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Challenging the postcollisional paradigm of double vergence in the Alps

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ABSTRACT

Deciphering the mechanisms that control the timing of onset of precollisional orogenic processes during oceanic subduction is key to understanding how precollisional lithospheric architecture may affect mountain building in the upper plate. Europe-Adria convergence triggered subduction of the Alpine Tethys below Adria in the Cretaceous. The occurrence of synsubduction metamorphism and oceanward thrusting in the outermost (northern) edge of Adria is well constrained, whereas the occurrence of coeval crustal shortening in more internal (southern) areas of the upper plate, the Alps retrobelt, remains debated. Here, we present new U-Pb ages from several regional structures of the Alpine retrobelt, revealing that S-vergent thrusting dates back to the Late Cretaceous, 50 m.y. before the Cenozoic Adria-Europe collision. Cretaceous thrusting was synchronous with retro-foredeep turbidite deposition and coeval with N-vergent nappe stacking and high-pressure metamorphism to the north, testifying for a double-vergent precollisional orogenic system. We propose that pre-Alpine inherited structures partitioned strain and localized deformation, promoting forced subduction and strong plate coupling during the early stages of Alpine oblique convergence. This configuration challenges the long-held view of the Southern Alps as a purely Cenozoic postcollisional belt and provides a new framework for understanding orogenic onset at complex plate margins characterized by oblique convergence and microplate interactions.

INTRODUCTION

The occurrence of precollisional double-verging orogens is largely documented in the upper plate of cordilleran-type systems, where it is expressed by retro-foreland–verging thrust belts (DeCelles, 2004).

The Alps stand out as a remarkable exception, because here the retrobelt development is generally interpreted as a Cenozoic postcollisional feature (e.g., Handy et al., 2010), postdating the collision between Europe and Adria, an Africa-related microplate located along its northern margin (Márton et al., 2025). Early involvement of the outermost (northern) upper-plate margin within the S/SE-directed subduction system of the Alpine Tethys is documented for the Adria-derived units (Austroalpine domain; Fig. 1) now located to the north of the Periadriatic Fault (PF). Here, precollisional Late Cretaceous W-directed thrusting (Ratschbacher, 1986; Montemagni et al., 2023) and high-pressure metamorphism (Thöni et al., 2008) are recorded. Although direct (Zanchetta et al., 2011, 2015) and indirect (Doglioni and Bosellini, 1987) lines of evidence suggest the occurrence of a precollisional S-vergent thrust south of the PF (European Southern Alps), this deformation is often neglected or underestimated. To date, this uncertainty reflects the scarcity of datable synsubduction metamorphic minerals and stratigraphic time constraints for contractional deformation.

To overcome these limitations, we investigated the timing of thrusting within the Mesozoic cover of the Southern Alps through in situ laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U-Pb dating of carbonate fault rocks and mineralization. Our results challenge previous interpretations and demonstrate that most of the exposed thrust sheets were stacked during the Late Cretaceous, long before the Europe-Adria collision. We integrated these findings into a geodynamic model where the interplay among Mesozoic hyperextended margins, forced subduction, trench kinematics (McCarthy et al., 2018), and strain partitioning during oblique convergence (sinistral in the Early Cretaceous and dextral in the Late Cretaceous; Le Breton et al., 2021) accounts for the birth of the Alps as a double-vergent orogen in the Late Cretaceous.

CENTRAL SOUTHERN ALPS

The central Southern Alps (CSA; Fig. 1) are a S-verging fold-and-thrust belt composed of a Variscan metamorphic basement overlain by a thick Permian–Mesozoic cover, the evolution of which was influenced by multiple rift events, culminating in the Jurassic opening of the Lombardian Basin, a proximal domain of the Alpine Tethys. Upper Cretaceous to Miocene synorogenic deposits form the frontal and southernmost part of the belt (Fig. 1; Fig. S1 in the Supplemental Material[1]; Zanchetta et al., 2015).

Structural analyses document S-vergence thrusting within the CSA (Fig. 2), developed above a basal décollement deepening from the Po Plain to the PF, with total shortening between 80 and 110 km (Schönborn, 1992).

