Geophysical Research Letters

RESEARCH LETTER

10.1029/2020GL092121

Key Points:

- Thermochronologic data in the Eastern Alps is consistent with a transient tectonic state toward complete slab reversal
- The pro-wedge has switched from north to south of the Periadriatic Fault along TRANSALP
- Mid-Miocene motion along the Tauern Ramp is the consequence of slab-reversal

Supporting Information:

- Supporting Information S1
- Table S1
- Table S2
- Table S3
- Table S4

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Citation:

Eizenhöfer, P. R., Glotzbach, C., Büttner, L., Kley, J., & Ehlers, T. A. (2021). Turning the orogenic switch: Slab-reversal in the Eastern Alps recorded by low-temperature thermochronology. *Geophysical Research Letters*, *48*, e2020GL092121. https://doi.org/10.1029/2020GL092121

Received 17 DEC 2020
Accepted 31 JAN 2021

Turning the Orogenic Switch: Slab-Reversal in the Eastern Alps Recorded by Low-Temperature Thermochronology

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Abstract Many convergent orogens, such as the eastern European Alps, display an asymmetric doubly vergent wedge geometry. In doubly vergent orogens, deepest exhumation occurs above the retro-wedge. Deep-seismic interpretations depict the European plate dipping beneath the Adriatic, suggesting the pro-wedge location on the north side of the orogen. Our new thermochronometer data across the Eastern Alps confirm distinct shifts in the locus of exhumation associated with orogen-scale structural reorganizations. Most importantly, we find a general Mid-Miocene shift in exhumation (in the Tauern Window and the Southern Alps) and focus of modern seismicity across the Southern Alps. Taken together, these observations suggest a subduction polarity reversal at least since the Mid-Miocene such that the present-day pro-wedge is located on the south side of the Alps. We propose a transient tectonic state of a slow-and-ongoing slab reversal coeval with motion along the Tauern Ramp, consistent with a present-day northward migration of drainage divides.

Plain Language Summary When tectonic plates collide, they bend downwards and form two lithospheric wedges dipping in opposite directions, such as in the Eastern Alps. We present new crustal cooling data along a transect in the Eastern Alps confirming that surface rocks across the central Tauern Window originated from the deepest structural levels along the transect. South of the Tauern Window rocks were exhumed from higher depths compared to those north of it and were exhumed more recently, while seismic activity is also focused across the Southern Alps. These observations suggest a subduction polarity reversal because they are inconsistent with the original southern and northern locations of overriding and subducting plates, respectively, >15 million years ago. This interpretation is contrary to lithosphere-scale tomography that shows no change in subduction polarity. Therefore, we propose a transient tectonic state, that is, a slow-and-ongoing subduction polarity reversal that initiated when Tauern Window rocks began their steep ascent to the surface along a deep-seated fault known as the Tauern Ramp. This study bridges observations in the mantle, crust and on the surface over geologic time.

1. Introduction

Subduction polarity reversals have been suggested in several orogens, including Taiwan (Teng et al., 2000), the Solomon Islands arc (Cooper & Taylor, 1985; Petterson et al., 1999), the European Alps (Lippitsch et al., 2002, 2003), and also in the Caledonide (Dewey, 2005) and Pamir orogens (Kufner et al., 2016). Seismic tomography results from the eastern European Alps have led to the hypothesis that a change in subduction polarity also occurred there (Handy et al., 2015; Kissling et al., 2006; Lippitsch, 2002; Lippitsch et al., 2003; Luth et al., 2013). The focus of this study is the effect of a "switch" in the direction (or polarity) of subduction on upper plate deformation, exhumation, and topography. Many convergent orogens can be described as "doubly vergent", such as in the European Alps (Argand, 1916), whereby pro- (material above the subducting plate) and retro- (material overlying the overriding plate) orogenic wedges develop (Willett et al., 1993). The pro- and retro-wedges develop as two critically tapered Coulomb wedges in response to a balancing of forces and provide a useful framework for understanding the evolution of deformation, exhumation, and topography in these settings (e.g., Davis et al., 1983; Beaumont et al., 1996; Willett & Brandon, 2002).

