Kinematics and extent of the Piemont-Liguria Basin – implications for subduction processes in the Alps

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Abstract. Assessing the size of a former ocean, of which only remnants are found in mountain belts, is challenging but crucial to understand subduction and exhumation processes. Here we present new constraints on the opening and width of the Piemont-Liguria (PL) Ocean, known as the Alpine Tethys together with the Valais Basin. We use a regional tectonic reconstruction of

15   the Western Mediterranean-Alpine area, implemented into a global plate motion model with lithospheric deformation, and 2D thermo-mechanical modelling of the rifting phase to test our kinematic reconstructions for geodynamic consistency. Our model fits well with independent datasets (i.e. ages of syn-rift sediments, rift-related fault activity and mafic rocks) and shows that the PL Basin opened in four stages: (1) Rifting of the proximal continental margin in Early Jurassic (200-180 Ma), (2) Hyper-extension of the distal margin in Early-Middle Jurassic (180-165 Ma), (3) Ocean-Continent Transition (OCT) formation with

20   mantle exhumation and MORB-type magmatism in Middle-Late Jurassic (165-154 Ma), (4) Break-up and "mature" oceanic spreading mostly in Late Jurassic (154-145 Ma). Spreading was slow to ultra-slow (max. 22 mm/yr, full rate) and decreased to ~ 5 mm/yr after 145 Ma while completely ceasing at about 130 Ma due to motion of Iberia relative to Europe during the opening of the North Atlantic. The final width of the PL Ocean reached a maximum of 250 km along a NW-SE transect between Europe and Adria (Ivrea). In the Cretaceous and Cenozoic, the amount of plate convergence between Adria (Ivrea)

25   and Europe during Alpine subduction (84-35 Ma, 420 km) and collision (35-0 Ma, 260 km) largely exceeded the width of the ocean. We suggest that at least 63 % of the subducted and accreted material was highly thinned continental lithosphere and most of the Alpine Tethys Ophiolites exhumed today derived from OCT zones. Our work highlights the importance of distal rifted continental margins during subduction and exhumation processes and provides quantitative estimates for future geodynamic modelling and a better understanding of the Alpine Orogeny.

30   **1 Introduction**

Over the last decades, new concepts on rifting processes, subduction initiation, depth and exhumation of high-pressure rocks during subduction emerged. The Alps are a natural laboratory to test ideas as it preserved a detailed record of continental margin and ophiolite evolution from the Alpine Tethys that were accreted or subducted, brought to ultra-high pressure and
35 later exhumed at the surface (Froitzheim and Eberli, 1990; Froitzheim and Manatschal, 1996; Bernoulli and Jenkyns, 2009; Mohn et al., 2010; Beltrando et al., 2014; Masini et al., 2014). Studies of hyper-extended magma-poor type of continental margins such as in the Alps have shed light on the tectonic complexities of distal and ocean-continental transition zones, along which various types of rocks such as continental allochthons, serpentinized mantle rocks, gabbros and basalts are put in contact by major detachment faults (e.g. Florineth and Froitzheim, 1994; Müntener and Hermann, 2001; Ferrando et al., 2004;
40 Manatschal, 2004; Manatschal and Müntener, 2009; Epin et al., 2019). These zones of inherited weakness and thermal anomalies may represent ideal candidates for localization of subduction initiation when plate motion becomes convergent (Beltrando et al., 2010; Tugend et al., 2014; Stern and Gerya, 2018; Kiss et al., 2020; Zhou et al., 2020).

Moreover, the Alpine chain is very enigmatic due to its very arcuate plate boundaries and switch of subduction polarity along
45 strike (Figure 1), episodes of slab break-off (e.g. Wortel and Spakman, 2000; Handy et al., 2014) and lack of a well-developed magmatic arc (e.g. McCarthy et al., 2018). Seismic tomography models beneath the Alps are thus extremely difficult to interpret (see Kästle et al., 2020 for a recent review). Thermo-mechanical modelling is a key tool to gain a better understanding of orogenic processes in the Alps (e.g. Gerya et al., 2002; Yamato et al., 2007; Duretz et al., 2011; Ruh et al., 2015; Reuber et al., 2016; Dal Zilio et al., 2018; Spakman et al., 2018) and potentially a better interpretation of seismic tomography models.
50 These models require, however, quantitative input such as estimates of the former extent and thickness of the continental margins and oceanic domains involved in subduction, paleo-location of plate boundaries through time, as well as direction and rate of plate convergence. Kinematic reconstructions are thus crucial, but challenging in such a tectonically complex area. First, regional geological reconstructions need to be globally connected and brought into a plate-mantle reference frame in order to assess mantle-plate-surface interactions through time (e.g. Müller et al., 2019). Second, there is growing consensus
55 that maximal burial depth of metamorphic rocks in subduction zones, as estimated from mineral phase equilibria and assuming lithostatic pressure, may be overestimated due to local overpressure and change of tectonic regime (Ford et al., 2006; Schmalholz and Podladchikov, 2013; Pleuger and Podladchikov, 2014; Reuber et al., 2016; Yamato and Brun, 2017; Moulas et al., 2019). This has significant implications for regional tectonic reconstructions that use an inferred amount of subduction based on peak depths of (ultra) high-pressure metamorphism and for conceptual models of exhumation of high-pressure rocks
60 (e.g. Brun and Faccenna, 2008).

The aim of this paper is to provide such quantitative constraints, especially for the opening of the Piemont-Liguria (PL) Ocean in Jurassic time and to discuss the style of rifting and extent of hyper-extended rifted margins versus oceanic domains that went into subduction during the Alpine Orogeny. For this, we present updated kinematic reconstructions of the Alpine-
65 Mediterranean area, with a focus on Corsica-Sardinia-Adria, that go back to Triassic time and are implemented within the

recent global plate model Müller et al. (2019). Furthermore, we test our kinematic scenario for geodynamic consistency with thermo-mechanical modelling of the rifting phase and compare our results with existing geological records from the Alps.
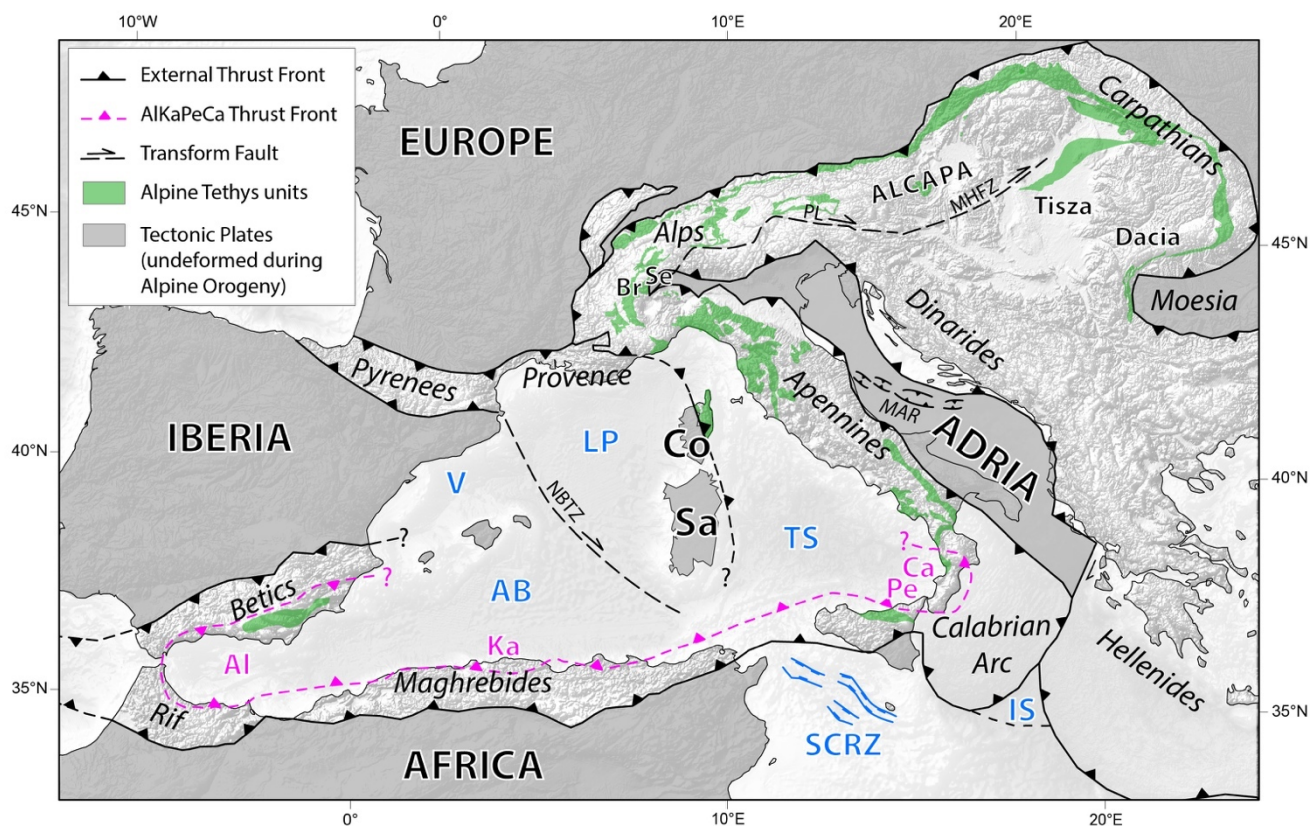
Figure 1. Simplified tectonic map of the Western-Central Mediterranean (modified after Le Breton et al., 2017; Michard et al., 2006; Guerrera et al., 2019; Schmid et al., 2020). Background topographic-bathymetric map from ETOPO1 model (Amante and Eakins, 2009). Abbr.: AB: Algerian Basin, Al - Alboran, AlCaPa - Alpine-Carpathians-Pannonian Mega-Unit, Br - Briançonnais, Ca - Calabria, Co - Corsica, V – Gulf of Valencia, Ka - Kabylides, IS - Ionian Basin, LP - Liguro-Provençal Basin, MAR Mid-Adriatic Ridge, MHFZ: Mid-Hungarian Fault Zone, NBTZ - North Balearic Transform Zone, Pe - Peloritani, PL - Periadriatic Line, Sa - Sardinia, SCRZ - Sicily Channel Rift Zone, Se - Sesia, TS - Tyrrhenian Sea.x

2 Geological Setting

The Alpine-Mediterranean belt results from a complex tectonic evolution that involved the closure of two oceans (Alpine Tethys and Neo-Tethys) and subduction-collision of several continental domains (Briançonnais, Sesia, AlCaPa, Tiszia, Dacia, Figure 1) between two major plates Eurasia and Africa that have been converging since Cretaceous time (e.g. Dewey et al., 1989). The Adriatic microplate (Adria) is a key player due to its central position between Eurasia and Africa. Today, Adria is entirely surrounded by orogens; the Alps to the north where Adria is the upper indenting plate, the Dinarides to the east and the Apennines to the west where Adria is the subducting lower plate (Figure 1).

The Alps contain the remains of two Jurassic- to Cretaceous-age basins (Piemont-Liguria and Valais) together referred to as
the Alpine Tethys (e.g., Stampfli, 1998; Figure 1), or, more recently, also as "Alpine Atlantic" to emphasize its kinematic link
with the Atlantic Ocean (Gawlick and Missoni, 2019). Here, however, we adopt the well-established term Alpine Tethys. In
Cretaceous and Cenozoic times, the former Adriatic continental margin was accreted to the upper plate of the Alpine Orogen,
represented today by the Austroalpine (part of "ALCAPA", Figure 1) and Southern Alpine units (south of the Periadriatic
Line, Figure 1). This upper plate also contains relics of an older ocean, the Neo-Tethys (also known as Meliata-Maliac-Vardar
ocean; Schmid et al., 2008, 2020). The Jurassic closure of Neo-Tethys, whose remnants are abundantly found in the Dinarides
(Vardar Ophiolites), was broadly coeval with rifting and spreading of the PL Ocean (Stampfli et al., 1998; Schmid et al., 2008).
In the following sections we will focus on the evolution of the Alpine Tethys and the Alps. We note that remnants of the PL
Ocean are also preserved in Miocene-to-Recent nappes of the Apennines (including Calabria), the Betic Cordillera and Rif
(southern Spain and northern Morocco), and the Maghrebides (northern Africa), as shown in Figure 1 (AlKaPeCa units,
Bouillin et al., 1986). Those nappes were emplaced during fast rollback of the subduction zone in the Cenozoic (e.g. Faccenna
et al., 2001; Michard et al., 2002; Rosenbaum and Lister, 2004), triggering upper-plate extension and the opening of the
Western Mediterranean basins (Algerian Basin, Gulf of Valencia, Liguro-Provencal Basin and Tyrrhenian Sea; Figure 1).