The northern sector exposes the Variscan basement, thrust southward along the Orobic Thrust on the Permian–Lower Triassic successions (Fig. 2; Zanchetta et al., 2015). The Mesozoic cover forms S-dipping thrust stacks, controlled by décollements accompanied by back thrusts (Fig. 2). The northern sector of the Triassic cover consists of Middle Triassic thrust sheets mainly made of thick carbonate platform

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[1]Supplemental Material. Field images and description of the structural features of the dated faults, petrographic characterization of the analyzed samples, and U-Pb LA-ICP-MS data. Please visit https://doi.org/10.1130/GEOL.S.32896880 to access the supplemental material; contact editing@geosociety.org with any questions.

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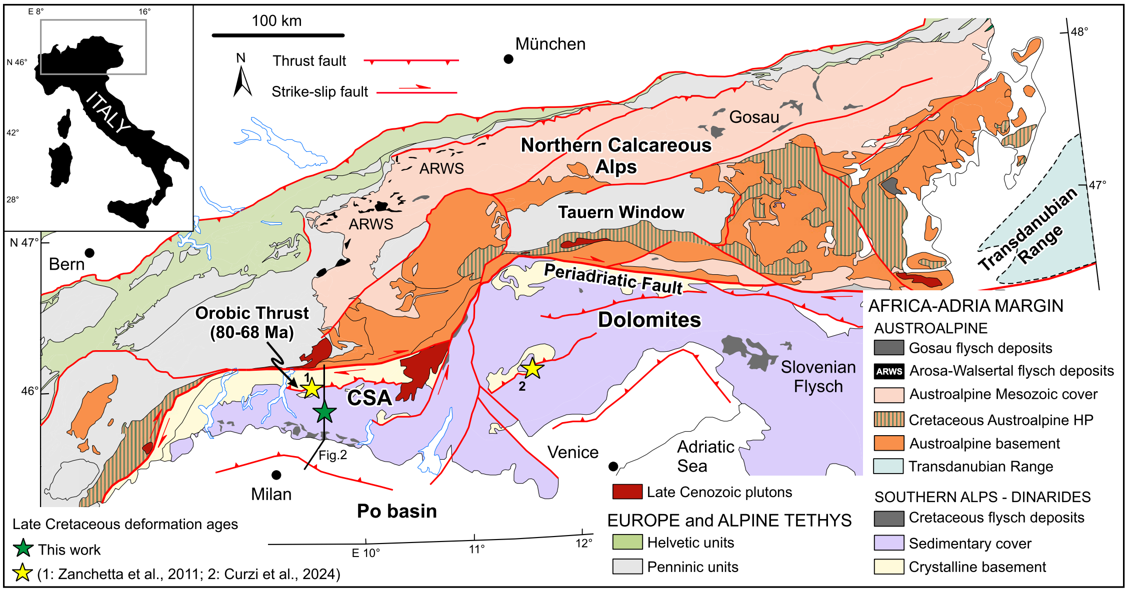

Figure 1. Structural map of Alps with location of Late Cretaceous compressional deformation in Southern Alps (modified from Zanchetta et al., 2012). CSA—central Southern Alps.

limestones; the intermediate zone features Upper Triassic dolostones overlain by basinal shales and carbonates up to 2 km thick (Fig. 2).

The frontal belt comprises folded Jurassic pelagic units, overlain by thick Upper Cretaceous turbidites (Fig. 2). Beneath the Po Plain, Maastrichtian–Eocene hemipelagic deposits are unconformably overlain by Oligocene–Miocene clastic deposits sourced from the erosion of the growing collisional orogen (Bersezio et al., 1993).

Available time constraints on the formation of the precollisional CSA belt comprise intrusive bodies (Adamello batholith and andesitic dikes; Fig. 2) that crosscut earlier regional folds and thrusts (D'Adda et al., 2011), and Late Cretaceous ages of pseudotachylytes along basement-on-cover thrusts (Zanchetta et al., 2011; Fig. 2). Late Cretaceous deformation events are also documented (Fig. 1) in the eastern southern Alps (Curzi et al., 2024). Post-Eocene (post-Adamello) thrusting affected the external part of the retrobelt and the Po Plain up to the late Miocene (Schönborn, 1992).