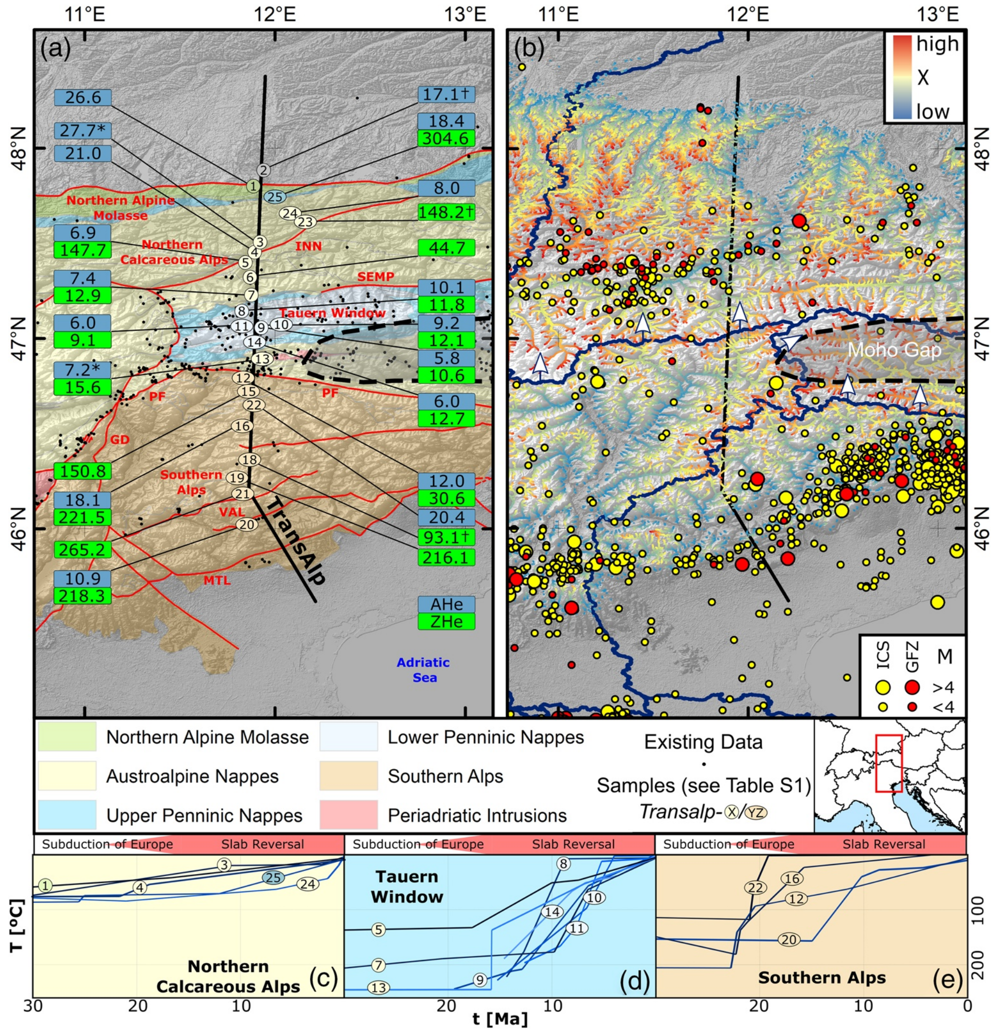

Figure 1. Crustal responses to proposed lower lithospheric slab-reversal in the eastern European Alps. (a) Geological map with new AHe and ZHe ages (in Ma) (b) Seismicity recorded by the International Seismological Center (ICS; Storchak et al., 2017) and the GEOFON Data Center (1993) over the past 10 years (GFZ), and drainage divide migration trends based on χ-analyses (Robl et al., 2017; Winterberg & Willett, 2019; divides outlined as blue lines; see also Text S3). (c) to (e) Best-fit t-T-path models of samples situated north of the INN ("Northern Calcareous Alps"), between the INN and the PF ("Tauern Window") and south of the PF ("Southern Alps"); see Text S2 and Table S4 for details. PF, Periadriatic Fault; VAL, Valsugana thrust system; MTL, Montello thrust; INN, Inntal fault; SEMP, Salzach-Ennstal-Mariazell-Puchberg fault; GD, Giudicarie fault; †, mixed age (detrital or partially reset); *, single grain age.

If a subduction polarity reversal takes place, the double-wedge system should reflect this change which could be observed through: (i) changes in the location of deepest exhumation in the retro-wedge, (ii) sequential fault activity in the "new" pro-wedge, and (iii) the location of the main drainage divide that separates minimum from maximum tapered topography along the orogenic wedges (e.g., Beaumont & Quinlan, 1994; Beaumont et al., 1996, Willett et al., 1993, 2001; Figure 1). If the Eastern Alps experienced a subduction polarity reversal, then flipping of the pro- and retro-wedges should be recorded in upper lithospheric deformation, exhumation, and topography. Recent seismic imaging of the Alpine Moho (Kästle et al., 2020; Kissling et al., 2006; Lippitsch, 2002; Lippitsch et al., 2003, and references therein) document the present-day structure of the lower lithosphere (Figure 2) and highlight the presence of two slab remnants beneath the Central and Eastern Alps. These slabs are located approximately along the Periadriatic Fault (PF; Figure 1a) at ~135–165 km depth. However, the slab geometry beneath the TRANSALP geophysical transect in the Eastern Alps (Lüschen et al., 2004, 2006) in the vicinity to the "Moho gap" (Figures 1a and 1b; Hetényi et al., 2018; Spada et al., 2013) has led to different interpretations invoking either a southward (Castellarin, Nicolich,

