Received: 16 November 2018 | Revised: 30 January 2019 | Accepted: 30 January 2019
DOI: 10.1111/ter.12377

PAPER

WILEY Terra Nova

Synchronous Periadriatic magmatism in the Western and Central Alps in the absence of slab breakoff

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Funding information
National Key R&D Program of China, Grant/Award Number: 2016YFC0600407; National Science Foundation of China, Grant/Award Number: 41572055; International Partnership Program of the Chinese Academy of Sciences, Grant/Award Number: GJHZ1776

Abstract
Periadriatic Alpine magmatism has long been attributed to slab breakoff after Adria–Europe continental collision, but this interpretation is challenged by geophysical data suggesting the existence of a continuous slab. Here, we shed light on this issue based on a comprehensive dataset of zircon U–Pb ages and Hf isotopic compositions from the main western Periadriatic intrusives (from Traversella to Adamello). Our zircon U–Pb data provide the first evidence of Eocene magmatism in the Western Alps (42–41 Ma in Traversella), and demonstrate that magmatism started synchronously in different segments of the Alpine belt, when subduction was still active. Zircon U–Pb ages define younging trends perpendicular to the strike of the European slab, suggesting a progressive Eocene–Oligocene slab steepening. We propose that slab steepening enhanced the corner flow. This process was more effective near the torn edge of the European slab, and triggered Periadriatic magmatism in the absence of slab breakoff.

1 | INTRODUCTION

The long-lasting debate on the origin of Periadriatic magmatism in the European Alps (Laubscher, 1983; Rosenberg, Berger, & Schmid, 1995) has led to the formulation of one of the most successful theories of modern geology, the slab breakoff model (Davies & von Blanckenburg, 1995; von Blanckenburg & Davies, 1995) that is now extensively adopted worldwide (Garzanti, Radeff, & Malusà, 2018 and references therein). Recent tomographic data for the Alpine region outline an unbroken European slab beneath the Western and Central Alps (Giacomuzzi, Chiarabba, & De Gori, 2011; Hua, Zhao, & Xu, 2017; Salimbeni et al., 2018; Zhao et al., 2016) (Figure 1a), which is incompatible with the hypothesis of oceanic slab detachment after Adria-Europe continental collision, either in the Eocene (von Blanckenburg & Davies, 1995) or in the early Oligocene (Dal Piaz, Bistacchi, & Massironi, 2003; Handy, Schmid, Bousquet, Kissling, & Bernoulli, 2010; Schmid, Pfiffner, Froitzheim, Schönborn, & Kissling, 1996). If tomographic data are correct, an alternative mechanism to explain Alpine magmatism is required.

