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Kinematic reconstruction of the Alpine Tethys and surrounding Mesozoic rifted margins

Gianluca Frasca^{1,2} · Gianreto Manatschal² · Pauline Chenin²

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Abstract

In plate kinematic reconstructions, the restoration of rifted margins and their fossil equivalents exposed in orogens remains challenging. Tight fit reconstructions rely on the mapping of margins rift domains, their restoration to their pre-rift crustal thickness, and the removal of the oceanic and exhumed mantle domains. At present-day margins, high-resolution wide-angle seismic imaging allows mapping and measurement of rift domains; however, restoring fossil margins is trickier because they are largely overprinted and partially lost during convergence. Here, we present a new kinematic model for the Mesozoic rifting along the Tethys–Atlantic junction, which relies on two assumptions: (1) the width of the fossil Alpine Tethys rift domains was comparable to that of their present-day analogs, and (2) the necking zones of the former tectonic plates can be mapped, dated and used as kinematic markers. This reproducible workflow allows us, for the first time, to restore the rifted margins of the Alpine Tethys. Our reconstruction shows: (1) a westward propagation of extension through the Ionian, Alpine Tethys and Pyrenean rift systems from the Triassic to the Cretaceous, (2) the segmentation of the Mesozoic Tethyan rifted margins by strike-slip corridors, (3) the opening of an oceanic gateway at 165 Ma as mantle was exhumed along the entire Alpine Tethys and (4) the subdivision of the Mesozoic oceanic domain into compartments that were later consumed during subduction. This new model is supported by published data from the Alps, the Ionian Sea, the Pyrenees and the southern North Atlantic.

Keywords Alpine Tethys · Adria · Iberia · Rifted margins · Margin ‘Building Blocks’ · Intracontinental strike-slip corridors

Introduction

Classical plate kinematic restorations of divergent plate boundaries consist in the progressive closing of oceanic domains fitting isochronous magnetic anomalies in the direction of fracture zones (Müller et al. 2019). In such reconstructions, the kinematic direction and velocities are well constrained. Conversely, the kinematic restoration of rifted margins and intracontinental deformation zones is much more challenging, and yet it is a prerequisite for tight fit restorations of the continents back to their pre-rift stage (Nirrengarten et al. 2018; Barnett-Moore et al. 2018; Frasca et al.

2021). The challenge is even bigger when former rift systems have been reactivated in convergence and have undergone continental collision and/or when most of the dense oceanic crust has been subducted and only remnants of the former rifted margin have been accreted in the orogen. In such circumstances, pre-convergence plate kinematic restorations are little constrained, as illustrated by the everlasting debates about the width and nature of the crust flooring the Alpine Tethys (McCarthy et al. 2021). This uncertainty is at the origin of the numerous and partly contradictory plate tectonic reconstructions of the Alpine Tethys realm (Stampfli and Hochard 2009; Vissers et al. 2013; van Hinsbergen et al. 2020; Angrand et al. 2020; Le Breton et al. 2021).

Here, we propose a new kinematic model of the Alpine Tethys and the surrounding Mesozoic rifted margins for the 230–83 Ma time interval based on the assumptions that: (1) the width of present-day and fossil rifted margins are comparable, (2) necking and mantle exhumation can be dated, (3) necking zones in orogens can be identified, mapped and used as markers to restore fossil margins, (4)

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strike-slip intracontinental corridors define the direction of plate motion, like fracture zones in oceanic domains and (5) gaps in pre-rift tight fit reconstructions can be minimized in fossil contexts. Our kinematic model allows us to propose a new tight fit restoration for the Alpine Tethys realm and to specify, for the first time, the kinematic evolution of its surrounding rifted margins during the Mesozoic. Although further studies are needed to confirm or challenge our model, in particular in the Ionian and Tyrrhenian domains, at present we are not aware of any data disproving our new kinematic restoration.

Tectonic setting

Plates, microplates and continental blocks

Figure 1 summarizes the present-day position of the continental blocks involved in the formation of the Alpine Tethys during the Mesozoic. The Alpine Tethys was bounded by the Iberia microplate to the west and the Adria microplate to the east. These were in turn surrounded by the North America (NAM), Africa (AFR) and Europe (EU) plates (Fig. 1). Here, we propose that both the Iberia and Adria microplates were transected by intracontinental deforming regions, referred to as strike-slip corridors, namely the Biscay–Iberian corridor (BIC) in the Iberia microplate (e.g., Nirrengarten et al. (2018) and Frasca et al. (2021)), and the proto-Insu-bric corridor (IC) and the proto-Mattinata corridor (MC) in the Adria microplate. We call “block” the parts