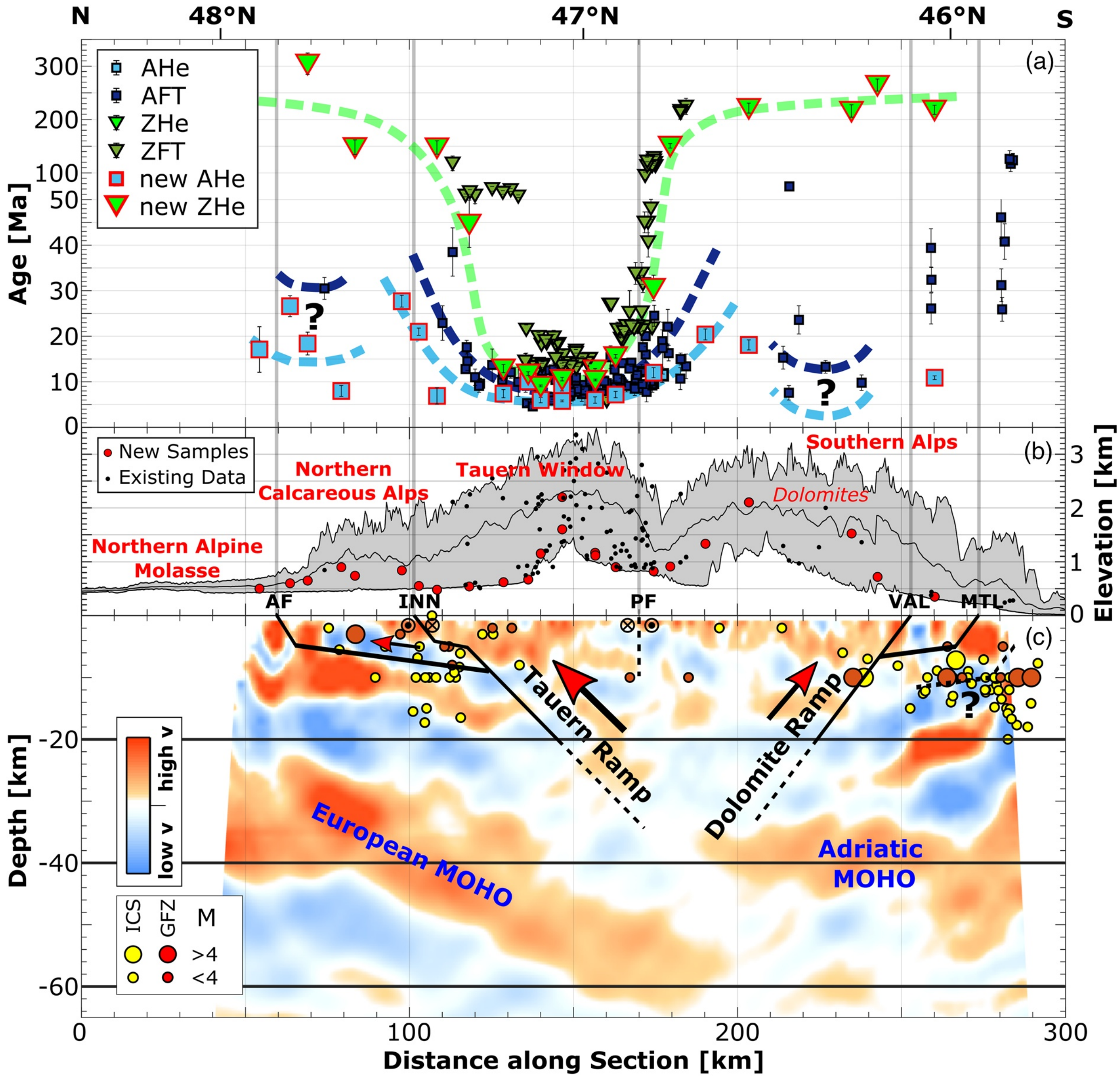

Figure 2. Cross-sectional N-S view of a 20 km swath along TRANSALP. (a) Distribution of thermochronologic ages. Green, dark blue, and light blue dashed lines outline proposed age trends (ZHe, AFT, and AHe, respectively), vertical gray lines correspond to major fault locations. (b) Topographic profile with locations of samples and published thermochronology data. (c) Locations of the European and Adriatic Moho based on receiver function analyses (Kummerow et al., 2004), simplified structural geometry and seismicity (GFZ, GEOFON Data Center, 1993; ICS, Storchak et al., 2017). Note the potentially continued southward shift of present-day fault activity south of the MTL (dashed, black line; Anselmi et al., 2011; Serpelloni et al., 2016). Arrows illustrate the general direction of displacement and relative magnitude of exhumation since continental collision. Fault acronyms as in Figure 1. AFT/ZFT data from Grundmann and Morteani (1985), Coyle (1994), Stöckert et al. (1999), Trautwein et al. (2001), Steenken et al. (2002); Most-Angelmeier (2003), Zattin et al. (2003, 2006) and Betrand et al. (2017).

et al., 2006; Lammerer et al., 2008) or northward (Handy et al., 2015; Kissling et al., 2006; Schmid et al., 2004) polarity of continental subduction. The latter case would require that the Adriatic plate is situated beneath the European, implying a slab reversal at some time since the onset of Eocene continental collision.

Here, we evaluate the hypothesis that a switch in subduction polarity occurred under the Eastern Alps. We do this using new and existing records of rock cooling and exhumation histories from low-temperature thermochronology along TRANSALP, and existing geophysical and topographic observations (Figures 1 and 2). Our results indicate a slow-and-ongoing reversal since at least the Mid-Miocene and may facilitate the identification of slab reversals in similar tectonic settings.