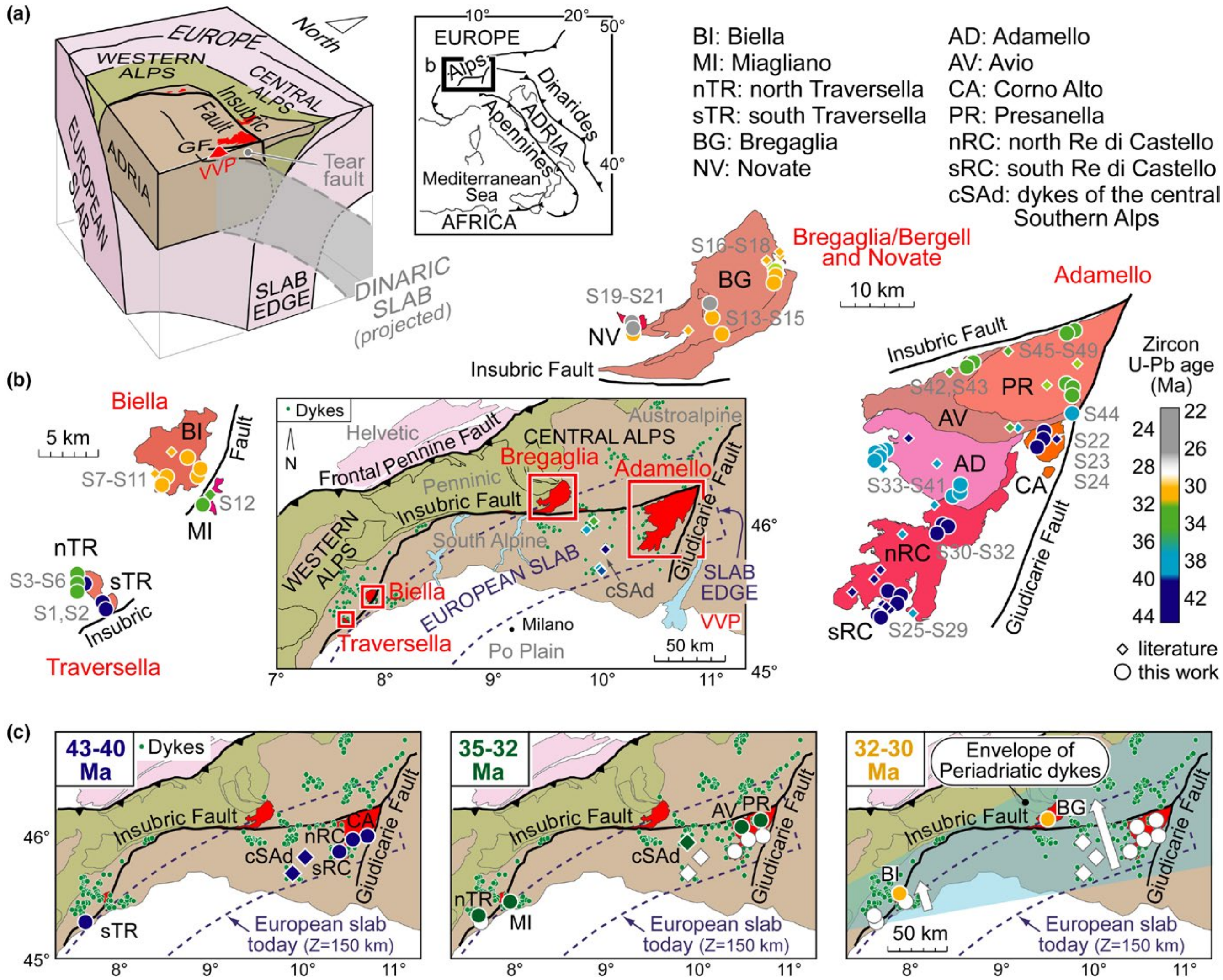

FIGURE 1 (a) Relationships between tectonic structure and Periadriatic magmatism in the Western and Central Alps (slab structure after Zhao et al., 2016). GF = Giudicarie Fault; VVP = Venetian Volcanic Province. (b) Summary of weighed mean ^{206}Pb–^{238}U zircon ages in the western Periadriatic intrusives (see Figures DR1–DR5 for detailed age maps and Concordia diagrams). S1–S49 = samples analysed in this work. Literature U–Pb ages (lozenges) compiled from: Berger et al., 2012; Bergomi et al., 2015; Broderick et al., 2015; D'Adda et al., 2011; Gianola et al., 2014; Hansmann & Oberli, 1991; Liati et al., 2000; Mayer et al., 2003; Romer et al., 1996; Samperton et al., 2015; Schaltegger et al., 2009; Schoene et al., 2012; Stipp et al., 2004; Tiepolo et al., 2011, 2014; von Blanckenburg, 1992. Green dots = Periadriatic dykes (after Bergomi et al., 2015; Bistacchi & Massironi, 2000; Kapferer, Mercolli, Berger, Ovtcharova, & Fügenschuh, 2012; Malusà, Philippot, Zattin, & Martin, 2006; Rosenberg, 2004). Dashed blue line = trace of the European slab according to the teleseismic tomography model of Zhao et al., 2016 (150 km depth slice, after Salimbeni et al., 2018). (c) Migration of Periadriatic magmatism in three steps (43–40, 35–32 and 32–30 Ma) and relationships with the European slab as outlined by seismic tomography (Zhao et al., 2016). The distribution of Periadriatic dykes (shaded blue area) forms a belt parallel to the European slab that gets progressively wider from the Western to the Central Alps. The southern boundary of this envelope is near-parallel to the alignment of Periadriatic intrusives emplaced at 43–40 Ma (sTR, sRC, nRC, CA), whereas the northern boundary is near-parallel to the strike of the slab (dashed blue line) and to the trend defined by intrusives emplaced at 32–30 Ma (BI and BG). White arrows = younging trends defined by zircon U–Pb ages

According to Davies and von Blanckenburg (1995), slab breakoff magmatism would be induced by the passive asthenosphere upwelling along the breakoff gap. Such magmatism should exhibit a mantle parentage, should be extremely localized, its trace should be nearly linear, its duration very short, and intrusions may display symmetrically younging trends with distance away from the breakoff gap (Davies & von Blanckenburg, 1995). Only part of these features are observed in the Alpine region: the Periadriatic plutons are indeed clustered along the Insubric Fault (Figure 1a,b), which probably favoured magma ascent (Rosenberg, 2004), but the widespread Periadriatic dykes (Bergomi, Zanchetta, & Tunesi, 2015; D'Adda et al., 2011) form a much wider belt parallel to the European slab (Figure 1b).

