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A reconstruction of Iberia accounting for W-Tethys/N-Atlantic kinematics since the late Permian-Triassic

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Abstract. The West European kinematic evolution results from the opening of the West Neotethys and the Atlantic oceans since the late Paleozoic and the Mesozoic. Geological evidence shows that the Iberian domain well preserved the propagation of these two rift systems and is therefore key to significantly advance our understanding of the regional plate reconstructions. The Late Permian-Triassic tectonic evolution of Iberian rift basins shows that they have accommodated significant extension, but this tectonic stage is often neglected in most plate kinematic models, leading to the overestimation of the movements between Iberia and Europe during the subsequent Mesozoic (Early Cretaceous) rift phase. By compiling existing seismic profiles and geological constraints along the North Atlantic margins, including well data over Iberia, as well as recently published kinematic and paleogeographic reconstructions we propose a coherent kinematics model of Iberia that considers both the Neotethyan and Atlantic evolutions. Our model shows that the Europe-Iberia plate boundary was a domain of distributed and oblique extension made of two rift systems, in the Pyrenees and in the Iberian intra-continental basins. It differs from standard models that consider left-lateral strike-slip movement localized only in the northern Pyrenees in introducing a significant strike-slip movement south of Ebro accounting for Late Permian-Triassic extension and by emphasizing the need for an Ebro microcontinent. At a larger scale it emphasizes the role played by the late Permian-Triassic rift and magmatism, as well as strike-slip faulting in the evolution of the western Neotethyan Ocean and their control on localization of the Atlantic rift.

1 Introduction

Plate tectonic reconstructions are based on the knowledge of magnetic anomalies that record age, rate and direction of seafloor spreading. Where these constraints are lacking or their recognition ambiguous, kinematic reconstructions rely on the description and interpretation of the structural, sedimentary, igneous and metamorphic rocks of rifted margins and orogens

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corresponding to diffuse plate boundaries. However, the required quantification and distribution of finite strain into deformed continents remain often uncertain due to the poor preservation of pre-kinematic markers.

A well-known example of this problem is illustrated by the contrasting Mesozoic plate kinematic models proposed for the Iberian plate relative to Europe with significant implications for the reconstructions of the Alpine Tethys and Atlantic oceans (Olivet, 1996; Handy et al., 2010; Sibuet et al., 2004; Vissers and Meijer, 2012; Barnett-Moore et al., 2016; Nirrengarten et al., 2018). This movement is proposed to be imposed by the northward propagation of the North Atlantic rifting during the Triassic-Early Cretaceous period (Olivet, 1996; Stampfli et al., 2001; Handy et al., 2010; Barnett-Moore et al., 2016; Nirrengarten et al., 2018). If all of the proposed reconstructions agree on the amplitude and kinematics of a 400-500 km left-lateral strike-slip motion between Europe and Iberia after the Variscan orogeny, its precise timing and spatial partitioning is debated and remains unresolved so far (e.g., Vissers and Meijer, 2012; Barnett-Moore et al., 2016). Because of the lack of constraints, these discussions are often exported onshore along the so-called North-Pyrenean Fault supposedly accommodating this pre-orogenic Europe-Iberia displacement (Fig. 1A) (e.g., Choukroune and Mattauer, 1978; Debroas, 1987, 1990; Lagabrielle et al., 2010; Jammes et al., 2009). Here again, former studies were not conclusive so there are currently no firm geological constraints nor geophysical evidence across the Pyrenees to argue for significant transcurrent deformation during the Jurassic or the Cretaceous (Olivet, 1996; Masini et al., 2014; Canérot, 2016; Chevrot et al., 2018). Other studies have suggested that this conclusion might hold true back to the Permian based on local geological evidence from the western Pyrenees (Saspiturry et al., 2019).

An alternative scenario has recently emerged, proposing a spatiotemporal partitioning of the deformation in a wider deformation corridor than the single Pyrenean belt. It suggests that the major strike-slip movement required to accommodate the eastwards movement of Iberia first occurred during the Late Jurassic-Early Cretaceous in northern Iberia along the NW-SE-trending Iberian massifs (Tugend et al., 2015; Nirrengarten et al., 2018). Indeed, several extensional basins with major subsidence have already been recognized along these massifs (Asturian, Cameros, Maestrat, Columbrets rift basins; Fig. 1B) (Tugend et al., 2015; Tavani et al., 2018; Aldega et al., 2019; Aurell et al., 2019) that are understood as a hundred-kilometer scale pull-part or en-echelon rift basins formed in a trans-tensional setting. These basins separate the Ebro continental block from the greater Iberia to the south. Ebro is delimited to the north by the Pyrenean system. Extension then migrated and localized to the north (Rat et al., 2019) leading to oceanic spreading in the Bay of Biscay and hyper-extension in the Pyrenean rift basins (Jammes et al., 2009; Lagabrielle et al., 2010; Mouthereau et al., 2014; Tugend et al., 2014, 2015).