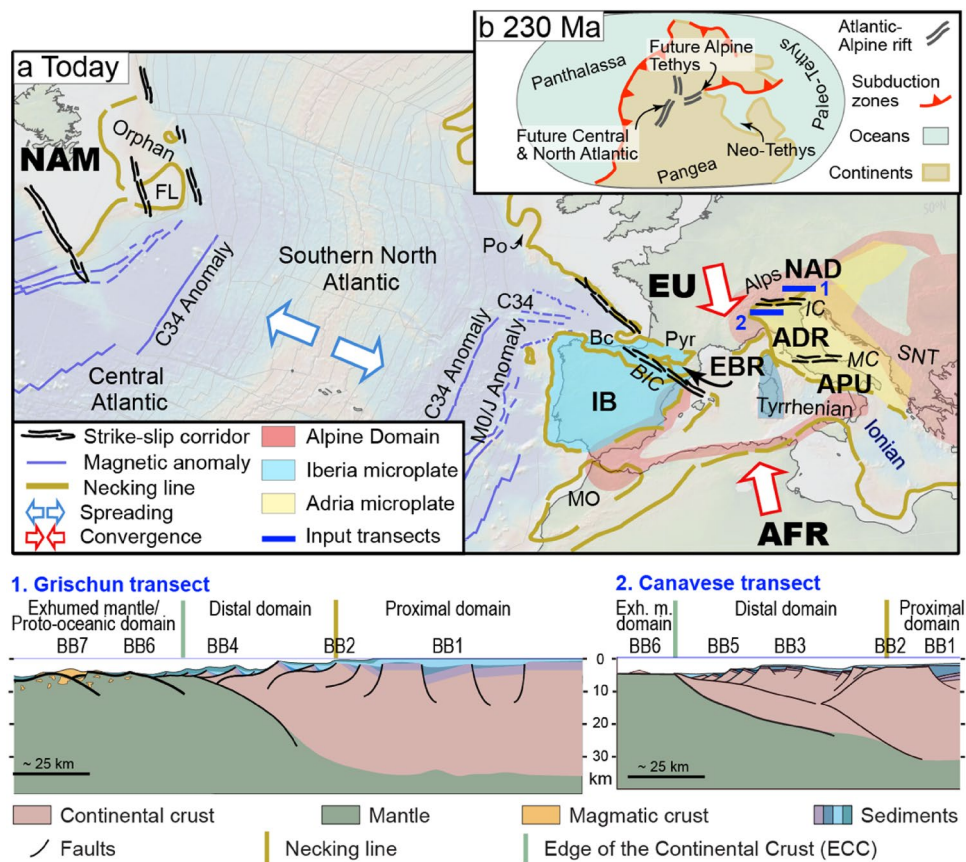


Fig. 1 Tectonic sketch of the Atlantic and Alpine domains with location of present-day and fossil necking lines. **a** Regional map of the Atlantic Ocean and Alpine collisional domain around the present-day Tyrrhenian. Topography obtained with GeoMapApp. *ADR* Adria block, *AFR* Africa, *APU* Apulia block, *Bc* Basque–Cantabrian basin, *BIC* Biscay–Iberian corridor, *EBR* Ebro block, *EU* Europe, *FL* Flemish Cap, *IB* Iberia block, *IC* proto-Insu-bric corridor, *MC* proto-Mattinata corridor, *MO* Morocco, *NAD* North Adria block, *NAM* North

America, *PO* Porcupine, *Pyr* Pyrenees, *SNT* subducted Neo-Tethys. The two restored transects used as model input are displayed in blue: The size of the large arrows is about 400 km. Input transect 1: Grischun; Input transect 2: Canavese (modified after Beltrando et al. 2015; Manatschal et al. 2022a). *BB* Building Blocks (see text for details). **b** Simplified paleotectonic map of the study area at the onset of the reconstruction. Redrawn after Müller et al. (2019)

of the microplates that lie on either side of such strike-slip corridors: in the Iberia microplate the Biscay–Iberian corridor separates the Iberia block (IB) from the Ebro/Sardinia/Corsica block (EBR) (Fig. 1). In the Adria microplate, the proto-Insubric corridor separates the North-Adria block (NAD) from the Adria block (ADR), and the proto-Mattinata corridor separates the Adria block (ADR) from the Apulia block (APU) (Fig. 1).

Kinematic restoration of the Iberia Microcontinent

A prerequisite to correctly reconstruct the Alpine Tethys and Adria Microcontinent paleogeographic evolution is to kinematically restore the present-day Atlantic margins to their pre-rift stage, to constrain the relative position of Iberia and Adria prior to their separation (Fig. 1b). Past plate kinematic reconstructions of the Iberia microplate were based on the restoration of the magnetic anomaly M0/J and did not incorporate the restoration of the up to 400 km extension accommodated by intracontinental deformation prior to the onset of seafloor spreading (Tucholke et al. 2007; Sibuet et al. 2007; Sutra et al. 2013). These restorations predicted a Late Jurassic to Aptian ocean in the Pyrenean domain that was subducted during the Albian (Sibuet et al. 2004; Vissers and Meijer 2012; van Hinsbergen et al. 2020), inconsistent with existing observations made in the Pyrenean domain (Chevrot et al. 2015). More recently, Nirrengarten et al. (2017) and Szameitat et al. (2020) showed that the M0/J anomaly in the southern North Atlantic does not correspond to an isochron, and hence cannot be used as such in plate kinematic restorations. Based on this finding and on the restoration of the continental margins to their pre-rift thickness, Nirrengarten et al. (2018), Barnett-Moore et al. (2018) and King et al. (2020) proposed full fit restorations for the southern North Atlantic. Angrand et al. (2020) and Frasca et al. (2021) defined intracontinental strike-slip corridors that allow reconciliation of the amount, timing and kinematic movement direction along the Iberia–Ebro–Europe plate boundary, here named Biscay–Iberian corridor (Fig. 1a), based on geological observations made in the peri-Iberian system (Ford et al. 2022; Asti et al. 2022). In our study, we build on the kinematic model of Frasca et al. (2021) to restore the Iberia microplate, a model that does not use the M0/J anomaly as an isochron and incorporates the tight fit restoration of the southern North Atlantic of Nirrengarten et al. (2018). Hence, in contrast to former studies, our new restoration of the Alpine Tethys: (1) is based on a kinematic solution for the Iberia microplate that is compatible with those of the major plates, (i.e., North American, African and European plates), (2) does not violate existing geological observations of the peri-Iberian system and (3) relies only on consensual magnetic anomalies and transform systems on the Atlantic side and on the existence of the Biscay–Iberian

strike slip corridor mentioned above (Angrand et al. 2020; Frasca et al. 2021).

Method

Age and location of rift domain boundaries and Building Blocks approach

To restore the fossil, reactivated and partly subducted rifted margins of the Alpine Tethys, we take advantage of the significant progress made in the description of magma-poor rift systems in the last decades (Chenin et al. 2022; Peron-Pinvidic and Manatschal 2019). We assume that the Alpine Tethys rifted margins used to display a comparable architecture and average rift domain widths as present-day ones (Fig. 2b), namely 110 km for the distal margin (necking plus hyperextended domain) and 60 km for the exhumed mantle domain (Chenin et al. 2017). Deformation occurring in the proximal domain is minor ($\beta < 1.2$) and is ignored in our restoration. We rely on field observations and previously published studies to identify the Building Blocks constitutive of the former rifted margins (Fig. 2a; see Manatschal et al. 2022a), as well as their present-day position and orientation. Building Blocks are kilometer-scale outcrops where primary rift relationships between basement rocks, fault structures and syn-rift sediments are preserved. They provide information about the nature of the basement, the accommodation space and the geometry and age of rift structures. We include the two best constrained Alpine transects that were restored to a pre-rift stage, namely the Grischun transect in eastern Switzerland (Manatschal et al. 2022a; transect 1 in Fig. 1) and the Canavese transect in the southern Alps (Beltrando et al. 2015; Decarlis et al. 2017; transect 2 in Fig. 1). We use present-day geophysical data by Tugend et al. (2019) to constrain the size and shape of the Ionian Sea.