The location and age of magmatism may also reflect parameters such as the distance from the slab, its angle and the polarity and rate of subduction. These parameters can vary during subduction thus modifying the time, location and geochemistry of

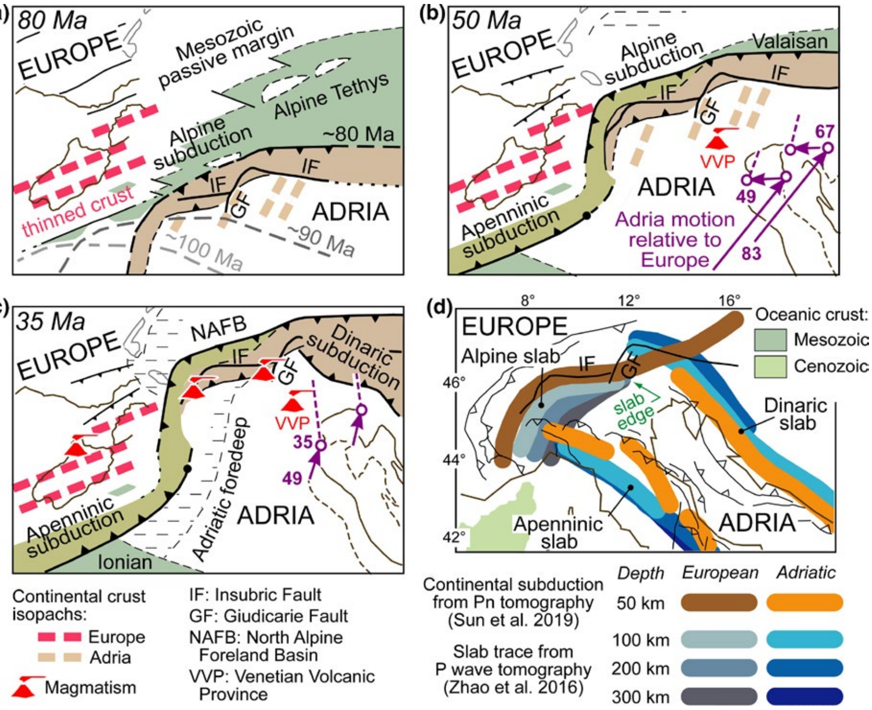

FIGURE 2 (a–c) Palinspastic reconstruction of the Adria–Europe plate boundary zone in three steps (after Carminati et al., 2012; Malusà et al., 2011, 2015; Zanchetta et al., 2012, 2015); purple arrows show the relative plate motion, numbers = ages in Ma (Dewey, Helman, Turco, Hutton, & Knott, 1989); note that Alpine subduction was oblique to the European passive margin, and the inception of continental subduction migrated progressively from the Western to the Central Alps. Colour codes as in Figure 1. (d) Present-day relationships between the Alpine (European) and Dinaric (Adriatic) slabs as outlined by the high-resolution teleseismic P wave tomography model of Zhao et al. (2016) and by the 3-D Pn tomography model of Sun. et al. (2019) (simplified after Sun. et al., 2019). The European slab edge, indicated by the green arrow, may result from vertical tearing of the Alpine slab after the onset of Dinaric subduction

the magmatism (Carminati & Doglioni, 2012; Mullen, Paquette, Tepper, & McCallum, 2018). Notably, only part of the Periadriatic plutons have been dated by modern techniques so far (e.g. Samperton et al., 2015; Tiepolo, Tribuzio, & Langone, 2011), and a full coverage of Hf isotopic analyses is still missing for most of these plutons (e.g. Broderick et al., 2015; Schoene et al., 2012; Tiepolo, Tribuzio, Ji, Wu, & Lustrino, 2014). In this work, we provide the first self-consistent dataset of zircon U–Pb ages and Hf isotopic compositions from the main Periadriatic intrusives of the Western and Central Alps. Age and isotopic trends resulting from our analyses are discussed within the framework of available geodynamic constraints for the Alpine region, shedding new light on the complex slab-mantle interactions during the latest stages of Alpine evolution.

2 | GEOLOGIC BACKGROUND

The European Alps are the result of Cretaceous-to-Palaeogene oblique subduction of the Alpine Tethys and adjoining European palaeomargin beneath Adria (Handy et al., 2010; Malusà et al., 2015) (Figure 2a–c). In the Western Alps, Alpine subduction was active until the late Eocene, as attested by (U)HP rocks that reached the eclogitic peak at ~35 Ma (Rubatto & Hermann, 2001) and were rapidly exhumed during upper-plate divergent motion by 32 Ma, corresponding to the age of the stratigraphic cover of the Voltri massif (Liao et al., 2018; Malusà, Faccenna, Garzanti, & Polino, 2011; Quaranta, Piazza, & Vannucci, 2009). In the Eastern Alps, Alpine subduction was active until the early Oligocene, as attested by eclogites of the Tauern Window that reached their pressure peak at ~31 Ma (Glodny, Ring, Kühn, Gleissner, & Franz, 2005) and then experienced crustal shortening (Rosenberg et al., 2018).