Although there are growing pieces of evidence in support of the major role played by intra-Iberia strike-slip deformation, no geological evidence for lithosphere-scale strike-slip movements is yet clearly defined.

Moreover, the contribution of pre-Late Jurassic/Early Cretaceous extension phases might have been substantial to the overall crustal attenuation and movements of Iberia (Fig 3A) (Fernández, 2019; Soto et al., 2019). Indeed, two major geodynamic events, the late Permian-Early Triassic breakup of Pangea and opening of the Neotethys and the Late Triassic-Early Jurassic Central Atlantic magmatic event preceding the opening of the North Atlantic Ocean are recorded in Iberia and contributed to the finite crustal thinning. Therefore, all full-fit reconstructions considering that extension between Iberia and Newfoundland only initiated by Jurassic times in the North Atlantic realm invariably overestimate the amount of strike-slip motion required in the Pyrenees and northern Iberia from the Jurassic onward (Barnett-Moore et al., 2016; Nirrengarten et al., 2018).

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Here, we examine the possible contribution of the late Permian-Triassic extension to the plate reconstruction of Iberia between the Neotethys and the North-Central Atlantic domains and its impact on the definition of the spatial and temporal distribution of strike-slip movement between Iberia and Europe. By integrating constraints from 270 Ma to 100 Ma, our reconstructions bring to light the connection between the Tethyan and the Atlantic oceanic domains.

2 Late Permian-Triassic rifting and magmatism in North-Atlantic and Western Europe

The tectonic and thermal evolution of the "Iberian buffer" between Africa and Europe at the Permian–Triassic boundary reflects the complex post-Variscan evolution of the Iberian lithosphere. This domain has in fact experienced significant Permian crustal thinning in relation to the post-orogenic collapse of the Variscan belt (De Saint Blanquat et al., 1990; de Saint Blanquat, 1993; Vissers, 1992; Saspiturry et al., 2019) and the fragmentation of the Gondwana margin more broadly (Schettino and Turco, 2011; Stampfli and Borel, 2002; Ziegler, 1989, 1990). However, this phase also resulted in lithospheric mantle delamination and thinning (Malavieille et al., 1990; Fabriès et al., 1991, 1998; Ziegler et al., 2004; Ziegler and Dèzes, 2006; Denèle et al., 2014). Crustal thinning is well documented in the Atlantic province and Northwest Europe continental shelves (Fig. 1B) (Ziegler et al., 2004; Ziegler and Dèzes, 2006; Leleu et al., 2016; Müller et al., 2016; Spooner et al., 2019; Soto et al., 2019), by thick late Permian-Triassic detrital basins of the North Western Approaches (Avedik, 1975; Evans, 1990; McKie, 2017), North Atlantic (Tankard and Welsink, 1987; Doré, 1991; Doré et al., 1999; Štolfová and Shannon, 2009; Peace et al., 2019) and North Sea (McKie, 2017; Jackson et al., 2019; Hassaan et al., 2020; Phillips et al., 2019) (Fig. 2). The late Permian-Early Triassic pre-salt extension is well imaged on seismic lines (Fig. 2). An angular unconformity is observed at the base of the late Permian-Early Triassic in the Western Approaches (Evans, 1990), West Iberia (Leleu et al., 2016), Nova Scotia (Welsink et al., 1989; Deptuck and Kendell, 2017), the Grand Banks (Balkwill and Legall, 1989), the Moroccan basins (Hafid, 2000), in the Pyrenees (Lucas, 1985; Espurt et al., 2019; Cámara and Flinch, 2017; Bestani et al., 2016) and throughout Iberia between the Paleozoic and the Permian-Triassic strata (Arche and López Gómez, 1996).