2.1 Opening of the Alpine Tethys

2.1.1 The Piemont-Liguria Basin

Tectono-stratigraphic, petrological, geochemical and geochronological constraints from the Alps indicate that the PL margin
represents a fossil example of an hyper-extended magma-poor continental margin, such as the Iberian margin today (e.g.
Manatschal and Bernoulli, 1999; Manatschal, 2004; Decarlis et al., 2015). A first phase of rifting of the proximal part of the
continental margin, with horst-and-graben structures bounded by high-angle faults, took place in Early Jurassic (c. 200-180
Ma; e.g. Lemoine et al., 1986; Froitzheim, 1988; Froitzheim and Eberli, 1990; Conti et al., 1994; Froitzheim and Manatschal,
1996; Masini et al., 2013). This was followed by necking of the continental lithosphere (Mohn et al., 2012) and hyper-extension
of the distal part of the margin between c. 180 and 165 Ma (e.g. Froitzheim and Eberli, 1990; Froitzheim and Manatschal,
1996; Masini et al., 2013).

Radiolarite sedimentation started at around 166 ± 1 Ma (Bill et al., 2001) covering both oceanic rocks and adjacent distal
margins, which would suggest post-rift sedimentation and a continental breakup around that time. However, extension related
to final rifting in the most distal part of the margin along the ocean–continent transition (OCT) can lead to juxtaposition of
extremely diverse types of rock such as slices of continental crust in contact with exhumed serpentinized mantle, pelagic
sediments as well as gabbros and basalts (e.g. Florineth and Froitzheim, 1994; Froitzheim and Manatschal, 1996; Hermann
and Müntener, 1996; Marroni et al., 1998; Müntener and Hermann, 2001; Ferrando et al., 2004; Manatschal et al., 2006;
Manatschal and Müntener, 2009; Epin et al., 2019). Indeed, some Alpine Tethys Ophiolites are interpreted as representing

former OCT rather than the "mature" PL Ocean, due to the presence of exhumed mantle and detachment faults associated with tectono-sedimentary breccias (Manatschal and Müntener, 2009). U-Pb ages on zircons from MORB-type gabbros and plagiogranites from Corsica, the Northern Apennines and the Alps give a range from c. 165 to 140 Ma (Manatschal and

120 Müntener, 2009; their Figure 6 and references therein), dating both the OCT formation and the "mature" oceanic spreading. The juxtaposition of pillow-lavas directly on mantle rocks and the lack of sheeted dykes in the Alpine Tethys Ophiolites (e.g. Barrett and Spooner, 1977; Lagabrielle and Cannat, 1990; Lagabrielle and Lemoine, 1997) indicate an ultra-slow type of spreading for the PL Ocean.

125 Transects across the proximal to distal parts of the former Adriatic margin are well preserved in the Southern Alps and Austroalpine units of the Eastern Alps (Mohn et al., 2012, their Figure 2). Parts of the continental European margin are preserved in the Alps within the Jura Mountains, the Helvetic and Penninic nappes as well as in the Briançonnais. The latter is a continental fragment that detached from Europe during the opening of another basin: the Valais Basin.

130 ## 2.1.2 The Valais Basin

It is commonly accepted that the opening of the Valais Basin was linked to the opening of the Bay of Biscay and rifting in the future Pyrenees in the Cretaceous (Frisch, 1979; Stampfli, 1993), contemporaneous with intracontinental subduction and nappe stacking in the easterly adjacent Eastern Alps, referred to as the Eo-Alpine Orogeny (c. 130-84 Ma; e.g. Faupl and Wagreich, 1999), which created the Austroalpine nappe stack. The motion of Iberia was accommodated along a major transtensional plate

135 boundary, the North Pyrenean Fault (NPF), as evidenced by the formation of en-échelon pull-apart basins in the future Pyrenees (e.g. Choukroune, 1992), such as the Organya Basin in Aptian-Albian time (Oliva-Urcia et al., 2011). More to the east, the opening of the Valais Basin separated the Briançonnais continental fragment from the European Plate (e.g. Stampfli, 1993). This is supported by the Early Cretaceous tectono-stratigraphic record between the Briançonnais and Valais domains (Florineth and Froitzheim, 1994) and the so-called "Valaisan trilogy" (Trümpy, 1951, 1954; Loprieno et al., 2011) whose oldest

140 stratigraphic unit (Aroley Fm) is dated to Barremian-Aptian (130-110 Ma).

Based on U/Pb zircon dating on metabasic rocks of the Valais domain, Liati et al. (2005) and Liati and Froitzheim (2006) proposed that the Valais Basin was floored by two generations of oceanic crust and resulted from "re-rifting" of oceanic crust that first formed during the opening of the PL Ocean at about 165-155 Ma and secondly during the opening of the Valais

145 Ocean at about 93 Ma. The existence of a Valais "Ocean" was, however, disputed by Masson et al. (2008) who dated the ophiolites of this domain to Early Carboniferous (U/Pb age). Beltrando et al. (2007) showed also evidence for Permian U/Pb zircon ages with only a few Cretaceous ages (110-100 Ma) in the rims of some zircons, interpreted as a thermal/fluid event related to extension rather than spreading. Characteristics of hyper-extended margin and OCT zone, with mantle exhumation and limited magmatic activity within the Valais Basin was later described by Beltrando et al. (2012). Moreover, the presence

150 of significant sedimentation pre-dating the onset of the Valaisan trilogy (Loprieno et al., 2011; Beltrando et al., 2012) confirmed the hypothesis of a multi-stage opening, as proposed by Liati et al. (2005).

Following these observations, we conclude that the Valais Basin was not a "mature" oceanic basin but a re-rifted, hyper-extended continental margin with exhumed mantle and a few magmatic rocks (OCT zone), that rifted away from Europe first

155 during the opening of the PL Basin in Jurassic but mainly during the opening of the North Atlantic and sinistral motion of Iberia relative to Europe in the Cretaceous.

2.2 Closure of the Alpine Tethys

Following tectono-stratigraphic and geochronological studies on syn-orogenic sediments, high-pressure metamorphic rocks

160 and thrust sheets in the Alps (e.g. Froitzheim et al., 1996; Stampfli et al., 1998; Schmid et al., 2008; Handy et al., 2010, 2014), the closure of the Alpine Tethys can be summarized in three stages:

(1) Intra-oceanic subduction of part of the PL Ocean from c. 130 to 84 Ma, overlapping in time with the opening of the Valais Basin and the Eo-alpine Orogeny as indicated by geochronological data on high-pressure metamorphic rocks within the

165 Austroalpine unit of the Eastern Alps (c. 120-84 Ma; Manzotti et al., 2014, their Figure 5 and references therein).

(2) South/Southeast-directed "Alpine" subduction of the PL Ocean, the Valais Basin and the distal European continental margin from 84 to 35 Ma. The subduction initiated at the Adriatic margin (Sesia, c. 85-65 Ma) and progressed from SE to NW across the PL ocean (c. 50-45 Ma), the Briançonnais (c. 45-42 Ma) and Valais Basin (c. 42-35 Ma) as indicated by the tectono-

170 metamorphic evolution of those units (e.g. Rubatto et al., 1998; Manzotti et al., 2014, 2018). The subduction phase is also dated by syn-orogenic foredeep (flysch) sediments, which began at c. 94-86 Ma in the PL Ocean, c. 70 Ma in the Valais Basin and ended at c. 32-35 Ma (Matter et al., 1980). Relics of this "Alpine" subduction and high-metamorphic rocks with ages ranging from 84 Ma (Lahondère and Guerrot, 1997) to 35 Ma (Martin et al., 2011) are also found in NE Corsica ("Alpine" Corsica, Figure 1; Molli, 2008).

175

(3) Collision in the Alps and "Apenninic" rollback subduction of the remaining PL Ocean and Ionian Basin since about 35 Ma. Onset of collision in the Alps is dated at about 35-30 Ma by the switch from underfilled to overfilled type of sedimentation in the Molasse Foreland Basin (Sinclair, 1997), onset of high temperature metamorphism within the orogen (Lepontine dome, Tauern Dome; e.g. Bousquet et al., 2008) and magmatism along the Periadriatic Line related to a potential slab-break-off (von

180 Blanckenburg and Davies, 1995). Rollback subduction occurred also in the Carpathians, the eastward continuation of the Alps, beginning in early Miocene time (e.g. Horváth et al., 2006) contemporaneously to indentation of the Adriatic Plate with Europe and lateral extrusion in the Eastern Alps (e.g. Ratschbacher et al., 1991; Scharf et al., 2013). Unlike the Alps, Apennines and Dinarides, however, the Carpathians do not border on the Adriatic microplate and were kinematically decoupled from the

latter. Rollback subduction was compensated by upper-plate extension (Pannonian Basin) and arcuation (Ustaszewski et al.,
185 2008), and involved little convergence between Europe and Adria (Royden and Burchfiel, 1989).

2.3 Existing kinematic scenarios and debates

Due to the complexity of the Alpine-Mediterranean area and based on different datasets and assumptions, several kinematic
scenarios back to Mesozoic time have been proposed (e.g. Le Pichon et al., 1988; Dewey et al., 1989; Srivastava et al., 1990;
190 Rosenbaum et al., 2002; Stampfli and Borel, 2002; Handy et al., 2010; Schettino and Turco, 2011; VanHinsbergen et al.,
2020). In most models, Adria is considered as a "promontory" of Africa (Channell et al., 1979) and thus is restored as moving
together with Africa. Handy et al. (2010), using tectonic reconstructions of the Alps, proposed an independent motion of the
Adriatic Plate since 84 Ma, which in return would imply significant deformation in the Ionian Basin. However, recent studies
have shown that the basement of the Ionian Basin is oceanic (Dannowski et al., 2019) and thus no significant deformation
195 should affect this basin since the end of spreading, which is dated to the early Mesozoic (Speranza et al., 2012; Tugend et al.,
2019). Only the Sicily Channel Rift Zone (SCRZ, Figure 1) records an extensional event and accommodates some divergence
between Africa and Adria, but only in Neogene time and of limited amount (Civile et al., 2010; Le Breton et al., 2017).

