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Research article

Geodynamics of Continents and Oceans – A tribute to Jean Aubouin

The Western Alpine arc: a review and new kinematic model

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Abstract. The arcuate shape of the Western Alps is commonly interpreted to result from collisional, NW-ward indentation of the Adriatic indenter. The radial pattern (≈180°) of collisional transport directions is difficult to explain, especially in the southern WNW–ESE to E–W striking arc segments. A mid-Cenozoic change, from NW- to W-directed indentation is often proposed, but poorly constrained. Based on a critical review of conceptual models for the formation of the Western Alpine arc and associated geodynamic processes, we conclude that an arcuate structure already exists before the onset of collision. NW-ward indentation of the Adriatic indenter amplifies this arc structure by oroclinal bending, but the E–W to ESE–WNW striking, southernmost segments of the Alpine arc mainly result from distinct geodynamic processes, other than Alpine convergence in the strict sense. The southernmost External Zone is mainly inherited from the Pyrenean orogeny and was weakly reactivated in the Miocene, probably accommodating very small parts of Africa–Europe convergence since Late Miocene times. In the Internal Zone, the E–W strike of the Ligurian Alps is probably associated with 50° counterclockwise rotation of the northern Apennines.

Keywords. Western Alpine arc, Structural inheritance, Collisional indentation, Adriatic indenter rotation, Gravitational tectonic.

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1. Introduction

Most mountain belts are characterised by arcuate shapes, whose amplitude and wavelength vary significantly as a function of different lithospheric structures and geodynamic processes [e.g., Wortel and Spakman, 2000, Schellart, 2004]. Such orogens are termed oroclines as proposed by Carey [1955] to describe mountain ranges whose structural trend changes along-strike, although later definitions suggest that this term should only refer to ranges evolving in time from straight to arcuate axes [Hindle and Burkhard, 1999]. Today, the term orocline is used to characterise arcuate mountain belts whose shape is acquired by bending an initially rectilinear orogen, as opposed to the primary arc whose shape is inherited from processes preceding the formation of the orogen [e.g. Yonkee and Weil, 2010].

A distinction can be made between arcs which develop in thin-skinned tectonics, and lithospheric-scale arcs, which affect entire mountain belts. The former concern mainly foreland chains like the

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Jura Mountains [Gehring et al., 1991, Hindle and Burkhard, 1999] or the arcs of Nice and Castellane in the southern French Alps. These arcs develop by the propagation of fold and thrust belts in divergent directions above a level of decollement [e.g., Hindle and Burkhard, 1999]. No lithospheric-scale bending is associated with these arcs, in contrast to the arcs of the Apennines [Lucente and Speranza, 2001, Rosenbaum, 2014, Rosenbaum and Lister, 2004a,b], the Scotia arc [Barker and Dalziel, 1983, Royden, 1993, Dalziel et al., 2013], the Taiwan arc [Hsu and Sibuet, 1995, Sibuet and Hsu, 1997, Malavieille et al., 2002, Sibuet and Hsu, 2004], or the western Alpine arc [Zhao et al., 2016, Kästle et al., 2020, Paffrath et al., 2021, Handy et al., 2021], which we therefore describe as lithospheric arcs.

The latter type of arcs bound most Mediterranean margins [Royden, 1988], including the Betic-Rif chains, the Apennines, the Calabrian arc, and the Aegean arc (Figure 1). Most of them are associated with a slab roll-back during subduction [Royden, 1988, Royden and Burchfiel, 1989, Rosenbaum, 2014, Rosenbaum and Lister, 2004a,b, Wortel and Spakman, 2000].

The arc of the Western Alps is characterised by a continuous topographic relief, forming a semi-circular structure, from the French–Italian Mediterranean coast in the south, to the western Swiss Alps in the north. This arcuate structure affects all major alpine tectonic units, but some ambiguity exists in the literature concerning its southwestern termination. Whereas some authors set it north of Nice [e.g., Staub, 1924, Laubscher, 1988, Roure et al., 1989], others set it further west, bounding the Rhone and Bresse graben structures, north of Marseille [e.g., Schmid and Kissling, 2000, Kempf and Pfiffner, 2004]. In the following we describe the arc of the Western Alps as the one coinciding with the entire topographic relief, i.e. extending as far as the Rhone graben and in the final discussion we argue whether this area as a whole is correctly described as an Alpine feature in terms of tectonic processes.

The Western Alpine arc is generally interpreted as a syn-collisional orocline, formed from the Priabonian onwards, by indentation of the Adriatic indenter into the European plate [e.g., Tapponnier, 1977, Choukroune et al., 1986, Ricou and Siddans, 1986, Vialon et al., 1989, Platt et al., 1989, Laubscher, 1991, Ceriani et al., 2001, Ford et al., 2006, Handy et al., 2010, Schmid et al., 2017], in contrast to most other Mediterranean arcs (Figure 1), which are inferred to develop during the subduction [Royden, 1988]. The semi-circular Western Alpine arc is characterised by northward tectonic transport in the North, westward transport in the West and southward transport in the South (Figure 2c) [Siddans, 1979, Choukroune et al., 1986, Platt et al., 1989, Handy et al., 2010, Schmid et al., 2017]. Such radial transport poses many questions regarding the lateral kinematic compatibility and deformation mechanisms of this arc. On the one hand, no systematic, large-scale, along-strike stretching of the orogenic wedge is documented by structural studies, a process required in order to accommodate progressive lengthening of the amplifying arc during the formation of the orocline [e.g., Yonkee and Weil, 2010]. On the other hand, indentation experiments [Lickorish et al., 2002], designed to investigate west-Alpine indentation, successfully produce radial shortening around more than half of the square indenters, but not along an entire, semicircular arc, if the indentation direction is constant throughout the experiment. As a consequence, many hypotheses such as structural/geometrical inheritance of the European margin, change of direction of Adriatic indentation, rotation of the Adriatic indenter and other domains of the Alps, are commonly invoked to explain the strong curvature of structures accommodating shortening all along the arc [e.g. Vialon et al., 1989, Collombet et al., 2002].

With the aim of understanding the processes that formed the Western Alpine arc, in the following we summarise more than a century of research on this subject and propose a new kinematic model. This model is based on the critical literature review, but also on a new analysis of structures in the southernmost External Zone. We show that the central and northern parts of the Western Alpine arc are most likely explained by syn-collisional, oroclinal amplification of a subduction arc, whereas the southern part of this arc results from a combination of processes including initial oroclinal bending, rotations controlled by Apenninic slab retreat and Upper Miocene inversion of the Ligurian margin, and asthenospheric flow around the southern limit of the European slab, possibly re-orienting crustal structures.

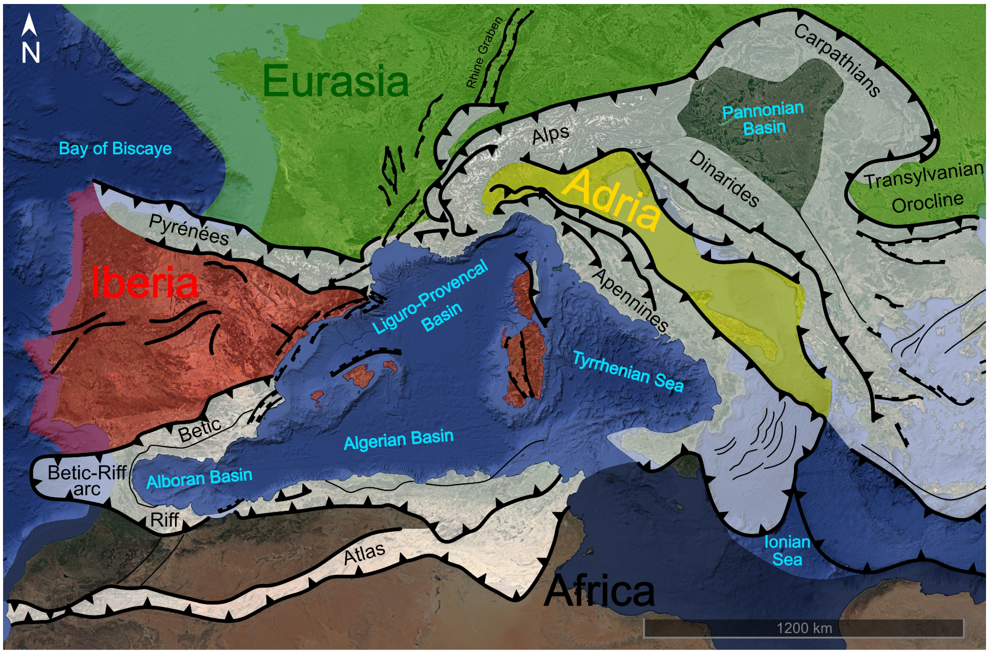

Figure 1. Arcuate mountain belts bounding the western Mediterranean [Tapponnier, 1977, Handy et al., 2010, Faccenna et al., 2014, van Hinsbergen et al., 2020, Jolivet et al., 2020, 2021].

2. Tectonic setting

The Western Alpine arc (Figure 2a) is a unique feature within the Alpine chain, which otherwise strikes ENE–WSW from the Eastern to the Central Alps. In the External Zone, the arc extends from the Jura mountains in the north to the Nice–Castellane arcs in the south (Figure 2a). In the Internal Zone, the arc extends from the northeastern margin of the Sesia Zone in the north to the Ligurian Alps in the south (Figure 2a).

Two major differences characterise the Internal and External Zones in terms of arc morphology of the Western Alps: (1) Alpine structures in the Internal Zone result from the subduction and the following collisional overprint, whereas those in the External Zone only result from collision [e.g., Handy et al., 2010, for a summary of tectonic events in these distinct domains]. (2) The Internal Zone forms a continuous 180° arc showing a progressive rotation of its main structures from the Lepontine Dome to the Ligurian Alps (Figure 2a). In contrast, progressive rotation of structures in the External Zone is only observed along an arc of 90° between the ENE–WSW structures north of the Central Alps and the N–S to NNW–SSE striking arc segment, terminating at the Guillaumes–Castellane Fault (Figure 2a). South of the Dignes nappe, the main structures abruptly change to an E–W orientation, producing an elbow, rather than an arc (Figure 2a).

Palaeogeographic reconstructions of the Mesozoic western Alpine domain point to the occurrence of three distinct, pre-Alpine continental areas separated by two oceanic and/or continental, extended domains [e.g., Stampfli, 1993, Froitzheim et al., 1996, Schmid et al., 2004, Agard, 2021].

The southernmost continental area corresponds to the Adriatic margin (Figure 2a), largely covered by the Molasse in the Po Plain, and bound to the west by the Ivrea body (Figure 2a). The latter is inferred to behave as an indenter during Alpine collision [e.g. Tapponnier, 1977, Channell et al., 1979, Dumont et al., 2011, Schmid et al., 2017]. It is a northern protuberance of the African Plate [Argand, 1924, Tapponnier, 1977, Channell et al., 1979, Anderson, 1987], whose displacement may partly differ from that of Africa during Neogene time [van Hinsbergen et al., 2014b]. The more distal part of this Adriatic margin