2. Geological Background

Continental collision in the Eastern Alps resulted in multiple tectonic events since the Eocene. In recent reconstructions (e.g., Handy et al., 2015; Schmid et al., 2004, 1996), initial southward oceanic subduction of the European slab focused upper lithospheric deformation north of the PF and ceased in the Eocene after contact between the European and Adriatic plates. Continental collision in the Oligocene led to upper lithospheric re-organization and the formation of retro-thrusts in the Southern Alps ("Pre-Adamello Phase"; Doglioni, 1992; Castellarin, Vai, & Cantelli, 2006). This produced a doubly vergent orogen with "pro" and "retro" wedges on the north and south sides of the orogen, respectively. During this time the Tauern Window retrograded from peak-metamorphic conditions ("Tauernkristallisation"; e.g., Favaro et al., 2015). Intrusions along the PF are interpreted to be the result of an Early Oligocene slab break-off along the European Plate (Blanckenburg & Davies, 1995). This is followed by a general relocation of deformation from north to south of the PF since the Late Oligocene (e.g., Handy et al., 2015; Schmid et al., 2004, 1996) despite some post-Eocene shortening across the Northern Calcareous Alps (Auer & Eisbacher, 2003). By the Early Miocene, the front of the advancing Alpine nappe stack had reached the Subalpine Molasse and came to a halt in Switzerland (Burkhard & Sommaruga, 1998), while reverse faulting occurred south of the PF (Handy et al., 2015). The indentation of Adria into Europe resulted in lateral extrusion tectonics in the Eastern Alps during the Miocene (Frisch et al, 1998, 2000; Ratschbacher et al., 1991; Rosenberg et al., 2018; Scharf et al., 2013), coinciding with strike-slip motion and thrust activity along E-W and N-S striking sections of the PF, respectively (Bartosch et al., 2017; Mancktelow et al., 2001; Müller et al., 2001; Pleuger et al., 2012; Wölfler et al., 2011; Zwingmann & Mancktelow, 2004, and references therein). Since the Mid-Miocene, active shortening along in-sequence thrust systems occurred south of the PF (Castellarin & Cantelli, 2000; Castellarin, Nicolich, et al., 2006; Schönborn, 1992, 1999) in contrast to a general absence of shortening north of the PF. Vertical orogenic growth took place throughout the Miocene as evidenced by Mid-Miocene rapid exhumation of core complexes along deep-seated, crustal-scale thrusts in the Central and Eastern Alps. Late Tauern Window exhumation is associated with displacement along the S-dipping Tauern Ramp (Bertrand et al, 2015, 2017; Rosenberg et al., 2018), whereas exhumation of the Lepontine Dome in the Central Alps is linked to displacement along the N-dipping PF (Herwegh et al., 2017; Vernon et al., 2009). However, across-strike orogenic growth is most evident in the Central to Western Alps as recorded by southward propagation of deformation beneath the Po Plain (Pieri & Groppi, 1981; Schönborn, 1992). The northern deformation front was revived in the Central Alps during Mid-Miocene to Pliocene thrusting of the Jura Mountains (Burkhard & Sommaruga, 1998; Schmid et al., 1996).

Present-day geophysical and geomorphic observations in the Eastern Alps provide additional insight into the present plate tectonic configuration of the Alpine system. Seismicity is most abundant across the Southern Alps at the Montello thrust, and less abundant north of the Tauern Window (Figures 1b and 2c). Shallow crustal (<20 km) seismicity beneath the Venetian Alps across the Montello thrust (e.g., Jozi Najafabadi et al., 2020) indicate buried south-verging thrusts (Anselmi et al., 2011; Serpelloni et al., 2016) and a high seismic potential (Barba et al., 2013; Galadini et al., 2005; Moratti et al., 2019). Deep-seismic reflection images and receiver function analyses in the Eastern Alps along the TRANSALP and EASI geophysical profiles (Gebrande et al., 2002; Hetényi et al., 2018; Kummerow et al., 2004; Lüschen et al., 2004) clearly denote south- and northward verging lower lithospheric European and Adriatic slabs (Figure 2c). Both characteristics confirm the doubly vergent architecture of the Alps (Argand, 1916). High-resolution seismic interpretations along EASI by Hetényi et al. (2018) imaged the Adriatic slab dipping beneath the European, consistent with previous works (Babuška et al., 1990; Karousova et al., 2013). Further to the SE the Dinaridic section of the Adriatic plate is subducting beneath the Dinarides since the late Cretaceous (e.g., Andrić et al., 2018; and references therein). Based on lower resolution tomography along TRANSALP, the precise relationship between the European and Adriatic plates, as well as the location of the Moho and geometry of overriding versus subducting slabs (Gebrande et al., 2002; Kästle et al., 2020; Kummerow et al., 2004; Lippitsch, 2002; Lippitsch et al., 2003; and references therein), remains elusive, especially in the vicinity of the "Moho gap" (Hetényi et al., 2018; Spada et al., 2013).