In our restoration, we track the position of: (1) the ‘necking line’, i.e., the continent-ward edge of the necking zone (yellow line in Figs. 1a, 2b and 3); (2) the edge of the continental crust (ECC), i.e., the inner edge of the exhumed mantle domain (green line in Figs. 2b and 3); and (3) the landward limit of oceanic crust (LaLOC; blue line in Figs. 2b and 3). At present-day magma-poor rifted margins, these domain boundaries can be mapped using reflection seismic data (for method and examples, see Tugend et al. 2014; Chenin et al. 2015). In collisional orogens, only the necking line can be mapped with some confidence. There, it is defined as the limit from which the syn-rift sediments change from shallow- to deep-marine facies (for details in the Alpine domain see Manatschal et al. 2022a). Each of these ‘lines’ (in reality they correspond to domains of some few tens of kilometer widths) can be associated with a datable tectonic event whose age has been previously

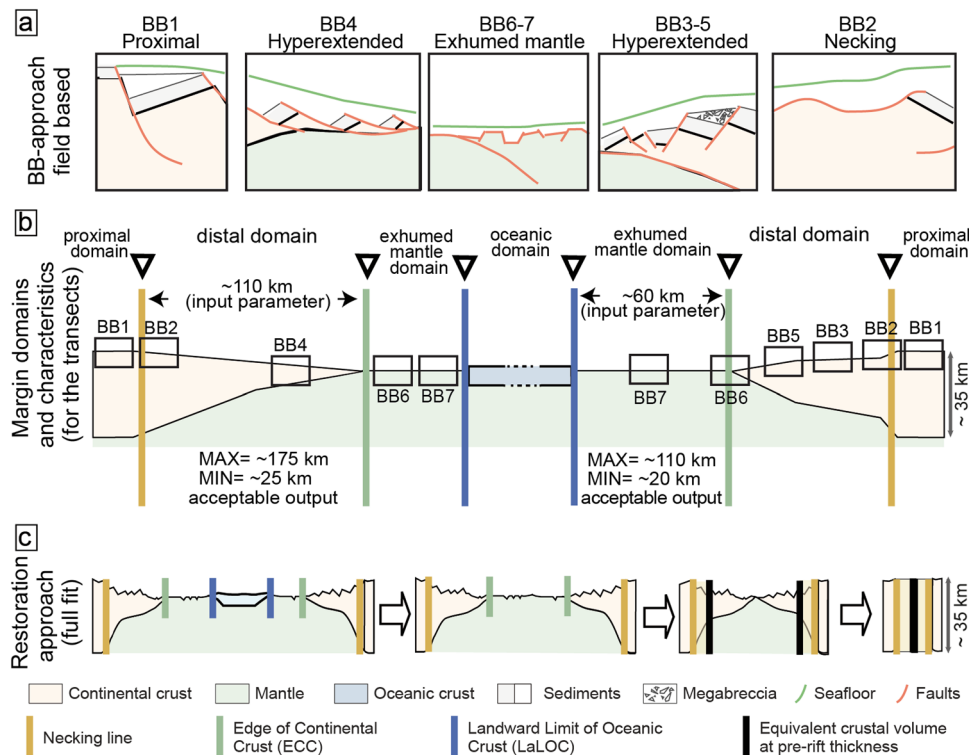


Fig. 2 Modeling strategy and approach. **a** The Building Block (BB) concept applied to the Alpine Tethys margins in the transects of Fig. 1 allows to define rift domains and—thanks to stratigraphy—the timing of their formation. Redrawn after Chenin et al. (2022). **b** Schematic cross section across a conjugate magma-poor rifted margin pair highlighting the different rift domains bounded by (1) the ‘necking line’ (yellow) at the outer edge of the proximal domain; (2) the Edge of the Continental Crust (ECC, green) at the inner edge of the exhumed mantle domain; and (3) the Landward Limit of Oceanic

Crust (LaLOC, blue). For each of these three domains we display the size given as input parameter. Redrawn after Chenin et al. (2022). **c** Step by step restoration of the rifted domains. Continental crust area balancing is used between the necking line and the ECC to determine the tight full fit position, while the oceanic crust and exhumed mantle domains are simply removed. The thick black lines represent the outer limit of the pre-rift margins when they have been restored to their pre-rift thickness assuming continental crust volume conservation. Redrawn after Nirrengarten et al. (2018)

constrained: necking is dated 225 ± 5 Ma in the Central Atlantic/Ionian/Neo-Tethys domain (Tugend et al. 2019), 185 ± 5 Ma in the Alpine Tethys (Manatschal et al. 2022a), 145 ± 5 Ma in the Iberia–Newfoundland domain (Mohn et al. 2015), and 125 ± 5 Ma in the Pyrenean domain (Masini et al. 2014; Lescoutre and Manatschal 2021). Mantle exhumation is dated 200 ± 5 Ma in the Central Atlantic/Ionian/Neo-Tethys domain (Tugend et al. 2019), 165 ± 5 Ma in the Alpine Tethys (Li et al. 2013, 2015), 125 ± 5 Ma in the Iberia–Newfoundland domain (Mohn et al. 2015), and 110 ± 5 Ma in the Pyrenean domain (Masini et al. 2014). Onset of seafloor spreading is dated 185 ± 5 Ma in the northern Central Atlantic/Ionian/Neo-Tethys domain (Schettino and Turco 2011; Tugend et al. 2019), 110 ± 5 Ma in the Iberia–Newfoundland domain (Mohn et al. 2015) and is not constrained either in the Alpine Tethys or in the Pyrenean system since we lack datable material testifying to steady-state seafloor spreading in these two domains (Picazo et al. 2016; McCarthy et al. 2021). We consider that these rifting phases were largely synchronous across each of these rift

systems, which is a reasonable assumption considering that we here seek to unravel only the first-order plate kinematic evolution.

Strike-slip corridors: direction of motion of continental blocks

To define kinematic directions, we use mappable strike-slip corridors, which we assume to mark segment boundaries perpendicular to necking zones, like present-day transform margins (e.g., Nemčok et al. 2023). Intracontinental strike-slip corridors are either diffuse or localized movement zones that act as flow lines defining the relative motion between continental blocks (Schettino and Turco 2011). Present-day examples of such strike-slip corridors include, on the one hand continental transform fault zones such as the Northern Anatolian Fault (Şengör et al. 2005) and San Andreas Fault (Powell and Weldon 1992), and on the other hand, plate boundaries separating oceanic and continental plates such as the Romanche Fracture Zone at the Equatorial margins

(Masclé et al. 1997; Basile et al. 2005) and the Davie Fracture Zone (Coffin and Rabinowitz 1987; Reeves et al. 2016). Here, we use the term strike-slip corridor instead of fracture zone or transform fault since such structures are commonly diffuse and linked to several faults.