Another key player in the reconstruction of the Western Mediterranean Area is Iberia. Its exact position in Mesozoic time –
200 prior to spreading and clear magnetic anomalies such as the Chron C34 (83.5 Ma; Macchiavelli et al., 2017) - is highly debated
depending on the interpretation of paleomagnetic studies on land, magnetic anomalies in the Atlantic and geological-
geophysical data from the Pyrenees. Some authors have reconstructed the motion of Iberia using the fit of the debated M0 or
"J"-anomaly (118 Ma; Bronner et al., 2011; Tucholke and Sibuet, 2012; Nirrengarten et al., 2017) in the North Atlantic (Sibuet,
2004) and paleomagnetic data in Spain that indicates a counter-clockwise rotation of 35º of Iberia in Early Cretaceous (Vissers
205 and Meijer, 2012; van Hinsbergen et al., 2020). These models imply subduction in the Pyrenees but also of part of the PL
Ocean between Iberia and Adria (future Northern Apennines) during that time (see maps of van Hinsbergen et al., 2020 at 140
Ma, 120 Ma and 110 Ma). However, geological records in the Pyrenees all lead towards the interpretation of a rifting phase
and hyper-extension rather than subduction in Early Cretaceous time (e.g. Jammes et al., 2009; Clerc and Lagabrielle, 2014;
Masini et al., 2014; Tugend et al., 2014). The transition from divergence to convergence is dated later at around 84 Ma
210 (Santonian; e.g. Mouthereau et al., 2014), which fits with onset of Alpine subduction more to the east (section 2.2) and the
Late Cretaceous age of syn-orogenic flysch sediments in the Northern Apennines (Marroni et al., 1992). The proposed Early
Cretaceous rotation of Iberia based on paleomagnetic data is strongly disputed due to possible remagnetization of sedimentary
rocks (Neres et al., 2012) and incompatibility with the Global Apparent Polar Wander Path (Neres et al., 2013; see also
discussion of Barnett-Moore et al., 2016, 2017 and van Hinsbergen et al., 2017) and may be explained by intraplate deformation
215 within Iberia, possibly along the Ebro block (Angrand et al., 2020).

Regarding the past extent and size of the PL Ocean, only a few models provide quantitative estimates. For example, the width of the entire basin varies from 450 km between Iberia-Adria to 675 km between Europe-Briançonnais-Adria in Vissers et al. (2013; their Figure 7) and from c. 500 km between Europe (France)-Adria and c. 900 km Corsica-AlKaPeCa-Adria in Handy

220 et al. (2010; their Figure 8b). However, those estimates do not distinguish between extended continental and oceanic domains, and are disputable considering their assumptions for the motion of Iberia and Adria, respectively, as mentioned above. Other studies, based on the age range of the Alpine Ophiolites and inferred ultra-slow spreading rates, propose a final extent of 300 km (Li et al., 2013; Manzotti et al., 2014) to 500 km (Froitzheim and Manatschal, 1996; their Figure 3) for the oceanic domain between Briançonnais and Adria, but lack kinematic constraints. Thus, the aim of this work is to provide robust kinematic

225 constraints and address the long-lasting controversy regarding the width of the PL Ocean.

3 Kinematic reconstructions of the Alpine-Mediterranean area

3.1 Approach

Reconstructing the past motion of the Adriatic Plate is challenging due to the broad deformation of its boundaries (Figure 1) but it is key to understand the geodynamic evolution of the area. Our approach is thus to reconstruct the tectonic deformation

230 that affected the plates during the Alpine Orogeny, with a focus on Adria and Sardinia-Corsica, to quantify the amount of divergence and convergence between stable parts of each plates, i.e. those not deformed during the Alpine Orogeny (in grey on Figure 1). To do so, we compile existing tectonic reconstructions and geological-geophysical data from the surrounding orogens (Alps, Provence, Apennines, Dinarides) and basins (Western Mediterranean Basins, Ionian Sea; Figure 2; see more details on the method in Le Breton et al., 2017 for Neogene time). The motion of Europe, Iberia and Africa is reconstructed

235 by fitting conjugate magnetic anomalies in the Atlantic and the rifting history of the continental margins. This step is crucial to provide a global frame for the regional reconstructions of the Alpine area. Major tectonic events are dated by syn-tectonic sediments, magmatic and metamorphic rocks, and magnetic anomalies in the Atlantic Ocean (magneto-chronostratigraphy), which allow us to draw tectonic maps at key times of the evolution of the Alpine Tethys (rifting and spreading) and Alpine Orogeny (subduction and collision). We then use GIS software (e.g. ArcGIS) and GPlates (www.gplates.org, Müller et al.,

240 2018) to digitize the tectonic maps, calculate rotation poles when needed and obtain a kinematic model back to 200 Ma. Moreover, GPlates (version 2.2) has the functionality to build plate motion models with continuously evolving topologies for rigid and deforming plates, and to include deformation both within the plates and along their boundaries (Gurnis et al., 2012, 2018; Müller et al., 2019). We are thus able to model the evolution of the deforming Adriatic Plate and the strong arcuation of its boundaries especially during the fast slab rollback and trench retreat in Cenozoic times (Faccenna et al., 2001; Rosenbaum

245 and Lister, 2004).

The workflow between the geological reconstructions (tectonic maps) and GPlates is based on an iterative approach (Figure 2). The tectonic reconstructions give us a range of possible amount of convergence/divergence between the plates and the kinematic reconstructions with GPlates allow us to visualize misfits in our tectonic reconstructions, i.e. overlaps between stable

250   parts of the plates, and thus indicate "problematic" areas in our tectonic maps that should be further studied. This approach is a never-ending endeavor as new geological and geophysical data from the Alpine-Mediterranean and the Atlantic are constantly being produced and/or are the subject of debated interpretations. Thus, here we present our current "best-fit" model for the Western Mediterranean-Alpine area and the main assumptions on which it lies. Our regional model for the Western-Central Mediterranean is part of the global plate model of Müller et al. (2019) and all reconstructions/rotation files are available

255   at https://www.earthbyte.org/webdav/ftp/Data_Collections/Muller_etal_2019_Tectonics/.
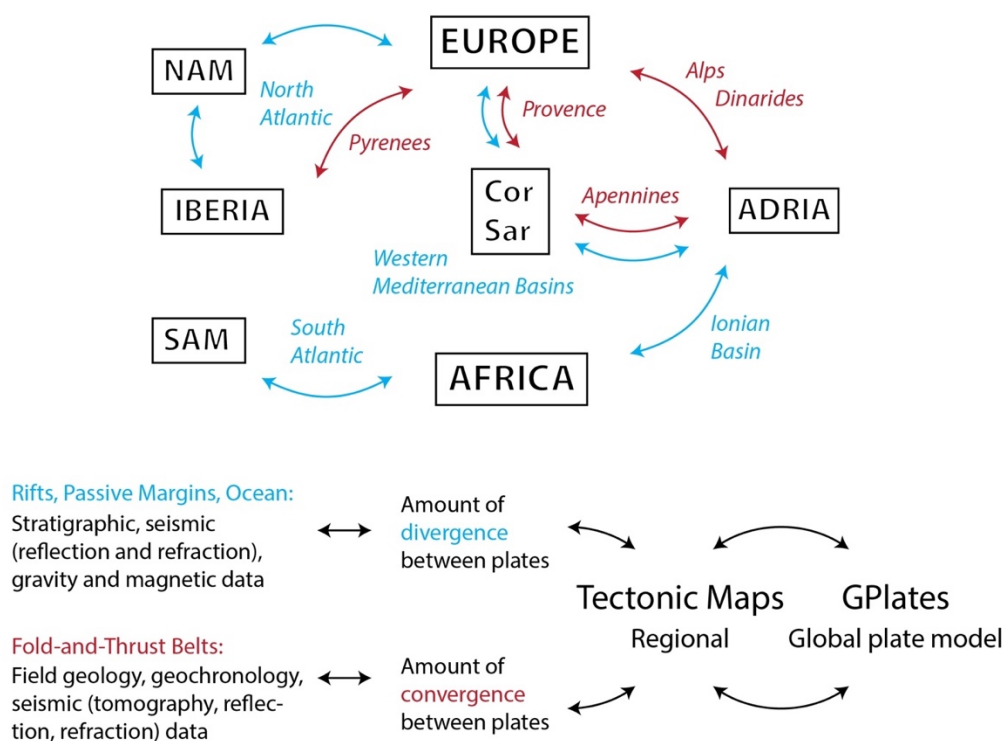
Figure 2. Approach and data used in this study to estimate the amount of deformation between plates in the Western-Central Mediterranean area and reconstruct their past plate motions within a global frame using GPlates. Abbr.: Cor – Corsica, NAM - North America, Sar – Sardinia, SAM - South America.

260   **3.2 Reconstructions of the Atlantic (Europe, Africa, Iberia)**

The motion of Europe, Africa and Iberia is well constrained by the fit of conjugate magnetic anomalies that formed during sea-floor spreading along the mid-Atlantic ridge (Müller et al., 1997, 1999 for the fit of South and North Americas vs Africa; Gaina et al., 2002 and Schettino and Scotese, 2005 for North America vs. Europe and Iberia, respectively). For the pre-breakup

phase, the global plate model of Müller et al. (2019) is built on the reconstructions of Kneller et al. (2012) for the Central
Atlantic, Heine et al. (2013) for the South Atlantic and Barnett-Moore et al. (2018) for the North Atlantic. Those models are
based on structural restoration of the conjugate Atlantic margins using the rift basins architecture and present-day crustal
thickness to approximate the amount and direction of extension, and also of intracontinental rift basins in Africa and South
America (Heine et al., 2013). We note that the model used for Iberia (Barnett-Moore et al., 2018) does not include the debated
Early Cretaceous 35º CCW rotation (see section 2.3) and in that respect fits best both the opening of the North Atlantic and
the geological evolution of the Pyrenees.

3.3 Reconstructions of Adria, Sardinia-Corsica

The Neogene tectonic evolution of Adria and Sardinia-Corsica is constrained by reconstructing the amount of convergence
along fold-and-thrust belts (Apennines, Alps, Dinarides, Provence) and coeval divergence along extensional basins (Liguro-
Provencal and Tyrrhenian basins, Sicily Channel Rift Zone) (Le Breton et al., 2017). Those reconstructions show that Adria
had a slightly independent motion from Africa and rotated counter-clockwise of about 5º relative to Europe since 20 Ma.
However, uncertainties increase and debates arise when going back in time, mostly due to the debate on the opening of the
North Atlantic and rotation of Iberia relative to Europe in the Cretaceous (see section 2.3). Geophysical data indicate that the
Ionian Basin between Africa and Adria is oceanic (seismic velocities; Dannowski et al., 2019) and opened in the Triassic (220-
230 Ma based on magnetic anomalies; Speranza et al., 2012). Thus, our main assumption is to avoid any significant
convergence or divergence between Adria and Africa between the end of spreading (220 Ma) and the Neogene (20 Ma).

The motion of the Corsica-Sardinia Block (CSB) in Oligo-Miocene times is associated with the opening of the Liguro-
Provencal Basin during the fast retreat of the Apenninic subduction zone (e.g. Faccenna et al., 2001). Syn-rift and post-rift
sediments along the Gulf of Lion date the onset of rifting at about 35 Ma and end of rifting at about 21 Ma (Séranne, 1999;
Jolivet et al., 2015). Paleomagnetic data indicates a clear rotation of Sardinia between 21 and 16 Ma (Speranza et al., 2002;
Gattacceca et al., 2007) which is interpreted as spreading along the Liguro-Provencal Basin. We reconstructed the motion of
Corsica relative to France back to 35 Ma using the amount of extension along the Liguro-Provencal Basin estimated to c. 115
km (c. 60 km rifting and 55 km spreading; Le Breton et al. 2017). This fits very well with the rotation pole and amount of
rotation proposed by Speranza et al. (2002, Table 1) for Sardinia based on paleomagnetic data.

The pre-Oligocene evolution of the CSB and its position with respect to Iberia is more uncertain. Two divergent views exist.
According to the first, the CSB was part of Iberia and moved to its present-day location during the motion of Iberia and opening
of the Valais Basin in Mesozoic time (e.g. Stampfli and Borel, 2002; Handy et al., 2010). According to the second view, the
CSB was always part of Europe and kept more or less the same location relative to France. This model is based on
paleomagnetic data that indicates c. 45 degrees pre-Oligocene rotation of Sardinia relative to Europe, different from the rotation

of Iberia and suggesting that these two plates moved independently (Advokaat et al., 2014). However, this model would imply c. 500 km of convergence between Iberia and Sardinia (Le Breton, 2020). The Oligo-Miocene rotation of the CSB during the opening of the Liguro-Provencal Basin implies the presence of a transform fault between Iberia and Sardinia, the North Balearic Transform Zone (NBTZ; e.g. van Hinsbergen et al., 2014). However, with no evidence for any shortening between

300   Eastern Spain and Sardinia, our approach is to avoid significant divergence-convergence between Iberia and the CSB and therefore to move them together relative to Europe prior to 35 Ma (first view described above). We implement a strike-slip motion between Iberia and the CSB along the NBTZ to accommodate extension during the opening of the Valais Basin in Mesozoic time (Table 1) and convergence in the Pyrenees-Provence belt (c. 155 km between Sardinia and Provence; Bestani et al., 2016). This independent motion may explain, at least in part, the different rotation of the CSB compared to Iberia

305   indicated by paleomagnetic studies without having a significant paleogeographic separation between the two domains.