The Periadriatic magmatic rocks were emplaced in the Eocene-Oligocene (Schmid et al., 1996; von Blanckenburg et al., 1998) within tectonic units already accreted to the Adriatic upper plate during the early stages of the Alpine evolution (Malusà et al., 2011; Zanchetta, Garzanti, Doglioni, & Zanchi, 2012; Zanchetta, Malusà, & Zanchi, 2015). In the Western Alps, the Traversella pluton (sTR and nTR Figure 1b) includes monzodiorites and gabbros (~31 Ma, Krummenacher & Evernden, 1960) encased into Sesia-Lanzo metamorphic rocks to the NW of the Insubric Fault, similarly to the Biella pluton (BI) that includes monzonites, syenites, granitoids and leucogranites dated at 31–30 Ma (Romer, Schärer, & Steck, 1996). On the opposite side of the fault, the nearby Miagliano tonalite (MI) was emplaced at ~33 Ma within lower crustal rocks of the Ivrea–Verbano Zone (Berger, Thomsen, Ovtcharova, Kapferer, & Mercolli, 2012). In the Central Alps, the Bregaglia pluton (BG) includes granodiorites and tonalites with minor gabbros and diorites, emplaced around 32–30 Ma into Austroalpine and Penninic units (Samperton et al., 2015), whereas the Novate leucogranite (NV) was dated at ~24 Ma (Liati, Gebauer, & Fanning, 2000). Farther east, the composite Adamello batholith was emplaced into South Alpine units between 43 and 32 Ma (Broderick et al., 2015; Mayer et al., 2003), forming distinct magmatic units now exposed between the Insubric and Giudicarie faults (Figure 1b). In the early Oligocene, Periadriatic plutons were also intruded in the Eastern Alps (e.g. Rensen, Rieserferner and Karawanken plutons, see Bergomi et al., 2015 for a review of available age constraints).

At the transition between the Central and Eastern Alps, the slab structure is particularly complex due to the onset of Dinaric subduction in the middle Eocene (Carminati, Lustrino, & Doglioni, 2012) (Figure 2c). Some authors (Handy, Ustaszewski, & Kissling, 2015; Schmid, Scharf, Handy, & Rosenberg, 2013), based on the Lippitsch, Kissling, and Ansorge (2003)'s teleseismic tomography model, suggest that a continental Dinaric slab was subducted beneath the Eastern Alps down to ~250 km depth during the Neogene. Rosenberg et al. (2018), based on the teleseismic tomography model by Mitterbauer et al. (2011), interpret the deep velocity anomaly beneath the Eastern Alps as stemming from an oceanic and detached slab. Recent and higher resolution tomography models that benefited from the opening of the European seismic databases (Sun, Zhao, Malusà, Guillot, & Fu, 2019; Zhao et al., 2016) depict a more complex interaction between the Alpine and Dinaric slabs (Figure 2d), and suggest the presence of a slab edge to the east of the Adamello batholith. Based on available tomographic and plate motion constraints (Figure 2), we suggest that this slab edge may have formed by vertical tearing of the Alpine slab in the Eocene, after the onset of Dinaric subduction.