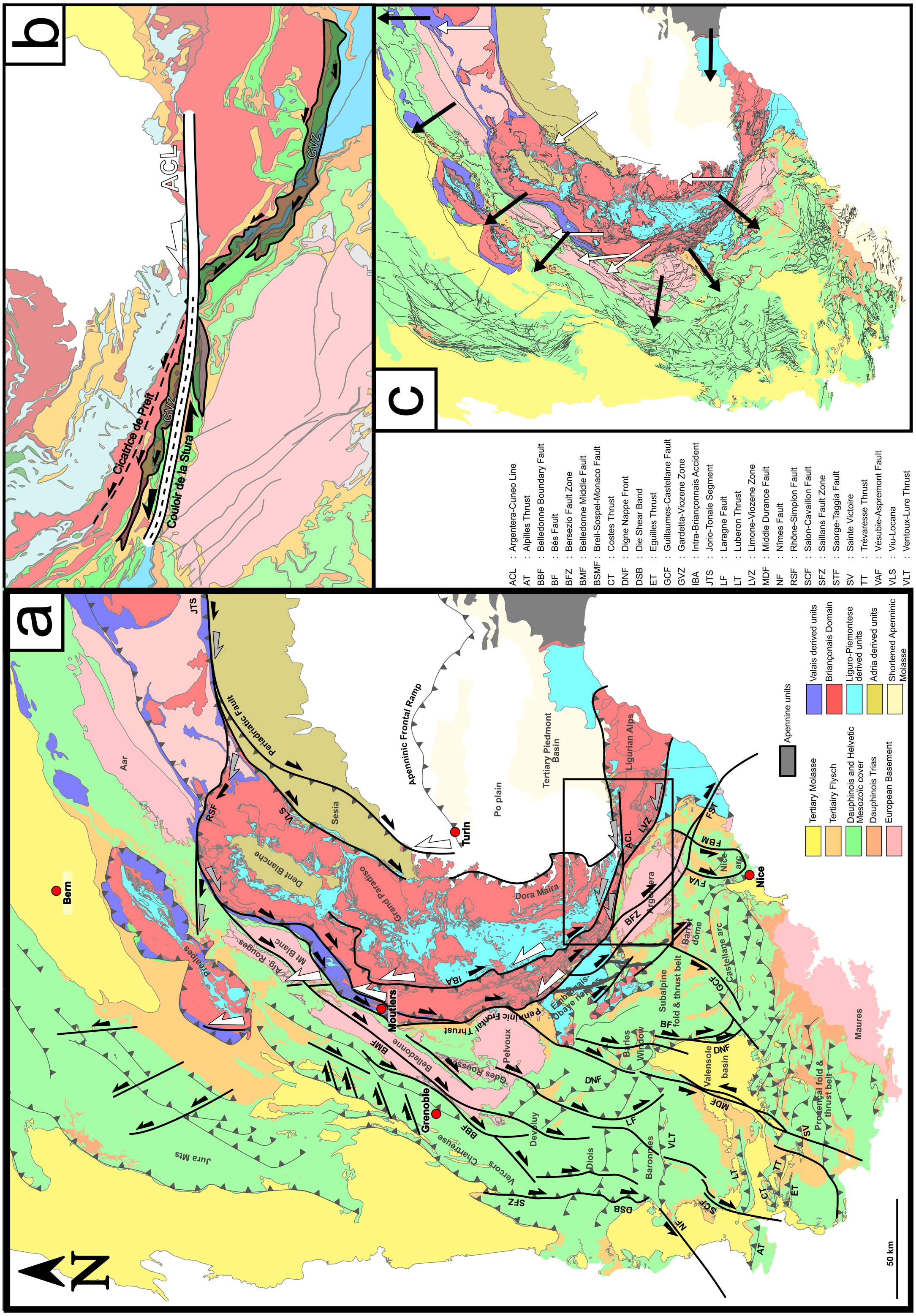

Figure 2. Caption continued on next page.

Figure 2. (**cont.**) (a) Synthesis of the strike-slip fault described in the literature in map. White semi-arrow: sinistral strike-slip movement associated with the northward translation of the Adriatic indenter between 80–90 and 25–30 Ma [Ricou and Siddans, 1986]; grey semi-arrows: sinistral strike slip movement to the south of the arc and dextral strike slip movement to the north of the arc associated with a westward indentation of Adria since the Oligocene [Laubscher, 1971, 1988, 1991, Lefèvre, 1984, Ricou, 1981, 1984, Ricou and Siddans, 1986, Ritz, 1992, Schmid and Kissling, 2000, Piana et al., 2009, 2021, Schmid et al., 2017]; black semi-arrows: numerous strike-slip faults, dextral and sinistral in the External Zone, and dextral reactivation of the PFT end the Periadriatic Fault [Vialon et al., 1989, Seward and Mancktelow, 1994, Giglia et al., 1996, Aubourg and Chabert-Pelline, 1999, Collombet et al., 2002, Bauve et al., 2014, Balansa et al., 2022]. (b) Sinistral strike-slip faults inferred to accommodate the westward indentation of Adria since 35 Ma [Laubscher, 1971, 1988, 1991, Lefèvre, 1984, Ricou, 1981, 1984, Ricou and Siddans, 1986, Piana et al., 2009, 2021, Schmid et al., 2017]. (c) Simplified Tectonic map with tectonic transport direction [Handy et al., 2010]. White arrows: pre-collisional tectonic transport direction (83–35 Ma); Black arrows: inferred collisional tectonic transport direction (35–20 Ma).

forms the Austroalpine nappe stack (Figure 2a), located to the N and NW of the Periadriatic Fault (Figure 2a). Below the Austroalpine nappes lies the Liguro–Piemont (L–P) Domain (Figure 2a), consisting of oceanic-derived crustal nappes. Its structurally uppermost units are formed by the barely metamorphic Helminthoid Flysch, whose basal thrust passed over the more external Dauphinois domains. The Briançonnais Domain (Figure 2a), lying in the footwall of the L–P Domain, consists of basement and cover nappes derived from the north-easternmost part of the paleo-Iberian continent [Stampfli, 1993] and lying above the Valais Domain (Figure 2a). The latter is exposed in the outermost part of the Internal Zone but it completely lacks south of Moutiers (Figure 2a). An open debate is still ongoing concerning the age of the oceanic basement included in its nappes [pre-Mesozoic, Jurassic, or Cretaceous; e.g., Loprieno et al., 2011, Beltrando et al., 2012] and on the nature of the Valaisan basement as a whole: continental [Masson et al., 2008], oceanic [e.g., Loprieno et al., 2011], or hyperextended and rifted margin [Le Breton et al., 2021]. The European margin (Figure 2a) with its Palaeozoic basement and Mesozoic cover are exposed in and around the External Crystalline Massifs (ECM). The external-most part of the cover is shortened mainly above Triassic or Liassic décollements, forming the subalpine ranges, and the Jura Mts and deforming the Cenozoic Molasse Basin.

The Valais, Briançonnais, L–P and Sesia domains form the Internal Zone of the Western Alps, as opposed to the External Zone, which corresponds to the European continental margin. The Internal Zone is delimited to the East by the Periadriatic Fault, which separates the "Backstop" (Adriatic indenter) from the orogenic wedge. To the west and north of the Internal Zone is delimited by the Penninic Frontal Thrust (PFT; Figure 2a), which displaces the internal units on the external ones, from the late stages of the subduction to the early stages of collision [Cardello et al., 2019]. The prolongation of the PFT in depth coincides with the lower plate-upper plate interface [e.g. Schmid et al., 2017; their figure 2]. In the External Zone, the shape of the arc is underlined by the NE–SW trending ECMs from the Aar to Belledonne, followed southward by the NW–SE trending ECMs between Pelvoux and Argentera. This map-scale trend parallels their internal fabric [Dumont et al., 2012], and it is partly tracked by the Digne Nappe Front (DNF, Figure 2a) and the Jura Mts in the more external parts of the Chain (Figure 2a).

Alpine orogeny initiates at around 85 Ma [e.g., Dewey et al., 1989, Stampfli and Borel, 2002, Berger and Bousquet, 2008], with south- and southeast-directed subduction of the Austroalpine Sesia slice, as testified by its HP metamorphism [Dal Piaz et al., 1972, Stampfli, 1993]. This first stage is followed by the subduction of the L–P Ocean, then by the Briançonnais domain, before ending with the Valaisan domain and part of the distal European margin [e.g., Dewey et al., 1989, Stampfli and Borel, 2002, Berger and Bousquet, 2008, Le Breton et al., 2021]. The transition from the subduction to collision takes place at around 34 Ma, possibly coinciding with slab break-off [von Blanckenburg and Davies, 1995], immediately preceding a pulse of magmatism along the Periadriatic Fault [Rosenberg, 2004]. This time is also characterised by the onset of molasse-type basin deposits in the foreland at 30–34 Ma [Matter et al., 1980, Sinclair, 1997], slightly preeceding Barrovian metamorphism in the Internal Zone [Engi et al., 2004, Bousquet et al., 2008], and thick-skinned tectonics in the External Zone [Burkhard and Sommaruga, 1998, Bellahsen et al., 2014].

3. Processes inferred to form the Alpine arc

In the following we critically review the interpretations suggested to explain the shape of the western Alpine arc, and eventually propose a new conceptual kinematic model.

3.1. *Structural inheritance*

Structural inheritance of the stretched Mesozoic continental margins may control both tectonic style and morphology of the orogen. Indeed, variations in the orientation, thickness and rheology of the lithosphere, inherited from extensional episodes, may significantly impact collisional deformation [e.g., Butler, 2017]. Inherited structures from Hercynian and post-Hercynian tectonics may influence both Mesozoic extension, and Alpine shortening.

3.1.1. *Variscan inheritance*

The very first conceptual model invoking pre-Alpine structures to explain the existence and orientation of the Alpine ones goes back to Argand [1916], who suggests that the arcuate shape of the Western Alps results from the adaptation of the internal alpine domains to a pre-existing "Hercynian hemicycle" during Alpine convergence. At that time, before the modern definitions of subduction and continental margins, Argand imagines pre-orogenic crustal-scale fold sequences, becoming amplified in a ductile crust by convergence against more rigid obstacles (the External Massifs). Argand [1916] suggests that Alpine convergence is directed NNW, thus with tectonic transport almost normal to the front of the chain in the North, but largely oblique to the margin underlined by the southern ECMs (Figure 3a,b).

The advance of the nappes on the outer "semi-circular slope" of the arc, corresponding to the European continental margin, is due to the push of a rigid edge ["môle méridional; môle propulseur"; Argand, 1916], nowadays termed the Ivrea Indenter [e.g., Laubscher, 1971, Tapponnier, 1977, Schmid and Kissling, 2000, Dumont et al., 2011, Rosenberg and Kissling, 2013, Schmid et al., 2017]. Only the latest phase of the arc's development, in terms of its shape, takes place during Alpine orogeny in the view of Argand [1916]. It corresponds to a relatively small displacement, bringing the southern (Argentera Massif) and northern (Aar Massif) ECMs closer to each other, thus slightly increasing the arc curvature.

On the base of modern knowledge, the existence of an intact Hercynian hemicycle is unlikely, considering that this region is the site of two post-Hercynian oceanic openings (Liguro–Piémont and Valais) and one subduction. However, palaeomagnetic data from Permian rocks in the Argentera massif indicate no significant rotation since that time [Henry, 1971, Bogdanoff and Schott, 1977]. The same is true for the Mesozoic cover of the ECMs located north of the Argentera Massif [Henry, 1992, Ménard and Rochette, 1992, Crouzet et al., 1996]. This implies that the 50° angle between the Hercynian foliations of the Aar, Mt Blanc/Aiguilles Rouges, Belledonne/Grandes Rousses massifs and those of the Pelvoux and Argentera already existed in the Permian [Westphal, 1973].

A different kind of inherited structure is provided by the "East Variscan Shear Zone" [EVSZ, Corsini and Rolland, 2009, Padovano et al., 2012], corresponding to the southern edge of the European plate. The EVSZ may affect Alpine tectonics, particularly by controlling the location and orientation of the Valaisan basin [Ballèvre et al., 2018, Angrand and Mouthereau, 2021], which in turn may control the location, distribution and style of deformation of the Alpine orogen [Bellahsen et al., 2014]. To conclude, the effect of these Variscan inherited structures remains hypothetical and their associated structures (crustal anisotropy, transform plate boundaries) are not yet well characterised.