Geomorphic studies on the mobility of present-day drainage divides (Robl et al., 2017; Winterberg & Willett, 2019) indicate that the Alpine landscape remains in disequilibrium and highlight a general northward migration of divides, especially in the transition zone from the Central to Eastern Alps (Figure 1b). These trends in divide migration were interpreted not as a consequence of glaciation but rather changes in base levels in basins surrounding the Alpine system (e.g., the Pannonian Basin and Mediterranean Sea). However, potential links to changes in lower lithospheric geometries have not been evaluated.

3. Methodology and Results

Low-temperature thermochronology provides insights into the cooling history of rocks in the upper lithosphere (e.g., Braun, 2003; McQuarrie & Ehlers, 2015, 2017; Willett et al., 2020). Erosion during mountain building is one mechanism for rock cooling as mass is advected (exhumed) toward the Earth's surface (e.g., Ehlers, 2005). Thermochronometer data record the time since a rock passes through an effective closure temperature (e.g., Reiners et al., 2005). Previous work suggests closure temperatures of 180–250°C for the zircon fission track (ZFT) system (e.g., Bernet, 2009), 140–220°C for the zircon (U-Th)/He (ZHe) system (Guenthner et al., 2013), 80–120°C for the apatite fission track (AFT) system (e.g., Ketcham et al., 2007) and 50–70°C for the apatite (U-Th/He) (AHe) system (e.g., Farley, 2000; Flowers et al., 2009) corresponding to upper lithospheric depths of ∼12–2 km assuming common geothermal gradients. Residence above the closure temperatures (e.g., following continental subduction and/or subsidence) resets thermochronologic ages, whereas partially reset ages may occur in rocks that were heated to temperatures close to the specific closure temperature. Our new thermochronometer data (Tables S1–S4) are densely spaced along the length of TRANSALP (Figures 1 and 2; Text S1 and S2) and complemented by existing data.

Two general trends in cooling ages are observable along TRANSALP (Figure 2a). First, ZFT and ZHe data in the Tauern Window reflect the location of the deepest levels of exhumation across the transect. Reset ZFT ages across the Tauern Window range from 30 to 10 Ma (Bertrand et al., 2017) implying >10 km of exhumation since at least 30 Ma. This observation is consistent with previous studies (v. Blanckenburg et al., 1989; Fügenschuh et al., 1997; Lammerer et al., 2008; Selverstone et al., 1995) suggesting deformation over the same period until the Pliocene as constrained by our youngest, reset AHe ages at ∼6 Ma (Figures 1a, 1c and 2a) and supported by our time-temperature (t-T)-path inversions. High cooling rates across the Tauern Window, sensu lato (i.e., the area between the Inntal fault and the PF), occur from the Middle to Late Miocene (Figure 1d; Text S2 and Table S4). In contrast, ZHe ages north and south of the Tauern Window are mostly unreset (>300 Ma) and become successively younger near the Tauern Window. Deep exhumation of >10 km is, thus, strictly limited to the Tauern Window as bedrock to the north and south did not cross isotherms that would completely reset the ZHe system during the Alpine orogeny. The symmetric "U-shape" distribution and systematic continuity in the distribution of thermochronometer ages when transitioning from the Tauern Window to the Southern Alps (Rosenberg et al., 2018), underlined by our new ZHe and AHe data (Figure 2a), does not require significant (i.e., >1–2 km) reverse faulting along the PF, and can readily be explained by displacement along the Tauern Ramp (Lüschen et al., 2004, 2006) during Miocene time (Lammerer et al., 2008; Ortner et al., 2006).

Second, AFT and AHe data show a similar "U-shape" distribution across the Tauern Window but have also been reset in the Northern Calcareous Alps and Southern Alps. Resetting occurred during the Alpine orogeny and the AFT ages reveal higher degrees of exhumation and younger active exhumation in the south (i.e., between 3 and 6 km exhumation) relative to the north since initial collision between the European and Adriatic plates. Across most of the Northern Calcareous Alps and Northern Alpine Molasse, the AHe system yields ages of 7–28 Ma, whereas the youngest ages (<10 Ma) north of the Tauern Window are restricted to the vicinity of the Inntal fault and potentially related to transpressional tectonics. An AFT age of 31 Ma may indicate overall shallower levels of exhumation (i.e., <3 km) since the Eocene and, importantly, during the time window of the proposed slab reversal. In contrast, recorded AFT ages in the Southern Alps (Zattin et al., 2003, 2006) range from 8 to 24 Ma (with AHe ages expected to be younger), and the AHe system yielded ages between ∼20 and 12 Ma to the north and south of the Dolomites, respectively (Figure 2a). These observations are additionally confirmed by our t-T-path models, which suggest not only that the Southern Alps (Figure 1e) witnessed higher temperatures relative to the Northern Calcareous Alps (Figure 1c) since the Eocene. Our t-T-path models indicate multiple episodes of increased cooling from higher temperatures in the Southern Alps in contrast to relatively slow cooling at lower temperatures north of the Inntal Fault (Figures. 1c vs. 1e), that is, at ∼23–20 Ma and at ∼15–10 Ma. Proposed timing of fault activity along TRANSALP (e.g., Lüschen et al., 2004) suggests Mid-Miocene to Pliocene and Late Oligocene to Late