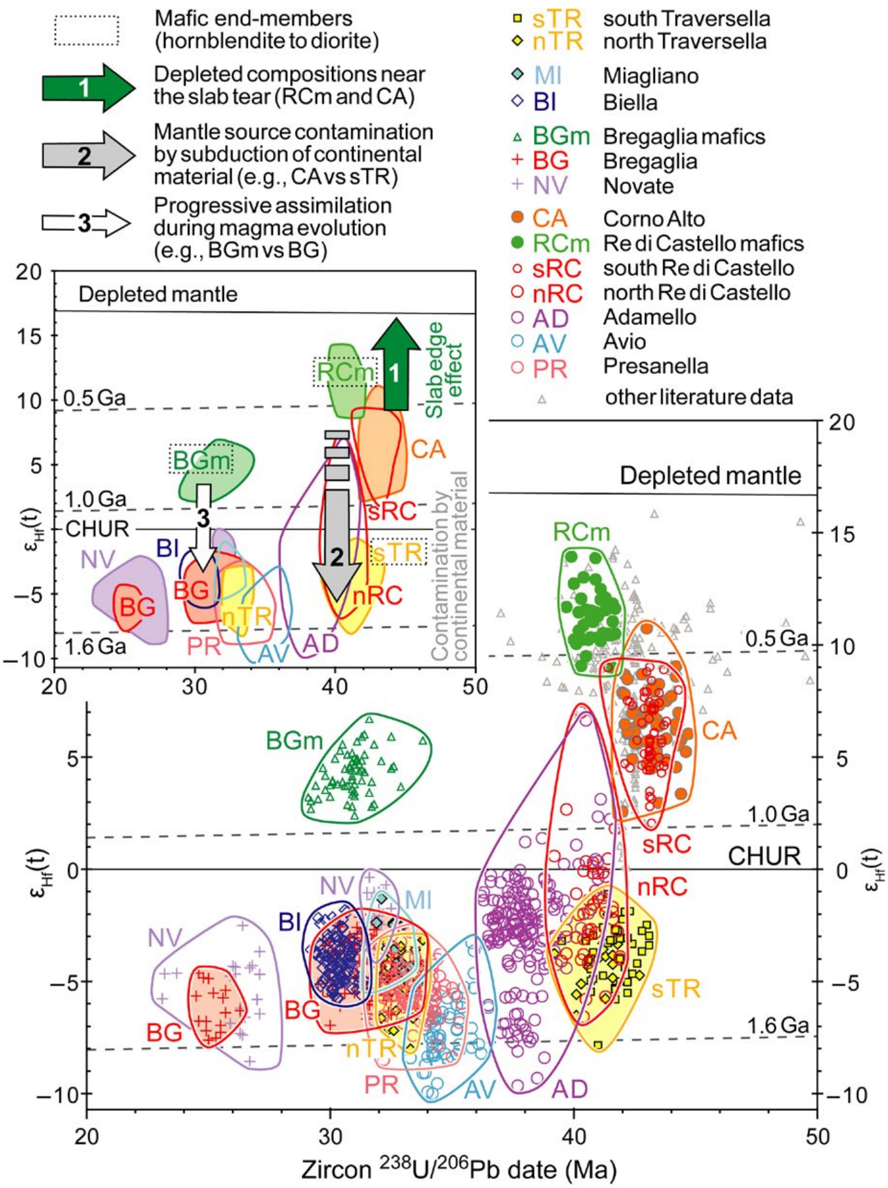

FIGURE 3 Single zircon ^{206}Pb–^{238}U dates and Hf isotope compositions from the main Periadriatic intrusions of the Western and Central Alps. The field for the Bregaglia mafic rocks is after Tiepolo et al. (2014); literature data from the Re di Castello unit (small grey triangles) are from Schoene et al. (2012) and Broderick et al. (2015). The inset on the top-left summarizes the main trends discussed in the text. Note the systematic $\varepsilon_{Hf}(t)$ decrease from east to west in the mafic end-members (RCm, BGm and sTR)

TABLE 1 Summary of zircon U–Pb and Hf isotope data

			Zircon U–Pb ages (Ma)		$\varepsilon_{Hf}(t)$	
Pluton	Unit	Sample	This work[a]	Literature[b]	This work	Literature
Traversella	sTR	S1, S2	42–41	–	−7.8/−1.1	–
	nTR	S3–S6	33 (41)	–	−8.0/−3.1	–
Biella	MI	S12	33	33	−5.2/−1.3	–
	BI	S7–S11	31–30 (30)	31–30	−8.0/−1.8	–
Adamello	CA	S22–S24	43	42	+2.6/+10.8	–
	RCm	S28–S29	41	43–40	+9.0/+13.9	+4.7/+14.4
	sRC	S25–S27	43	43–41	+2.1/+9.0	−0.4/+11.4
	nRC	S30–S32	41	39–38	−8.8/+7.0	–
	AD	S33–S41	38–37 (40, 38)	42–37	−9.6/+6.7	–
	AV	S42–S44	36–34 (34)	36–33	−10.0/−3.2	–
	PR	S45–S49	34–33	32	−8.5/−2.8	–
Bregaglia	BGm	–	–	31	–	+1.6/+5.5
	BG	S13–S18	32–30 (25)	32–30	−7.6/−2.0	–
	NV	S19–S21	27–24 (32)	24	−8.5/−0.3	–

[a]Sample mean ages as calculated in Figures DR1–DR5 and summarized in Figure 1b (data in round brackets are for mafic enclaves and in squared brackets for dykes). [b]See references in Table DR2.

3 | METHODS

We performed zircon U–Pb dating by LA-ICP-MS and in situ Hf isotope analyses on 49 rock samples (see locations in Figure 1b). A detailed description of the analytical procedures, detailed age maps, raw U–Pb and Hf isotope data and whole-rock major and trace element datasets are provided in the Data S1.

4 | RESULTS

Zircon U–Pb ages and Hf isotopic compositions are summarized in Figures 1, 3 and Table 1. Dioritic rocks from the southern part of the Traversella intrusion (S1, S2) yielded the first evidence of Eocene magmatism in the Western Alps (42–41 Ma), which contrasts with the ages of ~33 Ma given by the monzodiorites and granitic dykes in the northern part (S3, S5, S6). The only Eocene ages in northern Traversella were provided by a mafic enclave (S4) and by inherited grains in the monzodiorite (Figure DR1). The $\varepsilon_{Hf}(t)$ isotopic compositions of Traversella zircons range from −8.0 to −1.1 (Figure 3).