3.1.2. *Structures inherited from subduction*

Restoring collisional shortening in the External Zone all along the arc [Bellahsen et al., 2014, Rosenberg et al., 2021, and references therein] shows that the trace of the PFT in map view and the shape of the foreland basin [Ford et al., 2006] highlight the existence of a pre-collisional, Late Eocene "proto-arc" [Figure 4; Bellahsen et al., 2014]. These results,

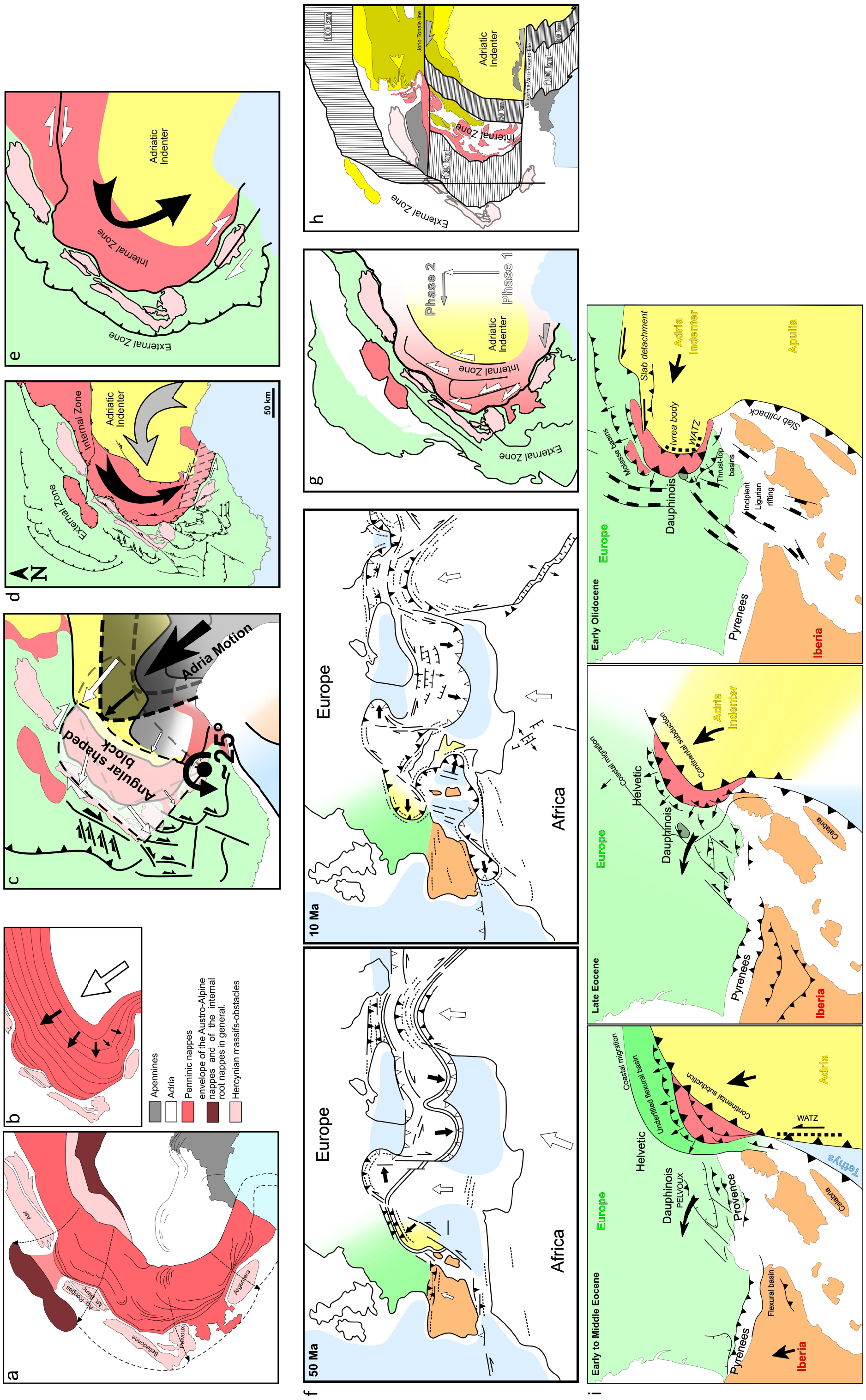

Figure 3. Continued on next page.

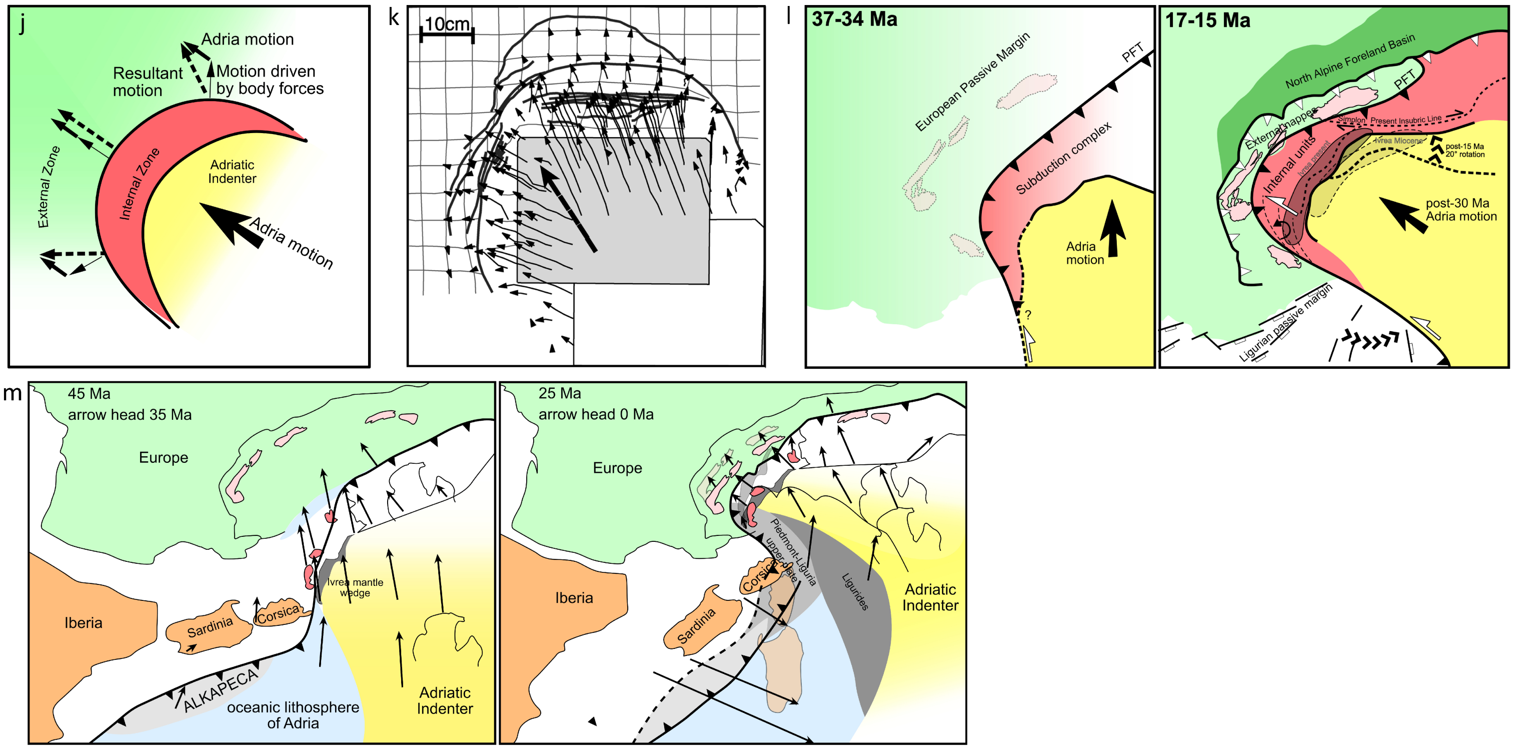

Figure 3 (cont.). Caption continued on next page.

Figure 3 (cont.). (a) Argands conceptual model of the “trouble surge” [modified from Argand, 1916]. The most external discontinuous line is the maximal extension of the internal nappes. The most internal discontinuous line is the prolongation of the Periadriatic Fault. The other internal discontinuous lines, at the southern end of the western Alpine arc, is probably the continuation of a major thrust in the Internal Zone, maybe between the Briançonnais units and the Helminthoid flysch. The black continuous lines in the Internal Zone (Penninic nappes) correspond to the trajectory of structures such as folds. The dashed arrows connect the different inflection points of these trajectories. (b) synthetic image of the “trouble surge” (“déferlement contrarié”) in the Alpine arc [modified from Argand, 1916]. White arrow: direction of push (=direction of the Adriatic indentation); Black arrows: direction of flow. The size of the arrows is proportional to the amount of flow. (c) Rotation model modified from Vialon et al. [1989]. This model proposes the counterclockwise rotation of an independent block located NW of the Adriatic indenter. This fragment of the Adriatic indenter is rotated in order to accommodate NNW indentation of the remainder of the Adriatic indenter to the east. (d) Rotation model modified from Collombet et al. [2002] suggesting counterclockwise rotation of about 20 degrees of the indenter accommodated by dextral reactivation of the PFT and the Periadriatic Fault. This rotation is accompanied by southward lateral extrusion of the Internal Zone and numerous dextral strike-slip faults showing a fan shape in map view. South of the arc, rotation inferred from paleomagnetic data increases and is interpreted as distributed sinistral zone (discontinuous lines). (e) Rotation model modified from Bauve et al. [2014] suggesting counterclockwise rotation of the Adriatic indenter associated with dextral kinematics in the south of the arc since at least 12 Ma, based on the inversion of structural data and focal mechanisms from the southern part of the western Alpine arc. (f) Tectonic deformation sequence in the Mediterranean area [modified from Tapponnier, 1977]. This model proposes that the peri-Mediterranean chains, and notably the Alps, are formed by the indentation of plastic domains (the European continental margin in the case of the Alps) by rigid promontories (the Adriatic indenter in the case of the Alps). We observe that a change of indentation direction, from NW-ward to westward, occurs between 50 and 10 Ma. (g) Northward displacement of the Adriatic indenter, followed by westward impingement (dashed faults), generates successive orthogonal thrust systems and their associated strike-slip faults [modified from Ricou and Siddans, 1986]. (h) Retrotranslation of the EW (horizontal hatching) and the NS (vertical hatching) components of the Adriatic indenter in the late Oligocene (post-30 Ma) to early Miocene (16 Ma) modified from Laubscher [1991]. (i) Palinspatic reconstruction modified from Dumont et al. [2012]. Note the inferred progressive rotation of Adriatic indenter convergence direction, from northward to WNW-ward. (j) Motion vectors produced by the interaction between the Adriatic indenter motion vector and body forces acting normal to the trand of a mountain belt; the latter should lie within 90° of the Adriatic indenter motion vector [modified from Platt et al., 1989]. (k) Sandbox experiment showing the development of an arcuate thrust belt due to diagonal indenter motion [Lickorish et al., 2002]. The plate-motion vector (large arrow) lies at 33° to the lateral edge of the indenter. The small arrows represent incremental displacement vectors of material points at grid intersections. (l) Palaeogeographical reconstructions of the western Alps during Priabonian and Burdigalian times modified from Ford et al. [2006]. It consists of a shift from a northward to a NW-ward indentation around 30 Ma [Ford et al., 2006], accommodated in particular by a sinistral strike-slip southwestern boundary of the Adriatic indenter. (m) Kinematic restoration of the Alps–Apennines orogenic system using Gplates reconstruction software [e.g. van Hinsbergen et al., 2014b] holding Europe fixed [modified from Schmid et al., 2017]. It implies a shift from a northward indentation to a WNW-ward indentation between 35 and 25 Ma.

are consistent with many Mediterranean subduction systems (Alboran, Aegean, Carpathian, Apenninic-Calabrian; Figure 1), whose arcuate shape is inferred to form during the subduction roll-back [Royden, 1993, Wortel and Spakman, 2000].

Several processes can explain arc formations during subduction. A break-off at the southwestern end of the slab, resulting in a southwestward traction decrease, could create a gradient in the amount of NW-directed roll-back, producing an arcuate morphology

