Precollisional development and Cenozoic evolution of the Southalpine retrobelt (European Alps)

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ABSTRACT

The retrobelts of doubly vergent collisional orogens are classically interpreted as late-stage postcollisional features. Here, we integrate literature data with new structural and thermochronological evidence from the European Alps in order to document the precollisional development of the retrobelt segment exposed in the central southern Alps. During the Late Cretaceous, by inversion of inherited extensional faults of Permian age, the Variscan basement of the central southern Alps was stacked southward onto the Permian–Mesozoic cover sequences of the Adria margin. These thrust systems were first deformed within regional-scale antiforms (the “Orobic anticlines”) and then cut by Eocene magmatic bodies. Our apatite fission-track data show that these units were largely structured and exhumed to shallow crustal levels before the intrusion of the Eocene magmatic rocks. Therefore, thrusting and folding in the Alpine retrobelt took place before the final closure of the Alpine Tethys and subsequent continental collision between Adria and Europe. Final exhumation and uplift in the northern part of the Southalpine retrobelt took place under a dextral transpressional regime largely coeval with the right-lateral strike-slip activity along the Insubric fault. In Neogene times, deformation propagated southward, leading to the formation of a frontal thrust belt that is largely buried beneath the Po Plain.

INTRODUCTION

The doubly vergent structure observed in many collisional orogens worldwide is commonly interpreted as the result of late back thrusting in the retrowedge and building of topographic relief along the suture zone (e.g., Willett et al., 1993; Beaumont et al., 1996; Jamieson and Beaumont, 2013). Such an interpretative framework has long been applied to the doubly vergent orogenic wedge of the European Alps, which formed in response to convergence and collision along the plate boundary between Europe and Africa-Adria (Dewey et al., 1989). In the central Alps, the S-vergent structures of the Southalpine domain are often considered as the Cenozoic retrobelt, developed well after the N-vergent structuring and exhumation of the metamorphic units exposed north of the Insurbic and Periadriatic faults (e.g., Dal Piaz et al., 2003; Castellarin et al., 2006; Handy et al., 2010). However, several authors, mainly based on indirect evidence, have suggested that the southern Alps retrowedge began to form during the Cretaceous (Brack, 1981 and 1984; Doglioni and Bosellini, 1987; Laubscher, 1985; Bersezio and Fornaciari, 1994; Bernoulli and Winkler, 1990; Zanchi et al., 1990b; Schönborn, 1992; Zanchetta et al., 2012), i.e., well before the onset of continental collision. In this perspective, a full understanding of the tectonic evolution of the southern Alps may provide valuable insights for the reconstruction of the early stages of the Alpine orogeny and, more generally, new interpretation keys for the analysis of doubly vergent orogenic belts worldwide. In spite of the results obtained through numerical modeling, precollisional doubly verging orogenic wedges are commonly observed in several mountain belts (e.g., Doglioni et al., 2007; Carminati and Doglioni, 2012; Malusà et al., 2015b), among which the Andes are one of the most outstanding examples (e.g., Allmendinger et al., 1990; Ramos, 1999; DeCelles and Horton, 2003).

The aim of this work is to provide new structural and low-temperature thermochronological data and to integrate them with existing geological information from the central southern Alps to demonstrate the formation and polyphase tectonic evolution of the Southalpine domain as an orogenic wedge in a precollisional geodynamic scenario. Our new data also provide constraints on the late Cenozoic syn- and postcollision tectonic and exhumation history of the central southern Alps. The original data are based on extensive field work all across the central southern Alps, from the Variscan basement to the frontal part of the belt, and they provide a full record of the surface structural features of the area.

The proposed reconstruction is then discussed in the context of orogen deformation front migration, and deep-seated structural changes of the Alpine retrobelt. Similarities with other precollisional orogens worldwide are then underlined.

ANATOMY AND TECTONO-STRATIGRAPHIC EVOLUTION OF THE SOUTHERN ALPS

Geological and Structural Setting

The southern Alps are the S-vergent retrobelt of the Alpine orogenic belt, juxtaposed to the N-vergent part of the orogen along the Insurbic fault, a major structure active at least since Oligocene times (Schmid et al., 1989; Müller et al., 2001). The southern Alps are divided into two parts by the left-lateral transpressive Giudicarie fault system (Fig. 1). This fault system developed since the Cretaceous along major structures inherited from Permain and Triassic rifting phases (e.g., Castellarin et al., 2006).

Striking differences exist between the eastern and the western sectors of the southern Alps (Fig. 1). The former consists of a very low-grade to nonmetamorphic fold-and-thrust belt, mainly developed since the Oligocene in response to N-S to NW-SE shortening due to Adria indentation beneath the European margin (Castellarin and Cantelli, 2000; Bertelli et al., 2003; Castellarin et al., 2006). Pre-Oligocene deformations were also described by Doglioni (1985) in response to SW-ward propagation of the Dinaric thrusts. In the area between the Giudicarie fault system
Figure 1. Geological setting of the central southern Alps. (A) Location of the central southern Alps in the orogenic belt of the Alps. EA—eastern Alps; WA—western Alps; cSA—central southern Alps. (B) Tectonic map of the central southern Alps with the main tectono-stratigraphic units. (C) Schematic cross section, redrawn and modified after Schönborn (1992); the depth and geometry of the central southern Alps sole thrust beneath the Po Plain are from Pieri and Groppi (1981). CE-A—Cedegolo anticline; GLF—Gole Larghe fault; MA-A—Monte Alto anticline; O-A—Orobic anticline; SSB—Southern Steep belt; TC-A—Trabuchello–Cà Bianca anticline; VVF—Valtorta–Valcanale fault. Some of the magmatic units of the Adamello batholith are abbreviated as CA (Corno Alto) and RdC (Re di Castello). Map is modified after Zanchetta et al. (2013). The age and stratigraphic position of units cited in Figure 1B are represented in detail in the stratigraphic column of Figure 2. J-C—Jurassic–Cretaceous.
and Lake Como, the tectonic style changes, with thrusts that deeply involve pre-Alpine basement units (unit 1 in Fig. 1), now exposed in the most-elevated northern sector (Laubscher, 1985; Blom and Passchier, 1997; Schönborn, 1992; Carminati et al., 1997). Despite the common involvement of basement units, Alpine metamorphism was weaker in the southern Alps than in the Austroalpine units exposed north of the Insubric fault, and it only reached lower-greenschist-facies conditions (Crespi et al., 1982; Spalla et al., 1999; Spalla and Gosso, 1999).

