpine orogen (Ruffini et al., 1997). Detrital zircon populations (n = 9268 zircons; see Figs. DR1–DR3 in the GSA Data Repository[1]) in sediments deposited between the initiation of convergence and Quaternary-age deposition in riverbeds preserve no magmatic zircon populations aged between 100 Ma and 45 Ma (Fig. 3). This is in contrast to known magmatic arcs where comparison of magmatic and detrital zircon populations shows that detrital zircon populations reflect the output of volcanic arcs, as erupted products are rapidly remobilized and redeposited in nearby basins (Cawood et al., 2012; Barth et al., 2017). Thus, the lack of both detrital magmatic zircons and any field evidence of arc magmatism in the Alps during ocean closure cannot be explained by lack of preservation of volcanic and/or plutonic edifices. We conclude that magmatism was sparse and confined to collision, ~50 Ma after convergence initiated.

Magma generated during collision in the Alps does share similarities with those of arcs, including negative Nb-Ta anomalies and hydrous arc-tholeiitic to calc-alkaline affinity (e.g., Hürlimann et al., 2016; Fig. DR4). However, unlike typical arc magmatism, Paleogene Alpine magmatism is sparse and is confined along deep-seated faults at the plate boundaries (Fig. 1), with the mantle source being unusually deep (~2.7 GPa) (e.g., Ulmer, 1988; Hürlimann et al., 2016). Such conditions are unlike arc environments, where magmatism is found as much as several hundreds of kilometers from the trench and where the conditions of mantle-wedge melting are distinctively shallower (1–2 GPa; e.g., Grove et al., 2012).

INDUCED SUBDUCTION INITIATION AT PASSIVE MARGINS

Paleomagnetic data showing the migration of North Africa northward, rotation of Iberia, and opening of the Bay of Biscay at ca. 100 Ma (e.g., Rosenbaum and Lister, 2005), as well as accretionary thrusting, trench-filling deposits, and upper-plate (Adria) compression at 85–100 Ma, imply that convergence and initiation of a southward-dipping subduction occurred along the southern passive margin at 85–100 Ma (Stampfli et al., 1998; Rosenbaum and Lister, 2005; Handy et al., 2010; Zanchetta et al., 2012). The lack of magmatism during subduction initiation (Figs. 2 and 3) contrasts sharply with evidence of subduction initiation in other settings. In the Izu-Bonin-Mariana arc, intra-oceanic slab foundering led to extensive trench-parallel seafloor spreading, producing forearc basalts ± boninites. This was followed in ≤10 Ma by stratovolcano-centered magmatism and deposition of arc sediments in adjacent basins (e.g., Ishizuka et al., 2018) (Fig. 2). Subduction initiation in the Neotethys is recorded by supra–subduction zone ophiolites containing hydrous arc tholeiites and boninites, greenschist- to granulite-facies metamorphic soles, and/or evidence of forearc extension coupled to long-lived arc magmatism (e.g., Maffione et al., 2017; Shervais, 2001) (Fig. 2). Though the dynamics of subduction initiation depends on plate age, strength, and stress,

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[1] GSA Data Repository item 2018401, methods, Figures DR1–DR4, and references to text Figures 2–4, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

compositionally distinct magmas may still be erupted from near the trench to several hundred kilometers distal from the trench (e.g., Leng and Gurnis, 2015; Stern and Gerya, 2017).

The nucleation of the Alpine subduction at a passive margin appears to have been quite unique, as both the age of modern OCTs (e.g., Iberia-Newfoundland, >100 Ma) and modeling of subduction initiation show that passive margins are remarkably stable and are unlikely to spontaneously localize and nucleate subduction (e.g., Müller et al., 2008; Leng and Gurnis, 2015). Documented examples of subduction initiation rather occur along crustal weaknesses such as transform faults and oceanic detachments (e.g., Stern and Gerya, 2017). The geodynamic evolution resulting from the northward migration of Africa therefore implies that Alpine subduction initiation was induced and not spontaneous. Alpine OCTs could then have accommodated compression in several distinct ways (Fig. 4). As a result of the formation of a rift-related serpentinization front along exhumed mantle domains, compression might be accommodated along a strong viscosity contrast between the base of the serpentinization front and exhumed peridotite (Figs. 4B and 4C) (e.g., Lundin and Doré, 2011; Tugend et al., 2014). This interface might have allowed for the preservation of upper sections of the Piemont-Liguria ocean floor by the sequential accretion of variably thick slivers of dismembered "oceanic" and continental fragments from the Adriatic to the European margin and preservation of pre-collisional tectonic features (Fig. 4C). Similar mechanisms were tested by numerical thermomechanical models of induced Alpine-type subduction, indicating shallow accretion of hydrated lithologies upon subduction (Ruh et al., 2015). Field and petrological data indicate that the southern margin of the Piemont-Liguria ocean preserves evidence of reactivation of rift-related OCTs (e.g., Mohn et al., 2011), which could further accommodate compression. Moreover, mantle exhumation during Jurassic rifting led to mantle domains with distinct rheological properties due to melt percolation during passive asthenospheric upwelling, with subcontinental mantle grading from inherited, depleted spinel-peridotites to predominantly refertilized plagioclase-peridotites oceanward (Fig. 4) (e.g., McCarthy and Müntener 2015; Picazo et al., 2016). This interface between mantle domains might further control the propagation of deformation at depth.