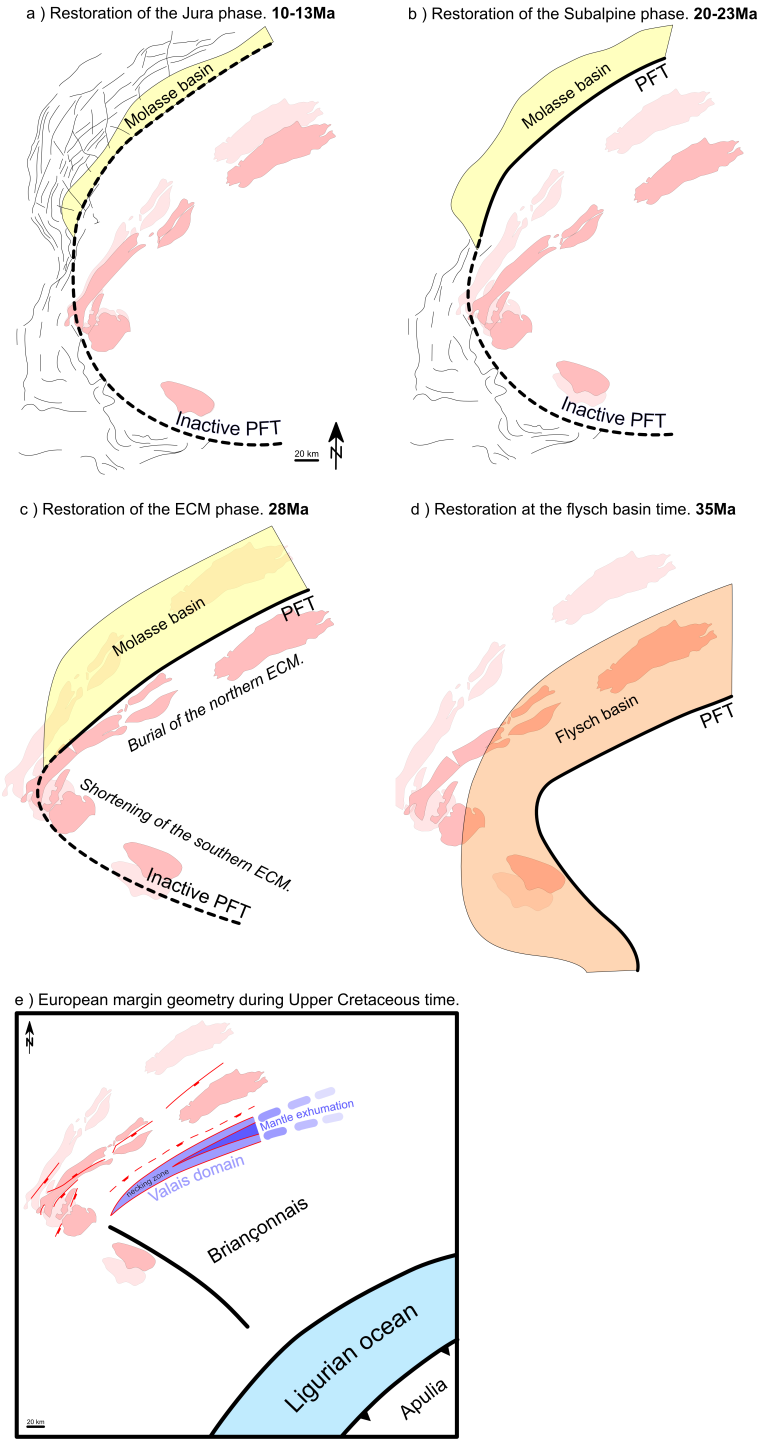

Figure 4. (a–d) Palinspastic reconstruction [from Bellahsen et al., 2014] showing the existence of a pre-collisional proto-arc amplified during Alpine collision. (e) European margin at Mesozoic time [Bellahsen et al., 2014] showing extent and position of Valaisan basin and the existence of a major NW–SE accident structuring the European margin in the southern part of the present Western Alpine arc.

prior to the collision [e.g., Wortel and Spakman, 2000, to explain peri-Mediterranean arcs shown in Figure 1]. This model is appropriate for the Alps, because tomographic sections indicate that the slab is detached everywhere except beneath the central Alps [Handy et al., 2021]. Alternatively, tear fault models described for other orogenic arcs of the peri-Mediterranean belts [Romagny et al., 2020, Jolivet et al., 2021] can explain subduction arcs. Indeed, a NW–SE transform fault along the present-day NE edge of the Argentera and Pelvoux massifs is inferred to have existed in some palaeogeographic reconstructions [Handy et al., 2010, Romagny et al., 2020].

3.1.3. *Pyreneo-Provençal inheritance*

Pyrenean orogeny takes place between late Santonian–Campanian or early Palaeocene and Priabonian [~85 Ma–35 Ma; Staub, 1924, Lutaud, 1924, Siddans, 1979, Philip and Allemann, 1982, Tempier, 1987, Bertrand, 1888, Zürcher, 1891, Kilian, 1892]. This event, linked to N–S convergence between Iberian and European plates [e.g., Lacombe and Jolivet, 2005, Schreiber et al., 2010, Advokaat et al., 2014, van Hinsbergen et al., 2020] produces the Pyrenean chain, whose EW structures extend all along the Mediterranean coast from Spain to the French–Italian border, in the Alpine foreland [Figures 1 and 5; Bertrand, 1888, Zürcher, 1891, Kilian, 1892, Lutaud, 1924, Lemoine, 1972, Siddans, 1979, Philip and Allemann, 1982, Tempier, 1987, Balansa et al., 2022], where they are termed Pyreneo-Provençal. These structures strike parallel to the southernmost part of the western Alpine arc, and are partly located within the latter area. Some of them clearly predate the Eo-Oligocene Molasse sediments, and are reactivated in the Miocene [Graham et al., 2012]. Hence, the question of an Alpine vs Pyrenean origin of this southernmost segment of the Alpine arc needs to be discussed. The occurrence, and interference of such Pyrenean and Alpine structures in the External Zone is described in the following paragraphs.

In the Diois and Baronnies, in the footwall of the Digne nappe and to a very small extent in the Digne Nappe itself (Figures 2a, 5a), folds and thrusts are oriented E–W, seeming more compatible with Pyrenean structures than with the sub-Alpine chains, which are oriented NNW–SSE in this area [Figure 5a; Lemoine, 1972, Siddans, 1979]. However, in the Nice–Castellane arc (Figure 5), at the southern edge of the External Zone, at least some of the E–W structures, are shown to be active even during the Miocene [e.g., Lemoine, 1972, Siddans, 1979, Jourdon et al., 2014, Balansa et al., 2022], hence after the termination of Pyrenean orogeny [Balansa et al., 2022; Figure 5a].

One may wonder if all E–W structures of the southern Dauphinois are not mere Pyreneo-Provençal structures, partly reactivated in the Miocene, rather than newly formed, late Alpine structures. However, the absence of exposed post-Eocene units in most of the area makes it difficult to assess the age of these structures. North-verging folds and thrusts are attributed to the Pyrenean event by some authors [e.g., Balansa et al., 2022], whereas south-verging ones to the Alpine event s.s., but this discrimination remains rather speculative.

In summary, structural inheritance in the Western Alps may be related to 3 distinct events: (1) by Mesozoic rifting potentially controlling the shape of the European continental margin, and/or of the Adriatic indenter; (2) pre-collisional structures related to the flexure of the orogenic wedge caused by bending of the subducting slab; (3) Pyrenean-Provençal structures; which affect the southern E–W segments of the subalpine ranges and in particular the Castellanne arc. If the latter structures are accepted to be of Pyrenean-Provençal origin, the topographically continuous 180° arc of the External Zone needs to be segmented into two parts in terms of its formation processes. Its northern area, drawing a 90° arc from the E–W orientation in the Central Alps to the N–S to NNW–SSE orientation south of the Western Alps corresponds to the Alpine arc s.s., resulting from Adria-Europe convergence. In contrast the southernmost, E–W striking segment of the arc (Figure 2a) is of Pyrenean-Provençal origin, formed during the convergence of Europe and Iberia and their Miocene reactivation. We discuss below (Section 3.6), which geodynamic causes may induce this reactivation.

3.2. *Collisional indentation*

Most collisional models of the western Alpine arc (Figure 3) are based on the idea that the European continental margin deforms in order to acquire the shape of the more rigid Ivrea indenter. This hypothesis is based first on the evidence that the amount of shortening in the Adriatic indenter is small compared to that observed in the Internal Zone and in the

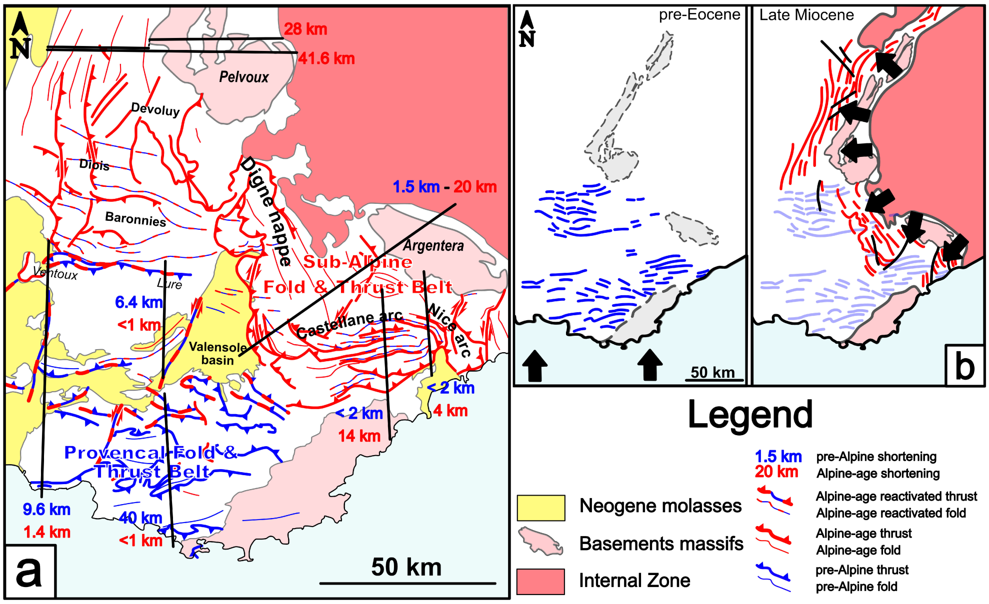

Figure 5. (a) Structural map of the External Zone with major structures and their inferred relative ages, from Balansa et al. [2022]. Black lines represent sections along which amounts of Alpine and pre-Alpine shortening are esimated [Ford et al., 2006, Bellahsen et al., 2012, Espurt et al., 2012, Jourdon et al., 2014, Bestani et al., 2015, 2016]. (b) Two-phase model of deformation for the External Zone [Lemoine, 1972, Siddans, 1979].

Dauphinois and Helvetic [for a review see Rosenberg et al., 2021], and second, on the fact that the structural grain of the Internal Zone is parallel to the indenter boundary, whereas structures within the indenter are not.

The larger strength of the Adriatic indenter is thought to be related to the occurrence of the strong, sub-vertical slice of mantle rocks of the Ivrea body, which borders its western edge [e.g., Schmid and Kissling, 2000, Schmid et al., 2017]. This body, imaged by seismic refraction, seismic tomography, and Bouguer anomaly analyses [Giese, 1968, Berckhemer, 1969, Giese et al., 1970, Fountain, 1976, Paul et al., 2001, Lardeaux et al., 2006, Diehl et al., 2009, Schmid et al., 2017], indents both the orogenic wedge and the European margin throughout Alpine collision.

Tapponnier [1977] is the first to propose an indentation model for the formation of the Alpine arc (Figure 3f), suggesting Adriatic indentation in the European margin first towards the North, in the Lower Cretaceous, and later towards the West, since the Upper Cretaceous. Laubscher [1991] provides the first indentation model which attempts to balance in map view displacements related to an inferred westward convergence of the Adriatic Indenter throughout Alpine collision (Figure 3h). Laubscher [1971, 1988, 1991] notes that the northern boundary of the "Ivrea mantle wedge" coincides with the dextral Periadriatic fault zone [Figure 2a: the Jorio–Tonale Segment; Laubscher, 1991]. By retrodeforming the western Alpine nappes, he concludes that this fault accommodates a westward translation of about 300 km of the Adriatic indenter between Oligocene and Lower Miocene. As a consequence, a similar accident in opposite shear sense needs to exist to the south of the arc [Laubscher, 1971, 1988, 1991], wich he terms Villavernia–Varzi–Levanto Line [Laubscher, 1991].

More recent models suggesting westward indentation include dextral strike-slip movements of approximately 100 km, also along the Periadriatic Fault [Schmid et al., 1996, Schmid and Kissling, 2000, Rosenberg et al., 2021], and sinistral strike slip (Figure 3i) along a structurally not yet characterised, nor precisely located zone in the South of the arc. Different sinistral structures, located in different areas, are proposed by different authors [Figure 2b; Laubscher, 1971, 1991, 1996, Ricou, 1981, 1984, Ricou and Siddans, 1986, Piana et al., 2009, d'Atri et al., 2016, Schmid et al., 2017, Piana et al., 2021]. The Acceglio–Cuneo Line (Figure 2b) of Schmid et al. [2017] and the Villavernia–Varzi–Levanto Line (Figure 2b) of Laubscher [1991], are based on geometric considerations and map view reconstructions. The sinistral Limone–Viozene Zone (Figure 2b), east of the Argentera, or its extension to the north of the Argentera, in the Gardetta–Viozene Zone [Figure 2b; Piana et al., 2009, d'Atri et al., 2016, Piana et al., 2021], or the Stura "corridor" and the Preit "scar" [Figure 2b; Ricou, 1981, 1984, Lefèvre, 1984, Ricou and Siddans, 1986], are interpreted on the base of structural field data. Alternatively, in the southernmost part of the arc a more distributed sinistral shear zone [Figure 3d–l; Collombet et al., 2002], possibly corresponding to a sinistral transpressive large-scale zone, as characterised by Michard et al. [2004], is also suggested. Interestingly, that in the southern part of the arc the structures drawn by Argand [1916], describe sigmoidal lines that could be interpreted as the result of sinistral shearing (Figure 3a).