Moving the CSB with Iberia back in Mesozoic time is also in agreement with Carboniferous-Permian paleo-reconstructions of Tuscany, Calabria and Corsica that indicate a paleogeographic continuity between these three domains (Molli, 2020) and of the Western Alps that indicate a paleogeographic separation between the External Crystalline Massifs (Helvetic Zone, Europe)

310   and the Briançonnais Zone (different pre-Triassic basement; Ballèvre et al., 2018). This implies in return significant strike-slip motion (max. 700 km) between Europe and Iberia-CSB-Briançonnais along the North Pyrenean Fault and the East Variscan Shear Zone, a Variscan transcurrent shear zone that was reactivated in Mesozoic time to accommodate the motion of Iberia relative to Europe during the opening of the North Atlantic, as proposed by previous authors (Choukroune, 1992; Matte, 2001; Stampfli and Borel, 2002; Sibuet, 2004; Guillot and Ménot, 2009; Guillot et al., 2009; Ballèvre et al., 2018). It also implies

315   significant strike-slip motion (c. 230 km) within the Adriatic Plate to avoid an overlap between Corsica and Northern Adria back to Triassic time (200 Ma, Figure 3). This overlap "problem" was already mentioned by Stampfli and Borel (2002) and implemented in Hosseinpour et al. (2016)"s kinematic model (based on rotation poles from Schettino and Turco; 2011; Table 1), in which they subdivided the Adriatic Plate in two plates, Northern Adria and Southern Adria (or Apulia), along a NW-SE trending fault zone that we call thereafter Mid-Adriatic Transform Fault (MATF) and correspond to a precursor of the present-

320   day Mid-Adriatic Ridge, as indicated by present-day GPS data (D"Agostino et al., 2008, Figure 3). Reflection seismic profiles show clear strike-slip flower structures along the Mid-Adriatic Ridge (Scisciani and Calamita, 2009). Moreover, strike-slip deformation and reactivation of Jurassic rift-related structures in Cretaceous-Eocene time have been reported from the Southern Alps (Castellarin et al., 2006) to the Central Apennines (Cipriani and Bottini, 2019a, 2019b). It is thus very likely that the entire Adriatic Plate actually deformed in a more diffuse way along a series of strike-slip faults in Cretaceous-

325   Paleogene time. However, it is extremely challenging to constrain the exact magnitude and timing of motion along those faults and would require further investigations in the future. For the sake of simplicity, we follow the model of Hosseinpour et al. (2016) and divide the Adriatic Plate into two plates along a single major strike-slip fault. Motion along this fault (c. 230 km) to "restore" Adria to its present-day configuration is accommodated progressively during the counter-clockwise motion of Africa relative to Europe, between c. 100-40 Ma.
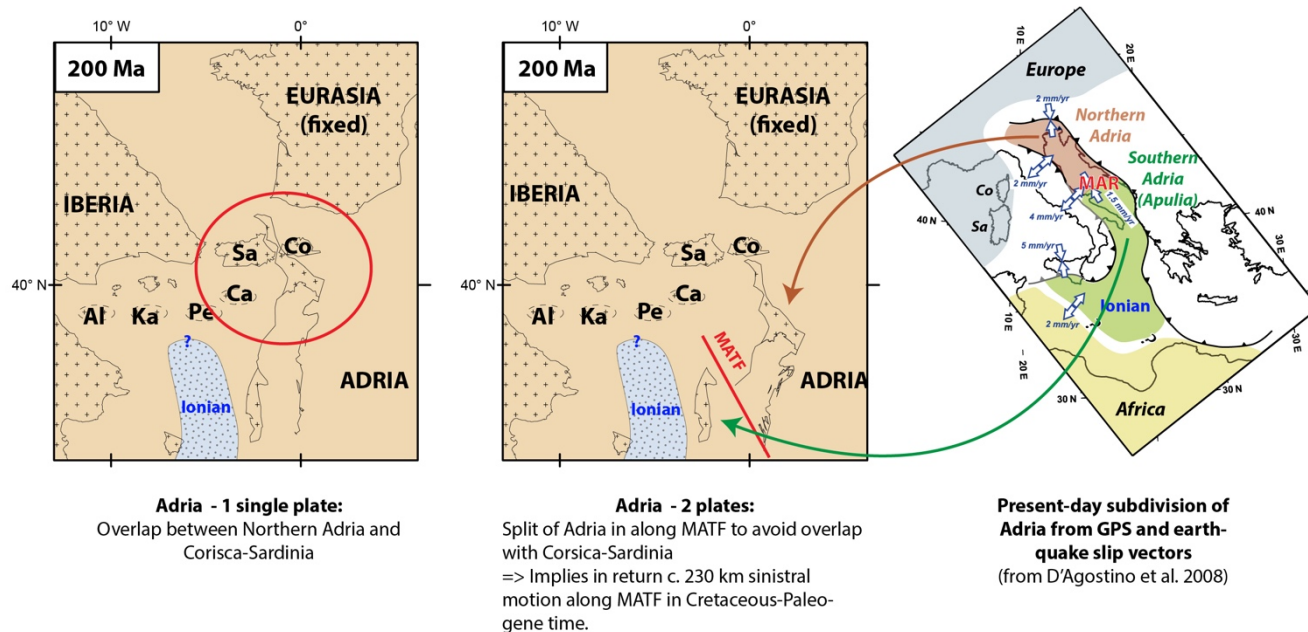
Figure 3. Contrasting paleo-reconstructions at 200 Ma, prior the opening of the Piemont-Liguria Basin. The left model shows the "overlap" problem between northern Adria and Sardinia-Corsica when moving back Adria as a single plate. This is solved in the right model by subdividing Adria in two plates along the Mid-Adriatic Transform Fault (MATF), precursor of the present-day Mid-Adriatic Ridge (MAR, Figure 1). This subdivision follows present-day GPS and earthquake slip vectors analyses (D"Agostino et al. 2008). See text for further explanations. Abbr.: Al - Alboran, Ca - Calabria, Co - Corsica, Ka - Kabylides, Pe - Peloritani, Sa – Sardinia

Table 1. Total reconstruction rotations used in this study for Sardinia-Corsica and Adria.

Age (Ma)	Latitude	Longitude	Angle	Moving vs Relative Plate	Reference
Corsica-Sardinia					
0.0	0.0	0.0	0.0	COR-SAR vs Europe	
16.0	0.0	0.0	0.0	COR-SAR vs Europe	Speranza et al. (2002)
21.0	43.5	9.0	-23.0	COR-SAR vs Europe	Speranza et al. (2002)
35.0	43.5	9.0	-53.2	COR-SAR vs Europe	This study (rifting Liguro-Provencal Basin)
83.0	42.7458	8.0933	-56.8041	COR-SAR vs Europe	This study (shortening Provence)
83.0	-44.7583	-168.868	47.0239	COR-SAR vs Iberia	Crossover (change in relative plate)
93.0	-44.4487	-168.6366	47.77	COR-SAR vs Iberia	This study (end opening Valais Basin)
144.7	-45.5809	-166.3455	42.7547	COR-SAR vs Iberia	This study (opening Valais Basin)
250.0	-45.5809	-166.3455	42.7547	COR-SAR vs Iberia	
Northern Adriatic Plate (Adria)					
0.0	0.0	0.0	0.0	Adria vs Apulia	
40.1	0.0	0.0	0.0	Adria vs Apulia	Schettino and Turco (2011)
47.0	-26.5	-166.58	1.0	Adria vs Apulia	Schettino and Turco (2011)
60.0	-26.5	-166.58	1.0	Adria vs Apulia	Schettino and Turco (2011)
70.0	-26.5	-166.58	2.0	Adria vs Apulia	Schettino and Turco (2011)
100.0	-26.5	-166.58	7.73	Adria vs Apulia	Schettino and Turco (2011)
250.0	-26.5	-166.58	7.73	Adria vs Apulia	Schettino and Turco (2011)

330

335

Age (Ma)	Latitude	Longitude	Angle	Moving vs Relative Plate	Reference
Southern Adriatic Plate (Apulia)					
0.0	0.0	0.0	0.0	Apulia vs Europe	
20.0	38.2028	-3.1628	-5.3474	Apulia vs Europe	Le Breton et al. (2017)
20.0	50.5636	21.1076	-2.9022	Apulia vs Africa	Crossover (change in relative plate)
220.0	50.5636	21.1076	-2.9022	Apulia vs Africa	Africa moving with Africa
220.0	49.4645	-0.0993	-68.068	Apulia vs Europe	Crossover (change in relative plate)
230.0	50.4113	-1.4579	-68.534	Apulia vs Europe	This study (opening Ionian Basin)
250.0	50.4113	-1.4579	-68.534	Apulia vs Europe	

340 **3.4 Reconstruction of the AlKaPeCa units**

West of Adria, remnants of the western Mediterranean subduction zone are found today in southern Spain (**Al**boran), northern Africa (**Ka**bylia), Sicily (**Pe**loritani) and southern Italy (**Ca**labria; Figure 1), together referred to as the AlKaPeCa units (Bouillin et al., 1986; Guerrera et al., 1993; Michard et al., 2002, 2006). These units are continentally derived, far-travelled nappes that acquire their present-day position during the fast rollback of the Gibraltar and Calabrian subduction zones in Oligo-
345 Miocene time. For this time period, we used the tectonic reconstructions of Van Hinsbergen et al. (2014) which is based on a compilation of shortening and extension estimates from the Atlas mountains, the Betic Cordillera, the Alboran domain, the Algerian Basin, the Gulf of Valencia and the Tyrrhenian Sea (Figure 1).

The similarity of the Triassic-Liassic stratigraphy and the Variscan basement between the AlKaPeCa units and coeval Tuscan
350 and Sesia domains on the Adriatic Plate suggest that the AlKaPeCa units were originally derived from a microplate that rifted away from the Iberian-CSB-Africa-Adria continental margins during the opening of the PL Basin in Jurassic time (Michard et al., 2002, 2006; Molli, 2008, 2020). Similar "Adria-like" features are found in Corsica within the Nebbio units (Molli, 2008) which also suggests a possible continuity of this continental microplate to the NE, between Corsica and Adria towards Sesia (Michard et al., 2002, 2006) and thus supports our reconstructions of the CSB (section 3.3.). This microplate has various names
355 in the literature (e.g. "Alcapecia" in Handy et al. 2010; "Mesomediterranean terrane" in Guerrera et al., 2019). To simplify, we refer only to "AlKaPeCa" here and want to point out that the exact extent of this microplate in Mesozoic times is very uncertain (hence the question marks on our tectonic maps, Figure 4). This microplate is important for the geodynamic evolution of this region as it separated a northern and a southern branch of the PL Ocean, supported by the presence of Tethys-derived ophiolite units in the Betic Cordillera (southern Spain) and in the Maghrebide Belt (northern Africa-Sicily), respectively
360 (Michard et al., 2002, 2014; Guerrera et al., 2019). In our tectonic reconstructions, we follow a "two-subduction" model in this area that implies first a southeast-dipping ("Alpine") subduction of the northern branch of the PL ocean in Late Cretaceous-Eocene time followed by a switch of subduction polarity to west-northwest ("Apenninic") subduction of the southern branch of the PL when the microplate entered the subduction zone at ~ 35 Ma (e.g. Michard et al., 2006; Molli, 2008; Molli and Malavieille, 2011).