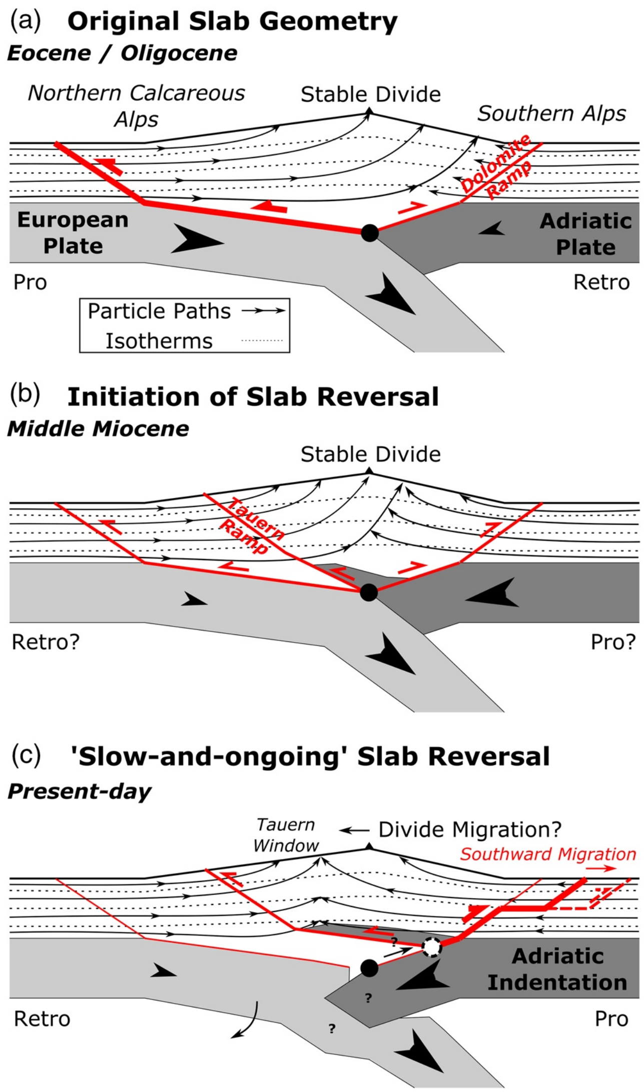

Figure 3. Conceptual model for the evolution of the lower lithospheric slab polarity reversal along TRANSALP in the Eastern Alps. (a) Initial doubly vergent orogen geometry prior to reversal (Willett & Brandon, 2002; Willett et al., 1993). (b) Initiation of slab reversal coeval with Tauern Ramp activity and overthrusting of the Adriatic plate. (c) Re-organization of the lower lithospheric subduction geometry, upper lithospheric fault activity and topographic response following the indentation of the Adriatic plate.

Miocene fault activity in the Southern Alps and the Northern Calcareous Alps, respectively. Hence, the southward migration of increased cooling in the Southern Alps is likely associated with in-sequence fault activity that took place prior to, and during rapid cooling across the Tauern Window (Figure 1d). Present-day active faulting in the southernmost section of TRANSALP across the Montello thrust (Anselmi et al., 2011; Serpelloni et al., 2016) appears to indicate a continuation of the southward migration of fault activity.

4. Discussion

Mechanical models for tectonics in doubly vergent orogens predict the deepest levels of exhumation occur in the retro-wedge side of an orogen as bedrock that is exposed there was sourced from the deepest crustal levels during continental collision (Figure 3a; Willett et al., 1993, 2001; Willett & Brandon, 2002). This relationship has been observed, for example, across the Southern Alps of New Zealand (Batt et al., 2000), the Olympic Mountains (Batt et al., 2001; Michel et al., 2018), Taiwan (Liu et al., 2001), as well as the Patagonian Andes (Fosdick et al., 2013). Strong climatic gradients may affect this exhumation pattern (Willett et al., 1993) but are negligible across-strike in the European Alps as moisture transport dominantly follows an Atlantic W-to-E trajectory since at least the Pliocene (e.g., Botsyun et al., 2020). Knowledge of the location of the deepest exhumation in a convergent orogen, hence potentially that of the retro-wedge, would be reflective of subduction polarity.