Whereas westward indentation, explains an arc shape whose bisector axis is oriented E–W, and whose inferred displacement directions may be nearly symmetric about such E–W axis (Figure 5b), the westward indentation is not coherent with the Africa/Adria convergence direction, which is inferred to be directed northward since the Cretaceous [Dewey et al., 1989, Faccenna et al., 2004] based on palaeomagnetic data. In order to reconcile the arc shape of the western Alps and its E–W symmetry axis with an inferred NW-ward directed Adriatic indentation, several kinematic models consider a change through time in the convergence direction of the Adriatic indenter. Generally, an early N–NW indentation in the collision history is followed by a W–NW one [Tapponnier, 1977, Ford et al., 2006, Handy et al., 2010, Dumont et al., 2012, Schmid et al., 2017]. Both the direction of indentation and the age inferred for these direction changes vary from one author to the other. Laubscher [1971, 1991, 1996], Tapponnier [1977] and Dumont et al. [2011, 2012] propose a net westward indentation, while Mancktelow [1992], Handy et al. [2010], Schmid et al. [2017] and Romagny et al. [2020] propose a WNW indentation. Alternatively, Platt et al. [1989] and Ford et al. [2006] suggest a more NW-directed indentation direction, as initially shown by Argand [1916].

Models suggesting a transition from northward to WNW-ward, or even to westward indentation favour its onset around 35 Ma [Ford et al., 2006, Dumont et al., 2012], or in the Middle Oligocene [Ceriani et al., 2001, Schmid et al., 2017].

Based on pressure–temperature–time data and the stratigraphic evolution of foreland basins around the western Alpine arc, Ford et al. [2006] propose a two-phase model (Figure 3l). In this model the first phase of inferred southward continental subduction and accretion of the Penninic nappes in the Eocene takes place during the northward indentation of the Adriatic indenter. The second phase of Oligo–Miocene age accommodates NW-directed indentation [Ford et al., 2006].

Based on chronostratigraphic and metamorphic compilations associated with structural analysis especially in the westernmost MCE (Pelvoux, Grandes Rousses and Belledonne massifs, Figure 2a), Dumont et al. [2012] suggest a three-step model. This model starts with N–S convergence during the Pyrenean phase, from late Cretaceous to Eocene [Michard et al., 2010, Dumont et al., 2012] followed by N–S to NNW–SSE convergence in the Eocene (Figure 3i). Their third step is termed "Oligocene revolution" [Dumont et al., 2012], because of an inferred change of 90° in the transport direction, which becomes E–W at the end of the Lower Oligocene. It is after this revolution that westward indentation would lead to the development of the western Alpine arc.

However, WNW-ward indentation is difficult to reconcile with large-scale plate displacements [Dewey et al., 1989, Jolivet and Faccenna, 2000, Jolivet et al., 2021]. Throughout Alpine collision, the African plate, to which the Adriatic indenter is probably attached, is inferred to move northward and eventually NW-ward with respect to Europe based on palaeomagnetic data [Dewey et al., 1989] and kinematic reconstructions [Jolivet and Faccenna, 2000, Jolivet et al., 2021], but not WNW- or westward.

In summary, indentation models face two major problems: (1) assessing the existence and the amount of displacement accommodated along the shear zones bounding the indenter, and (2) assessing the indenter displacement direction(s) and their compatibility both with large-scale reconstructions and with structures all along the arc. We discuss these two points below.

(1) If indentation has a significant westward component it must be accommodated along lateral structures, i.e., nearly E–W striking dextral strike-slip in the north and sinistral in the south, according to the conceptual model of Laubscher [Figure 3h; Laubscher, 1971, 1991]. The "Jorio–Tonale line" [Figure 3h; Laubscher, 1971, 1991] is inferred to accommodate this dextral displacement that extends towards the western front of indentation along the Rhone-Simplon Fault (Figure 2) [Laubscher, 1971, 1991, 1996, Schmid and Kissling, 2000, Ford et al., 2006, Schmid et al., 2017]. Bulk displacement is estimated at 100 km by map-view reconstructions [Schmid and Kissling, 2000]. However, several authors, based on geomorphological arguments [Garzanti and Malusà, 2008], and kinematic compatibility in map scale [Müller et al., 2000, Viola et al., 2001] suggest that the offset along the Periadriatic Fault does not exceed 40–50 km. In addition, as described above, no agreement exists yet on the required sinistral, E–W striking fault, with an equivalent displacement, accommodating westward indentation at the southern margin of the indenter. The strongest argument to suggest some 50 km of sinistral offset along the ACL [Figure 2b; Schmid et al., 2017] is the apparent offset of the Briançonnais Front across this line. But this line is not described as a clear discontinuity between the two offset Briançonnais segments and a large part of this apparent offset could result from a bend in the original structure, i.e. a progressive rotation of the southern part of the arc during its formation, without a discontinuity in the PFT.

(2) An outright westward indentation is consistent with many measured stretching lineations [Malavieille et al., 1984, Choukroune et al., 1986, Schmid and Kissling, 2000], with the inferred westward displacement along the PFT as observed in the Pelvoux and Belledonne sectors [Ceriani et al., 2001, Dumont et al., 2012], and more importantly with the N–S orientation of the Chartreuse and Vercors sub-alpine Chains (Figure 2a) and all other N–S first-order structures located along the westernmost segment of the arc.

NW-directed indentation does not provide a satisfying explanation for the southern segments of the arc, oriented WNW–ESE and E–W. Analogue models of the western Alpine indentation following a NW-ward convergence direction [Lickorish et al., 2002; Figure 3k] show that fold and thrust belts striking sub-parallel to the margin of the indenter develop a more or less continuous arc shape, whose south-western segment strikes NNW–SSE and bends progressively northward until it reaches an E–W orientation in front of the E–W margin of the indenter, corresponding to the Central Alps, thus forming an arc of some 100–110° around the northern and western margins of the rigid indenter. Therefore, an indentation to the NW could produce the 86 km of ENE–WSW shortening to the SW of the arc [Rosenberg et al., 2021, and references therein] compared to the more than 200 km of SSE–NNW shortening in the central Alps [Rosenberg et al., 2021, and references therein]. However, this setting cannot result in the formation of an arc, but not one of nearly 180°, i.e., including the southern E–W striking segment that would correspond the southern termination of the Western Alpine arc. The latter would easily develop with a strong westward component of displacement [e.g., Mancktelow, 1992] or a late rotation towards such an orientation [e.g., Dumont et al., 2012, Schmid et al., 2017].

Changes in indentation direction from north to west or to WNW [e.g., Dumont et al., 2012] would result in dramatic slowing of N–S shortening in the Eastern and Central Alps and an equally dramatic increase in E–W shortening in the western Alps. However, the NW–SE shortening in the Jura fold and thrust belt [e.g. Homberg et al., 1999] occurred between Serravallian and early Pliocene times [Bolliger et al., 1993, Steiniger et al., 1996, Kalin, 1997, Becker, 2000, Bellahsen et al., 2014], which is rather incompatible with a strictly westward indentation since the Oligocene. In addition, bulk shortening and exhumation of the latter massifs increases from the Pelvoux to the Aar massifs [e.g., Bellahsen et al., 2014, Rosenberg et al., 2021]. Furthermore, thermochronological data suggest that the Pelvoux External Massif (Figure 2a) begins its exhumation before the Mont Blanc [Bellahsen et al., 2014, and references therein]. Interpolation of multiple thermochronological data [Fox et al., 2016] suggests that the higher exhumation rates progress from the Central Alps to the southern part of the arc of the Western Alps, but larger exhumation of the Western Alps compared to the Central Alps are only assessed in the time span of 2–0 Ma [Fox et al., 2016], along the

Mt Blanc–Pelvoux NE-striking axis (Figure 2a), which is perfectly oriented to accommodate NW indentation. In addition, the northern deformation front of the Alps, striking from Switzerland to Austria is active as a N-directed thrust between 15 and 4 Ma [Mock et al., 2020], a displacement that is incompatible with a net westward displacement of the Adriatic indenter. Therefore, based on the arguments above there is no evidence to justify a shift from a NW-ward to a westward or WNW-ward indentation at 35 or 25 Ma. Finally, large westward-directed components of displacements of the Adriatic indenter pose some severe kinematic problems if the northeastern part of the Adriatic indenter is also taken into account. Its northeastern margin also forms an indenter (Dolomites indenter) and the deformation pattern around it is incompatible with large displacement components towards the west [Rosenberg et al., 2007].

3.3. *Rotation of the Adriatic indenter*

Some studies attempt to overcome the difficulties of linking radial collisional transport directions (Figure 2c) with simple, uni-directional indentation (Figure 3f–m) [Gidon, 1974, Vialon et al., 1989, Dumont et al., 2012], by considering a rotation of the Adriatic indenter, as inferred from some palaeomagnetic studies [e.g., van Hinsbergen et al., 2014b] and GPS data [Caporali and Martin, 2000, Nocquet and Calais, 2004, D'Agostino et al., 2006].

Gidon [1974] suggests a "whirlwind origin" for the West Alpine arc. He formulates an analogy between atmospheric vortices, and the morphology of the Alpine arc [Gidon, 1974]. He bases this analogy on the presence of major dextral faults along the edges of the chain, corresponding to the PFT and the Periadriatic fault, which would allow the Adriatic indenter to rotate, sliding along the edge of the (European) margin [Gidon, 1974]. He also considers that the pattern of deformation in the External Zone traces a "fan" shape in map view, emphasised by the frontal thrusts of the ECMs in the north, the DNF (Figure 2a) in the west and the dextral Bersezio Fault Zone (BFZ, Figure 2a), passing into the Argentera Massif in the south (Figure 2a). The pole of rotation, would be located close to Turin (Italy), just as in recent rotation models, based on GPS data, structural, seismic and palaeomagnetic analyses [Westaway, 1990, Ward, 1994, Collombet et al., 2002, Nocquet and Calais, 2004, Bauve et al., 2014].

Vialon et al. [1989] interpret the syn-collisional southward transport directions in the southwestern External Zone of the Alps to activate several inferred dextral, N–S to NE–SW striking faults, cross-cutting the External Zone (Figures 2a and 3c). These dextral faults are arranged in a fan shape around the PFT, which is itself reactivated as dextral strike-slip fault [Vialon et al., 1989; Figure 3c]. For this reason, the arc of the Western Alps results, according to Vialon et al. [1989], from a "ring shear" model [Mandl et al., 1977], in which counterclockwise rotation of a cylindrical block leads to the development of dextral faults around it. These faults develop in directions oriented at 45° from the interface between the block and the outer domain. The authors associate these dextral strike-slip movements, interpreted mainly according to focal mechanisms [Fréchet, 1978, Ménard and Fréchet, 1989], with the rotation of a block decoupled from the Adriatic indenter since the Cenozoic and up to the present day. Under the effect of NW indentation of the Adriatic indenter, this block would rotate counterclockwise and move towards the WNW. The existence of this rotating block is no more than hypothetical because its boundary faults are not documented by field studies and because no geophysical or structural data support decoupling of such a block in the NW corner of the Adriatic indenter.

Most of the recent models suggesting rotation of the Adriatic indenter compare explicitly [Collombet, 2001] or not explicitly [Collombet et al., 2002, Bauve et al., 2014], the present morphology of the arc, the distribution of inferred dextral faults, and in particular their fan-shaped arrangement, with rotation models such as that of Mandl et al. [1977]. This counterclockwise rotation is inferred to affect the whole Adriatic indenter and it is extended to the whole of the Internal Zone by making the tacit assumption that these two parts of the Alps are strongly coupled (Figure 3d) [Collombet et al., 2002, Bauve et al., 2014].

The model of Mandl et al. [1977] is tested by analogue experiments that show the development of weakly overlapping dextral fan-shaped faults and very arcuate thrusts within sand layers surrounding a rotating, rigid disk, also covered by sand layers [Collombet, 2001]. This model nicely reproduces arcuate transpressive structures, but they surround the rotating disc all around its 360°. Structures around the western part of the disc could recall the ones of the western Alps, but those surrounding the eastern half of the disc are far from structures known to exist in the Alps. Even those analogue models [Collombet, 2001] that replace the disc with a rotating object whose shape is similar to the present-day Adriatic indenter create a deformation pattern along its eastern margin that is not consistent with the tectonic pattern of the Southern Alps. However, the link between indenter rotation and nucleation of fan-shaped pattern of dextral faults possibly explains the numerous dextral faults of the western Alps (Figure 2a).