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3.5 Reconstruction of the AlCaPa-Tisza-Dacia units

Other tectonically complex and far-travelled nappes are found east of Adria in the Eastern Alps, Carpathians and beneath the Pannonian Basin: the AlCaPa-Tisza-Dacia units. The AlCaPa ("**Al**ps-**Ca**rpathians-**Pa**nnonian Basin") unit is derived from the Adriatic Plate and corresponds to the Austroalpine nappes of the Eastern Alps and the Inner West Carpathians (Schmid et al.,

370 2008; Figure 1). The Tisza and Dacia units, presently beneath the Pannonian Basin, consists of tectonic units with a mixed European and Adriatic affinities (Schmid et al., 2008; Handy et al., 2014). These three tectonic units comprise a long and complex tectonic evolution from the opening and closure of several oceans (Neo-Tethys and part of Alpine Tethys; e.g. Schmid et al., 2008, 2020). During the Neogene, they underwent significant extension and rotation during the fast rollback of the Carpathian subduction zone and upper-plate extension with the opening of the Pannonian Basin (e.g. Ustaszewski et al., 2008

375 and references therein). Thus, it is extremely challenging to reconstruct their past position and former extent. For the Jurassic, we follow Schmid et al. (2008) and Vissers et al. (2013) who proposed that Tisza-Dacia separated from Europe during the opening of the eastern part of the PL Ocean. This in return implies a strike-slip motion along the Dobrogea Fault Zone NE of Moesia, which remains poorly constrained (question marks on Figure 4). After the opening of the PL Ocean, convergence between Africa and Europe was accommodated within the AlCaPa unit along an intracontinental subduction zone (Eo-Alpine

380 orogen; Stüwe and Schuster, 2010). The accretion of the Austroalpine nappes was complete by c. 84 Ma and the "Alpine" south-dipping subduction of Alpine Tethys initiated (Handy et al. 2010). For the Late Cretaceous-Cenozoic, our model is based on the tectonic reconstructions of Handy et al. (2014) and Ustaszewski et al. (2008). This area remains extremely simplified in our tectonic maps (Figure 4) as this is out of scope of our study; a more detailed review and reconstruction of this area can be found in Schmid et al. (2020) and van Hinsbergen et al. (2020).

385

4 Results

4.1 Tectonic maps back to 200 Ma

Following the geological records and kinematic constraints summarized in the past two sections, we constructed a series of tectonic maps of the Alpine-Mediterranean area (Figure 4) for key times covering the opening of the Piemont-Liguria Ocean

390 (200-130 Ma) and the Alpine Orogeny (83-0 Ma). Those maps are a deliberately simplified representation and aim at showing the main plates and plate boundaries through time. They do not show intraplate deformation, nor rifting along the continental margins. Those regional reconstructions are incorporated into the global plate model of Müller et al. (2019). Animations showing the evolution of the Alpine-Mediterranean back to 250 Ma and age-grids of the PL Ocean are available at: https://www.earthbyte.org/webdav/ftp/Data_Collections/Muller_etal_2019_Tectonics/.

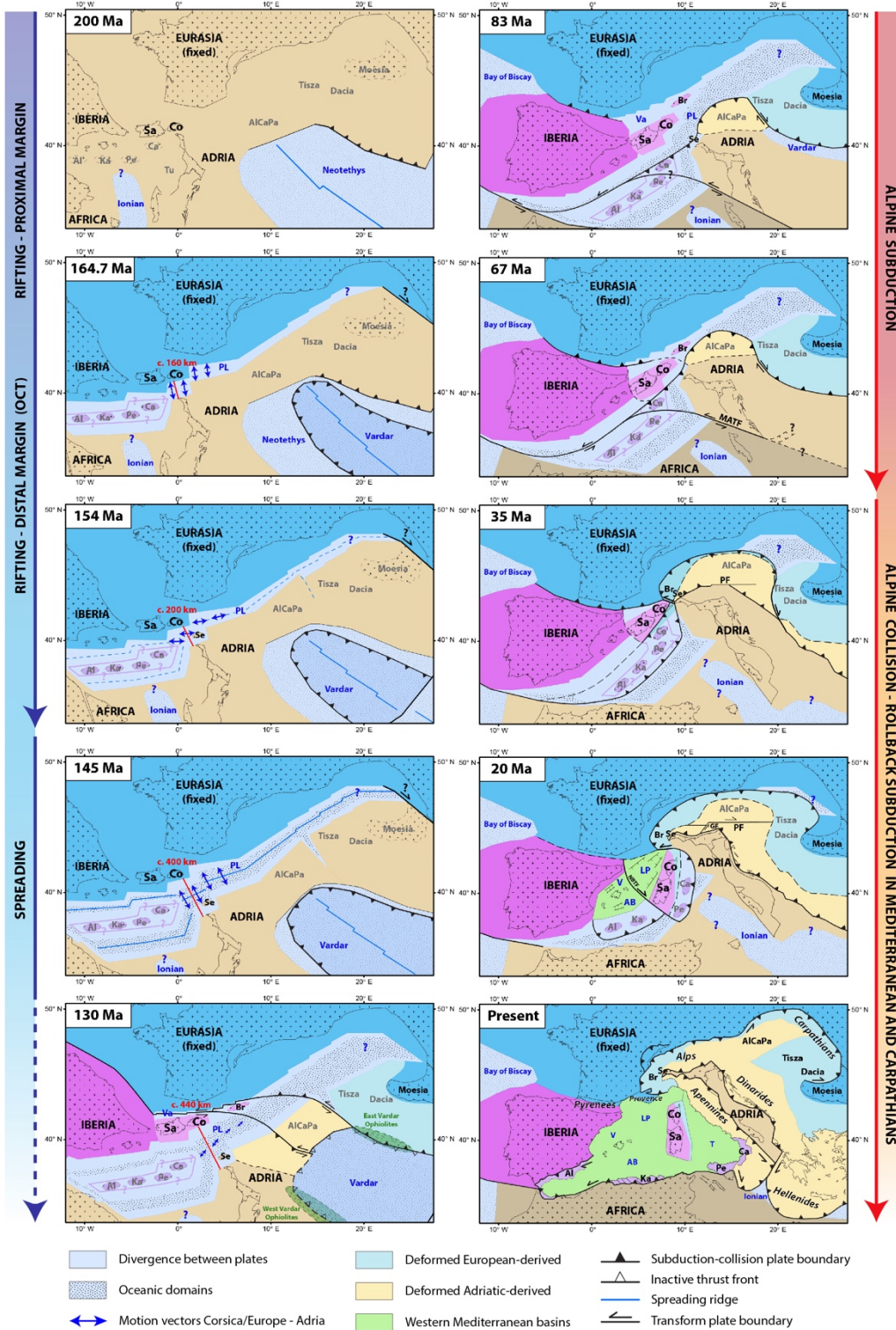
395

The divergent motion between the two major plates, Europe vs. Africa (Adria), in the Jurassic (blue vectors on Figure 4, obtained with the "flowline" tool on GPlates) shows different stages of opening of the PL Basin. First, a NNW-SSE directed (relative to Europe fixed) divergence between 200 and 164.7 Ma (Early-Middle Jurassic) followed by an oblique E-W directed motion until 154 Ma (Middle-Late Jurassic). Then the main divergent phase occurs between 154 and 145 Ma (Late Jurassic)

400 in a NW-SE direction. At 145 Ma (Early Cretaceous), Iberia and CSB start moving relative to Europe due to the opening of the North Atlantic. This oblique motion significantly decreases the divergence in the PL Basin, which totally ends at about 130 Ma. The different stages of opening of the PL Basin (200, 164.7, 154, 145 and 130 Ma) are derived from the stages of opening of the Central Atlantic (Kneller et al., 2012) and the North Atlantic (Barnett-Moore et al., 2018).

405 Based on the review of geological events given in sections 2 and 3, we can summarize the main stages of convergence (right panel of Figure 4) as follows. From 130 Ma, the motion between Europe, Iberia and Africa (Adria) is mostly strike-slip. Subduction of parts of the PL Ocean to the east starts in response to the eastward motion of Iberia-CSB and is kinematically linked with the Eo-Alpine Orogeny within the AlCaPa unit. At 83 Ma, the oblique motion of Iberia and Africa relative to Europe becomes more orthogonal. The "Alpine" south-directed subduction starts, with Adria and the accreted AlCaPa unit as
410 part of the upper plate. The subduction progresses from SE to NW, with the progressive subduction of Sesia, the PL ocean, the Briançonnais, the Valais Basin and finally the European margin. At 35 Ma, collision starts in the Alps while subduction continues more to the East along the Carpathians and switches to the "Apenninic" northwest-directed subduction in the Western Mediterranean. Finally, since 35-20 Ma, fast rollback of the Gibraltar and Calabria subduction zones in the western Mediterranean, of the Hellenic subduction in the eastern Mediterranean and of the Carpathians is accompanied by indentation
415 of the Adriatic Plate into Europe, lateral extrusion of the Eastern Alps towards the east and upper-plate extension and opening of the Pannonian Basin, the Western Mediterranean basins, and Aegean Sea, shaping the complex arcuate and broadly deformed plate boundaries that we can observe today.

420 **Figure 4 (next page): Simplified tectonic maps of the Alpine-Mediterranean area from 200 to 130 Ma (Divergent phase – Left panel) and from 83 to 0 Ma (Convergent phase – Right panel), relative to Eurasia fixed, showing the main plate boundaries and divergence between Europe-Corsica and Adria (blue vectors). Amount of divergence along a 2D transect between Corsica and Adria is indicated in red. Note these maps do not show intraplate deformation and rifting along the continental margins but the divergence between plates when considered rigid. This study focuses on the area between Corsica-Europe and Adria, as the exact paleo-location of the AlKaPeCa units to the west and AlCaPa-Tisza-Dacia units to the east is poorly constrained. Present-day coastlines are represented for orientation. Abbr.: AB: Algerian Basin, Al - Alboran, AlCaPa - Alpine-Carpathians-Pannonian Unit, Br - Briançonnais, Ca - Calabria, Co - Corsica, GF – Giudicarie Fault, Ka - Kabylides, LP - Liguro-Provençal Basin, NBTZ - North Balearic Transform Zone, Pe - Peloritani, PF - Periadriatic Fault, PL – Piemont-Liguria Basin and Ocean, Sa - Sardinia, SCRZ - Sicily Channel Rift Zone, Se - Sesia, Tu – Tuscany, T - Tyrrhenian Sea, V – Gulf of Valencia, Va – Valais Basin.**

430

4.2 Velocities of rifting and spreading along the PL Basin

We estimate the velocities of plate divergence during the opening of the PL basin (Figure 5) using the motion vectors between
435 Europe (Corsica-Briançonnais) and Adria (blue vectors on Figure 4). Full-rates of opening are first very slow (c. 4 mm/yr from SW to NE) between 200-164.7 Ma. They accelerate first to c. 15 mm/yr (16 to 14 mm/yr from SW to NE) between 164.7 -154 Ma and secondly to c. 22 mm/yr (ranging from 24 to 21 mm/yr from SW to NE) between 154-145 Ma. They decrease significantly at 145 Ma down to c. 5 mm/yr until 130 Ma. We assess an uncertainty of ± 5 km in measuring the vector length, which - once divided by the shortest time period (154-145 Ma) - leads to an error bar up to ± 0.5 mm/yr in the calculated rates.
440 The slight increase in rate from SW (Corsica-Adria) to NE (Briançonnais-Adria) indicates a triangular-shape opening of the PL Basin.