In our reconstruction, we define three strike-slip corridors. The Biscay–Iberian corridor (BIC in Fig. 1a) separating the Ebro and the Iberian block was already introduced by Angrand et al. (2020) and Frasca et al. (2021). In addition, we propose two strike-slip corridors transecting the Adria microcontinent: the proto-Insubric corridor (IC) between Northern Adria and Adria, and the proto-Mattinata corridor (MC) between Adria and Apulia. We use the prefix “proto” for these two corridors because both systems were reactivated during later Cenozoic Alpine convergence and are primarily known as Alpine structures.

Handy et al. (1999) (see their Fig. 11e) introduced the term “proto-Insubric line” that was later used by Decarli et al. (2017) to account for the segmentation and change in polarity of the Adriatic margin during the Jurassic rifting. Handy et al. (2010) also referred to a proto-Periadriatic transform in their kinematic model, to account for the decoupling and segmentation between their Adria and Alcapia plates. Our proto-Insubric corridor corresponds to both these formerly defined proto-Insubric line and proto-Periadriatic transform. Note, however, that the strong overprint during the later Alpine convergence renders it difficult to identify this structure in the field and deduce its kinematics.

In the present study, we introduce the intracontinental proto-Mattinata corridor to allow for a pre-rift tight fit between the Apulia and Iberia blocks, and hence avoid the presence of a Paleozoic oceanic domain for which no evidence exists, although it has been proposed in former paleogeographic maps (Dercourt et al. 2000; Stampfli and Borel 2002). Left-lateral, strike-slip motion post-dating the early Cretaceous, as well as Pleistocene to present-day tectonic activity are well constrained along this strike-slip corridor (Argnani et al. 2009). A change from right- to left-lateral strike-slip motion has been proposed within this corridor based on local studies (Salvini et al. 1999; Tondi et al. 2005). Schettino and Turco (2011) used the Mattinata fault trend to accommodate Cretaceous motion in their reconstruction. In our study, we propose a motion along this system to already occur during the Late Triassic linked to the opening of the Ionian and Lagonegro basins in the Apennines. The strong Cenozoic overprint and the lack of outcrops render it difficult to identify this structure in the field and to confirm its Late Triassic activity.

Using the rift domain boundaries defined above and their assigned ages as kinematic markers and using the strike-slip corridors as kinematic flow lines, Gplates 2.2 free software allows us to build a robust and coherent kinematic model of the Alpine Tethys rift system. We minimize potential gaps

in our pre-rift boundary conditions (230 Ma) thanks to the restoration of rifted margins in the Ionian domain as illustrated in Fig. 2c. Such a tight full fit allows us to determine the potential available space for the Mesozoic rifted margins and (proto-)oceanic domain in the Paleo-Tyrrhenian domain.

Results

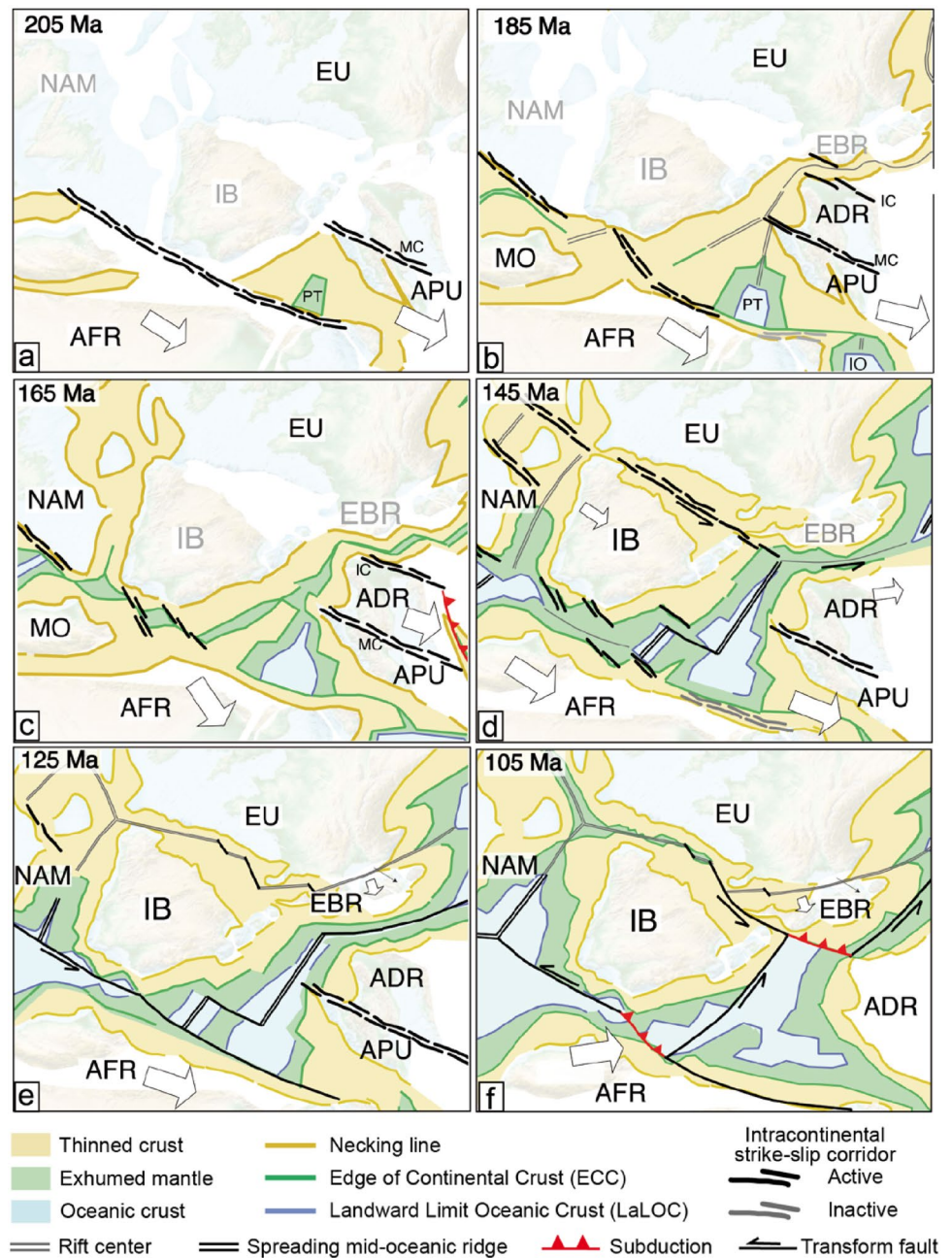
In the present study, we aim at unraveling the kinematic evolution of the Alpine Tethys rift system and its relationship with the surrounding plates during the 230–83 Ma time interval (Figs. 3 and 4). The relative positions of the North American, European and African plates are relatively well constrained at both the reconstruction onset (230 Ma) and end (83 Ma) (Barnett-Moore et al. 2016; Macchiavelli et al. 2017; Müller et al. 2019). In Fig. 3, we present snapshots at 205, 185, 165, 145, 125 and 105 Ma (snapshots at 165 and 83 Ma are shown in Fig. 5), which we consider being key moments in the evolution of the Alpine Tethys. We include the evolution of the Atlantic Ocean because it is the key input of the reconstruction. Below, we discuss the kinematics of the main plate boundaries, namely the North America–Africa and North America–Europe plate boundaries, and most important for this study, the Africa–Europe plate boundary. The latter is stepping through time, resulting in the formation of microplates and crustal blocks separated by transient strike-slip corridors (see IC and MC in Fig. 1a, Fig. 3). A movie documenting the complete kinematic evolution between 225 and 85 Ma, as well as a more detailed description of the input parameters and poles of rotation are provided in the Supplementary Material. Figure 4 shows the motion in time of selected points in the Alpine Tethys and the relative velocities between blocks/microplates obtained by the model.