Based on new and compiled palaeomagnetic data, Collombet et al. [2002] propose a post-Oligocene counterclockwise rotation of the Adriatic indenter attaining at least 25° since the Miocene, accommodated by dextral strike-slip movements along the Periadriatic fault and the PFT (Figure 3c–e). Collombet [2001] associates the development of dextral strike-slip along major faults of the External Zone, such as the DNF (Figure 2a), with this rotation, as previously suggested by Vialon et al. [1989].

Arguments based on the present-day and palaeostress fields, on focal mechanisms of earthquakes and on structural analyses indicate that the southern part of the arc, particularly in the Argentera region, is characterised by a transtensional regime marked by N140° striking dextral strike-slip faults, inferred to nucleate between 20 and 26 Ma and still active today [Bauve et al., 2014], consistent with the inferred counterclockwise rotation of the Adriatic indenter since the Miocene [Vialon et al., 1989, Collombet et al., 2002].

GPS data [Caporali and Martin, 2000, Nocquet and Calais, 2004, Nocquet, 2012, D'Agostino et al., 2006] represent the strongest and most direct evidence for present-day counterclockwise rotation of Adriatic indenter. However, these data only show current movements and their extrapolation backward in time to infer Cenozoic kinematics, is only possible if independent evidence also indicates the occurrence of counterclockwise rotation throughout Oligo–Miocene time. Interestingly, an analysis of palaeomagnetic data compiled for the entire peri-Adriatic region [Maffione et al., 2008] strongly suggests that the Adriatic indenter has not rotated since the Middle Miocene, thus questioning all models reported above that involve large counterclockwise post-Miocene rotation (some 25° counterclockwise) [Figure 3d, Collombet et al., 2002].

Several authors link an inferred change in indentation direction to a counterclockwise rotation of the Adriatic indenter [Platt et al., 1989, Schmid and Kissling, 2000, Ford et al., 2006, Dumont et al., 2011, Schmid et al., 2017], with rotation amounts varying according to the authors, from about 15° [Platt et al., 1989, Schmid and Kissling, 2000] to 25° [Collombet et al., 2002], or to even larger, not precisely quantified values [Dumont et al., 2011]. The driving force of this rotation is inferred to be the rollback of the Apenninic slab [Dumont et al., 2012]. However, such a rollback does not necessarily induce any rotation of the Adriatic indenter. Indeed, the counterclockwise rotation of the Apennines through the Neogene is compensated by southeastward increasing amounts of rollback and of extension in the upper plate, not by rotation of the Adriatic Plate. There is therefore no satisfactory explanation nor a robust data set to support an "Oligocene revolution" or a radical change in indentation direction.

In addition, all models invoking significant rigid body rotations of the Adriatic indenter around a pole close to Turin are faced with a major kinematic problem: an eastward progressive increase of northward displacement of the Adriatic indenter, which is not supported by any shortening gradient based on structural studies of the Alpine Chain [e.g., Le Breton et al., 2021, Rosenberg et al., 2021]. If the rotation pole is set elsewhere, e.g. south of the Po Plain or south of the Adriatic indenter as in the hypotheses tested by van Hinsbergen et al. [2014a], large amounts of Neogene extension would appear in the Ionian Basin, also not corresponding to what is currently known [van Hinsbergen et al., 2014a]. Therefore, if any counterclockwise rotation takes place, it may be limited to approximately 5° as suggested by numerical modelling [Le Breton et al., 2017]. Larger counterclockwise rotations of the Adriatic indenter would be attested by obvious indicators of dextral shear around it. However, apart from the Periadriatic Fault, dextral faults in the western Alps only accommodate very modest displacements (Figure 2a), such as the Bersezio Fault [Corsini et al., 2004, Sanchez et al., 2011] with displacements not exceeding 5–10 km. As a consequence, we conclude that Neogene significant counterclockwise rotation is very unlikely and does not explain the Alpine arc shape nor the NNE–SSW displacements in its southern part.

3.4. *Effect of deep-seated mantle flow on crustal structures*

The southern E–W segment of the Alpine arc terminates at the transition between the Alps and Apennines (Figure 2a). This segment is characterised by a crust of normal thickness [Paul et al., 2022; Figure 6b] and lies along the transition between the Alpine slab dipping eastward and the Apenninic slab dipping westward [Vignaroli et al., 2008, Molli and Malavieille, 2011]. The Apennine slab is affected by the eastward roll-back, thus extending the European upper plate during Oligocene times and opening the Liguro-Provençal and Tyrrhenian Basins since 23 Ma [Speranza et al., 2002, Ferrandini et al., 2003], and also causing an oroclinal flexure in the Apennines [Speranza et al., 2002, Rosenbaum and Lister, 2004a,b]. Numerical models of adjacent, but opposite-dipping slabs suggest that the lateral margins of these slabs rotate towards a direction that tends to parallel the dip direction of the slabs themselves, thus creating a sigmoidal structure at depth [Király et al., 2016, 2021]. In the southern Alpine arc this direction would be approximately E–W. How, and if, such structure is transferred towards the upper crust is not known nor modeled yet, but it is likely that the large-scale orientation of the slabs at depth controls the orientation of the orogenic prism, hence creating approximately E–W striking structure between the Alpine and Apennine arcs [Király et al., 2016]. Irrespective of the interaction between adjacent slabs, the map scale pattern of SKS anisotropy directions [e.g. compilation in Király et al., 2018] indicates an abrupt change at the southern end of the arc, where N–S directions paralleling the N–S striking arc segment suddenly become E–W oriented. This change is inferred to be due to toroidal flow, with mantle flow parallel to the European slab in the north, and bordering the southern end of the European slab in the south [Figure 7; Király et al., 2018].

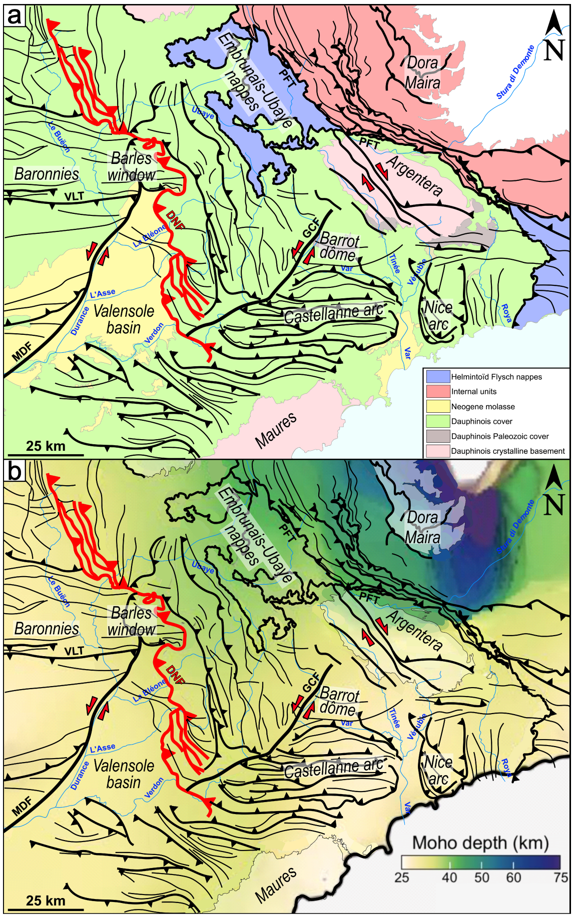

Figure 6. (a) Structural map of the SW External Zone. Thin lines represent fold axes. (b) Structural map of the SW External Zone above coloured layer illustrating Moho proxy map from Paul et al. [2022]. A Moho depth gap striking E–W, located along the northern part of the Argentera Massif separates structures oriented N–S to NW–SE, where the crust is thick (>55 km), from an area to the south, where structures are WNW–ESE to E–W and the crust is less than 40 km thick both in the Internal and External zones. Red lines: Digne nappe frontal thrusts; Blue lines: main rivers. DNF: Digne Nappe Front; GCF: Guillaumes–Castellane Fault; MDF: middle Durance Fault; PFT: Penninnic Frontal Thrust; VLT: Ventoux-Lure Fault.

3.5. *Gravitational tectonics*

Gravitational processes are often considered as driving forces for the formation and displacement of

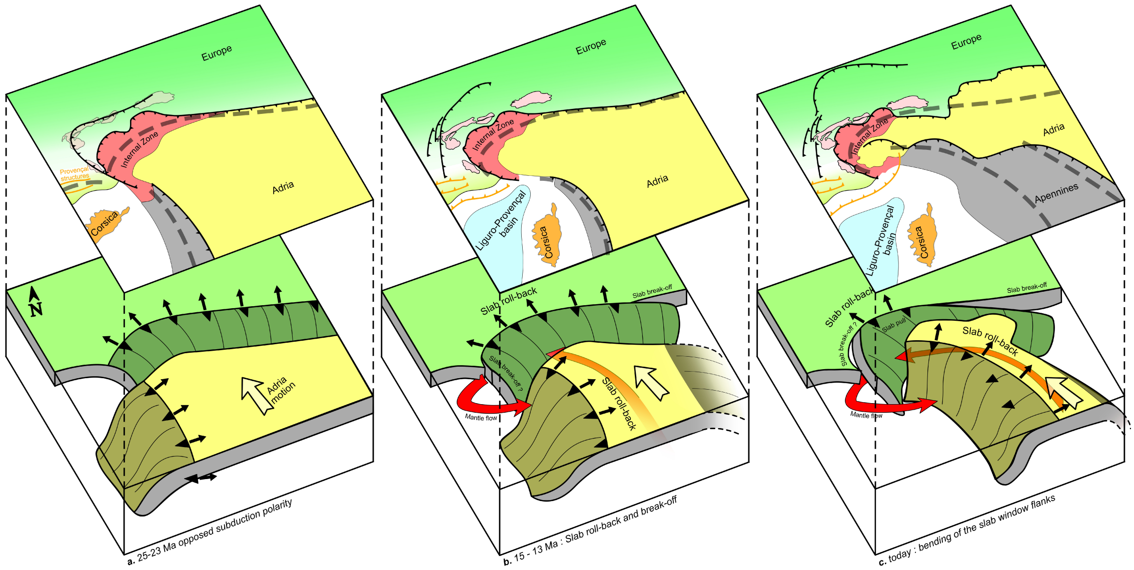

Figure 7. Map-view displacement model of the bending of the Alpine and Apenninic slabs terminations, after Király et al. [2016, 2018]. First there is a space between the E to SE dipping Alpine slab to the North and the W to SW dipping Apennine slab to the South. This "slab free" area is first oriented NNW–SSE and becomes progressively reoriented WNW–ESE during eastward retreat of the Apennine slab. Interaction between slabs of opposite polarity during their retreat bends their edges producing a lithospheric sigmoidal structure ultimately amplified by mantle flow, which invades the growing space between the two slabs. The existence of slab break-off south of the Western Alps arc is suggested by some numerous [e.g. Lippitsch et al., 2003, Kästle et al., 2020, Handy et al., 2021, Paffrath et al., 2021], but not all authors [e.g. Malusà et al., 2021, Zhao et al., 2016], thus it is represented on these diagrams in spite of some doubts. Red arrows: asthenospheric toroidal flow.

Alpine nappes, folds and faults, since the early works of Gignoux [1948a,b] and later ones by Kerckhove [1969], Merle and Brun [1984], Labaume [1987], who suggest that folding and thickening of the Internal Zone cause gravitational flow, displacing the subalpine chains westward. Recent works suggest that the present Western Alps may be undergoing gravitational collapse [Sue, 1998, Sue et al., 1999, Sue and Tricart, 2003, Selverstone, 2005, Sue et al., 2007, Larroque et al., 2009, Le Pichon et al., 2010, Rangin et al., 2010]. This process occurs when the gravitational potential energy in areas of thickened crust exceeds the force exerted by plate convergence [Dewey, 1988, Jamieson and Beaumont, 1989, Rey et al., 2001, Selverstone, 2005]. Therefore, thinning of previously thickened areas allows for a transfer of gravitational potential energy from the core of the chain to adjacent areas [Selverstone, 2005]. Thus, foreland-directed, radial displacement may be triggered by gravitational processes, which in turn may play a fundamental role in creating an arc structure. Indeed, based on stretching lineations and their relative chronology, Platt et al. [1989], suggest that the Adriatic indenter moves NW-ward, but displacement around the indenter margin is parallel to the sum of the vectors corresponding to indenter displacement and to gravitational collapse of the chain (Figure 3j). Therefore, bulk displacement deviates from NW convergence, becoming W-directed and N-directed in the southwestern and northern parts of the chain, respectively (Figure 3j). This interpretation assumes that an arcuate, thickened structure already exists at the onset of collision and that the rheology of the crust allows for its collapse.