The first slow phase (c. 4 mm/yr) coincides in time with the opening of the Central Atlantic (Kneller et al., 2012) and tectono-stratigraphic record of rifting along the PL Basin (Figure 5; section 2.1.1; e.g. Froitzheim and Eberli, 1990). The first acceleration at c. 165 Ma fits with an increase in spreading rate in the Central Atlantic (from ultra-slow to slow; Kneller et al.,
445 2012) and onset of deep-sea sedimentation, mantle exhumation and MORB-type magmatism in the PL Basin (Figure 5; section 2.1.1; e.g. Bill et al., 2001; Manatschal and Müntener, 2009). The fastest rates of divergence are found on a very short time period of 9 Myr (154-145 Ma) and are in the range of slow to ultra-slow spreading ridge (< 20 mm/yr; Dick et al., 2003). The drop at 145 Ma coincides with a decrease in spreading rates in the Central Atlantic (Kneller et al., 2012) and the opening of the North Atlantic (Barnett-Moore et al., 2018).

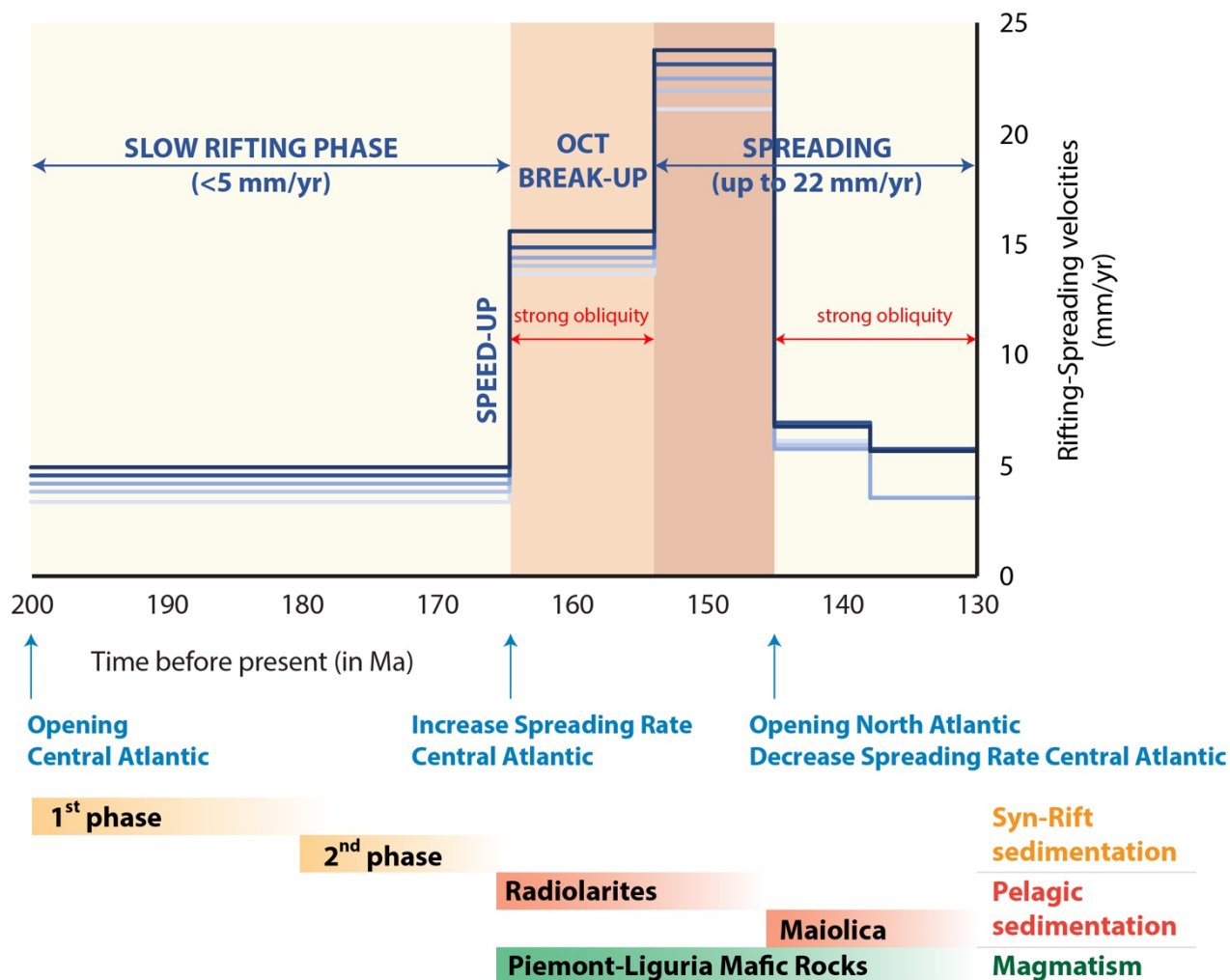



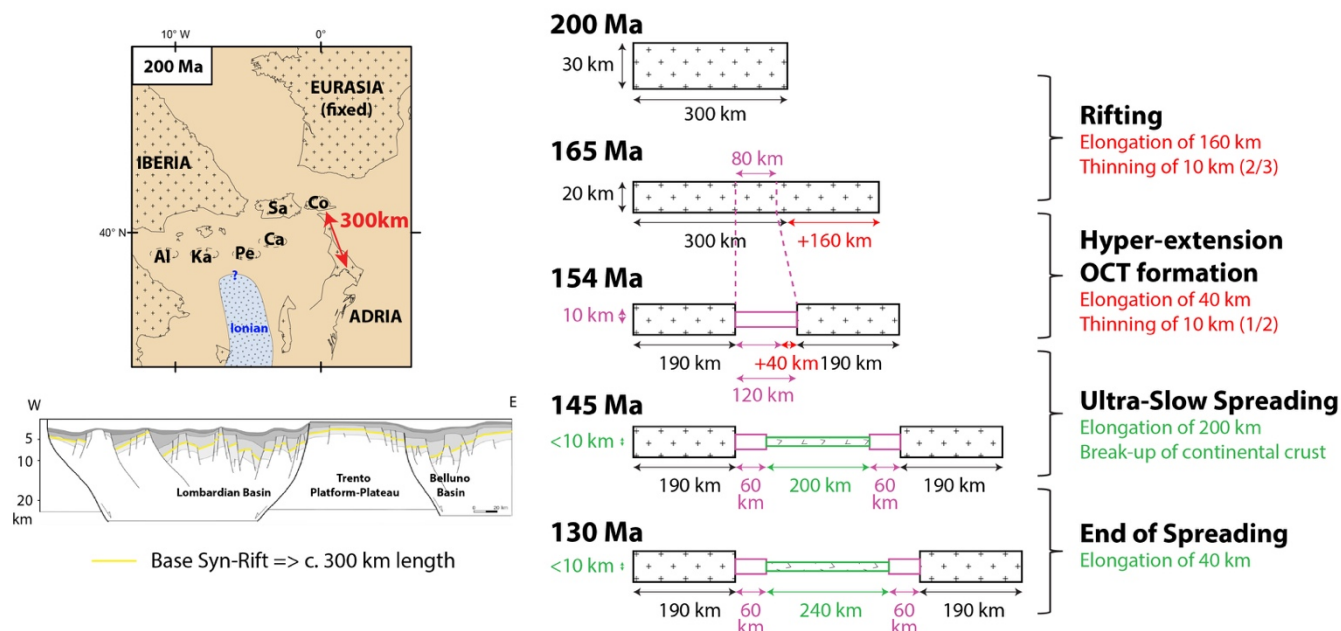
Figure 5. Velocities (full-rate) of rifting and spreading along the PL basin between Europe (Corsica-Briançonnais) and Adria (blue vectors on Figure 4) in Jurassic-Early Cretaceous time. Timing of syn-rift sedimentation from Froitzheim and Eberli (1990), deep-sea pelagic sedimentation from Bill et al. (2001) and Ferrando et al. (2004), and U/Pb ages on zircons from mafic rocks of the PL ocean from Manatschal and Müntener (2009 and references therein). Note the slight increase in velocities from SW to NE (dark to light blue curves) and the strong acceleration at 164.7 and 154 Ma for all curves.

4.3. Thinning of the continental margins

The total amount of divergence along a NW-SE directed transect between Corsica and Northern Adria (in red on Figure 4) equals c. 440 km and can be subdivided into 160 km between 200-164.7 Ma, 40 km between 164.7-154 Ma, 200 km between 154-145 km and 40 km between 145-130 km. However, this does not represent the actual width of the basin but the amount of total horizontal divergence (elongation). To estimate the final length of the rifted margins and ocean, we use a simple "pure-shear" (symmetric and uniform) stretching approach (McKenzie, 1978) for which we need to assume the initial length of area affected by rifting. Here we presume an initial length of c. 300 km, obtained from restoring the length of the base of syn-rift

horizons across the present-day Southern Alps and Adriatic Foreland affected by rifting in the Jurassic (Masetti et al., 2012)

465   and facing "stable" (i.e. not affected by rifting) Corsica in our reconstructions back to 200 Ma (Figure 6). The present-day W-E orientation of the rift basins becomes NNW-SSE relative to Europe once back-rotated with Adria at 200 Ma (Figure 6), which fits well with the kinematics of opening of the PL Basin obtained from our reconstructions (Figure 4; section 4.1). Assuming an initial crustal thickness of 30 km (Masini et al., 2013) and a localization of the rift after the slow rifting phase described above (200-165 Ma) along a zone of 80 km (typical for Narrow Rift such as the East African Rift today, Ebinger et

470   al., 1999; Corti, 2009; Brune et al., 2017), we estimate a total length of 380 km for the proximal margins (> 10 km thick), 120 km for the hyper-extended/OCT zone (< 10 km thick) and 240 km of oceanic crust (Figure 6). This remains a simple approximation as it does not take into account asymmetry during rifting, necking and hyper-extension, but nevertheless provides a first-order estimate.

475   **Figure 6. Thinning of continental crust and extent of rifted margins along a 2D transect from Europe/Corsica and Adria using amount of divergence (elongation) from kinematic reconstructions (red transect on Figure 4) and a pure-shear approach (McKenzie, 1978). The initial length of 300 km is assumed by restoring length of base of syn-rift horizons along Southern Alps and Adriatic Foreland (down left, redrawn from Masetti et al., 2012). Note the present-day W-E orientation becomes NNW-SSE relative to Europe once back-rotated with Adria at 200 Ma as shown on our tectonic map (up left, red arrow).**

480

4.4. Geodynamic consistency

In order to test our kinematic model in the context of rifting and thinning of the PL Basin in more detail, we use a 2D thermo-mechanical modelling approach that is based on the geodynamic finite-element software SLIM3D (Popov and Sobolev, 2008). This model is driven solely by boundary velocities while localization of rift faults, lithospheric necking, continental break-up

485   and subsequent sea-floor spreading evolves in a purely self-consistent manner. The model involves four layers (upper crust,

lower crust, strong and weak mantle), which all deform in accordance with corresponding flow laws (wet quartzite, wet anorthite, dry olivine and wet olivine, respectively). The initial Moho depth is set at 33 km and the Lithosphere-Asthenosphere Boundary (LAB, 1300ºC) at 120 km. The LAB is slightly elevated (5 km) in the center of the model to avoid rift localization at the model boundaries (Figure 7A). We follow a model setup that has been extensively used in modelling narrow rifting and

490   rifted margin formation (Brune et al., 2012, 2013, 2017a, 2017b; Brune, 2014) and for a more detailed description of the employed boundary conditions, initial conditions, weakening mechanisms and material parameters, we refer the reader to Brune et al. (2014).