U-Pb CALCITE THRUST DATING

We conducted in situ LA-ICP-MS U-Pb dating (see Data S1 for U-Pb ages) on syntectonic calcite fault rocks and associated mineralization sampled along key thrusts within the CSA Mesozoic cover (Fig. 2; Figs. S1–S7), building on extensive structural analyses (D'Adda et al., 2011; Zanchi et al., 2012; Zanchetta et al., 2015).

Samples were collected along major structures from the internal, median, and frontal sectors of the belt, including calc-mylonites, shear veins, syntaxial fibrous veins, and slickenfibers (Tables S1 and S2; Figs. S3–S8).

Tera-Wasserburg diagrams display a well-defined spread of U-Pb ratios, with ages ranging between 98 ± 15 Ma and 55 ± 9.5 Ma and mean standard weighted deviation (MSWD) between 0.2 and 2.0 (Fig. S2; Data S1).

In the northern part of the Mesozoic cover, we dated the structurally highest thrusts, interpreted as the southward continuation of the Orobic thrust involving Middle Triassic carbonates. These thrust planes show thin (20–100 cm) calc-mylonites overprinted by brittle low-angle reverse faults. U-Pb ages (Fig. 2) from calc-mylonites span from 98 ± 15 Ma to 55.8 ± 7.3 Ma, whereas low-angle shear veins range between 65 ± 11 Ma and 60 ± 16 Ma. In the median sector, where thrust sheets developed within Upper Triassic carbonates, five U-Pb ages were obtained from the lowermost thrust fault (Fig. 2). Syntaxial fibrous veins yield ages between 98.2 ± 9.9 Ma and

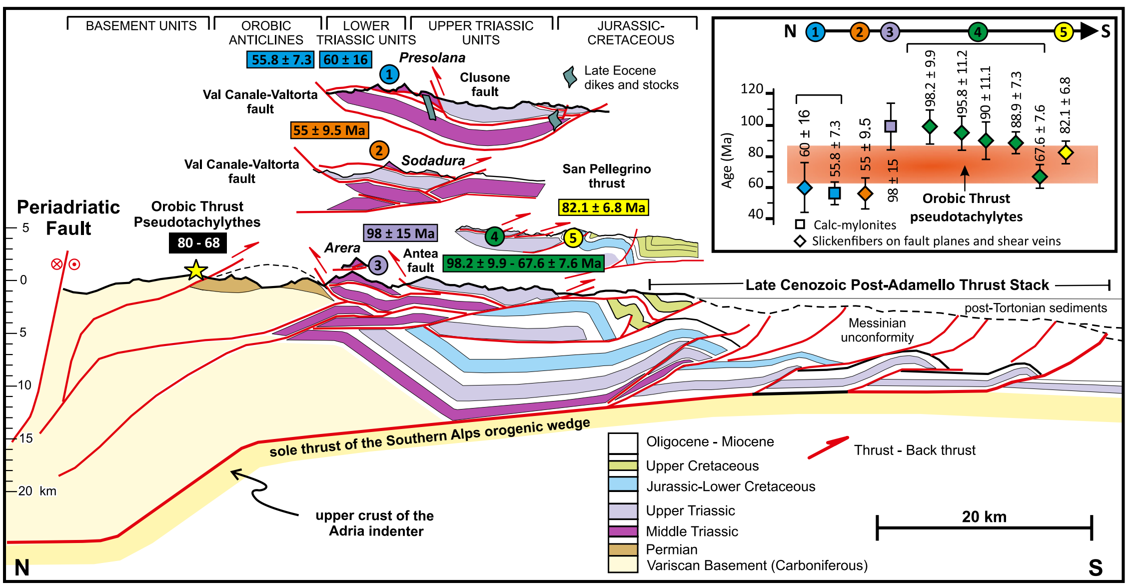

Figure 2. Cross section of central Southern Alps (CSA) (modified from Schönborn, 1992; Zanchetta et al., 2015) with new U-Pb ages related to Late Cretaceous to Paleogene thrust stacking. Post-Adamello deformation is also shown.

90 ± 11.1 Ma, whereas closely related shear veins span from 95.8 ± 11.2 Ma to 67.6 ± 7.6 Ma. In the frontal sector of the CSA (Fig. 1), a U-Pb age of 82.1 ± 6.8 Ma was obtained from slickenfibers in Aptian–Albian marls along a thrust plane, stacking Tithonian–Aptian pelagic limestones southward.