The pre-Alpine basement of the central southern Alps was thrust to the south onto the Permian–Mesozoic cover along the Orobie-Porcile-Gallinera thrust system, which extends E-W for more than 80 km (Fig. 1). South of the Orobie-Porcile-Gallinera thrust system, the central southern Alps form several structural belts, each characterized by a peculiar stratigraphy and tectonic arrangement (Figs. 1 and 2). Directly to the south of the basement units, an array of three basement-corner anticlines, with a dextral en échelon arrangement, occurs (the Orobie anticlines of De Sitter and De Sitter-Koomans [1949] and Schönborn [1992]). These regional folds have WSW-ESE–trending axes and mainly consist of Permian volcanic, volcanioclastic, and siliciclastic rocks, also including Upper Carboniferous (Basal Conglomerate) and Lower Triassic units (Servino and Carniola di Bovegno; Fig. 2; Forcella and Jadoul, 2000; Berra and Siletto, 2006).

Moving southward, thrust sheets made of Lower Triassic to Carnian carbonates are back thrust upon the southern limb of the Orobie anticlines along the Valtorta-Valcanale fault system (Figs. 1B and 1C; Laubscher, 1985; Schönborn, 1992). Another S-dipping fault system (the Clusone fault; Zanchi et al., 1990a) forms the tectonic boundary between the Lower to Middle Triassic thrust sheets and another E-W–trending belt consisting of imbricated Upper Triassic successions (Figs. 1B and 1C). The Upper Triassic units are bounded to the south by the Albino thrust (Fig. 1C), which represents the southernmost exposure of the Norian Dolomia Principale. Farther south, the youngest portion of exposed central southern Alps belt (including the Flessura Pedemontana of Desio, 1929) consists of uppermost Triassic, Jurassic, and Cretaceous units, unconformably covered by the Gonfolite clastic wedge accumulated in the Southalpine foredeep and back thrust (Gonfolite back thrust; Fig. 1B) onto the Mesozoic units during the late Miocene (Garzanti and Malusà, 2008; Malusà et al., 2011a).

The frontal part of the belt, ~50 km wide, is mostly buried below Pliocene to Quaternary clastic sediments of the Po Plain. The belt consists of deformed Cenozoic sediments resting atop of Mesozoic carbonates (Bersezio et al., 2001; Fantoni et al., 2004). The Gonfolite thrust fades out westward, beneath the western Po Plain, in a regional syncline bounded by a N-verging back thrust to the north (Bermoulli et al., 1989; Gelati et al., 1991) and a S-verging thrust to the south (Fantoni et al., 2004). The base of the entire orogenic wedge of the central southern Alps is defined by a major detachment documented by seismic data (Pieri and Groppi, 1981; Schönborn, 1992; Montrasio et al., 1994; Scrocca et al., 2003) that increasingly deepens from the southernmost thrust front toward the Insubric fault (Fig. 1C).
Time Constraints on Alpine Deformation in the Central Southern Alps: A Summary

In the central and eastern parts of the central southern Alps, where basement-cover structures are best preserved and exposed, a straight distinction between Alpine and pre-Alpine deformation has long been established (Milano et al., 1988; Albini et al., 1994; Cadel et al., 1996; Blom and Pascsher, 1997). These studies represent the starting point for the classical reconstruction of the deformation history envisaging two main pre-Alpine synmetamorphic phases (D₁ and D₂; Spalla and Gosso, 1999) followed by two shortening phases that took place during the Alpine orogenesis, involving both basement units and the Upper Paleozoic–Mesoozoic cover. Pre-Alpine structures (mainly extensional detachments and normal to strike-slip faults) related to the Permian and Triassic extensional phases (e.g., Jadoul et al., 1992) are preserved along the Orobie-Porcle-Gallinera thrust system and adjacent areas. They were later involved in Alpine compressional deformation, giving rise to complex structures (Blom and Pascsher, 1997; Fritzscheim et al., 2008).

Two main Alpine deformational events, generally referred to as D₃ and D₄ in previous works (Carminati and Siletto, 2005), can be recognized in the northern sector of the central southern Alps belt, both in the hanging wall and in the footwall of the Orobie-Porcle-Gallinera thrust system (Figs. 1B and 1C).

Brack (1981 and 1984) first noticed that the western units of the Adamello batholith intruded the eastern termination of the Gallinera thrust and the basement-cored Cegedolo anticline (Figs. 1B and 1C). As radiometric data (Del Moro et al., 1983; Villa, 1983) provided a late Eocene intrusion age, Brack (1984) pointed out that a significant amount of shortening in the northern sector of the central southern Alps occurred before the late Eocene. Since then, pre- and post–late Eocene tectonic stages have been distinguished on the basis of crosscutting relationships between magmatic rocks and deformation structures (Brack, 1984). Other constraints have been derived from crystallization ages obtained through various methods (U-Pb on zircon—D’Adda et al., 2011; K-Ar on amphibole—Zanchetta et al., 1990b; Fantoni et al., 1999) from basaltic to anadestic dikes crosscutting Alpine thrust faults and folds, and from ⁴⁰Ar/³⁹Ar dating of pseudotachylites (Meier, 2003; Zanchetta et al., 2011). The ⁴⁰Ar/³⁹Ar data from pseudotachylites of the Orobie-Porcle-Gallinera thrust system confirm the occurrence of Late Cretaceous tectonic activity (Meier, 2003; Zanchetta et al., 2011) related to S- to SE-vergent thrusting since 80 Ma. These data suggest that this first deformational phase likely lasted up to the early middle Eocene, and it thus predated the emplacement of the oldest Adamello units (ca. 42 Ma; Callegari and Brack, 2002, and references within) and the oldest anadestic dikes in the central southern Alps (Bergomi et al., 2015).

In the SW sector of the central southern Alps foreland basin, a NW-SE–trending system of extensional faults postdates the hemipelagic Scaglia Formation (middle Eocene; see Fig. 2) and predates the late Oligocene deposition of the Gofonfite clastic wedge (Fantoni et al., 2004), testifying to a short time interval when tectonic shortening was not active.

Since the early Burdigalian, deformation has also affected the Cenozoic clastic units. Folding and N-vergent back thrusting occurred south of Lake Como (Sciunnach and Tremolada, 2004) and in the Varese-Ticino areas (Bernoulli et al., 1989; Malusà et al., 2011a). Folds and thrusts affecting the Gofonfite clastic wedge are in turn unconformably covered by Messinian (“Ghiaie di Serragno”; Fantoni et al., 2004) and Pleistocene (Felber et al., 1994) fluvial conglomerates and marine sediments that mark the end of late Neogene shortening. Deformation was thus not younger than the Tortonian, at least in the external sector of the central southern Alps, although Schönborn (1992) and Fantoni et al. (2004) have proposed the occurrence of Messinian out-of-sequence thrusting along the exposed front of the belt (“Flessura Pedemontana”).