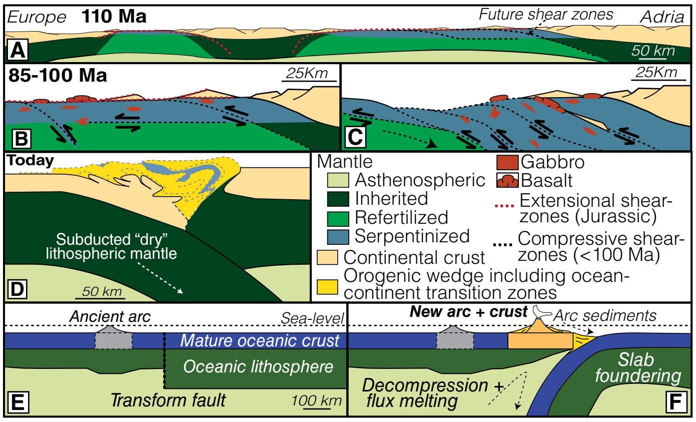

Figure 4. A: Rifting leads to exhumation of subcontinental mantle and formation of buoyant ocean-continent transition zones (OCTs) and sparse oceanic magmatism. B,C: Convergence is accommodated along preexisting detachment faults and the serpentinite-peridotite interface followed by accretion of dismembered crustal fragments, serpentinites, and oceanic sediments into wedge-type geometry. D: Subducting "dry" lithospheric mantle leads to amagmatic closure of the basin. For the sake of clarity, we have not drawn oceanic or trench sediments, and have slightly exaggerated thickness of the serpentinization front. E,F: Illustration of Benioff-type intra-oceanic subduction initiation showing foundering of an older oceanic slab at a transform fault, leading to upper-plate extension, formation of supra–subduction zone–affinity oceanic crust, and arc magmatism (after Ishizuka et al., 2018).

SUBDUCTION OF "DRY" LITHOSPHERIC MANTLE LEADS TO AMAGMATIC BASIN CLOSURE AND THE "ARC GAP"

The lack of magmatism in the Alps during subduction, or the "arc gap," has previously been attributed to flat-slab subduction, slow and oblique subduction, and/or subduction of continental slivers combined with smaller sections of ocean crust (e.g., Bergomi et al., 2015; Zanchetta et al., 2012). However, arc magmatism is driven by dehydration (± melting) of altered oceanic crust fluxing the mantle wedge (e.g., Grove et al., 2012) although decompression melting also occurs (e.g., Sisson and Bronto, 1998). Within the Alpine domain, exposed remnants of the Piemont-Liguria ocean are composed of oceanic sediments, trench deposits (flyschs), serpentinites, sparse gabbros and basalts, and isolated continental fragments. Therefore, a slow (1–2 cm/yr) and oblique Alpine oceanic subduction, coupled to along-strike changes in subduction polarity (e.g., Schmid et al., 2004; Berger and Bousquet, 2008; Vignaroli et al., 2008), implies prolonged heating of the slab and slab edges by the convective asthenospheric mantle, inducing shallower slab dehydration (≤2 GPa), enhanced flux melting of the mantle wedge, and possible slab melting. Such conditions would allow for the production of significant volumes of arc magmas (e.g., van Keken et al., 2011) similar to other slow and oblique subduction zones, as exemplified by the western Aleutians (e.g., Yogodzinski et al., 2015). Such a scenario is, however, inconsistent with thermobarometric studies indicating that Alpine high-pressure rocks reached >2.5 GPa during the "arc gap" (Figs. 2 and 3). Moreover, recorded flat slabs have been transient and may have either inhibited magmatism over shorter time scales (~10 Ma) or led to the migration of arc magmatism away from the trench (Ramos and Folguera, 2009), which is also inconsistent with a 50 Ma "arc gap." The isotopic composition of erupted magmatic products ($\varepsilon_{Hf(t)}$ ≤15, $\varepsilon_{Nd(t)}$ ≤10) over the past 300 Ma as well as alkaline magmatism of the Veneto volcanic province (Fig. 3) do not indicate an ultra-depleted mantle that would inhibit magmatism. Thus, the accretion of hydrated lithologies in a wedge-type geometry (Figs. 4C and 4D) would largely prevent the transport of water to mantle depth. Such a "dry" Alpine-type subduction may be an example of Ampferer-type subduction (Ampferer and Hammer, 1911), related to the amagmatic closure of magma-poor areas formed of thinned continental crust, magma-poor oceanic crust, and exhumed mantle (or OCTs) (Figs. 4A–4D), as opposed to more common Benioff-type subduction, which implies the subduction of mature oceanic lithosphere, the efficient subduction of hydrous rocks, and the production of voluminous arc magmatism (Figs. 4E and 4F). The concept of subduction of a "dry" lithospheric slab (Fig. 4D) allows us to bridge the gap between two apparently contradictory observations, namely tomographic images showing evidence of a southward-dipping Alpine slab (e.g., Lippitsch et al., 2003) and a lack of Alpine arc magmatism. Consequently, the efficiency of subducting hydrous rocks is an important parameter for arc magmatism. Voluminous exposed seafloor serpentinites and blueschist- to eclogite-facies rocks such as those in the Alps indicate that deep subduction of hydrous rocks was inefficient and could explain the arc gap.

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