TOWARD AN INTEGRATED MODEL FOR THE EARLY ALPINE OROGENY IN THE LATE CRETACEOUS

Stratigraphic Evidence of Precollisional Tectonics in the CSA

Altogether, our new U-Pb ages from syntectonic calcite and Ar-Ar pseudotachylyte ages (Zanchetta et al., 2011) indicate that the CSA began forming as a fold-and-thrust belt during the Late Cretaceous, coeval with turbidite deposition.

The stratigraphic record of the CSA shows a major reorganization in the Aptian, when the deposition of pelagic limestones ended. The Jurassic N-S–trending rift basins were replaced by an E-W–striking foredeep accumulating up to 2500 m of turbidites in a bathyal setting. Turbiditic sedimentation rates increased from the Albian to Santonian (Fig. 3), accompanied by significant synsedimentary tectonic activity (megabeds and intrabasin unconformities; Bersezio et al., 1993). Garnet, staurolite, and sillimanite clasts in mid–upper Turonian sediments testify to the erosion of deeper basement units (Bernoulli and Winkler, 1990). Turbidite deposition continued with decreasing rates up to the Campanian, with the occurrence of Santonian megabeds (Fig. 3) sourced from Paleozoic and Cretaceous carbonate platforms likely fed from the eastern Southern Alps and Austroalpine units (Bernoulli and Winkler, 1990), suggesting decreasing tectonic activity up to the Paleogene. Overall, the Cretaceous Lombardian successions formed in a retro-foredeep during Late Cretaceous erosion of a thick-skinned belt involving Adria-derived basement units.

Late Cretaceous Precollisional Deformation and Metamorphism North of the Periadriatic Fault

The Adria-derived Austroalpine units of the eastern Alps north of the PF were deeply involved in Cretaceous precollisional deformation and metamorphism. They preserve relics of Late Cretaceous (95–80 Ma) high-pressure (HP) metamorphism (Fig. 3) along an E-W belt extending over 150 km (the Koralpe-Wölz complex; Thöni et al., 2008; Handy et al., 2010). The HP metamorphism was broadly coeval with NW- to W-directed nappe stacking during dextral transpression (Ratschbacher, 1986; Linzer et al., 1995).

Late Cretaceous deformation (89–72 Ma; Handy et al., 1996) is also recorded in the

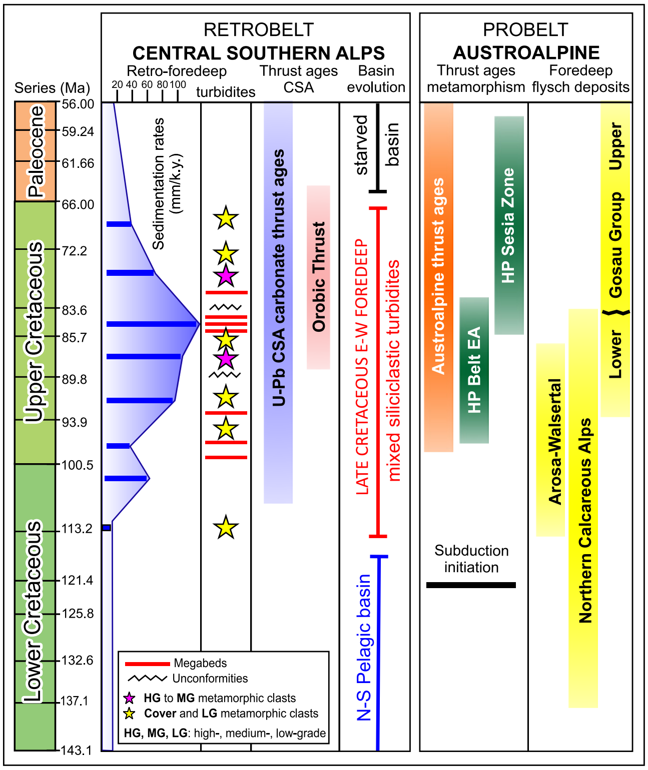

Figure 3. Geochronologic and tectono-stratigraphic constraints on Eoalpine (EA) the evolution of central Southern Alps (CSA) compared to Austroalpine units. All references are given in text. HP—high pressure.

central Alps along the boundary between oceanic (Penninic domain) and Adrian (Austroalpine) continental units. Here, subduction and W-directed thrusting were active from ca. 110 Ma to 91–83 Ma (Ring et al., 1988; Villa et al., 2000).