Kinematic evolution of the Alpine Tethys

225–205 Ma (Fig. 3a) Neo-Tethys subduction in the east is coeval with the onset of distributed rifting in the future Central Atlantic in the west. The two domains are linked by the Ionian (IO) and Paleo-Tyrrhenian (PT) basins. The latter is inferred in this model to minimize gaps between the Iberia and Apulia blocks in our pre-rift restoration (see supplementary material). Sinistral strike-slip motion is accommodated along the proto-Mattinata corridor, and likely also along the proto-Africa–Europe plate boundary located between the Ionian and Paleo-Tyrrhenian basins that are forming.

205–185 Ma (Fig. 3b) The Africa–Europe plate boundary between the embryonic Central Atlantic Ocean and the Neo-Tethys starts to reorganize and localizes between Iberia and Adria, resulting in necking and formation of an incipient plate boundary in the Alpine Tethys domain. It generates

Fig. 3 Snapshots of the kinematic reconstruction at selected time slices in an absolute reference frame. **a** 205 Ma, **b** 185 Ma, **c** 165 Ma, **d** 145 Ma, **e** 125 Ma and **f** 105 Ma. When plates/blocks are named in grey, they are not individualized but belong to one of the major plates. See text for details. *ADR* Adria block, *AFR* Africa, *APU* Apulia block, *EBR* Ebro block, *EU* Europe, *IB* Iberia block, *IO* Ionian, *NAD* North Adria block, *NAM* North America, *IC* proto-Insu-Subic corridor, *MC* proto-Mattinata corridor, *PT* Paleo-Tyrrhenian. In **e** and **f** thin black arrow indicates the position of the Corsica–Sardinia block inside EBR. Large white arrows represent the direction of motion of plates and continental blocks relative to fixed Europe



left-lateral movements along the proto-Insu-Subic corridor and likely also along other strike-slip corridors located further north between northern Adria and Europe (not represented in Fig. 3). Oceanic crust forms in the Ionian basin and presumably also in the Paleo-Tyrrhenian basin during this period.

185–165 Ma (Fig. 3c) Subduction along the Neo-Tethys in the east is coeval with both the end of spreading in the Ionian basin and the onset of steady-state seafloor spreading in the northern Central Atlantic at ca. 185 Ma. The Africa–European plate boundary localizes between the Iberia/Ebro/Europe and Africa/Adria plates and continued

extension results in mantle exhumation along the entire Alpine Tethys rift system. At this stage, the Adria block is conjugate to the future Iberia block and limited to the north by the proto-Insu-Subic corridor, while the Northern Adria block is conjugate to the future Ebro/Sardinia/Corsica block (EBR in Fig. 3). Dextral motion is accommodated along the proto-Mattinata corridor. At the same time, extension starts localizing in the southernmost North Atlantic between the Iberia block and North America.

165–145 Ma (Fig. 3d) During this period, the Africa–Europe plate boundary is localized within the Alpine Tethys, which forms a (proto-)oceanic domain opening a

gateway between the Central Atlantic and the Neo-Tethys system. This stage also coincides with the onset of more focused rifting in the Iberia–Newfoundland domain, resulting in mantle exhumation in the south and movements between the Iberia block and Europe.

145–125 Ma (Fig. 3e) During this period, spreading continues within the Alpine Tethys and extension along the future Iberia–Newfoundland margin culminates in the creation of a new plate boundary between North America and Iberia/Europe. At 125 Ma, which corresponds to the M0 anomaly in the Central Atlantic, a major change in the kinematic evolution of Iberia/Ebro system occurs: a well-defined necking stage starts in the Pyrenean domain (Masini et al. 2014; Miró et al. 2021) and is responsible for an acceleration of the movement of the Ebro block towards the south relative to Europe. At the same time, Adria starts moving northeastwards relative to Europe.

125–105 Ma (Fig. 3f) At 125 Ma (Aptian), the main active spreading center steps from the Alpine Tethys to the southern North Atlantic, between Iberia and Newfoundland, separating North America from Iberia. In the north, the Iberia–Europe boundary localizes along the Biscay–Iberian corridor. Simultaneously, a left-lateral strike-slip movement starts in the Alpine Tethys, moving Adria northward relative to Iberia and Europe. Thus, extension in the Pyrenean–Biscay domain occurs simultaneously with both a change in kinematics in the Alpine Tethys and subduction in the northeastern Tethys domain, as indicated by first occurrence of eclogites (e.g., Koralpe/Saualpen, Froitzheim et al. 1996).