The Permian tectonic phase is contemporaneous with widespread magmatism related to breakup of Pangea, and its transition toward diffuse extension. This is observed in present-day rifted margins of the North Atlantic such as the North Sea and Norwegian-Danish Basins (Glennie et al., 2003), the Western Approach (McKie, 2017), the Scottish Midland Valley (Upton et al., 2004) and in the basement of Cenozoic collision belts around Iberia, for instance, in the Pyrenees (Lago et al., 2004a; Denèle et al., 2012; Vacherat et al., 2017; Saspiturry et al., 2019), Iberian Range (Lago et al., 2004b), Catalan Coastal Ranges (Solé et al., 2002), and in the Betic Cordillera (Sánchez-Navas et al., 2017).

An expression of the continued lithospheric thinning during the Permian (McKenzie et al., 2015) and the Triassic and abnormally high heat flow is recorded by the emergence of the widespread tholeiitic magmatic CAMP (Central Atlantic Magmatic Province) event at the Triassic-Jurassic boundary (200 Ma) in the Central Atlantic (Olsen, 1997; Marzoli et al., 1999; McHone, 2000). The CAMP extends to Iberia as large-scale volcanic intrusions such as the Messejana-Plasencia dyke (Cerbiá et al., 2003) in Iberia and the Late Triassic-Early Jurassic ophitic magmatism in the Pyrenees (e.g., Azambre et al., 1987). The CAMP may have favored heat dispersion that triggered the subsequent Early Jurassic continental breakup in the Central

Atlantic. Extension and salt movements in the North Sea basins during the Late Triassic further point to the propagation of the North Atlantic rift (Goldsmith et al., 2003).

The persistence of shallow-marine to non-marine deposition during this period contrasts with the large accommodation space that is required at larger scale to sediment the giant evaporitic-province in the late Permian (Jackson et al., 2019) and in the Late Triassic (Štolfová and Shannon, 2009; Leleu et al., 2016; Ortí et al., 2017). Crustal thinning expected for this period therefore does not follow McKenzie's prediction of subsidence (McKenzie, 1978).

A first hypothesis to explain the difference with this model is that crustal attenuation induced density reduction of the thinned lithosphere by mantle phase transitions to lighter mineral phases during lithosphere thinning (Simon and Podladchikov, 2008) or due to the trapping of melt in the rising asthenosphere before breakup(Quirk and Rüpke, 2018) in addition to magmatic re-thickening of attenuated crust by underplating. Another possible hypothesis for the Permian-Triassic topographic evolution of the Iberian basins relies on the complex post-Variscan evolution of the Iberian lithosphere. Recent studies have shown that during the existence of Pangea supercontinent (∼300 to ∼200 Ma), temperature in the asthenospheric mantle increased due to the thermal insulation by the continental lid (Coltice et al., 2009; Ganne et al., 2016). Such mantle thermal anomaly could have further inhibited lithospheric mantle re-equilibration after late-Variscan mantle delamination over a long-time span. Once mantle temperature dropped as a consequence of the Pangea breakup and magmatic emission at the Triassic/Jurassic boundary, lithospheric mantle started to cool and thicken, causing isostatic subsidence of the thinned Iberian crust and resulting in topographic drop.

This argues for a protracted period of ∼100 Myr (late Carboniferous to Late Triassic) of continental lithosphere thinning and magmatism prior to Jurassic break-up of the North Atlantic but contemporaneous with the Tethyan evolution. One main consequence is that the late Permian-Triassic extension has been so far underestimated in plate reconstructions, despite evidence for continuous extension.

3 From late Permian-Early Triassic rifting to Late Jurassic-Early Cretaceous rifting in Iberia

The Permian-Triassic basins of Iberia are exposed in the inverted Mesozoic rift basins of the Basque-Cantabrian and Pyrenean belts, the Iberian Ranges, the Catalan Range and the Betic Cordillera (Figs. 1B and 3A). The coincidence between the orientations of the Alpine orogenic segments and the spatial distribution of Permian-Triassic depocentres (Figs. 1B and 3A) suggest that the Cenozoic orogenic cycle largely inherits the earliest stages of the Tethyan rift evolution. In addition, these Permian-Triassic depocentres are superposed over Variscan structures (Fig. 1B), suggesting antecedent tectonic control of the Tethyan continental rift segment by the late Variscan evolution.