In the western Alps, Late Cretaceous HP metamorphism affected the Sesia zone, part of the Jurassic Adria hyperextended margin, between 85 and 60 Ma (e.g., Babist et al., 2006; Vho et al., 2020). Folds and thrusts developed between 97 and 80 Ma in the SW Alps and Provence (Bilau et al., 2023).

Widespread synorogenic turbidites document the growth and erosion of an orogenic wedge in the Austroalpine domain since the Early Cretaceous. These sediments were deposited in a prowedge setting, recording the transition from an extensional to a dextral transpressive margin (Ratschbacher, 1986). Austroalpine nappes of the central Alps contain Cenomanian–Turonian turbidites overlying pelagic deposits enriched in chromite derived from eroded ophiolites (Bernoulli and Winkler, 1990). Similar clastic deposits rich in chromite and HP minerals (glaucophane and lawsonite) occur along the external margin of the Northern Calcareous Alps, indicating exhumation of subducted units at the Penninic-Austroalpine domain boundary (Winkler, 1988). Aptian to Cenomanian piggyback basins in the Austroalpine units of the eastern Alps are filled by sediments rich in HP and low-temperature (LT) minerals, while older Barremian trench-slope deposits occur in a more internal position (Figs. 1 and 3). Turonian–Paleogene continental to deep-marine sediments, rich in chrome spinel, garnet, staurolite, and zircon (Gosau Group; Fig. 1), overlie thrust nappes. They were deposited in pull-apart basins along NW-SE dextral faults, coeval with thrust stacking (Winkler, 1988; von Eynatten and Gaupp, 1999; Wagreich and Decker, 2001).

Linking the Southern Alps and the Austroalpine Domain

Paleomagnetic reconstructions (Le Breton et al., 2021) show that Adria's northward movement started around 110 Ma, followed by continued migration to the northeast since 84 Ma (Fig. 4A). This motion led to the progressive closure of the Alpine Tethys, forcing its subduction beneath the northern Adria margin and promoting tectonic erosion (Zanchetta et al., 2012). Preexisting Jurassic low-angle extensional faults facilitated subduction of crust of the hyperextended margin (Zanchetta et al., 2012; McCarthy et al., 2018). Models for the Late Cretaceous orogeny in the Austroalpine domain of the eastern Alps typically consider intracontinental subduction (Stüwe and Schuster, 2010) or the closure of oceanic basins east of the Alpine Tethys (Thöni et al., 2008; Handy et al., 2010). However, these models fail to fully explain the Late Cretaceous HP metamorphism of the Austroalpine Sesia zone (western Alps; Vho et al., 2020), W-directed thrusting in the central Alps (Ring et al., 1988), and the coeval structuring of the CSA. We propose that the HP metamorphism and tectonics of the Austroalpine units along the entire Alps orogen, and the coeval