We interpret the presence of reset thermochronometric ages across the western Tauern Window to represent the present locus of deepest exhumation along TRANSALP and indicative of a retro-wedge position of the Eastern Alps north of the PF. Orogen-parallel extrusion tectonics amounting to ~50 km of E-W extension (e.g., Rosenberg et al., 2018; Wolff et al., 2020) are not expected to affect the fundamental N-S oriented doubly vergent wedge mechanical framework in the Eastern Alps. The Tauern Ramp therefore represents a deep-seated back-thrust system active from at least the Mid-Miocene to Pliocene based on our t-T-path models (Figure 1d) and the youngest AHe ages (Figures 1a and 2a). This scenario is consistent with the Early Miocene initiation of exhumation of the Tauern Window post peak-metamorphic conditions during the Oligocene "Tauernkristallisation" (Schmid et al., 2013; Favaro et al., 2015), a general southward stepping of fault activity and youngest episodes of increased cooling rates in the Southern Alps (Figure 1e), and low cooling rates within the Northern Calcareous Alps (Figure 1c). Rapid Miocene exhumation of the Tauern Window can be interpreted as retro-wedge deformation consistent with fault-propagation folding on the largely blind, crustal-scale Tauern Ramp (Ortner et al., 2006) with a maximum shortening of ~14–17 km fed into the basal thrust of the northern wedge (Lammerer et al., 2008). Earlier periods of fast cooling in the Southern Alps, prior to the time of Tauern Ramp activity, may be either (i) associated with the original retro-wedge position of the Southern Alps and displacement along the Dolomite Ramp, or (ii) interpreted as an incipient pro-wedge response of the Southern Alps to the Oligocene phase of Tauern Window exhumation not linked to Tauern Ramp activity (Figure 3a).

The timing for a switch between pro- and retro-wedge positions, therefore, is structurally most reconcilable with the onset of motion along the Tauern Ramp. Earlier exhumation across the Tauern Window prior to activity along the Tauern Ramp likely took place in a pro-wedge position potentially associated with prior duplex formation (e.g., Lammerer et al., 2008). Following this interpretation, shallow exhumation along back-thrust systems, sometimes reactivating pre-existing faults (e.g., Auer & Eisbacher, 2003), took place in the Northern Calcareous Alps during the Mid-to Late Miocene as topography developed above the Tauern Ramp (e.g., Frisch et al., 1998). Consequently, the Southern Alps developed into a pro-wedge not later than after the initiation of Tauern Window exhumation along the Tauern Ramp since the Mid-Miocene (Figure 3b). The Southern Alps respond to their new role as a pro-wedge through increased fault activity, southward thrust front propagation and lengthening of the wedge (Figure 3c; Castellarin & Cantelli, 2000; Castellarin, Nicolich, et al., 2006; Petricca et al., 2019; Zattin et al., 2003, 2006). The youngest phase of rapid cooling at ~15–10 Ma in the Southern Alps is observed at the southernmost section of TRANSALP (Figure 1e). This observation is corroborated by the in-sequence activation of the Valsugana and Montello thrust systems since the Mid-Miocene (Castellarin & Cantelli, 2000; Castellarin, Nicolich, et al., 2006).

The relocation of deformation within the orogenic system serves to (i) accommodate within the subducting plate an increase in strain above a detached lower lithospheric slab, (ii) decrease its taper to a new critical state by adding imbricate thrust sheets at the deformation front as active deformation shifts sequentially southwards, and (iii) balance the accretionary influx to re-establish exhumational steady-state. These lines of thought are in agreement with present-day seismic and kinematic observations. For example, present-day seismic activity is predominantly centered to the south of the Alps (Figures 1b and 2c; Danesi et al., 2015; Petricca et al., 2019). GPS-based kinematics of upper lithospheric deformation (Nocquet & Calais, 2004) suggest the regions of highest strain are at the southernmost extent of TRANSALP. A high seismic potential has been associated with buried south-verging thrust sheets across the Montello thrust (Moratto et al., 2019; Serpelloni et al., 2016) indicating a continued, sequential migration of south-verging thrust faulting.

Several lines of evidence suggest that subduction polarity has switched along TRANSALP (Figures 1 and 2) since the Mid-Miocene. Contrary to the thermochronologic, structural and present-day seismicity record, deep geophysical images show no clear evidence of a subduction polarity reversal (Figure 2c; Kästle et al., 2020; Kummerow et al., 2004, and reference therein). The region between the Adriatic and European plates beneath TRANSALP has a low velocity contrast ("slab gap," Handy et al., 2015) and no definite subduction polarity (Lippitsch, 2002; Lippitsch et al., 2003). The ongoing indentation of the Adriatic plate (Figure 3c), however, provides a tectonic mechanism that is able to initiate a subduction polarity reversal while remaining consistent with: (i) recent deep seismic images if interpreted as a transient lithospheric state toward complete slab reversal (Figure 2c), and (ii) the thermochronologic, structural and present-day earthquake record (Figures 1 and 2) that are best explained by a switch between pro- and retro-wedges. Continued southward subduction without invoking a slab reversal (Castellarin, Nicolich, et al., 2006; Lammerer et al., 2008), could only be reconciled with a switch between pro- and retro-wedges in a decoupled lithosphere architecture where the Adriatic plate is wedging into European crust as proposed for the Central Alps (e.g., Rosenberg & Kissling, 2013). However, the lack of evidence for Moho overlaps along both, TRANSALP (Kummerow et al., 2004) and EASI (Hetényi et al., 2018), favors a polarity change of lithospheric mantle subduction. Seismic tomography results beneath EASI, ~100 km east of TRANSALP, are interpreted to show a steeply dipping Adriatic slab. Higher resolution seismic tomography is required to resolve the relative coupling of crust and lithospheric mantle.