ANALYTICAL APPROACH

Reconstruction of the Alpine deformation history in the central southern Alps greatly relies on the relationships among basement, post-Carboniferous cover successions, and Cenozoic magmatic rocks. Until now, the structural evolution of the central southern Alps was mainly reconstructed on the basis of data separately collected “in” basement or cover units. Our approach addresses this issue “across” faults, by combining structural and kinematic analyses of major faults, existing radiometric data on fault rocks (Zanchetta et al., 2011) and intrusive dikes (D’Adda et al., 2011; Bergomi et al., 2015), and new apatite fission-track (AFT) data.

We selected several key areas (Fig. 1B) characterized by the occurrence of specific features, such as intrusive bodies showing clear crosscutting relationships with major structures, and rocks suitable for AFT studies (see Table 1 for AFT methods and sample description). Study areas include the Variscan basement, the Orobie anticlines, the Lower to Middle Triassic units, and the Upper Triassic units.

The southernmost exposed part of the central southern Alps, south of the Albino thrust (Figs. 1B and 1C), was not investigated due to the lack of Cenozoic magmatic rocks and the unfavorable rock types for AFT dating. Moreover, vitrinite reflectance data on post-Toarcian rocks indicate that organic matter never reached a temperature within the oil window in that area (Berszio and Bellentani, 1997); therefore, detrital apatites were probably not reset.

Regional Alpine thrusts mapped in previous works (D’Adda and Zanchetta, 2015; Ghiselli et al., 2015) were further investigated to assess their relationships with ductile deformations recorded in the overriding basement units (areas 1, 2, and 6 of Fig. 1B) and Cenozoic intrusives (area 7 of Fig. 1B). The allochthonous Lower Triassic to Carnian carbonate units (areas 3 and 5 in Fig. 1B) and the Upper Triassic units (area 4 in Fig. 1B) were also analyzed.

RESULTS

We illustrate here the relative chronology of Alpine deformation based on our structural and AFT data from the central southern Alps. In de-
scribing the deformational events, we adopted the classical distinction between pre-Alpine (D1 and D2) and Alpine phases, and between a “pre-Adamello” (Late Cretaceous–middle Eocene, from D4 onward) and a “post-Adamello” (late Eocene–Miocene, from D3 onward) stage.

**Structural Analysis**

**First Pre-Adamello Compressional Stage (D3a)**

The oldest structures related to the early compressional history in the central southern Alps are the Orobic-Porcle-Gallinera thrust system and associated folds in basement and cover units.

Open to closed chevron folds (Figs. 3C, 3D, 4A, 4B, 5A, and 5B) with no axial planar foliation occur in the basement (areas 1, 2, 6, 8, and 9 in Fig. 1B) in association with S-vergent shear zones characterized by mylonitic to cataclastic fabrics. A N- to NW-dipping foliation (Figs. 3D and 5A) pervasive slaty cleavage formed parallel to the axial plane of folds in the footwall of the Orobic-Porcle-Gallinera thrust system in the Permian-Collio Formation, the Verrucano Lombarbi, and the Lower Triassic Servino Formation (Figs. 2, 4C, and 4D).

Structural analysis performed within the basement and Permian to Lower Triassic cover successions (areas 1, 2, 6, 8, and 9 in Fig. 1B) indicates N-S shortening during this early Alpine deformation. Also within unit 3 (Lower to Middle Triassic), kinematic data along thrust zones and folds affecting mainly carbonate cover (Fig. 3A) show a similar southwest direction of tectonic transport during this stage.

The Variscan basement (unit 1), in the hanging wall of the Orobic thrust (area 2 in Fig. 1B), is characterized by the occurrence of open to tight folds with N- to NW-dipping fold axes. These folds have been ascribed to Alpine deformation (Carminati and Siletto, 2005). In area 2, however, the folds deviate from the dominant orientation (NE-SW–to E-W–striking fold axes) observed in other areas of the central southern Alps. Field structural analyses suggest that such folds predate the mylonites formed along the Orobic and Porcle thrusts (Figs. 3D and 5C), as mylonitic foliations crosscut and partially transpose these folds. The greenschist-facies mylonitic foliation and later brittle structures within the basement can be geometrically associated with folding and with the development of an axial planar cleavage in the Permian–Triassic cover successions, here exposed in the footwall of the Orobic thrust. We ascribe the mylonites and the S-vergent folds observed in the cover rocks to an early D1 phase (D1a in our reconstruction). At present, no reliable data exist concerning the Alpine versus pre-Alpine (Ghiselli et al., 2015) age of folds with N- to NW-plunging fold axes predating the Orobic thrust.

The transition from plastic (mylonites and folding in cover rocks) to brittle deformation (faulting and formation of pseudotachylites) along the Orobic-Porcle-Gallinera thrust system resulted in a strong cataclastic overprint on the existing fabrics, often associated with friction-induced melting of fault rocks. Pseudotachylytes were also found in the eastern portion (faulting and formation of pseudotachylytes) along the Orobic and Porcle thrusts (Figs. 3C, 3D, and 5C), as mylonitic foliations crosscut and partially transpose these folds. The greenschist-facies mylonitic foliation and later brittle structures within the basement can be geometrically associated with folding and with the development of an axial planar cleavage in the Permian-Triassic cover successions, here exposed in the footwall of the Orobic thrust. We ascribe the mylonites and the S-vergent folds observed in the cover rocks to an early D1 phase (D1a in our reconstruction). At present, no reliable data exist concerning the Alpine versus pre-Alpine (Ghiselli et al., 2015) age of folds with N- to NW-plunging fold axes predating the Orobic thrust.

A later deformation stage (D3b) involved deeper structural levels of the central southern Alps belt prior to Adamello batholith intrusion, and it displays a different deformational style. This event was likely related to the southward propagation and wedging of the Orobic anticlines beneath the previously formed thrust sheets.

**Second Pre-Adamello Compressional Stage (D3b)**

A later deformation stage (D3b) involved deeper structural levels of the central southern Alps belt prior to Adamello batholith intrusion, and it displays a different deformational style. This event was likely related to the southward propagation and wedging of the Orobic anticlines beneath the previously formed thrust sheets.