It is well-established that the rift velocity exerts key control on the structural evolution of a rift (Huismans and Beaumont,

495   2003; Pérez-Gussinyé et al., 2006; Tetreault and Buiter, 2018). In order to test the impact of our kinematic plate tectonic model, we derive rift-perpendicular velocities from the 2D transect between Corsica-Adria (red transect in Figure 4) as input for the geodynamic modelling by means of the following steps: (1) 4 mm/yr for the first 46 Myr (200 km divergence between 200-154 Ma); (2) 22 mm/yr for 9 Myr (200 km divergence between 154-145), and (3) 3 mm/yr for 15 Myr (40 km divergence between 145-130 Ma). We point out that the first acceleration shown in Figure 5 (15 mm/yr between c. 165-154 Ma) is obtained

500   from the plate motion vectors (blue vectors on Figure 4) and reflects the strong obliquity of motion during that phase, however, along a 2D transect the net divergence is only 40 km between 164.7-154 Ma (3.6 mm/yr). Thus, this phase is accounted for in the first step of our model (with rates of 4 mm/yr).

The modelling results are available as an animation in supplementary material (movie S1). The results after 1 Myr (model

505   setup), 20 Myr, 35 Myr, 46 Myr, 55 Myr and 70 Myr are shown on Figure 7 and allow us to distinguish different rifting stages (Figure 7A-D, constant velocity of 4 mm/yr). First, the entire domain is affected by normal faults (Figure 7A) until lithospheric necking commences at about 12 Myr into the model runtime. The rift localizes along a zone of about 110 km width and the onset of hyper-extension (< 10 km crustal thickness; Lavier and Manatschal, 2006) starts after 20 Myr (Figure 7B). The onset of mantle exhumation occurs after 35 Myr (Figure 7C) and is accompanied by the detachment of continental allochthons.

510   Finally, the continental lithosphere breaks up rapidly when the rift velocity increases to 22 mm/yr at 46 Myr (Figure 7D). This is the moment when the lithosphere shallows drastically (< 10 km; Figure 7D; movie S1), as observed beneath present-day ultraslow-spreading ridges (e.g. Mohns Ridge; Johansen et al., 2019), which would lead to decompression melting and onset of sea-floor spreading.

515

A. Time: 1 Myr

Initial stage: 33 km continental crust

200 - 180 Ma
Stretching phase
-> Proximal Domain

B. Time: 20 Myr

180 Ma: Onset of hyper-extension
(<10 km crustal thickness)

180 - 165 Ma
Thinning phase
-> Hyper-extended Domain

C. Time: 35 Myr

165 Ma: Onset of mantle exhumation

165 - 154 Ma
Exhumation phase
-> Ocean-Continent Transition

D. Time: 46 Myr

154 Ma: Break-up of continental lithosphere

154 - 145 Ma
Spreading phase (22 mm/yr)
-> Oceanic Lithosphere

E. Time: 55 Myr

145 Ma: Decrease spreading rates

145 - 130 Ma
Spreading phase (3 mm/yr)
-> Oceanic Lithosphere

F. Time: 70 Myr

Figure 7 (previous page). 2D high-resolution thermo-mechanical modelling of the opening of the PL Basin using velocities from our kinematic reconstructions (red transect between Europe and Adria on Figure 4). Material phases are indicated in Panel A. Strain
520 **rate is visualized as black transparent overlay. Deep lithospheric and asthenospheric temperatures are depicted by brownish overlay and 1200°C isotherm (black line). Extent of necking zone (30-10 km thick), hyper-extended and OCT (< 10 km thick) and oceanic domain is indicated in white. See text for further discussion. Animation of model results can be found as supplementary movie (S1).**

5 Discussion

525 **5.1 Opening and extent of the PL Basin**

Using our kinematic reconstructions and geodynamic modelling of the rifting phase, we can identify and date the following four stages of opening of the PL Basin (Figures 5, 6, 7), as defined by Lavier and Manatschal (2006):

    (1) "Stretching Phase": rifting of the proximal continental margin and necking of the lithosphere between 200-180 Ma (first rifting phase);

530   (2) "Thinning Phase": hyper-extension of the distal continental margin between 180-165 Ma (second rifting phase);

    (3) "Exhumation Phase": OCT formation with mantle exhumation between 165-154 Ma;

    (4) "Spreading Phase": break-up and slow to ultra-slow oceanic spreading between mostly 154-145 Ma.

Our results fit very well with independent datasets (tectono-sedimentary, geochemical, geochronological) from the Alps (section 2.1.1; Figure 5) that show two-rifting phases (c. 200-180 Ma, 180-165 Ma; e.g. Froitzheim and Eberli, 1990; Mohn et
535 al., 2010), activation of the necking zone around 180 Ma (Mohn et al., 2012), onset of mantle exhumation and magmatism along typical magma-poor OCT at about 165 Ma (e.g. Manatschal and Müntener, 2009).

Our kinematic reconstructions show an increase in obliquity and rate of plate motion between 165-154 Ma (Figures 4 and 5) and a progressive opening of the PL Basin from SW to NE (Figure 5). Thus the transition between stages 3 and 4, i.e. break-
540 up and onset of spreading, was most likely a propagating process from SW to NE. Interestingly, abrupt plate acceleration such as the one at c. 165 Ma ("Speed-up" on Figure 5) is commonly observed along other continental margins worldwide (Brune et al., 2016). On other margins, this acceleration corresponds to the shaping of the distal part of the margins, pre-dating continental breakup of about 5-10 Ma, and reflects a strength-velocity feedback mechanism during rifting ("dynamic rift weakening"; Brune et al., 2016). Moreover, Brune et al. (2018) showed a clear correlation between rift obliquity and increase
545 in plate motion velocities, as we observed between 165-154 Ma (Figure 5). However, it is the effective rift-perpendicular velocity that leads to lithospheric thinning and thus oblique segments need more time to reach breakup than orthogonal rifts. This corroborates our interpretation that stage 3 (165-154 Ma) corresponds to the formation of the (hyper-)distal OCT zone, with the juxtaposition of pelagic sediments, serpentinized mantle, gabbros, basalts (e.g. Epin et al., 2019), prior break-up. The detachment of continental allochthons, such as Sesia (Figure 4; e.g. Babist et al., 2006), occurs also during that stage, which
550 fits with the crystallization age (164-156 Ma) of zircons within syn-magmatic shear zones south of the Sesia zone (U/Pb zircon age; Kaczmarek et al., 2008). We therefore diverge from Li et al. (2013) who interpret this phase as oceanic spreading. We rather suggest that most of the preserved mafic rocks came from the OCT domain rather than the "mature" oceanic domain, mostly lost to subduction, which is supported by the sub-continental (refertilized) mantle-type composition of most peridotites

of the ophiolites preserved in the Alps (Picazo et al. 2016). Our interpretation does not exclude the possibility that first
"immature" or "embryonic" oceanic domains, such as the Chenaillet-Montgenèvre Ophiolite (oceanic mantle-type, Picazo et al. 2016; U/Pb ages ranging from 148-156 Ma to 165 Ma; Costa and Caby, 2001; Li et al., 2013 respectively) have formed already during this phase of very oblique plate motion. Still we propose that formation of "mature" oceanic crust took place when the plate motion became more orthogonal and rates of opening reached c. 22 mm/yr (Figures 4 and 5). Indeed, our modelling results show that break-up of the continental lithosphere occurs when the rift-perpendicular velocity increases (Figure 7). "Mature" oceanic spreading was slow to ultra-slow and very short-lived (9 Ma), as the divergence along the PL domain decreased significantly at 145 Ma and completely ceased at 130 Ma.

Our geodynamic modelling, constrained by our plate reconstructions, reproduces the kinematics of the different rifting phases recorded in the Alps, but also the first-order structures of the hyper-extended margins. The final "shape" of the distal rifted margin obtained from our modelling (Figure 7E) agrees with geological reconstructions of the Alpine Tethys margins (Mohn et al., 2012, their Figure 2). Moreover, we provide quantitative constraints on the final width of the different domains: (1) 45-65 km for the necking zone (thinning of the crust from 30 to 10 km; Figure 7); (2) 40-80 km for the distal margin (crust thinner than 10 km, hyper-extended and OCT domains; Figure 7); (3) maximum 250 km for the oceanic domain (Figures 4, 6 and 7). Hence, the total width of the PL Basin, including both the rifted continental margins (thinner than 30 km) and the oceanic crust featured a total extent of 480 km (Figure 7E).

The kinematic evolution of the comparably small PL Basin is closely linked to the much larger neighboring Atlantic Ocean and the variation of rifting/spreading velocities coincides with changes in divergence rates of the Central Atlantic (Figure 5). The PL Ocean opened as a third arm of the Central Atlantic Ocean in Jurassic time (as previously proposed; e.g. Stampfli and Borel, 2002) and "died out" when the North Atlantic took over at c. 145 Ma (Barnett-Moore et al., 2018). It then closed due to the opening of the South Atlantic (e.g. Müller et al., 1999) and ensuing counter-clockwise motion of Africa relative to Europe in Cretaceous-Cenozoic times.

5.2 Assessing the model

The kinematics of the opening of the PL Basin is primary governed by the motion of Europe and Adria, as Iberia-Sardinia-Corsica started to move at 145 Ma, i.e. after the opening of the PL Basin. In our model, it is more precisely governed by the motion of Europe and Africa since we assume Adria rigidly connected with Africa after the opening of the Ionian Basin in Triassic time and prior the strike-slip motion along the MATF in Cretaceous-Cenozoic time (see section 3.3). Thus our results are extremely dependent on the kinematic reconstructions used for the opening of the Central Atlantic in the Jurassic, here the model of Kneller et al. (2012). The latter is based on a non-rigid inversion method that restores incrementally crustal stretching allowing a better restoration of the syn-rift to breakup phase and producing realistic subsidence and crustal thinning patterns that are consistent with field observations. Other recently published model for the Central Atlantic, such as Labails et al (2010),

show, however, significant gaps in palinspastic restorations of the margins (see further discussion in Kneller et al., 2012). Moreover, when using the rotation poles of Labails et al (2010) for the Central Atlantic, we obtain a phase of convergence

590   rather than divergence between 190 and 170 Ma in the PL domain between Europe-Adria. This is in contradiction with the clear record of syn-rift basins of Early Jurassic age in the Alps (section 2.1.1) while our kinematic model using Kneller et al. (2012) fits the geological record of rifting and spreading along the Alpine Tethys (section 5.1).

We assume that the Ionian Basin opened in the Triassic (Speranza et al., 2012). However, Tugend et al. (2019) recently re-

595   evaluated the age of opening of the Ionian Basin to Late Triassic-Early Jurassic (rifting) and late Early Jurassic-Middle Jurassic (spreading), i.e. overlapping in time with the two first rifting stages of the PL Basin. However, uncertainties remain on the exact amount and direction of extension between Africa and Adria that took place at that time. Indeed, the Ionian Basin probably resulted from several phases of extension as indicated for example by the presence of Permian oceanic basins in Sicily (Catalano et al., 1991) and the exact direction and amount of spreading cannot be clearly reconstructed as most of the

600   oceanic domain is now subducted. We tested nevertheless an alternative scenario with moving Adria (Apulia) relative to Africa (Tunisia) in Early-Middle Jurassic (200-164.7 Ma) of the total width of the present-day Ionian Basin (c. 350 km, fitting together the Malta and Apulian escarpments; Tugend et al., 2019, their Figure 13a) in a NW-SE opening direction following Frizon de Lamotte et al. (2011). This would increase the rate of rifting in the PL domain (9 mm/yr) and increase significantly the obliquity between Europe and Adria and thus reduce considerably the width of the rifted domain between Europe-Adria. Therefore, our

605   calculated extent of the LP Basin and subsequent amount of convergence (below) constitutes maximum estimates.