Zircons from the Biella monzonitic, syenitoid and granitoid complexes (S7–S11) yielded ages at 31–30 Ma, whereas those from the Miagliano tonalite (S12) are around 33 Ma. Both results are consistent with literature ages (Berger et al., 2012; Romer et al., 1996). Zircons from Biella and Miagliano have $\varepsilon_{Hf}(t)$ isotopic compositions ranging from −8.0 to −1.3.

U–Pb zircon ages from the Bregaglia granodiorites (S13, S16), tonalites (S14, S17) and leucogranites (S18) confirm the literature U–Pb ages of 32–30 Ma (e.g. Samperton et al., 2015), whereas a leucogranitic dyke from the central part of the pluton (S15) provided a much younger age at 25 Ma. In the Novate intrusion, a tonalitic enclave (S19) yielded an age at 32 Ma, consistent with the crystallization age of the nearby Bregaglia tonalite. Younger ages (27–24 Ma) were provided by a biotite granite (S20) and a garnet-bearing two-mica granite (S21). Zircon $\varepsilon_{Hf}(t)$ values in Bregaglia and Novate range between −8.5 and −0.3. Positive $\varepsilon_{Hf}(t)$ values were reported in Bregaglia mafic rocks (BGm in Figure 3) (Tiepolo et al., 2014).

In the Adamello batholith, the Corno Alto trondhjemites (S22–S24) and various lithologies from the Re di Castello unit (S25–S32) yielded similar ages, in the range of 43–41 Ma. A trend of NW-ward decreasing ages (from 38 to 33 Ma) is observed across the Adamello, Avio and Presanella units. All the Adamello dates are consistent with available U–Pb literature ages on zircon (Broderick et al., 2015; Mayer et al., 2003; Schoene et al., 2012; Stipp, Fügenschuh, Gromet, Stünitz, & Schmid, 2004; Tiepolo et al., 2011). Different units of the Adamello batholith display different zircon Hf isotopic compositions (Figure 3). Positive Hf isotopic values are found in samples from Corno Alto and south Re di Castello, and are particularly high ($\varepsilon_{Hf}(t) > 10$) in hornblendites and gabbros (RCm in Figure 3) as also reported by Broderick et al. (2015). Samples from north Re di Castello show negative $\varepsilon_{Hf}(t)$ values. Large variations in Hf isotopes are observed in the Adamello, Avio and Presanella units where negative $\varepsilon_{Hf}(t)$ values are dominant.

5 | DISCUSSION

Our results can be interpreted in the light of the slab structure outlined by the tomography models of Zhao et al. (2016) and Sun et al. (2019), with particular emphasis on the attitude of the European slab and the role of the slab edge formed by vertical tearing. As shown in Figure 1c, the middle Eocene zircon U–Pb ages

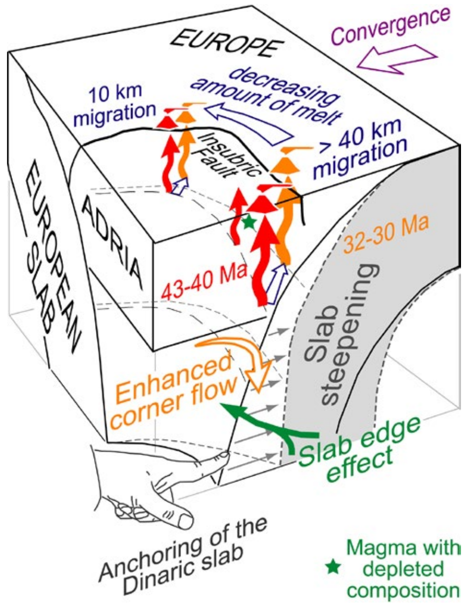

FIGURE 4 3-D model showing the proposed relationships between slab steepening and Periadriatic magmatism in the absence of slab breakoff. Slab steepening enhances the corner flow, more asthenospheric material is involved in source partial melting thus triggering magmatism. This process is more effective in the Central Alps (right side of the model) because of (i) the free boundary represented by the slab edge, (ii) the anchoring of the Dinaric slab that may have pushed back the European slab, and (iii) a minor amount of buoyant continental crust subducted at the trench. Migration of magmatism (10 km in the Western Alps, >40 km in the Central Alps) is based on Figure 1c and on plutons only. The estimate for the Central Alps is conservative, and may increase for greater amounts of dextral strike-slip accommodated along the Insubric Fault. Magmas with depleted compositions (green star) are generated in the vicinity of the torn edge of the European slab, due to the greater contributions of juvenile components during source melting (slab edge effect in the cartoon)