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**Note:** Sample coordinates are in the Gauss-Boaga reference system.
Evolution of the Southalpine retrobelt

Figure 3. (A) Mesoscopic structural data from area 5 (Presolana). a1—S-verging drag folds in the Wengen Formation, hanging wall of the main thrusts within the Lower to Middle Triassic succession (unit 3); a2—S-verging folds in unit 3; a3—Alpine thrust faults crosscutting calc-mylonites along the main thrust zones; a4—conjugate secondary faults measured in the Presolana thrust stack. (B) Regional E-W–trending thrust-related folds in area 3. The Branchino fold is a S-verging footwall syncline south of the Valtorta-Valcanale fault. The Vaccaro syncline is an E-W overturned kilometer-scale syncline in the hanging wall of the Arera thrust sheet. (C) Alpine structures in the basement of the southern Alps (area 9, Venina and Scais valleys). In the Scais area, these folds are crosscut by andesitic dikes. (D) Mesoscopic data from area 2 (San Marco and San Simone Pass). d1—from left to right: greenschist-facies mylonitic foliation along the Orobic thrust fault zone, faults in the hanging wall along the Orobic thrust, pseudotachylites along the main thrust zone, post-D3 shear planes crosscutting at low angle previous structures. d2—from left to right: faults in the hanging wall along the Orobic thrust, strike-slip faults in the Collio Formation, forming a duplex in the footwall of a minor thrust (for structural map of this area, see D’Adda and Zanchetta, 2015), post-D3 shear planes crosscutting at low angle previous structures, structures in the Triassic units exposed in the footwall of the Orobic thrust. All projections are equal area, lower hemisphere. Sa—poles to axial plane cleavage; Pa—poles to fold axial planes; Sb—poles to bedding; Aa—fold axes; faults are represented as great circles with striations and sense of motion. Data from the San Marco Pass area are after Zanchetta et al. (2011).
Figure 4. (A) Alpine D$_3$ folds in mica schists of the central southern Alps basement, area 9, Val Venina; D$_3$ folds refold D$_2$ folds of Variscan age. (B) D$_3$ folds within paragneiss in the central southern Alps basement unit bounded by the Porcile thrust to the north and the Orobic thrust to the south, NW corner of area 2. (C) D$_3$ folds associated with slaty cleavage (subparallel to the pencil) development in the siliciclastic levels of the Collio Formation, area 6, Lake Barbellino. (D) D$_{3a}$ thrust-related folds in the Collio Formation, tight chevron-type D$_3$ folds developed in the footwall of the Orobic thrust, area 6. (E–F) Fault rocks along the Orobic thrust fault zone in area 6. (G) Andesitic dike (area 9) crosscutting D$_3$ folds in the Variscan basement of the central southern Alps. (H) Curò andesitic dike (sample CU1, area 6) crosscutting D$_3$ cleavage in the Collio Formation. The orientation of each photo is indicated in the lower-left corner.
Evolution of the Southalpine retrobelt

**Area 6: Lake Barbellino**
- a1: Orobic Thrust: Rif. Curò
- a2: Orobic Thrust: River Serio
- a3: Orobic Thrust: Loc. Simba
- a4: D, basement: Lake Gelt3
- a5: D in the Basal Conglomerate3
- a6: D in the Collio Fm.
- a7: Gallinera Thrust
- a8: D, transpression: Lake Gelt
- a9: Late thrust faults: post-CU1 dike

**Area 1: Biandino Valley**
- Orobic Thrust: faults
- Gallinera Thrust
- pseudotachylytes

**Area 7: Gallinera Valley**
- d1: Gallinera Thrust (D3 faults)
- d2: Gallinera Thrust (D4 faults)
- d3: Gole Strette Fault
- c1: Mylonites
- c2: Brittle thrust - basement
- c3: Brittle thrust - Verrucano
- c4: Mylonites
- c5: Casera lakes
- c6: Portorella pass

**Area 8: Porcile Thrust**
- c1: Mylonites
- c2: Brittle thrust - basement
- c3: Brittle thrust - Verrucano
- pseudotachylytes
- c4: Mylonites
- c5: Casera lakes
- c6: Portorella pass

**Figure 5.** (A) Mesoscopic data of Alpine structures in area 6 (upper Serio Valley) along inverted Permian normal faults related to the Collio basins (a1, a2, a3; see Fig. 6 for location), Alpine folds and foliations in the basement and cover (a4, a5, a6), oblique reverse dextral faults along the Gallinera thrust (a7, a8), and small reverse faults crosscutting a Cenozoic dike at Lake Gelt (a9). (B) Reverse faults and pseudotachylytes at Bocca di Trona, upper Biandino Valley (area 1). Left-lateral motions follow in time the main dip-slip thrust motions. Bedding refers to Verrucano Lombardo and Servino in the footwall of the main fault. (C) Mesoscopic data along the Porcile thrust zone in the SW sector of area 8 (between Porcile lakes and Val Madre) measured in the basement (c1, c2; after Zanchetta et al., 2011) and the sedimentary cover in the footwall (c3). Structural data and fault slip data of the Porcile thrust in the NE corner of area 8: c4—mylonites along the Porcile thrust; c5—fault data and mesoscopic structures at Casera lakes measured in the sedimentary cover along the footwall of the Porcile thrust (Verrucano Lombardo and Servino Formations); c6—cataclastic foliation and shear zones at Portorella Pass, at the core of the fault zone. (D) Equal-area, lower-hemisphere stereographic projections of structural data and fault slip data of the Gallinera thrust, area 7: d1—fault data of the Gallinera thrust in the basement (hanging wall); d2—dextral transpressive reactivation of the Gallinera thrust, measurement from the Gallinera valley; d3—fault data of the Gole Strette fault. Aa3—fold axes of deformation phase D3; Pa3—axial planes of folds of deformation phase D3; S3—stratigraphic surfaces; S3—that foliation of deformation phase D3 in basement units; SA3—axial plane schistosity of deformation phase D3; Uc3—ultracataclasite bands related to D3 thrusting.
Figure 6. (A) Simplified geological map of the Barbellino area (area 6, Fig. 1). In this area, Alpine shortening interplayed with preexisting Permian normal faults, giving rise to a complex tectonic setting, where young-over-old thrusts frequently occur. (B) Separation diagram constructed for the Vacca thrust (segment of the Orobic-Porcile-Gallinera thrust system) from River Serio (SW) to Lake Barbellino (NE). (C) Cross sections along the Orobic-Porcile-Gallinera thrust system showing the structural relationships between hanging-wall and footwall units along the thrust. Fold geometry in the basement is based on field data along profile B–B′ and D–D′, where interleaved orthogneiss lenses have been used as structural markers. Fold geometry along the other profiles has been traced in order to give an idea of the deformation style and fold vergence.
along the Valtorta-Valcanale fault in the forelimb of the Orobic anticlines (Fig. 7). Regional tilting of thrust planes is also evident farther south, as all the main thrust surfaces gently dip to the south across the whole study area (Fig. 1C).

Folded thrusts, formed during the D<sub>3</sub> phase, occur spectacularly in area 3 (Fig. 7), where older thrust surfaces are folded and dip southward below the Clusone fault, along which Upper Triassic strata have been back thrust onto Middle Triassic strata. Such peculiar structures were likely induced by the southward propagation of deep thrust surfaces that underlie the Orobic anticlines (Zanchi et al., 2012).

Steepening of the older Late Cretaceous reverse fault systems in areas 2 and 6 can be related to the same reactivation of these deep thrust surfaces. Late Paleocene to middle Eocene ages (56.4 ± 1.1–43.4 ± 2.1 Ma) yielded by pseudotachylite veins along the Orobic and the Porcile thrusts (Zanchetta et al., 2011) point to a reactivation of these faults, also after the Late Cretaceous.