5.3 Implications for subduction processes in the Alps

Using the motion path of NW Adria (Ivrea) relative to Europe, we can estimate the magnitude, direction and rate of Adria-Europe convergence since the onset of "Alpine" south-directed subduction at about 84 Ma (Figure 8; Table 2). Our model

610   indicates a total amount of plate convergence of c. 680 km towards the NW (relative to Europe) since 84 Ma, subdivided into c. 420 km during subduction (84-35 Ma; average rate of 8.6 mm/yr) and c. 260 km during collision (35-0 Ma; average rate of 7.4 mm/yr). If we take into account that the PL had a maximum width of 250 km (in the same NW-SE direction), we can furthermore estimate that at least 63% ((680-250)/680 x 100) of the material involved in the Alpine Orogeny was extended continental lithosphere and OCT zones of the PL and Valais basins (Figure 4). This may explain why the Alps are such a

615   singular mountain belt, e.g. with the absence of well-developed magmatic arc during the alpine subduction (McCarthy et al., 2018, 2020) and widespread high-pressure metamorphosed continent-derived rocks (e.g. Kurz et al., 1999; Berger and Bousquet, 2008; Bousquet et al., 2008; Nagel et al., 2013; Sandmann et al., 2014; Fassmer et al., 2016).

Our estimates of plate convergence are lower than the one obtained from geological reconstructions of the Alps (Handy et al., 2010, 2014), especially for the subduction phase during 84-35 Ma (c. 200 km difference; Table 2). The 615 km of motion

620   obtained by Handy et al. (2010, 2014) between 84 and 35 Ma is based on a projection (465 km) of the estimated c. 400 km shortening in the eastern Central Alps from (Schmid et al., 1996) between 67-35 Ma, added to the estimated 150 km subduction

of Sesia between 84-67 Ma based on the depth of high-pressure nappes of this unit (Babist et al., 2006). A major part of the 400 km shortening in the Central Alps estimated by Schmid et al. (1996) is itself based on an inferred width of the Valais Basin and Briançonnais that went into subduction between 65-50 Ma and an inferred amount of subduction also based on depth

625 of high-pressure metamorphism of the Adula Nappe (150 km) between 50-40 Ma. Two possible sources of error arise and may explain the discrepancy with our results: (1) the past extent of the Valais/Briançonnais domain inferred by Schmid et al. (1996) was not kinematically constrained and (2) the depth of high-pressure rocks – and thus the amount of subduction – may be overestimated due to possible tectonic overpressure (Ford et al., 2006; Schmalholz and Podladchikov, 2013; Pleuger and Podladchikov, 2014; Yamato and Brun, 2017).

630

We note that our estimates of plate convergence are, however, slightly higher than the recent model proposed by van Hinsbergen et al. (2020; Table 2), due to the different assumptions we made for the motion of Iberia, Sardinia-Corsica and Adria as previously discussed (sections 3). The major difference impacting the amount and rate of plate convergence is that we consider a sinistral strike-slip motion within Adria of c. 230 km along the MATF (Figure 3) between 100-40 Ma (Schettino

635 and Turco, 2011; Hosseinpour et al., 2016). This remains poorly constrained and may lead to a slight overestimation of the convergence between Adria-Europe during that time. Thus, our amounts and rates of plate convergence should be taken as maximum values. To solve the remaining problematic areas, future work should focus on quantifying, and incorporating into kinematic reconstructions, the tectonic deformation within the Iberian and Adriatic plates, and between Corsica and France. Interestingly, Dannowski et al. (2020b) re-evaluated the nature of basement beneath the Liguro-Provencal Basin to be hyper-

640 extended continental crust (only a few km thick) and exhumed mantle, rather than oceanic crust. Moreover, compressional earthquakes and inverted structures have been observed within the Liguro-Provencal Basin and along the northern African margin, which suggest that those hyper-extended margins and OCT zones may represent incipient subduction zones accommodating the present-day Africa-Europe convergence (Billi et al., 2011; Hamai et al., 2018; Dannowski et al., 2020b). This reflects once more the importance of those domains as inherited weakness for potential subduction initiation processes

645 (Beltrando et al., 2010; Tugend et al., 2014; Kiss et al., 2020; Zhou et al., 2020).

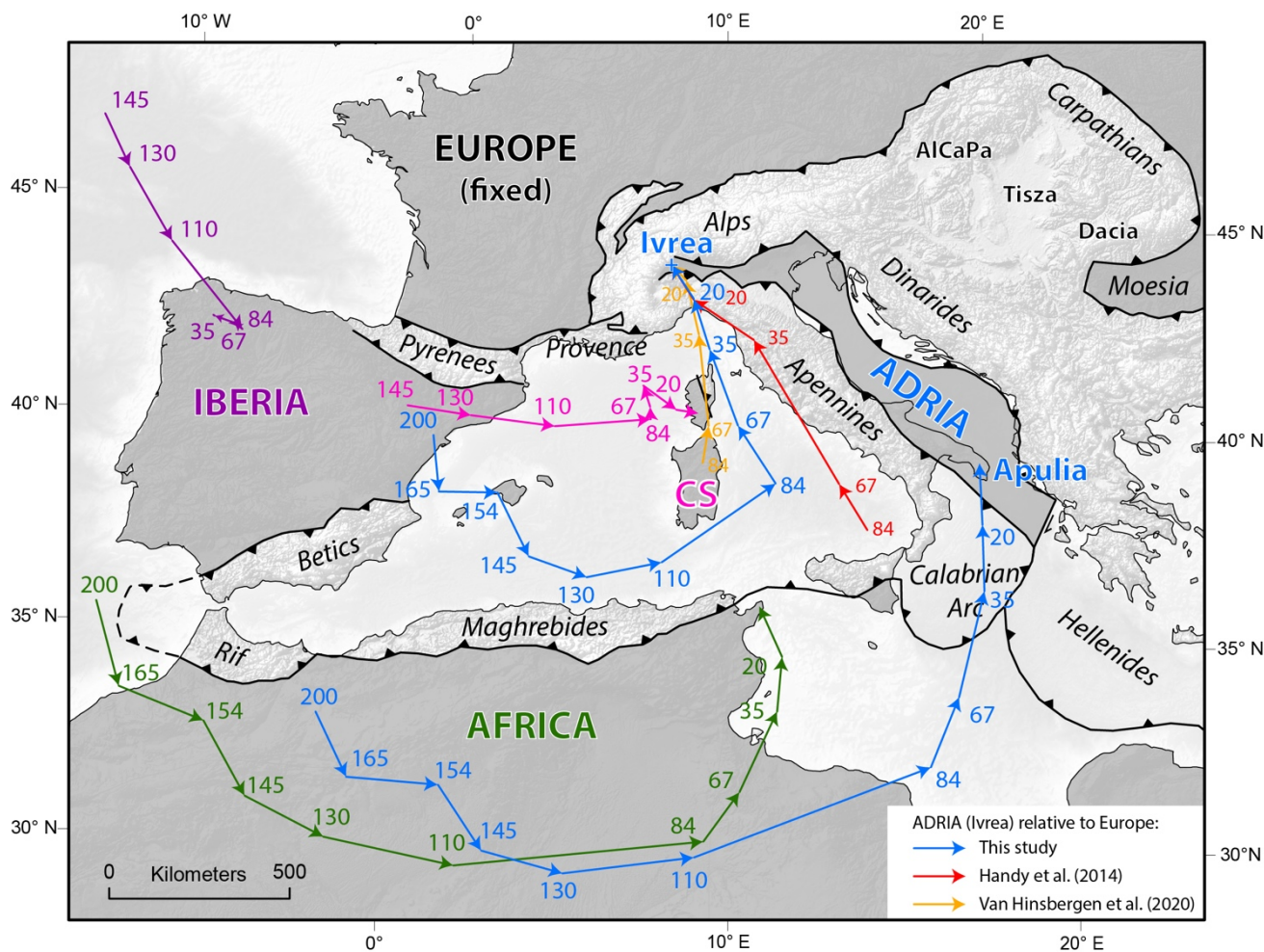



Figure 8: Motion paths of northern (Ivrea) and southern (Apulia) Adria (blue), Iberia (dark purple), Corsica (light purple) and Africa (green) relative to Europe stationary back to 200 Ma (time step indicated in Ma) using our kinematic reconstructions. Alternative motion paths of northern Adria are also shown for comparison (Handy et al., 2014 in red and van Hinsbergen et al., 2020 in orange). Amount, direction and rate of convergence of Adria (Ivrea) – Europe are given in Table 2.

Table 2: Amount, mean direction (azimuth) and mean rate of Adria (Ivrea) - Europe convergence during Alpine collision (35-0 Ma) and subduction (84-35 Ma). Comparison with model of Handy et al. (2010, 2015) and van Hinsbergen et al. (2020).

Time Period	Adria (Ivrea) – Europe Convergence			Reference
	Amount	Azimuth	Rate	
35-0 Ma **Alpine Collision**	313 km	315°	8.9 mm/yr	Handy et al. (2014)
	260 km	**335°**	**7.4 mm/yr**	**This study**
	210 km	338°	6 mm/yr	van Hinsbergen et al. (2020)
84 - 35 Ma **Alpine Subduction**	615 km	330°	12.6 mm/yr	Handy et al. (2014)
	420 km	**335°**	**8.6 mm/yr**	**This study**
	350 km	358°	7.1 mm/yr	van Hinsbergen et al. (2020)

6 Conclusions

655   In this study, we focused on the divergent Mesozoic history of the Alpine region, which is crucial to better understand the complex tectonic evolution of this mountain chain. By updating the regional reconstructions of the Western-Central Mediterranean area, implemented into a global plate circuit and complemented by thermo-mechanical modelling, we shed new light on the past extent and opening kinematics of the Piemont-Liguria Ocean. The opening of the Central Atlantic in Jurassic times led to divergence between Europe and Africa and the opening of the Piemont-Liguria Ocean in four stages. Two

660   successive phases of stretching and thinning of the continental crust (> 10 km thick, 200-180 Ma; < 10 km thick, 180-165 Ma) were followed by mantle exhumation and MORB-type magmatism along the hyper-distal (OCT) part of the margin (165-154 Ma). "Mature" oceanic spreading in a NW-SE direction (relative to Europe) was short-lived (154-145 Ma) and was slow to ultra-slow (up to 22 mm/yr), ceasing progressively in the Early Cretaceous (145-130 Ma). This led to the formation of a small oceanic domain of maximum 250 km width. This kinematic evolution is in strong agreement with independent geological

665   records of rifting in the Alps and the age of the Alpine Tethys Ophiolites. The opening of the North Atlantic at 145 Ma led to a period of mostly strike-slip tectonics along this domain. South-directed "Alpine" subduction of the PL Ocean initiated at about 84 Ma, at rates of c. 8.6 mm/yr, and progressed from SE to NW until collision of the Adriatic Plate with the European proximal margin at about 35 Ma. We highlight that at least 63 % of the subducted lithosphere was highly thinned continental lithosphere and OCT zones, which emphasizes the importance of the distal domain of continental margins in subduction

670   processes. We provide new kinematic constraints (maximum extent of oceanic crust and plate convergence direction and rates) that can be used as set-up for future geodynamic modelling and a better understanding of subduction initiation, magmatism and exhumation processes during the Alpine Orogeny.

Data availability

All reconstruction files of the kinematic model presented in this paper, as well as animations and age-grids, are available at

675   https://www.earthbyte.org/webdav/ftp/Data_Collections/Muller_etal_2019_Tectonics/ or by contacting the first author.

Video supplement

Results of the 2D thermo-mechanical modelling of the opening of the Piemont-Liguria Basin, using velocities derived from our kinematic reconstructions, are shown in an animation (Movie S1) in supplement to this manuscript.

Author contribution

680 ELB developed the research concept, acquired funding, carried out the kinematic reconstructions and their interpretation, designed the figures and wrote the manuscript with input from all authors. SB performed the thermo-mechanical modelling and contributed to the interpretation and discussion of the rifting phase. UK participated in the conceptualization of the initial project and in discussion on regional tectonics reconstructions. SZ, MS and DM were involved in the implementation of the regional kinematic reconstructions into the global deforming plate model using GPlates. SZ and MS generated animations
685 centered on the Mediterranean and age-grids of the PL Ocean. DM welcomed ELB for a research stay at the EarthByte Group, University of Sydney in 2017, which initiated this collaborative work.

Competing interests

The authors declare that they have no conflict of interest.

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