Seismo-tectonic studies and structural analyses indicate that the Internal Zone of the Western Alps is affected by an extensional regime since the Pliocene [Sue, 1998, Sue et al., 1999, Sue and

Tricart, 2003]. A switch from orogen-parallel to orogen-perpendicular extension in the Internal Zone is inferred to take place during the Pliocene [Sue et al., 2007], as indicated by the activation of orogen-parallel normal faults, and extensional re-activation of the PFT, according to seismo-tectonic and structural analyses [Sue, 1998, Sue et al., 1999, Sue and Tricart, 2003, Sue et al., 2007, Larroque et al., 2009]. Based on the spatial distribution of earthquake focal mechanisms, orogen-perpendicular extension affects the Internal Zone, where the crust is thickened [Sue et al., 2007], and it is contemporaneous with orogen-perpendicular shortening, and orogen-divergent shortening in the foreland [Sue et al., 2007].

Recently, the concept of gravitational tectonics has been specifically applied to the southernmost Alpine arc [Le Pichon et al., 2010, Rangin et al., 2010], suggesting that deformation in the Diois-Baronnies area (Figure 2a), i.e. its E–W-striking thrusts and associated folds result from gravity sliding of the Mesozoic cover along Triassic evaporites. In the subalpine chains and the Provençal basin, the top of the basement is barely affected by shortening of inferred Alpine age, and seismicity only affects the cover [Le Pichon et al., 2010]. An additional argument supporting the interpretation of gravity collapse is the absence of any documented convergence between Eurasia and the Corsica–Sardinia block [Le Pichon et al., 2010], hence the lack of a plate tectonics process driving N–S shortening. The latter leads to southward gravity sliding of the cover units along Triassic evaporites during basement uplift in the Pelvoux Massif [Le Pichon et al., 2010, Rangin et al., 2010].

The exhumation of the Pelvoux massif cannot produce a southward slope of the basement roof in the Diois and Baronnies (Figure 2a), since it lies to the northeast. In addition, no direct evidence of such a basement flow exists, in terms of structures exposed at the surface or in seismic sections.

Concerning the seismo-tectonic evidence [Sue, 1998, Sue et al., 1999, Sue and Tricart, 2003] the structures described are outcrop-scale, not map scale structures, suggesting that the amount of arc-perpendicular extension is of minor importance. It might explain subsidiary Miocene reactivation of E–W Pyrenean structures, as observed in the Diois, Baronnies, and in the Nice–Castellane arc, but this process is not expected to create large-scale, first-order structures that shape the Alpine arc.

To conclude, nearly all studies that infer that gravitational processes shaped, at least in part, the western Alpine arc, assume that displacements are triggered by lateral gradients of crustal thickness and topography. Hence, if the radial character of the structures in the arc were to be related to gravitational processes, a previously arcuate belt needs to exist. In other words, gravitational processes in the arc of the Western Alps may be the consequence of the arc shape, not the cause of its formation.

3.6. *Post-Tortonian N–S shortening*

Numerous E–W striking structures in the southernmost part of the arc of the Western Alps accommodate small amounts of post-Tortonian N–S shortening (e.g. 1:50,000 geological map, 999, Grasse-Cannes, BRGM), potentially accentuating its southernmost E–W grain. We discuss below the possible causes of this shortening.

Seismo-tectonic [Ritz, 1992, Chaumillon et al., 1994, Bigot-Cormier et al., 2006, Larroque et al., 2009, 2012, 2021, Bauve et al., 2014] and bathymetric studies of the Ligurian sea [Morelli et al., 2022] suggest that the Liguro-Provençal margin is being inverted, since Tortonian times, along ENE–WSW trending thrusts. Some models link the compressive seismic events offshore with large-scale structures onshore, reaching into the core of the Alpine orogen [Larroque et al., 2009, Bigot-Cormier et al., 2006] and exhuming its European basement in the Argentera Massif [Bigot-Cormier et al., 2006]. These processes cause N–S shortening in the southernmost segment of the arc and may thus reactivate E–W striking Pyrenean-Provençal structures.

The inversion of the Liguro-Provençal margin can only start after the termination of extension of the Liguro-Provençal basin, i.e. after 15 Ma, based on the age of the Corsica–Sardinia block rotation [Speranza et al., 2002, Ferrandini et al., 2003]. Inversion of the northern margin of the Liguro-Provençal Basin initiates from the Plio-Quaternary times according to structural studies, seismic profiles and sedimentological considerations [Ritz, 1992, Chaumillon et al., 1994, Morelli et al., 2022]. Such inversion could be related to Late Miocene N–S shortening onshore, in the southernmost part of the Alpine arc. The absolute amount of this post-11.6 Ma N–S shortening is not assessed yet, however, based on maps and sections, post-Miocene shortening is between 4 and 14 km only [Jourdon et al., 2014].

Some of these post-Tortonian structures (e.g., the Trévaresse thrust, Figure 2a) are located far to the west of the Alpine arc, suggesting that Alpine shortening cannot be the cause of these displacements. Significant topographic and crustal thickness gradients, as existing in the southernmost part of the arc (Argentera Massif region) are absent in the latter area, precluding gravitational processes as a driving force of N–S shortening. Therefore, the most likely cause of these few km of N–S shortening is linked to the geodynamic process at the origin of the inversion of the Ligurian-Provençal margin.

This interpretation is challenged by GPS data, which suggest that convergence between Africa and Europe is absorbed to 90% along the northern African margin, thus very little is left to induce convergence between the Corsica–Sardinia block and the European Plate [Nocquet, 2012]. Hence, barely any convergence may exist at present between Corsica and southern France. However, based on recent datasets of global satellite system networks, Corsica is inferred to converge northward towards Europe at a rate of 0.4 mm/yr [Masson et al., 2019], and this motion results in NNW–SSE shortening north of Corsica. If this rate of convergence was held constant and extrapolated backward to Tortonian time, some 4 km of N–S shortening would be required to accommodate it. Similar field-based values are inferred to correspond to post Tortonian N–S shortening in the southern part of the Alpine arc and further west [e.g., Jourdon et al., 2014].

Alternatively, post-Tortonian N–S shortening is suggested to result from the activation of large NE dipping thrust faults rooted in the core of the Alpine orogen [Larroque et al., 2009]. However, the southwestward propagation of an Alpine crustal ramp [Larroque et al., 2009] is hardly compatible with northward or NW-ward convergence between Adriatic Indenter and European margin (see Section 3.2), and it is not supported by structural evidence nor geophysical imaging.

In summary, no geodynamic process by itself satisfactorily explains the small amounts [4–14 km in the Castellane arc, Jourdon et al., 2014] of N–S, post-Tortonian onshore shortening observed all along the Ligurian Sea margin, in the Valensole basin and in the Castellane arc [Ritz, 1992, Chaumillon et al., 1994, Bigot-Cormier et al., 2006, Larroque et al., 2009, 2012, 2021, Bauve et al., 2014, Morelli et al., 2022]. However, in spite of the present-day, but only short-term record of GPS data, it may be argued that even very low convergence rates between Corsica–Sardinia block and Europe [Masson et al., 2019], may well induce several km of shortening over the long term (Miocene to present). This process, conceivably associated with minor gravitational tectonics, is likely to explain the seismicity [Larroque et al., 2016] and late Neogene reactivation of Pyrenean-Provençal structures in the south of the arc.

4. New tectonic model

In the following we propose a new kinematic model for the formation of the western Alpine arc that is based on the critical review presented above and on new views on the structure of the External Zone.

4.1. *Map-view structural analysis of the southern External Zone*

In order to better understand the relationship between the Pyreneo-Provençal belt and the Alpine one, a structural map of the External Zone, sketched on the base of 42 1:50,000 geological sheets of the BRGM, is shown in Figure 6 and discussed in the following paragraphs. This map illustrates the traces of fold axial planes and thrusts, and to a minor degree strike-slip faults. Although the structures shown in Figure 6 are aligned to the axis of the Alpine arc in several areas, this is not everywhere the case.

In particular, the NE–SW striking Guillaumes–Castellane Fault (GCF, Figure 2a), inferred to be a sinistral fault [Figure 2a: GCF; Ritz, 1992] and sometimes termed Rouaine–Daluis Fault [Sonnette et al., 2014, Balansa et al., 2022], abruptly separates areas characterised by differently oriented structures. Structures strike NNW–SSE to the north of this line, and E–W to the south (Figure 6), where they are continuous and parallel to the Pyrenean-Provençal Chain. The NNW–SSE-striking structures exposed north of the latter line is parallel to structures exposed further east, in the internal parts of the External Zone and in the Internal Zone, hence parallel to the trend of the orogen at this latitude, and they terminate westward along the NNW–SSE striking Digne nappe thrust (Figure 6). The transition from the E–W striking structures and the NNW–SSE ones, forms a discontinuous 90° elbow rather than a continuous arc.

In the Baronnies and Diois (Figure 6a), all structures strike E–W, sub-parallel to the Pyreneo-Provençal chain exposed further south [Balansa et al., 2022; their figure 1]. The region between the southern coast of France and the Diois is affected by Pyreneo-Provençal structures, whose N–S extent is larger than west of the Salon-Cavaillon Fault (Figures 2a and 5b). Except for minor N–S striking fold and thrusts in the westernmost Baronnies (located west of the map of Figure 2a), along the margin of the Rhone Graben, the entire area between the latter graben and the Digne Nappe is not affected by N–S striking folds and thrusts (Figure 6). Considering that the spatial change in orientation is abrupt and so clearly defined along the front of the Digne nappe we interpret it as the western front of the Alpine orogen, which overrides the Pyrenean-Provençal one. In detail, N–S folds can be recognised structurally in some areas below the Digne Nappe but they are limited to the immediate footwall and most likely linked to nappe emplacement.

The Digne Nappe is classically inferred to accommodate SSW-ward displacement [Gidon and Pairis, 1986, Faucher et al., 1988, Gidon and Pairis, 1992, Gidon, 1997, Graham et al., 2012], based on the orientation of striae on fault planes. However, E–W and WSW–ENE-oriented maximum stress axes are described all along the western front of the Digne thrust [Ritz, 1992, Lickorish and Ford, 1998, Lickorish et al., 2002, Balansa et al., 2022], and inferred to be both of Miocene and Pliocene age [Ritz, 1992]. Similar orientations of shortening axes inferred from ASM measurements also characterise the western front of the Digne thrust [Collombet, 2001, Sonnette, 2012]. These orientations are consistent with the NNW–SSE direction of the thrust front, accommodating WSW-oriented transport. In addition, several large-scale observations indicate that the main displacement direction is likely to be close to westward. First, the longest segment of the Digne Nappe front is oriented NNW–SSE (Figure 6) and it consists of a thrust, not a dextral strike-slip fault (as would be expected for the lateral ramp of a SSW-directed thrust). Second, the internal structures of the Digne Nappe strike N–S to NNW–SSE (Figure 6), being consistent with a major westward component of displacement and the NNW–SSE striking front. Third, at its southern end, above the Valensole Basin (Figure 6) the frontal thrust of the Digne Nappe separates into different sub-parallel, close to N–S striking segments, as classically observed at the terminations of large fault planes. E–W striking thrust planes that could represent the front of a large nappe do not really exist. Those that strike E–W seem to accommodate small amounts of shortening and be related to a wide, distributed fold and thrust zone, which forms the eastern continuation of the Pyreneo-Provençal belt (Figure 6).

In summary, we conclude that the Digne Nappe is displaced dominantly WSW-ward (N255°), as also suggested by a recent study [Schwartz et al., 2017]. Hence, minimum displacements estimated along NNE–SSW sections [e.g. Graham et al., 2012, Balansa et al., 2022] are likely to be significantly overestimated. Another outcome is that the afore-described boundary between E–W striking and N–S striking structures along the Guillaumes–Castellane Fault (Figure 6) would coincide with a transition between W-directed and S-directed displacement. Therefore, the transition from NNW–SSE to E–W structures in the External Zone is abrupt. Continuous, radial, arc-perpendicular displacements do not exist there, excepted for the areas in the immediate surroundings of the Argentera Massif.