We interpret the Valtorta-Valcanale fault system and the Clusone faults as back thrusts (Figs. 1C, 8, and 9), following the interpretation of Schönborn (1992), who considered the Orobic anticlines as compressional rather than wrench-related structures. Some lines of evidence supporting this hypothesis are: the perfect wrench-related structures. Some lines of evidence indicate a strong r<sub>amaté</sub>u de tectonic activity since the Oligocene, i.e., during the late stages or shortly after the intrusion of the Adamello batholith, as also suggested by significant deformations along the Insubric and Giudicaric faults (Martin et al., 1991; John and Blundy, 1993; Stipp et al., 2004; Garzanti and Malusà, 2008). This tectonic event postdates the thrust-related folds in the northern part of the central southern Alps, the growth of the Orobic anticlines, and the southward to southeastward thrusting along the Orobic-Porcile-Gallinera thrust system.

The northern portion of the central southern Alps also shows evidence of important reactivations along previous fault zones during this stage. Rotated and steepened mylonitic to ultracataclastic shear zones active during the D<sub>3</sub> and D<sub>4</sub> phases are crosscut by brittle shear planes ascribed to the D<sub>5</sub> deformational event (Fig. 3D, area 2), together with a spaced disjunctive cleavage cutting the D<sub>3</sub>b fabrics (Albini et al., 1994; Carminati and Siletto, 2005). Our meso-scale analyses along these fault zones point to mainly dextral oblique and strike-slip motions along the major thrust zones. The Orobic thrust is crosscut by a complex pattern of right- and left-lateral strike-slip faults in area 2 (Figs. 1B and 3D), whereas left-lateral faults dominate in area 1 (Figs. 1B and 5B). Dip-slip reverse motions suggesting NW-SE shortening, and mixed populations of reverse and dextral reverse faults (Fig. 5C) crosscutting older cataclastic and mylonitic shear zones characterize the evolution of the eastern segment of the ENE-WSW Porcile Line. Reverse dip-slip and oblique reverse dex-

**Figure 7.** Cross sections through the southern limb of the Trabuchello–Cà Bianca anticline and the Lower to Middle Triassic units of the central southern Alps, depicting the relationships among the older thrust surfaces, the anticline, and the back thrust of the Valtorta-Valcanale fault system. See Figure 1 for cross-section traces. Geological-structural data used for cross sections derive from original field work and published maps (Jadoul et al., 2012).

An—Angolo Limestone; Bo—Carniola di Bovegno; Br—Breno Formation; Bu—Buchenstein Formation; CÀr—Monte Cà Bianca rhyolite;Cb—Basal Conglomerate; Cr—Castro Sebino Formation; Cs—Collio sediments; Cv—Collio volcanics; Dp—Dolomia Principale; Dz—Dolomie Zonate; Es—Esino Limestone; Go—Gorno Formation; Mt—Mettaliferous Limestone; Lo—Lozio shale; Pr—Prezzo Limestone; SE—Edolo Schists (Variscan basement); Sg—San Giovanni Formation; Sv—Servino; Vr—Verrucano Lombardo; Wn—Wengen Formation; Zo—Zorzino Limestone.
Figure 8. Tectonic map of the central southern Alps (cSA) with the location and apatite fission-track (AFT) ages of the measured samples. The Upper Triassic units display identical ages within error, suggesting exhumation above ~2 km during the Bartonian. Lower to Middle Triassic units (samples VZ1 and VZ2) were exhumed later, close to the Oligocene-Miocene boundary. In the northern sector of the central southern Alps, the Orobic anticlines and the Variscan basement were progressively exhumed through the apatite partial annealing zone since the Bartonian. AD—Adamello batholith; BG—Bergell pluton; CE-A—Cedegolo anticline; MA-A—Monte Alto anticline; O-A—Orobic anticline; TC-A—Trabuchello–Cà Bianca anticline; VVF—Valtorta-Valcanale fault; WA—western Alps; EA—eastern Alps.

Figure 9. Schematic cross section of the central southern Alps (cSA) along the A–A′ and B–B′ traces (Fig. 8). Apatite fission-track (AFT) ages are displayed together with intrusion U-Pb ages of basic and intermediate dikes (Bergomi et al., 2015). BG—Bergell Tonalite; SSB—Southern Steep belt. Figure is modified after Zanchetta et al. (2013).
eral faults (Fig. 5A) occur in area 6 (Fig. 1B), major along splays of the Gallinera thrust. In this area, crosscutting relationships between older high-angle brittle-ductile shear zones and the younger brittle oblique faults are particularly evident.

Dextral strike-slip faults cut older fabrics along the Gallinera fault system within the Adamello batholith (Gallinera Pass; area 7 in Fig. 1B). This fault zone directly merges into the Gole Strette fault, which cuts across the West Adamello close to its contact with the Avio unit. The Gole Strette fault is a splay of the Gole Larghe fault zone (Di Toro and Pennacchioni, 2005), which also shows the same kinematics and merges to the west into the Insubric fault. Dextral strike-slip fault populations with minor reverse and normal components have been measured (Fig. 5D) west of Gole Strette Pass and are particularly evident.

The younger brittle oblique faults are described in the vicinity of the Insubric thrust also NE of the Giudicarie fault system, in the eastern Alps (Aglardi et al., 2009; Bargossi et al., 2010).

Apatite Fission-Track Data

Low-temperature thermochronology data may provide useful time constraints to tectonic activity (e.g., Malusà et al., 2006, 2009). However, in the central southern Alps, such data are only available for the Upper Eocene-Lower Oligocene intrusive units (e.g., Reverman et al., 2012) and are virtually lacking in their country rocks, with very few data reported in Bertotti et al. (1999) and in Viola (2000). Available AFT data in the study area (Viola, 2000; Reverman et al., 2012) are chiefly related to the Insubric fault, and these yielded middle-late Miocene ages ascribed to erosional exhumation during transpressional activity along this structure (Viola, 2000; Stipp et al., 2004) and the nearby Giudicarie fault ("Giudicarie phase" in Martin et al., 1998).

In order to complement the existing data set, we collected additional samples for AFT analyses from Cenozoic basaltic to andesitic dikes and stocks showing clear crosscutting relationships with D1 structures. We additionally collected basement and cover rock samples along a N-S transect orthogonal to the Oroblitic thrust (San Marco pass, area 2, along section A-A' in Fig. 1B). Details on sample locations are summarized in Table 1. Results of AFT analysis are reported in Table 2.