105–85 Ma (Fig. 5c) At this time, seafloor spreading propagates northward in the southern North Atlantic while left-lateral movement takes place along the Biscay–Iberian corridor between the Iberia block and Europe/Ebro block. This movement occurs simultaneous with necking and mantle exhumation in the Pyrenean domain, northward migration of Adria and subduction and high pressure both in the eastern Alps (Froitzheim et al. 1996) and locally in the Western Alps, as recorded by the oldest ages of high-pressure metamorphism retrieved in Sesia (Regis et al. 2014).

Discussion

Transient plate boundaries, microcontinents, crustal blocks and (proto-)oceanic domains

Our kinematic model illustrates the evolution of the Mesozoic rifted margins at the Tethys–Atlantic junction, from the Atlantic Ocean to the Ionian Sea (Fig. 4). Our model relies on the kinematic directions inferred from mappable markers such as strike-slip corridors and necking zones. The multistage rifting in the Tethys–Atlantic realm is not a result but an input in our model. Our new kinematic reconstruction

of the Alpine Tethys rifting shows with unprecedented details how multiple hyperextended and (proto-)oceanic domains and their bounding microcontinents and/or continental blocks evolved during the Mesozoic. Our reconstruction implies the reorganization of the Africa–Europe plate boundary linked to the formation of hyperextended and (proto-)oceanic domains and the westward stepping of rift-related depocenters (Fig. 5a). Evidence for this evolution includes the younging of the necking and exhumation ages from 225–200 Ma in the Central Atlantic/Ionian/Neo-Tethys domains (Tugend et al. 2019), to 185–165 Ma in the Alpine Tethys (Manatschal et al. 2022a), to 145–125 Ma in the Iberia–Newfoundland domain (Mohn et al. 2015), to 125–110 Ma in the Pyrenean domain (Masini et al. 2014) (Fig. 5a). In our model, rift basins along the Alpine Tethys form simultaneous and are kinematically linked with strike-slip corridors that connect extensional systems in the Atlantic with convergent systems in the Neo-Tethys domain. Strain partitioning combined with the reorganization of the Africa–Europe plate boundary result in the formation of microcontinents and continental blocks (Fig. 5a).

Three points are particularly important in our model. The first point is the sequential slicing-up of the Adria microcontinent into the Apulia, Adria and Northern Adria crustal blocks, and the successive stepping of the Africa–Europe plate boundary from south to north, localizing along strike-slip corridors (from Figs. 3a–c and 5a). Implicit in this successive reorganization and the stepping of the Africa–Europe plate boundary is the formation of transient, short-lived immature plate boundaries, which gives a new view on the debate on whether or not Adria was attached to Africa (see e.g., Muttoni et al. 2013; Channell et al. 2022). In our model, blocks of the Adria microplate change sequentially from a European to an African position between 205 and 165 Ma, before the Africa–Europe plate boundary finally localizes in the Alpine Tethys. The second point is the rapid acceleration of each of these blocks when necking occurs (Fig. 5b). This acceleration is accompanied by a northward stepping of the Africa–Europe plate boundary during simultaneous subduction in the east. Slab pull from the east is therefore likely a driver for extension in the Alpine Tethys. The third point is the change from extension to transtension along the Adria–Europe plate boundary that initiates already in Aptian time. This change is a consequence of the westward migration of the Africa–Europe Euler pole (see supplementary material) and related successive stepping of the main tectonic activity from the Alpine Tethys system into the southern North Atlantic system from the Lower Cretaceous onwards.

The complex kinematic evolution of the successive Africa–Europe plate boundaries described in our model displays a deformation style comparable to that observed in magma-poor rift systems worldwide, forming continental

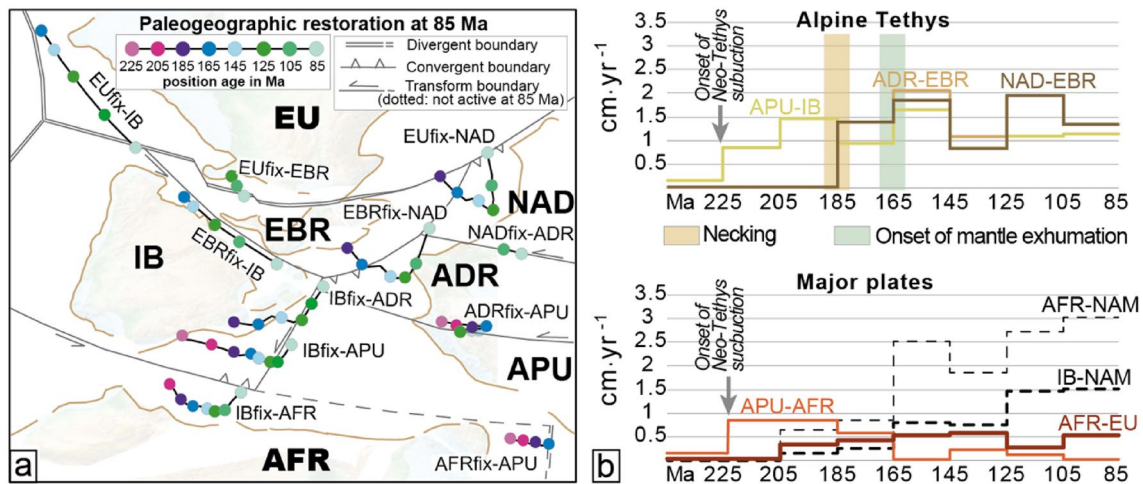


Fig. 4 Results of the model. **a** Motion paths of different points near the block/(micro)plate boundaries. Near each motion path, the name of the blocks kept fixed (fix) and moving is reported. **b** Absolute velocity of blocks and microplates in the Alpine Tethys realm (top

panel) and of the major plates (Europe, North America and Africa) and of the Apulia block (bottom panel). *ADR* Adria block, *AFR* Africa, *APU* Apulia block, *EBR* Ebro block, *EU* Europe, *IB* Iberia block, *NAD* North Adria block