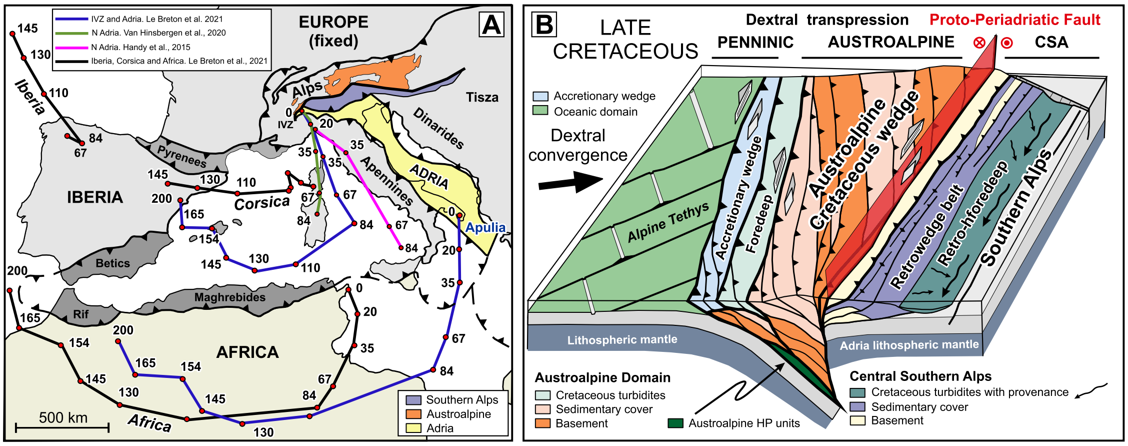

Figure 4. (A) Plate motion relative to stable Europe over the past 200 m.y., with Adria's convergence (Le Breton et al., 2021). (B) Late Cretaceous double-verging precollisional Alps with strain partitioning accommodated by dextral proto–Periadriatic Fault resulting from oblique convergence along northern Adria margin. CSA—central Southern Alps; HP—high pressure; IVZ—Ivrea-Verbano Zone.

development of the CSA belt, reflect growth of a single orogenic wedge. Eclogite exhumation occurred rapidly in the rear of the prowedge, with the Adria lithosphere acting as a backstop that limited surface flow (Butler et al., 2011), enhanced mechanical coupling between the two plates, and transferred compressive stresses to the internal parts of the upper plate, causing thrust stacking in the CSA.

Lithospheric discontinuities inherited from the Variscan orogeny and Mesozoic rifting acted as precursors of the PF, partitioning dextral transpression since the Late Cretaceous, accommodating oblique convergence, and promoting S-vergent thrusting in the CSA and NW- to W-vergent emplacement of the Austroalpine nappes (Fig. 4B). Forced subduction driven by Europe-Africa convergence led to strong mechanical coupling between the lower and upper plates (McCarthy et al., 2018), transferring deformation to the rigid and colder Adria lithosphere. This is supported by a marked change of Adria motion at ca. 84 Ma (Fig. 4A; Màrton et al., 2025), promoting a switch from sinistral to dextral convergence. This switch is broadly coeval with HP metamorphism and deformation in the Austroalpine domain and thrust stacking in the CSA. These features indicate an advancing subduction trench in the Cretaceous, where total convergence exceeded the rate of subduction, resulting in significant horizontal shortening transmitted to the upper plate.

Although the structure of the cordilleran accretionary orogens markedly differ from the Cretaceous Alps in terms of geodynamic evolution, plate dimensions, and subduction mechanisms, notable similarities are observed in their retrobelts. In fact, they involve the crystalline basement of the upper plate (DeCelles, 2004), register strain partitioning (with trench-parallel strike-slip faulting and thrusting; Alvarado et al., 2016), and record a marked stress transfer and significant contraction of its internal parts. This recalls similar actualistic scenarios like the active Indonesian margin (Hutchings and Mooney, 2021). In this area, precollisional double-verging belts, strain partitioning along transform faults, and abrupt changes in the stress/strain patterns prevail at a regional scale due to intricate interference among distinct crustal blocks in a complex frame of motion and subduction zones.

After the Eocene emplacement of the Periadriatic plutons, contractional deformation affected the external part of the retrobelt and the Po Plain (Schönborn, 1992; Zanchetta et al., 2015), and Cretaceous thrust sheets were mainly passively transported on top of younger ones. In this period, frontal thrust stacking was coeval with dextral transpressive movements along the PF (e.g., Handy et al., 2010), indicating that strain partitioning has been a persistent characteristic of Alpine tectonics.

CONCLUSIONS

New U-Pb ages on synkinematic carbonates, combined with existing Ar-Ar ages on pseudotachylytes, indicate that thrust stacking in the CSA occurred during the Late Cretaceous since ca. 100 Ma, forming a retrowedge ahead of an E-W–oriented retro-foredeep basin, accumulating thick turbidite deposits from the end of the Early Cretaceous. The growth of the CSA was coeval with dextral transpression, nappe stacking, and HP metamorphism in the Austroalpine domain, and the deposition of synorogenic turbidites along the northern active margin of Adria.

All these data are consistent with the development of a precollisional, double-verging orogenic belt formed under strong plate coupling within an advancing trench system, driven by forced subduction. The oblique convergence between Adria and Europe generated strain partitioning, favored by inherited structures such as a proto-PF, which explains the different kinematics observed in the two portions of Adria.

These new chronological data significantly revise our understanding of the Cretaceous evolution of the European Alps, challenging the prevailing interpretation that their double vergence is solely a postcollisional feature.

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