Following the structural scheme depicted in Figure 1, analyzed AFT samples belong to unit 1 (Variscan basement in the hanging wall of the Oroblitic-Porcelain-Gallinera thrust system), unit 2 (basement-cored Oroblitic anticlines), and unit 3 (allochthonous Lower Triassic-Carnian units). Samples belonging to unit 4 (from D’Adda et al., 2011) were collected from Eocene magmatic rocks. When interpreted within the conceptual geochronological model for magmatic complexes illustrated in Malusà et al. (2011a), AFT data indicate that dikes were intruded above the partial annealing zone (PAZ of Gleadow and Duddy, 1981) of the AFT system, because AFT ages are indistinguishable (within error) from U-Pb ages yielded by magmatic zircons hosted in the same rocks (D’Adda et al., 2011; Bergomi et al., 2015). Assuming a paleogeothermal gradient of 30°C/km (cf. Malusà et al., 2006), the inferred intrusion depth was thus shallower than 2–3 km.

Unit 3, consisting of Lower Triassic to Carnian rocks, is bounded to the north by the Valtorta-Valcanale fault system and to the south by the Clusone fault. Samples VZ1 and VZ2, deriving from andesitic dikes (Table 2; Figs. 8 and 9), display younger AFT ages (VZ1: 25.0 ± 1.9 Ma; VZ2: 24.3 ± 1.7 Ma) than U-Pb ages yielded by magmatic zircon in the same rocks (ca. 42 Ma; D’Adda et al., 2011; Bergomi et al., 2015). Therefore, these dikes were intruded within or below the apatite PAZ (Malusà et al., 2011a).

Samples from the Variscan basement in the hanging wall of the Oroblitic-Porcelain-Gallinera thrust system yielded AFT ages of 24.4...
Time-Temperature Paths

The time-temperature paths derived from modeling of confined track-length distributions are shown in Figure 10A (see Table 2 for raw data). These paths refer to samples from unit 3 (VZ1 and VZ2), from the San Marco Pass transect (MOR3, MOR2, FIOR1, MOR1, SRV1, SE1), and from the basement of unit 1 (CU1b). Results show two well-defined cooling pulses: a Burdigalian pulse recorded by the Lower-Middle Triassic rocks of unit 3 (samples VZ1 and VZ2 in Fig. 10A), and a younger pulse (Tortonian) consistently recorded by samples from different elevations in the northern units (Orobic anticlines and Variscan basement). This later cooling pulse was not recorded by the southern units, because they were already exhumed above the PAZ of the AFT system at that time.

Figure 10B illustrates a possible erosional evolution that is simultaneously consistent with both the thermal histories of samples from the Orobic thrust hanging wall (MOR3, MOR2, FIOR1, MOR1) and with available geological constraints pointing to a Tortonian tectonic phase in the central southern Alps (Fig. 11). The thermal evolution under an erosive topography shown in Figure 10B was modeled with the program TERRA (Ehlers et al., 2005) according to a steady-state two-dimensional (2-D) advection-diffusion equation. The wavelength and amplitude of the topographic surface were derived from the elevation profile along the study transect, as the drainage network in the study area was already established in Oligocene times (Garzanti and Malusà, 2008). According to AFT data, all of the samples in the hanging wall of the Orobic thrust still resided within the apatite PAZ in the middle Miocene (first stage of Fig. 10B), when erosion rates were on the order of 0.1 km/m.y. Relatively fast erosion (1 km/m.y.) during the Tortonian tectonic phase was responsible for heat advection and upward motion of isothermal surfaces (second stage in Fig. 10B), followed by thermal relaxation since 7 Ma, when erosion rates slowed down to 0.2 km/m.y. (third stage in Fig. 10B). Such a thermal reequilibration is consistently recorded by fast cooling in samples from different elevation, as illustrated by the time-temperature paths in Figure 10A.

DISCUSSION

Early Evolution of the Central Southern Alps

Reactivation of inherited structures and pervasive basement folding took place in the central southern Alps during the earliest stages of Alpine compression. According to Laubscher (1985) and Schönborn (1992), this early Alpine compressive event led to the emplacement of the Orobic thrust sheet (thrust system 1 in Schönborn, 1992), including basement and Lower to Middle Triassic units. Both basement and cover rocks were thrust southward, forming an imbricate thrust stack.

This long-lasting compressive phase was Late Cretaceous in age (80–68 Ma), as indicated by 40Ar/39Ar dating of fault-related pseudotachylites along the Orobic and Porcile thrusts (Meier, 2003; Zanchetta et al., 2011). Most of the Lower to Middle Triassic imbricates between the Valtorta-Valcanale and Clusone faults (Figs. 1B and 1B) were possibly stacked southward during this phase following a break-forward thrusting sequence (D’Adda et al., 2011; Zanchetta et al., 2012). Evidence for thrust stacking south of the Clusone fault was recently suggested by the occurrence of Upper Triassic klippen that have been related to the oldest stages of thrust emplacement (area 4; for details, see D’Adda et al., 2011).

Close to the basement-cover boundary along the northern margin of the easternmost of the Orobic anticlines (TC-A in Fig. 8), the early Alpine deformation was strongly influenced by the structural grain inherited from the Permian to Middle Jurassic tectonic evolution of the Adria margin (Milano et al., 1988; Bertotti et al., 1993a, 1993b, Albini et al., 1994; Cadel et al., 1996; Blom and Passchier, 1997). ENE-WSW to N-S-striking extensional faults, which controlled the tectono-stratigraphic evolution of the Collio basins since the Early Permian (Cadel et al., 1996; Cassignis et al., 2008), were inverted during Alpine convergence, thus explaining the structural complexity of the eastern part of the central southern Alps belt. Evidence of complete to partial inversion of Permian extensional faults is illustrated in area 6 (Fig. 1B) by the systematic analysis of the vertical throw along one branch of the Orobic-Porcile-Gallinera thrust system (Fig. 6), which highlights an incomplete progressive inversion of a Permian normal fault that was part of a fault system originally bounding the basins in which the Permian volcanoclastic succession was deposited.

Folding in basement and cover rocks associated with an axial planar cleavage in the sedimentary successions, and S-vergent thrusting along the Orobic-Porcile-Gallinera thrust system also occurred during the D3 phase. The D3 event has been already considered pre- to syn-thrusting (Carminati and Siletto, 2005), marking the transition from plastic to brittle deformation during Alpine shortening.

The oldest pseudotachylite ages (80–68 Ma; Zanchetta et al., 2011) in the San Marco Pass area constrain the onset of fault activity along the Orobic and Porcile thrust to the Late Cretaceous (area 2 in Fig. 1B). Microstructural analysis of deformation processes along fault planes attests that pseudotachylites and cataclasis postdate greenschist-facies mylonites. Zircon fission-track data from the Southalpine basement west to the Giudicarie Line (99–92 Ma; Viola, 2000) suggest a Cenomanian age for basement exhumation above 7–8 km, under the assumption of a 30 °C/km paleogeothermal gradient (Malusà et al., 2009, their Fig. 3). Because pseudotachylites along the Orobic thrust were formed under brittle conditions, they must postdate basement exhumation above the zircon PAZ.