blocks and ribbons (e.g., Flemish Cap, FL; Fig. 1a) and failed, hyperextended rift basins (e.g., Orphan, Porcupine, and Basque-Cantabrian, basins; Fig. 1a), just to mention few examples in the southern North Atlantic (Péron-Pinvidic and Manatschal 2010; Nirrengarten et al. 2018) and peri-Iberian system (Saspiturry et al. 2021; Asti et al. 2022). Transient plate boundaries may develop during the early stages of plate separation, prior to the onset of steady-state seafloor spreading. Plate boundaries may become stable when magmatic systems and/or steady-state seafloor spreading begins. A similar stepping of plate boundaries resulting in the formation of microcontinents/continental blocks may be observed during the rifting and early breakup at the junction between Africa, India, Australia and Antarctica (e.g., Madagascar and Seychelles; Reeves 2014). Similarities may also exist in the role of magmatic provinces controlling the early stages of rifting. Indeed, initial rift phases were linked to and/or triggered by magmatic systems both between Africa and Antarctica and between Africa and South America, namely by the Karoo plume (Cox 1992; Delvaux and Weiss 2001) and the Central Atlantic Magmatic Province (CAMP) (Cirincione et al. 2014; Denyszyn et al. 2018; Marzoli et al. 2019), respectively. However, further studies are necessary to understand the role of such magmatic events on the breakup of Pangea.

Comparison with previous kinematic models

Numerous kinematic models exist for the paleogeographic evolution of Iberia and Adria (for a review see Jolivet 2023). It is important to note that models proposed prior to 2016 do not include tight full fit restorations in the Atlantic based on

the mapping and restoration of rift domains. Moreover, most of these models use the M0/J magnetic anomaly to restore the southern North Atlantic. Thus, it is not surprising that these models result in large “gaps” and conflicting restorations, in particular in the Pyrenean domain (e.g., van Hinsbergen et al. 2020). Since the plate kinematic reconstruction of the Alpine domain depends on a correct restoration of the Iberia microplate kinematic evolution, these older models fail to propose reliable restorations for the Alpine Tethys realm. Among the most debated points in recent models are the nature and location of the Iberia–Europe plate boundary, also referred to as the “Iberia–Sardinia” problem by Le Breton et al. (2021). Frisch (1979) and Stampfli and Hochard (2009) proposed a Lower Cretaceous Iberia–European plate boundary that connected the Pyrenean and Alpine domains. In these kinematic models a Cretaceous ocean formed in the Alpine Tethys, the so-called Valais Ocean, however, hard data supporting this scenario are still missing to date (Beltrando et al. 2012; Célini et al. 2020; Nouibat et al. 2022). Here, we follow Frasca et al. (2021) to solve the Le Breton et al. (2021) “Iberia–Sardinia” problem by proposing a new crustal block, the Ebro/Sardinia/Corsica block (EBR in Figs. 1 and 3). This solution enables us to account for the kinematics and amount of extension observed in the Pyrenean domain during the Mesozoic (Tavani et al. 2018; Lescoutre and Manatschal 2021) and the Jurassic age of the Valais Basin (Beltrando et al. 2012). It is also in line with the paleomagnetic data suggesting that the Ebro/Sardinia/Corsica is part of Europe (Edel et al. 2015; van Hinsbergen et al. 2020; Siravo et al. 2023). As a consequence, the main plate boundary between Europe and Iberia has to be located along the Biscay–Iberia corridor (BIC in Figs. 1 and 3). This

solution has also been proposed by Angrand et al. (2020) and King et al. (2023). Model predictions about when and where convergence/subduction initiated and how the Adria microplate moved relative to the African plate in the Alpine domain allows us to test the different models. In contrast to Angrand et al. (2020), we do not predict an acceleration of the Iberian plate during the Aptian–Albian time relative to Africa. In our model, the onset of subduction in the Alps is in line with the occurrence of dated high pressure rocks (Froitzheim et al. 1996; Miller et al. 2005). Furthermore, the acceleration of Adria occurs when the microplate starts subducting (Fig. 4). Concerning the relative movements of Adria relative to Africa, a point that remains ambiguous in most models, our model predicts a transient northward stepping of a sinistral plate boundary during the Triassic to Middle Jurassic, resulting in the sequential dogging of the “Adriatic” crustal blocks to the eastward-moving African plate. This process is, however, difficult to constrain by direct field observations due to the later Cenozoic overprint of the proto-Insubric and inferred proto-Mattinata corridors.

Our model is the first to predict the overall shape of the rift domain boundaries along the entire Alpine Tethys in the regions where the boundaries were not used as model inputs.

From confined rift basins to gateways

Since Steinmann’s work in the beginning of the last century (Steinmann 1905), many studies in the Alps have dealt with the stratigraphic and sedimentary evolution of the Alpine Tethys, showing a change from shallow- to deep-marine sedimentation as rifting progresses (Bernoulli and Jenkyns 2009). That the same deep-marine facies (Radiolarian Cherts and Maiolica facies) and fauna can be mapped from the Central Atlantic across the Alpine Tethys up to the Neo-Tethys allowed Weissert and Bernoulli (1985) to demonstrate the existence of a gateway that formed at the time of mantle exhumation in the Alpine Tethys, that is in the late Middle Jurassic (ca. 165 Ma) (Scandone 1975; Dal Piaz and Polino 1989; Bernoulli and Jenkyns 2009; Baumgartner 2013) (Fig. 5b). Linking sediment evolution to plate kinematics at the scale of the Alpine Tethys requires the integration of the rift evolution in high-resolution kinematic models. Timing and position of “necking” can be then defined all along the Europe–Africa boundary. Indeed, recent studies suggest that rifting goes across a stage characterized by local uplift and formation of yet confined and segmented basins, referred to as “necking” (Manatschal et al. 2022a). In the Alpine Tethys, “necking” occurred at ca. 185 Ma (Ribes et al. 2019). Our model shows that early segmentation and stepping of the plate boundary may explain the formation of such confined basins during the rifting of the Alpine Tethys. Later, large oceanic gateways have linked the Atlantic and Tethyan systems from the early Late Jurassic onward (Bill