reported in the Traversella pluton demonstrate that magmatism started synchronously in the Western and Central Alps. The oldest (43–40 Ma) Periadriatic intrusives (sTR, sRC, nRC, CA) and dykes (cSAd, Bergomi et al., 2015) define an ENE-WSW alignment parallel to the southern boundary of the Periadriatic dyke distribution (shaded blue area in Figure 1c). We observe a regular NW-ward progression of decreasing U–Pb ages in a direction perpendicular to the strike of the European slab (Figure 1c), also appreciated in the maps of Figure 1b. In the Central Alps, zircon U–Pb ages decrease from ~43 to ~30 Ma from the southeastern sector of the Adamello batholith (Corno Alto and Re di Castello) to Bregaglia, where younger ages are only found in a leucogranitic dyke coeval with the Novate intrusion. A similar trend of younging ages is also observed in the Western Alps. Diorites of the southern part of the Traversella pluton were emplaced at 42–41 Ma. The northern Traversella monzodiorites and the Miagliano tonalites were intruded at 33 Ma. The Biella monzonitic, syenitoid and granitoid complexes were intruded at 31–30 Ma (Figure 1b,c).

The post-Oligocene dextral movements along the Insubric Fault (Malusà, Anfinson, Dafov, & Stockli, 2016; Schmid, Aebli, Heller, & Zingg, 1989) may have an impact on the above age trends. The Insubric Fault is an inherited Permian structure (Muttoni et al., 2003) lying at ~30° relative to the strike of the European slab (Figure 1c). Post-Oligocene movements along this fault are minor in the Western Alps (Bistacchi & Massironi, 2000; Malusà, Polino, & Zattin, 2009), but estimates of right-lateral slip in the Central Alps range from 10 to 20 km (Garzanti & Malusà, 2008) or ~30 km (Müller et al., 2001) to >100 km (Schmid & Kissling, 2000; Schmid, Kissling, Diehl, van Hinsbergen, & Molli, 2017). In this latter case, both the original distance between the Bregaglia and Adamello plutons and the migration of magmatism inferred from Figure 1c would have been much larger. However, for very large fault offsets, some plutons would be located too far from any slabs, inconsistent with magma generation in a supra-slab environment as constrained by trace element compositions.

The incompatible trace element compositions of the Adamello, Bregaglia and Traversella mafic rocks are in fact supportive of a subduction related origin, and in particular of mantle sources fluxed by slab-derived components (Tiepolo et al., 2014). As shown in Figure 3, the Hf isotopic ratios of these mafic end-members systematically decrease from east to west, from the Adamello batholith (RCm in Figure 3) through the Bregaglia pluton (BGm in Figure 3) to southern Traversella (sTR in Figure 3). The mafic rocks from the Bregaglia pluton and the Adamello batholith were demonstrated to be almost unaffected by shallow level crustal contamination, and reflect the primary Hf isotopic signature of the mantle wedge (Tiepolo et al., 2014). Diorites from Traversella were suggested to register limited crustal contamination (De Lummen & Vander Auwera, 1990), an hypothesis in line with the absence, in diorites, of zircon inheritance (Table DR4), and with trace element compositions resembling those of uncontaminated Bregaglia and Adamello mafic rocks (Table DR6). However, the chemical features of the Traversella diorites contrast with the extremely low $\varepsilon_{Hf}(t)$ values, that are similar to those observed for the Novate leucogranite. This $\varepsilon_{Hf}(t)$ signature requires the addition of ^{176}Hf-depleted crustal material to the mantle source during subduction. Notably, the higher potassium contents at almost comparable SiO_2 in mafic rocks, and the higher concentrations of Ba and Th (Table DR6 and Figure DR9), are all supportive of a higher continental flux in the mantle wedge of the Western Alps compared to the Central Alps. We interpret the $\varepsilon_{Hf}(t)$ systematic decrease from the Central to the Western Alps as the evidence of an increased input of continental material into the mantle source by subduction. This scenario is in line with palinspastic reconstructions showing that the inception of continental subduction migrated progressively from the Western to the Central Alps (Ford, Duchêne, Gasquet, & Vanderhaeghe, 2006; Malusà et al., 2015, 2018) (Figure 2a–c).

In the southeastern part of the Adamello batholith (south Re di Castello and Corno Alto units), depleted compositions during the early stages of Periadriatic magmatism are observed not only in mafic end-members (weighted $\varepsilon_{Hf}(t)$ > 10), but also in felsic rocks (weighted $\varepsilon_{Hf}(t) > 5$). These values may reflect greater contributions of juvenile components during source melting, consistent with the vicinity to the slab tear at the junction between the Alpine and Dinaric subductions (Figure 2d). Slab tear may also account for the adakite-like melt compositions observed in mafic rocks from the Re di Castello Unit (Tiepolo & Tribuzio, 2005), and for the voluminous early-stage magmatism in the Adamello area.