Indirect evidence of the D3 tectonic stage in the Southalpine foredeep is the deposition of the Cenomanian to Campanian turbiditic successions of the Lombardian Flysch (Duglioni and Bosellini, 1987). Petrographic analyses on these turbidites indicate an orogenic provenance (Bernoulli and Winkler, 1990; Bersezio et al., 1993), including both basement and sedimentary cover sources (Figs. 11 and 12). These features are consistent with a tectonic scenario of a growing orogenic wedge involving Adria-derived basement and cover units since the Late Cretaceous (Zanchetta et al., 2012).

A second deformation phase (D4) involved deeper structural levels, leading to the southward propagation of the Orobic antcline system. The northward back thrusting along the Valtorta-Valcanale and Clusone faults, together with the tilting of the imbricated Middle Triassic carbonate units (Fig. 9), is ascribed to this second deformation phase. AFT data from the footwall of the Orobic thrust indicate that the northern limb of the Orobic antcline was exhumed above the apatite PAZ in the late Eocene (sample SRV1: 32.5 ± 4.8 Ma). Therefore, the Orobic anticlines were structured at crustal levels deeper than the apatite PAZ before the late Eocene. No differen-
Figure 10. (A) Time-temperature paths, modeled with HeFTy (Ketcham, 2005), based on apatite fission-track (AFT) age and track-length distribution with no additional external constraint; the best-fit path (thick black line) is only valid inside the partial annealing zone (PAZ), where it is marked by a continuous line; the gray area is the envelope of the good-fit paths (GOF—goodness of fit). MTL—mean track length; SD—standard deviation. (B) Isotherm evolution under an eroding topography, calculated with the program TERRA (Ehlers et al., 2005) according to a steady-state two-dimensional (2-D) advection-diffusion equation. Wavelength and amplitude are according to transects in Figures 1 and 8. Input values: surface temperature = 2 °C; lithosphere base temperature = 1350 °C; lithosphere base depth = 110 km; surface temperature lapse rate = 0.005 °C/m; diffusivity = 10^-6 m^2 s^-1; surface volumetric heat production = 10^-6 W m^-3; specific heat = 900 J kg^-1 K^-1; density of the crust = 2.7 kg m^-3; near-surface geothermal gradient = 30 °C km^-1; thermal conductivity = 3.61 W m^-1 K^-1.
Figure 11. (A) Synoptic table of the geochronological and tectono-stratigraphic constraints on the Alpine evolution of the central southern Alps. (B) Cartoon of the paleogeographic evolution of the Alps area since the Late Cretaceous (modified after Malusà et al., 2015a, 2015b). Purple points and arrows represent Africa motion relative to Europe at different times (numbers are Ma) following Dewey et al. (1989). AA—Aar-Gotthard; AG—Argentera; MB—Mont Blanc; PE—Pelvoux. References in are as follows: 1—Zanchetta et al. (2011); 2—Müller et al. (2001); 3—Meier (2003); 4—Villa (1983); 5—Del Moro et al. (1983); 6—Hansmann and Oberli (1991); 7—von Blanckenburg (1992); 8—Hansmann (1996); 9—D’Adda et al. (2011); 10—Bergomi et al. (2015); 11—Fantoni et al. (1999); 12—Bersezio and Fornaciari (1988); 13—Bersezio and Fornaciari (1994); 14—Gelati et al. (1988); 15—Elter et al. (1999); 16—Di Giulio et al. (2001); 17—Doglioni and Bosellini (1987); 18—Fantoni et al. (2004); 19—Sciunnach and Tremolada (2004); 20—Bernoulli et al. (1989); 21—Felber et al. (1994); 22—Roure et al. (1990).
Evolution of the Southalpine retrobelt

Figure 12. Tectonic evolution of the central southern Alps (cSA) in the frame of Alpine orogenesis. The evolution of the frontal wedge is largely based on the reconstruction by Malusà et al. (2015b). Purple points and arrows represent Africa motion relative to Europe at different times (numbers are Ma) following Dewey et al. (1989). Ad—Adamello batholith; AT—Alpine Tethys; AU—Austroalpine units; Bg—Bergell Tonalite; Bi—Biella volcanic suite; BS—central southern Alps basement; CF—Clusone fault; IF—Insubric fault; O-A—Orobic anticlines; PF—Periadriatic fault; Rs—Rensen and Riesenferner plutons; SB—subduction front; Ss—Sesia ultrapotassic dikes; TB—Tyrrhenian basin; VVF—Valtorta-Valcanale fault. AFT—apatite fission track; FTB—fold-and-thrust belt.
tial exhumation is observed between the Orobi anticlines and the basement rocks north of the Orobi thrust (unit 1 in Fig. 1B).

In the eastern sector of the central southern Alps, the Re di Castello and Western Adamello magmatic units intruded the Cedegolo anticline at a depth of 5–6 km (John and Blundy, 1993) during the 40–35 Ma time interval (Callegari and Brack, 2002, and references therein). The regional fold axes of the Orobi anticlines gently plunge to the southwest. This structure results in a deeper structural level exposed at the eastern termination of the Cedegolo anticline, at the contact with the Adamello batholith. Exhumation of the Cedegolo anticline may thus be considered broadly coeval with the exhumation of the Orobi anticline farther west. The $^{40}\text{Ar}/^{39}\text{Ar}$ dating of pseudotachylites along the Orobic and Porcile thrusts (Zanchetta et al., 2011) displays, in addition to Late Cretaceous ages, an age cluster at 55–43 Ma (Fig. 11), which may be ascribed to $D_9$ reactivation of the thrust system during the formation of the Orobi anticlines.

The oldest AFT ages found in the central southern Alps are from the central-southern part of the belt, where 42–30 Ma dikes crosscut major thrust surfaces in the thrust stacks consisting of Lower Triassic–Carnian units (areas 3 and 4 in Fig. 1B; Fig. 12). Fission-track ages obtained on magmatic apatites separated from the dikes (D’Adda et al., 2011) are virtually indistinguishable from U-Pb ages on zircon grains from the same rocks (Bergomi et al., 2015), suggesting that intrusion occurred in country rocks already exhumed above the PAZ of the AFT system (2–4 km depth; Malusà et al., 2011a). The frontal part of the central southern Alps north of the Albino thrust (units 4 and 5 in Fig. 1B) has been thus largely exhumed above the apatite PAZ since the Bartonian. Therefore, the presently exposed central southern Alps belt was largely structured and exhumed in pre–late Eocene times (Figs. 9 and 12), and most crustal shortening and thrust stacking were accomplished during the pre-Adamello $D_9$ and $D_{10}$ phases.