4.2. *Interpretation of structures in the southern External Zone*

Interestingly, the abrupt transition described above, between N–S to NNW–SSE and E–W structures, is located along a NE–SW fault which is aligned with the southern termination of the crustal root below the Internal Zone [Figure 6; Paul et al., 2022]. The deepest part of the orogenic wedge strikes N–S to NNW–SSE, parallel to the orogen axis, from the Argentera Massif northward, and it is interrupted along a nearly E–W line east of the Argentera massif (Figure 6b). South of this line the crust of the Internal-, and to a minor degree also of the External Zone, is much thinner. This sudden E–W interruption of the otherwise N–S striking Moho surface (Figure 6b), coincides with the southern termination of the Ivrea body [e.g., Kissling et al., 2006, Schmid et al., 2017], which represents the base and margin of the Adriatic crust. Its southern termination coincides with the southern termination of the Adriatic mantle and Adriatic Plate in their upper plate position.

Because no significant extensional faults are known in this area, the thickness change indicated by the Moho proxy map (Figure 6b) must result from significantly smaller amounts of shortening in the area south of the Argentera Massif. This observation is consistent with the idea that different tectonic processes acting independently from one another to shape the NW–SE segment and the internal and external E–W segments of the arc. Alpine shortening in the strict sense, i.e. in terms of accommodation of convergence between Adria and Europe, probably does not affect the area located south of the southernmost Argentera Massif, namely the E–W segment of the arc. As a consequence, the complete shape of the arc would result from the juxtaposition of two distinct structural domains, one located north of the Guillaumes–Castellane Fault (Figure 2a) belonging to the Alps s.s. and one located south of this line belonging to the Pyreneo-Provençal orogen.

In summary, E–W striking structures extending from the Pyrenees to the External Zone in the Western Alps, notably in the Castellane arc and the Baronnies area, are of Pyrenean origin [Staub, 1924, Lemoine, 1972, Siddans, 1979, Balansa et al., 2022], as indicated by their pre-Eocene–Oligocene age, and by their spatial distribution of shortening, whose amount a dramatical decrease towards the Alpine Chain. Thus, in spite of incomplete dating of the E–W striking structures, the spatial distribution of shortening, the abrupt transition between E–W and N–S shortening, and the non-parallel orientation between E–W structures and the axis of the Alpine Chain, all suggest that Alpine-age shortening in the southern, E–W segment of the External Zone is kinematically unrelated to Alpine collision s.s., i.e. to the accommodation of Adria-Europe convergence. The Neogene reactivation of these structures is discussed in the paragraphs below.

The radial character of the inferred Alpine transport directions [Figure 2c; e.g., Platt et al., 1989] is thus limited to a progressive change from northward- in the Central Alps to W- or WSW-directed displacements in the Digne nappe (Figure 5a). In the External Zone, from the Nice arc to the Vercors (Figure 2a), no additional gradual change to SSW- or southward displacement is observed, but a sudden change from westward or WSW, to southward.

These arguments and conclusions provide a rationale to the different past interpretations on the western extent of the Alpine arc. Some authors include all the Chaînes Subalpines, incorporating Diois and Baronnies, into the arc of the Western Alps [e.g., Schmid and Kissling, 2000, Kempf and Pfiffner, 2004], others terminate it along the outer boundary of the Castellane arc and Nice arc [e.g., Staub, 1924, Laubscher, 1988, Roure et al., 1989]. The present interpretation differs from all previous ones as it excludes not only the Baronnies and Diois chains, but also the Castellane–Nice one of the arc of the Western Alps s.s., i.e. from the arc formed by NW-directed collision of the Adriatic Indenter and the European margin.

The latter interpretation links the arcuate structure of the External Zone of the Alps with two distinct processes: (1) an uni-directional NW-directed indentation of Adria against Europe to form the Central Alps and the Northwestern Alps (the NW Alps being defined as the structures striking from the Pelvoux and Dora Maira massifs northward); (2) a Pyrenean origin for the southern, E–W striking part of the arc, with some post-Tortonian reactivation, possibly due to the Europe–Africa convergence, hence associated with the inversion of the Liguro-Provençal Basin.

4.3. *Building the southern, E–W-striking arc segment in the Internal Zone*

The E–W striking Ligurian Alps underwent a counterclockwise rotation of 50° between lower- and mid-Miocene [23 Ma; Speranza et al., 2002] as indicated by numerous palaeomagnetic data in the Tertiary Piedmont Basin (Figure 2a) [Maffione et al., 2008]. This rotation [Maffione et al., 2008] is contemporaneous with an anti-clockwise rotation of the northern Apennines is linked to an oroclinal flexure of this orogen [Speranza et al., 1997]. Therefore, the E–W orientation of the Ligurian Alps likely results from the Apennine flexure rather than from Alpine collision.

Indeed, the Ligurian Alps are in the hanging wall of the Apenninic Frontal Ramp (Figure 2a). Thus N–S shortening recorded in this northernmost part of the Apennines likely affects the Ligurian Alps and can explain its E–W orientation. This implies that at present and during collision, the Ligurian Alps belong to the upper plate of the Apenninic subduction system and not to the lower plate of the Alpine orogen.

In addition, the interaction between the southern and northern terminations of the Alpine and Apenninic slabs, respectively, each of them migrating away from the other, can result into the lateral bending that would also rotate them towards an E–W orientation [Király et al., 2016, 2018]. The effect of such a toroidal mantle flow (Figure 7) on surface structures is not really described. The implication of this process in the E–W orientation of the Ligurian Alps is therefore speculative.

All these processes may explain the E–W orientation of the southern segment of the Alpine arc, even in the Internal Zone, i.e. east of the Pyrenean-Provençal belt.

4.4. *New kinematic model*

In summary, we propose a new kinematic model for the formation of the Alpine arc, that we describe in the following.

During Eocene times (i.e., before 35 Ma, Figure 8a), the Internal Zone is already arcuate as a consequence of subduction processes, as indicated by retro-deformation of collisional shortening, [Figure 4, Bellahsen et al., 2014]. This structure is probably associated with slab retreat, as described by Royden [1993] and Wortel and Spakman [2000] for the development of all peri-Mediterranean orogenic arcs (Aegean, Alboran, Carpathian, Apenninic-Calabrian; Figure 1). Hence, against the vast majority of the literature [Tapponnier, 1977, Laubscher, 1991, Schmid et al., 2004, Handy et al., 2010, Dumont et al., 2011, 2012] we suggest that shortening linked to Adriatic indentation only amplifies an already existing arc structure.

Meanwhile, the Pyrenean-Provençal belt produces E–W structures reaching as far as the Alpine foreland, giving rise to the present-day E–W arc segments in the External Zone (e.g., Castellane arc). At 35 Ma (Figure 8b), Alpine collision leads to the amplification of the 90° arc in the External Zone, from the Aar to the Argentera Massifs, as a result of NW indentation of the Adriatic Plate into the European margin. The southern termination of this arc corresponds to the Pyrenean-Provençal belt in the West (External Zone) and to the Ligurian Alps in the East (Internal Zone). Several processes can explain the E–W orientation of the Internal Zone: (1) between 23 and 13 Ma [Maffione et al., 2008; Figure 8c], oroclinal bending of the Northern Apennines causes 50° of counter-clockwise rotation also affecting the Ligurian Alps, as suggested by palaeomagnetic data from the Tertiary Piemont Basin [Maffione et al., 2008], which overlies with a discordant sedimentary contact the Internal Zone. Such rotations may be linked to N–S shortening along the Apenninic frontal ramps exposed north of the Ligurian Alps (Figure 2a). Alternatively, and/or in addition to the latter process, counterclockwise rotation of the Ligurian Alps may follow a deep-seated bending of slab terminations (Alpine and Apenninic) dipping in opposite directions [Király et al., 2016].

Further West, the E–W striking part of the Alpine arc in the External Zone records small amounts of Miocene N–S shortening, which can be dated to post-Tortonian time (Figure 8d) in several areas. The exact origin of this event, reactivating the Pyrenean structures remains debatable. Based on the arguments presented in Section 3.6, we suggest that convergence between the Corsica–Sardinia block and the European margin is the most plausible cause, despite the small amounts of present-day convergence rates between these two domains, as shown by analysing datasets derived from global navigation satellite system [Masson et al., 2019].

5. Conclusion

Rigid indentation of the Adriatic indenter, generally thought to generate the arcuate shape of the Western Alps cannot explain by itself the formation of the entire arc, because it cannot create a radial pattern of displacement, encompassing 180°. Given the generally accepted NW-convergence direction during the collision, the fundamental question concerns the origin of N–S oriented shortening in the southern part of the arc. The hypothesis of changing convergence direction through time, from NW- to W, in order to better explain N–S striking structures and even NW–SE striking ones is not compatible with the increase in Cenozoic arc-perpendicular shortening from the Western to the Central Alps, with the existence of significant Miocene and Pliocene N–S shortening in Central Alps, and even less with Miocene tectonics of the Eastern Alps.

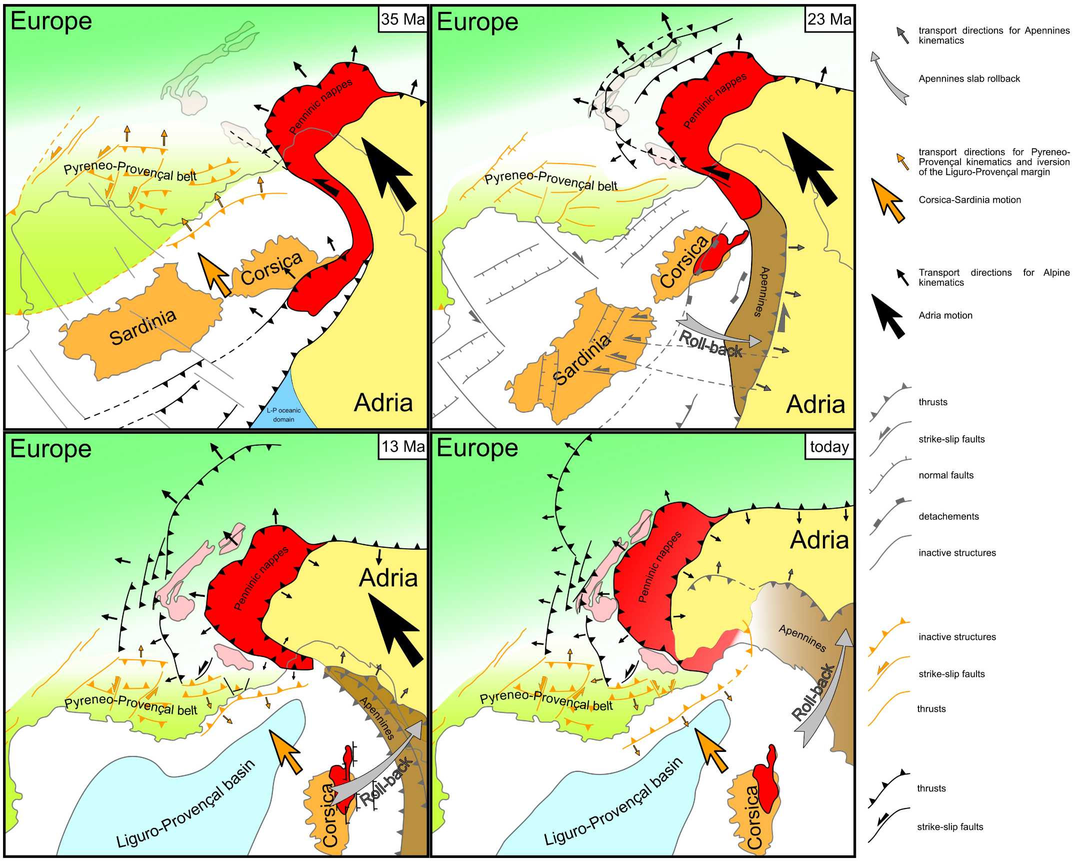

Figure 8. Tectonic model of the Alpine collision [modified from the reconstruction of Romagny et al., 2020].

Our kinematic model solves this problem by considering that, in spite of its topographic continuity and its structural continuity in the Internal Zone, the arc results from distinct geodynamic processes acting at different times and in different areas. Following the formation of an arc during subduction, as manifest in the Internal Zone, NW-directed Adriatic indentation amplifies this arc in its northern and western parts. In contrast, its southern E–W striking segment is shaped first (Paleogene) by the eastern termination of the Pyrenean orogen, and later by post-Tortonian shortening on the European margin. Also, during the Miocene, the eastern continuation of this southern segment, namely the Ligurian Alps, are affected by an Apennines-related counterclockwise rotation. Hence none of these processes is caused by the indentation of Adria and should not be considered as part of Alpine collision.

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

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