The observed migration of Periadriatic magmatism in the Western and Central Alps (Figure 1c) may reflect a progressive steepening of the European slab in the absence of slab breakoff (Figure 4). Bergomi et al. (2015) have previously suggested slab steepening to explain a trend of northward-decreasing ages in the Periadriatic mafic dykes of the central Southern Alps (cSAd in Figure 1b,c). According to current models, they interpreted the emplacement of the main Periadriatic plutons in terms of slab breakoff. Our dataset supports a much more decisive role of slab steepening for magma generation. Slab steepening may have enhanced the corner flow, with more asthenospheric material involved in source partial melting. This process was more effective in the Central Alps than in the Western Alps (Figure 4) due to: (a) the free boundary represented by the slab edge after tearing; (b) the potential anchoring of the Dinaric slab that may have pushed back the European slab; (c) a minor amount of buoyant continental crust subducted at the trench (as confirmed by Hf isotopes). Recent tomography models (Zhao et al., 2016) confirm the presence of a steeper slab beneath the Central Alps (dip angle ~70–80°) compared to the Western Alps (dip angle ~60°).

During progressive slab steepening, major magma batches now forming the Periadriatic plutons ascended along different segments of the Insubric Fault (progressively westward in the Central Alps and progressively northward in the Western Alps) due to the obliquity of the fault relative to the slab. As shown in Figure 1c, the Biella and Bregaglia plutons lay exactly along the strike of the European slab outlined by seismic tomography, which suggests that slab steepening ended ~30 Ma ago, synchronously with the cessation of the main magmatic burst. The presence of major faults was not crucial for the ascent of smaller magma batches now forming the Periadriatic dykes. Their distribution even better marks the progressive steepening of the European slab, and gets progressively wider towards the Central Alps, where slab steepening was more pronounced (Figure 1c).

6 | CONCLUSIONS

Our comprehensive datasets of zircon U–Pb ages and Hf isotopic compositions shed new light on the debated origin of Periadriatic magmatism. Zircon U–Pb data demonstrate that magmatism started synchronously in the Western and Central Alps when subduction was still active. Hf data are supportive of varying input of continental material into the mantle source by subduction, which can be accounted for by an oblique subduction relative to the Mesozoic passive margin. High $\varepsilon_{Hf}(t)$ values in eastern Adamello are consistent with the presence of a slab edge as constrained by seismic tomography, which determined a greater contribution of juvenile components during the early stages of source melting. Zircon U–Pb age trends suggest a progressive slab steepening during the Eocene-Oligocene. We propose that slab steepening enhanced the corner flow. This process was more effective near the torn edge of the European slab, and may have triggered Alpine magmatism in the absence of slab breakoff.

ACKNOWLEDGEMENTS

This work was funded by the National Key R&D Program of China (2016YFC0600407), the National Science Foundation of China (grant 41572055) and the International Partnership Program (GJHZ1776) of the Chinese Academy of Sciences. We thank T. Cawood for discussions, R. Braga for assistance in the field, J. Brendan Murphy, S. Guillot, G. Pe-Piper, and four anonymous reviewers for insightful comments, and C. Rosenberg for constructive criticism and advice that greatly improved the clarity of the article.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure DR1. Zircon U–Pb dating results, the Traversella intrusion.

Figure DR2. Zircon U–Pb dating results, the Biella and Miagliano intrusions.

Figure DR3. Zircon U–Pb dating results, the Bregaglia and Novate intrusions.

Figure DR4. Zircon U–Pb ages from Adamello samples.

Figure DR5. Zircon U–Pb concordia diagrams, Adamello batholith.

Figure DR6. SiO_2 vs. (K_2O+Na_2O) diagrams.

Figure DR7. SiO_2 vs. K_2O diagrams.

Figure DR8. Chondrite-normalized rare earth element diagrams, and primitive mantle-normalized trace element variation diagrams.

Figure DR9. Plots of Ba vs. Ba/Ta (a) and Ba/Ta vs. Th/Ta (b)

Figure DR10. Selected CL images for the dated zircons.

Table DR1. Data reporting Template (Information) for LA-ICP-MS U–Pb and Hf data.

Table DR2. Summary of related U–Th–Pb ages in literature.

Table DR3. Summary of zircon U–Pb age and Hf isotope analytical results.

Table DR4. Zircon U–Pb dating results (in separated file).

Table DR5. Zircon Hf isotope analytical results (in separated file).

Table DR6. Whole-rock major and trace element analytical results (in separated file).

How to cite this article: Ji W-Q, Malusà MG, Tiepolo M, Langone A, Zhao L, Wu F-Y. Synchronous Periadriatic magmatism in the Western and Central Alps in the absence of slab breakoff. *Terra Nova*. 2019;00:1–9. https://doi.org/10.1111/ter.12377