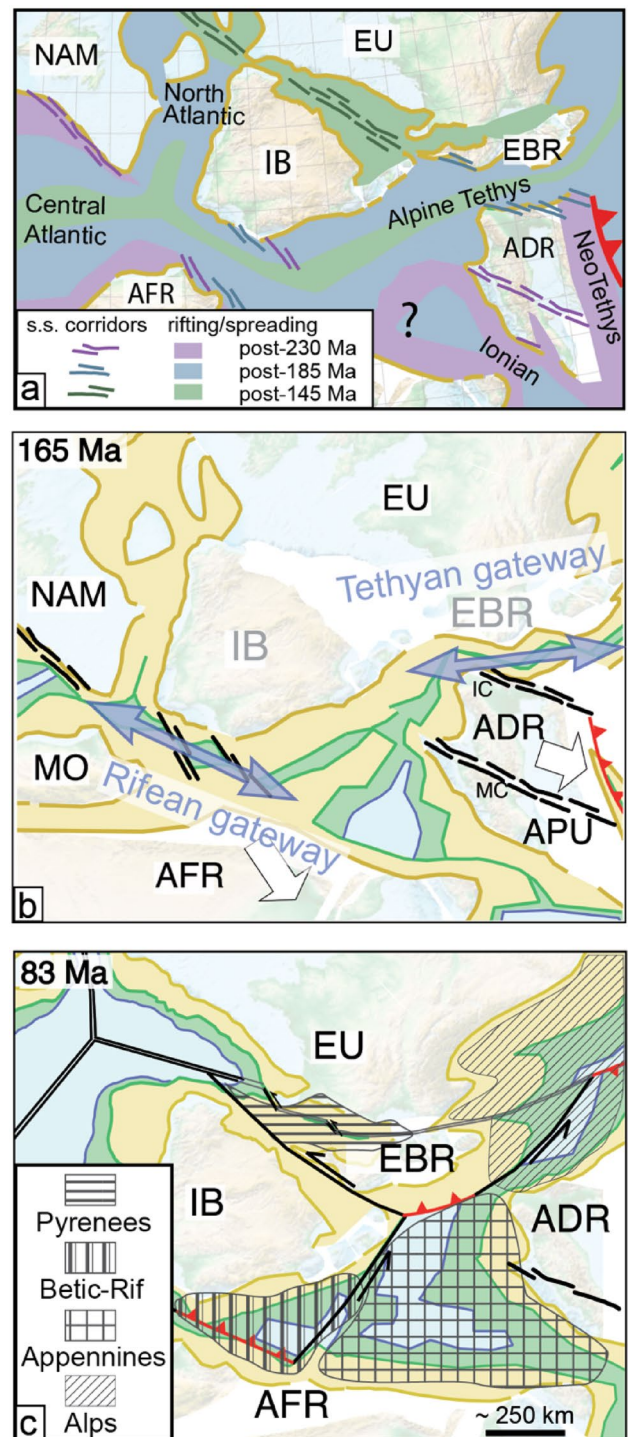


Fig. 5 Model implications: westward shift of the deformation, gateways and boundary conditions for convergence. **a** Westward stepping of rift and (proto-)oceanic domains at the beginning of the Cretaceous. **b** Map at 165 Ma when mantle is exhumed everywhere along the Alpine Tethys, forming a Tethys–Atlantic gateway. **c** Width and nature of the rift domains at the onset of convergence between AFR and EU at 83 Ma. *ADR* Adria block, *AFR* Africa, *APU* Apulia block, *EBR* Ebro block, *EU* Europe, *IB* Iberia block, *NAM* North America, *IC* proto-Insubric corridor, *MC* proto-Mattinata corridor

et al. 2001; Baumgartner 2013). Another important point is that no evidence for a Penrose-type crust exists in the Alpine Tethys, suggesting wide domains of exhumed mantle and (proto)oceanic and/or slow spreading oceanic crust. Such wide domains are observed at present-magma-poor rifted margins, as shown for the Southern Australia margin (Gillard et al. 2015; Williams et al. 2019) and the Iberia–Newfoundland margins (Szameitat et al. 2020).

From proto-oceanic domain to convergence

Our kinematic model provides a consistent view of how the Alpine Tethys may have formed during its Mesozoic rifting. It also displays its architecture prior to onset of subduction, including the distribution of its rifted margins that were subsequently either accreted or subducted during the Cretaceous–Cenozoic convergence (Fig. 5c). Our model is based on the integration of realistic widths and plausible orientations for the Alpine Tethys rifted margins. Consequently, our plate kinematic reconstruction provides a solid scenario for the shape, size, and composition of the available space in between the Tethys continental rifted margins. This space, shown in Fig. 5c, filled by exhumed mantle and (proto-)oceanic crust, is now subducted and is possibly visible in tomographic images as slabs (Monna et al. 2019; Civiero et al. 2020; Handy et al. 2021). At 83 Ma, proto-oceanic domains in the Alpine Tethys are divided into three regions, which include the Paleo-Tyrrhenian, the Liguria/Ionian and the Piemonte/Valais (proto-)oceanic domains. Sizes of these domains are, in our model, less than 300 km wide in the dip direction, and up to 800 km along strike (Fig. 5c). The position of the proto-oceanic domains mimics the present-day position of the Mediterranean back-arc basins (Faccenna et al. 2001; Rosenbaum and Lister 2004). In addition, our model shows the 3D architectural complexity of the Alpine rift system prior to its shortening. Subduction started during Cretaceous time (Fig. 3f) in agreement with data from Corsica and the Alps (Miller and Thöni 1997; Molli and Malavieille 2011; Regis et al. 2014). The segmentation of the continental margins (Fig. 5c) may also explain the arcuate shape, the non-cylindricity and the different timing of continental collision across the orogen (Handy et al. 2010; Schmid et al. 2017; Manatschal et al. 2022b).

Conclusions

The main novelty of this study is the plate kinematic reconstruction of the Alpine Tethys realm during its Mesozoic rifting, and more particularly the reconstruction of its rifted margins. The significant results of the kinematic restoration can be summarized as follows: (1) extension stepped westward from the Ionian to the Alpine Tethys to the Pyrenean

rift system from the Triassic to the Cretaceous, (2) the Mesozoic Tethyan rifted margins were segmented by strike-slip corridors, (3) oceanic gateways connecting the Atlantic and Neo-Tethys domains were largely established at the time of mantle exhumation (165 Ma) between Africa and Europe, (4) large regions of mantle were exposed at the seafloor in the Late Jurassic and (5) oceanic crust—now gone—likely formed until Cretaceous time in compartments that mimicked the present-day distribution of the back-arc basins in the Mediterranean.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00531-024-02407-9>.

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Data availability The data supporting the findings of this study are available in the supplementary materials. For further inquiries regarding the data, please contact the corresponding author.

Declarations

Conflict of interest The author(s) declare no competing interests.

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