Indirect evidence of the time lapse that occurred between $D_9$ and $D_{10}$ may be found in the sedimentation history of the Southalpine foredeep. The sedimentary record shows a starved stage from the latest Cretaceous up to the early Eocene (Bersezio et al., 1993; Di Giulio et al., 2001). Both in the Lombardian basin and in the Giudicarie area, the up to 2000-m-thick Cretaceous turbiditic succession was followed by hemipelagic sedimentation (Scaglia and Scaglia Rossa Formations; Fig. 2; Doglioni and Bozellini, 1987). This kind of sedimentation could be related to a relative tectonic quiescence, in the absence of uplift and exhumation in response to crustal shortening (Fig. 11). An extensional tectonic regime is recorded in the western Po Plain during this period (Di Giulio et al., 2001).

### Late Evolution, Exhumation, and Unroofing of the Central Southern Alps

The central southern Alps foreland belt buried beneath the Po Plain (the Milano belt Austratum) was chiefly structured during the $D_9$ compressional phase, when the deformation front migrated 30 km southward (Figs. 9 and 12), and the belt developed with a break-forward sequence in the footwall of the southern-most exposed structures, i.e., south of the Albino thrust (Figs. 1 and 9) and of the pre-Alps foothills (Flessura Pedemontana). Seismic data locate the basal décollement of the Milano belt, also representing the sole thrust of the central southern Alps orogenic wedge, within the Carnian units beneath the Dolomia Principale (Figs. 2 and 9; Schönborn, 1992; Fantoni et al., 2004; Ravaglia et al., 2006). Décollement localization was controlled by the rheological behavior of the sedimentary succession, as also observed farther north (Berra and Siletto, 2006) in unit 3 and unit 4 (Fig. 1). Deformation in the buried frontal belt is documented until the Tortonian, and it involved the Cenozoic elastic wedge (Gelati et al., 1991; Fantoni et al., 2004; Malusà et al., 2011b). The already structured northern sector of the central southern Alps was poorly involved in this deformation phase and was passively transported toward the south, leading to an out-of-sequence reactivation of early structures along the Flessura Pedemontana at the end of the Miocene (Schönborn, 1992; Fantoni et al., 2004).

Postcollisional exhumation of Adria beneath the orogenic wedge was accompanied on the northern side of the central southern Alps by the Insurbic fault (Schmidt et al., 1989; Stipp et al., 2004), leading to the exhumation and back thrusting of the central Alps nappe pile (including the Leponine Dome and the Bergell pluton) within a dextral transpressional regime (Garzanti and Malusà, 2008; Malusà et al., 2011b). The effects of such dextral transpression are also observed in the central southern Alps. Dextral strike-slip motion is documented in fact both along the Orobic-Porcile-Gallinera thrust system and the Tonale segment of the Insurbic fault, during the intrusion of the northern Adamello magmatic units (Martin et al., 1991; Stipp et al., 2004). The post-Eocene vertical throw accommodated by the Orobic-Porcile-Gallinera thrust system cannot be resolved by using thermal chronological data, and it is possibly negligible, as these structures were chiefly reactivated as strike-slip or transpressional faults.

AFT data show that exhumation of the major units of the central southern Alps was diachronous, and of decreasing amount toward the south (Figs. 8 and 9). Structural units in the south were already exhumed by the Eocene; the Lower Triassic unit 3 records an exhumation pulse of Burdigalian age, whereas the northern units 1 and Unit 2 were exhumed in the Tortonian. Rapid late Neogene cooling is documented not only in the study area, but also in nearby areas such as those in the Adamello region and north of the Insurbic fault (Martin et al., 1998; Viola, 2000; Reverman et al., 2012).

Because the Tortonian exhumation is only observed in the northern sector of the central southern Alps but did not take place to the south, a climatic trigger (Willett et al., 2006) can be ruled out. Data presented in this work favor instead a prominent tectonic control on erosion, as also demonstrated by recent AFT data from the Northern Apennines (Malusà and Balestrieri, 2012). We propose that uplift and erosion of the central southern Alps basement north of the Orobic-Porcile-Gallinera thrust system was possibly linked to the progressive indentation of Adria lithosphere beneath the Cretaceous wedge.

The pre-Tortonian thermal history of the central southern Alps strongly differs from that experienced by other parts of the Alps retrobelt. East of the Giudicarie fault system, in the Dolomites area, the basement in the hanging wall of the Valsugana thrust recorded an exhumation pulse around 10 Ma (Zattin et al., 2003; Zattin et al., 2006), with the entire Dolomites area being exposed to subaerial erosion from the Serravallian onward. The Cretaceous orogeny that shaped the central southern Alps belt was related in the eastern southern Alps to dramatic changes in basin sedimentation and configuration (e.g., Doglioni, 1985), but it was not accompanied by significant shortening or exhumation. Compressional deformation is recorded in the eastern southern Alps only from the middle to late Miocene onward (Zattin et al., 2006).

### Central Southern Alps as a Precollisional Orogen

The central southern Alps thick-skinned fold-and-thrust belt has been active since the Late Cretaceous and was structured well before Adria-Europe continental collision (Fig. 12A). With the early subduction of the Alpine Tethys, the broadly S- to SE-directed Cretaceous subduction beneath the Africa-Adria margin promoted a doubly vergent orogenic wedge (Zanchetta et al., 2012; Malusà et al., 2015b).
As a fold-and-thrust belt developed in the Alps retrodeformed, the central southern Alps would be expected to grow following propagation of the central southern Alps with literature data from chronologic analyses from key areas of the central southern Alps belt. We de- mocranium age, is ascribed to the southward thrusting and fault-rock ages constrain this deformation phase to the early to middle Eocene.

Our low-temperature thermochronologi- cal data combined with available geochrono- logical data on fault rocks and intrusion ages of magmatic rocks demonstrate that the central southern Alps retrobelt was already structured and largely exhumed in pre-late Eocene times, at least to the north of the present-day position of the Albino thrust front. Our new structural analyses suggest that post-Eocene shortening (D 3 phase) was mostly confined to the frontal part of the central southern Alps belt, buried be-neath the Po Plain. Postcollision deformation in the present-day exposed central southern Alps was mainly accommodated by transpressional to strike-slip reactivation of the Orobie-Porcile- Gallinera thrust system, which was linked to right-lateral strike-slip activity of the Insubric fault further north. The late Cenozoic evolu- tion of the central southern Alps was eventually characterized by the diachronous exhumation of tectonic units that culminated in the Tortonian pulse recorded by the crystalline basement unit in the hanging wall of the Orobie-Porcile-Galli- nera thrust system.

We can thus conclude that the central southern Alps, unlike current models of postcol- lisional retrobelt activation, was initially built through a polyphase tectonic evolution on the upper plate of the Alpine Tethys subduction zone, well before Adria-Europe continental collision. This implies that the European Alps developed as a doubly vergent orogenic wedge since latest Alban–Cenomanian times.

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