Interpreting the main drainage divide as the point between minimum and maximum critically tapered topography can be used to define the surface expression of pro- and retro-wedges (Figure 3a; Willett et al., 1993, 2001). Slab reversal would induce a transient period of landscape disequilibrium expressed through divide migration toward the new retro-wedge (Figure 3b). Northwards migrating divides in the Central to Eastern Alps (Figure 1b; Robl et al., 2017; Winterberg & Willett, 2019) are supportive of this line of thought and may, hence, represent the transient response to an ongoing switch from initially southward to presently northward directed continental subduction along TRANSALP.

Multiple factors control the occurrence and timing of slab reversal in continent-continent collisional settings such as material properties, maturity of the orogen (i.e., internal temperature regimes) and external stress fields (Beaumont et al., 1996; Dewey, 2005; Houseman et al., 1981, 2000; Luth et al., 2013; Pysklywec et al., 2000; Pysklywec, 2001). Numerical models that explore the conditions for slab reversal (Pysklywec, 2001) indicate the onset of slab reversal after indentation of the retro-into the pro-lithospheric mantle leads to slab break-off of the subducting slab given sufficiently low geothermal gradients. The Eastern Alps may have provided favorable conditions that promoted lower lithospheric slab reversal in a continent-continent collisional setting during the Miocene. Oligocene slab break-off may have raised the European lower lithosphere toward shallower levels causing not only regional surface uplift above the subducting plate but also enabling Adria to indent into and initiate subduction beneath Europe. The Adriatic plate (or indenter) is generally regarded as more rigid than the thickened European plate as quartz-rich basement rocks in the latter face lower lithosphere in the former. At upper lithospheric levels, the Austroalpine units experienced lower degree metamorphism in contrast to the higher degree metamorphic Penninic units across the Tauern Window (e.g., Handy et al., 2015; Scharf et al., 2013). This rheologic contrast between Europe and Adria perhaps continues at depth despite the Oligocene intrusions along the PF (e.g., Willingshofer & Cloetingh, 2003; Rosenberg, 2004). Slowing plate tectonic convergence between Europe and Adria from initially ~7.5 to ~5 mm/yr since ~20 Ma (Schmid et al., 1996; Müller et al., 2019) may have contributed to prolonging the process of slab reversal. Thus, we suggest that the Mid-Miocene initiation of slab reversal is still in progress while Moho signatures along TRANSALP are interpreted to reflect the ongoing indentation of Adria into Europe (Figures 2c and 3b; Gebrande et al., 2002; Kummerow et al., 2004). This interpretation is in line with recent interpretations of seismic tomography (Kästle et al., 2020) where Adriatic subduction is suggested to be minor.

5. Conclusions

Recent interpretations of seismic data along TRANSALP in the Eastern Alps (Figure 2c; Gebrande et al., 2002; Kummerow et al., 2004; Lüschen et al., 2004, 2006) confirmed a doubly vergent orogen geometry (Argand, 1916; Willett et al., 1993, 2001; Willett & Brandon, 2002). The across-strike distribution of thermochronometer ages identify the location of deepest levels of exhumation across the Tauern Window and favor a present-day southern and northern location of the pro- and retro-wedges, respectively. This interpretation entails a reversal in subduction polarity at least since the onset of motion along the Tauern Ramp in the Mid-Miocene. Northward migration of drainage divides, kinematic and seismic observations (Figures 1 and 2) not only support this line of arguments but also suggest a slow-and-ongoing reversal accompanying the indentation of European mantle lithosphere by the Adriatic plate (Figure 3c). The proposed scenario is in contrast to a fast-and-completed Miocene slab reversal (e.g., Handy et al., 2015) and explains the lack of a clear subduction polarity in geophysical images (Kummerow et al., 2004). This tectonic state along TRANSALP may represent a transition between the Central Alps and the Eastern Alps. In the former, where the Lepontine Dome would demark the location of the retro-wedge position prior to the onset of European slab rollback (Schlunegger & Kissling, 2015), slab reversal did not occur, whereas the process of subduction polarity reversal is potentially completed in the latter (Kästle et al., 2020). Higher resolution tomographic images beneath TRANSALP, shedding more light onto the lower lithospheric slab geometries, that is, ongoing indentation versus full slab reversal, would strengthen the here proposed mantle-to-surface link between slab reversal and its long-to short-term hinterland denudational response in continent-continent collisional settings.

Data Availability Statement

Our new thermochronology data can be accessed from the GFZ Data Services (https://doi.org/10.5880/fidgeo.2020.048). Seismic data were taken from the International Seismological Center (Storchak et al., 2017) and the GEOFON Data Center (1993). Digital elevation models were produced by the U.S./Japan ASTER Science Team (2000). Geomorphic analyses were performed through "TopoToolbox V2" (Schwanghart & Scherler, 2014). Receiver function analysis was adopted from Kummerow et al. (2004).

Acknowledgments
This study was supported by the German Research Foundation (DFG, GL724/8-1 to C.G., KL 495/28-1 to J.K., and EH329/19-1 to T.A.E.) under the priority program 4D-MB and is a contribution to the AlpArray initiative. This manuscript benefitted from discussions with Mark Handy. The authors thank the Editor Lucy Flesch and three anonymous Reviewers for constructive comments that greatly improved the manuscript.

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