We analyse subsidence reconstructed based on a compilation of well data and synthetic stratigraphic section in the Aquitaine Basin (Brunet, 1984), Cameros and Iberian basins (Salas and Casas, 1993; Salas et al., 2001; Omodeo-Salé et al., 2017), West Iberia (Spooner et al., 2019), and the Betics (Hanne et al., 2003), to estimate 1D mean tectonic subsidence evolution in these areas (Fig. 3B, see Supplementary Material for individual tectonic subsidence curves in each region). For each region, we calculated the mean tectonic subsidence, following the approach of Spooner et al. (2019) for which wells that do not sample

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the entire stratigraphy are corrected based on the oldest well of the region. We then calculated the mean crustal stretching (β factor, Fig. 3C) for each tectonic subsidence curve based on isostatic calculation (Watts, 2001).

During the late Permian-Early Triassic, a first phase of significant tectonic subsidence, up to 500 m, is recorded in the Maestrat basin and on the Iberia paleomargin of the Betic basins (Salas and Casas, 1993; Van Wees et al., 1998; Salas et al., 2001; Hanne et al., 2003; Soto et al., 2019) (Fig. 3B-C). The westward migration of marine deposition in the Iberian basins during the middle Triassic (Anisian-Carnian, 240-230 Ma) (Sopeña et al., 1988) argues that Tethyan rifting propagated westward inboard Iberia. The same evolution is suggested by the stratigraphy and the depositional evolution constraints from the Catalan and Basque-Cantabrian basins (Sopeña et al., 1988), and in the Aquitaine domain (Fig. 3B) although ill-defined for the Permian times.

During the Late Triassic (220-200 Ma), the regional tectonic subsidence in all regions is found associated with the deposition of evaporites that spread all over Iberia, in the Betics, West Iberia and in the Aquitaine Basin (Fig. 3A). The distribution of salt terrane in Iberia and its surrounding (Fig. 3A) highlights a very large subsiding domain for this period. A maximum mean subsidence of 700 m is inferred in the Maestrat basin for the Triassic times. The relatively rapid subsidence in the Triassic contrasts with the slower subsidence observed during the Early-Middle Jurassic. A notable exception is depicted by the slight increase of subsidence between 200 and 150 Ma in the Betics (Fig. 3B-C), consistent with rifting across the Iberia-Africa boundary (Ramos et al., 2016; Fernández, 2019).

A third Late Jurassic-Early Cretaceous phase (150-110 Ma) is marked by the increase of tectonic subsidence in the Iberian basins, coeval with the expected timing of strike-slip deformation and rifting in Cameros (e.g., Rat et al., 2019; Aurell et al., 2019) and Columbrets (Etheve et al., 2018) basins as well as the initiation of mantle exhumation in the Atlantic domain (Fig. 1A) (Murillas et al., 1990; Mohn et al., 2015). The most recent extension is recorded in the Aquitaine Basin at 120-100 Ma that reflects the onset of oceanic spreading in the Bay of Biscay (Fig. 3B-C).

Subsidence analyses show thinning events in Iberia that reveal control by Tethys and Atlantic rifting (late Permian-Late Triassic) and later by the intra-Iberian-Pyrenean rift events (Late Jurassic-Early Cretaceous). In the Iberian basin, this latter event is characterized by a relatively large and short-lived subsidence (1.5 km in 30 Myrs) localized in narrow basins that suggests the strike-slip nature of the boundary between Ebro and Iberia in the Late Jurassic. The long-lasting rift evolution however show an average low stretching factor of about 1.2.

4 Kinematics of Iberia between Atlantic and Tethys

A plate reconstruction from late Permian to Cretaceous is presented in Fig. 4 based on a kinematic modelling using GPlates version 2.1 (Müller et al., 2018). This reconstruction aims to present the partitioning of the deformation within Iberia into a larger coherent kinematic model of the Tethys and Atlantic Oceans. A critical step in determining the pre-rifting configuration is to restore rifted margins. Here, we adopted the reconstructed continental crust geometry of Nirrengarten et al. (2018) based on a kinematic model of southern North Atlantic. Polygons from the model of Seton et al. (2012) were re-defined by including new

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smaller polygons (continental microblocks) separated by deformed areas in Iberia and Adria to account for internal deformation (Fig. 1B).

As full-fit cannot be reconstructed along the whole Iberia margin (Fig. 4A), we restore used full-fit only between Northwest Iberia (Galicia) and North America (Flemish Cap) to minimize the strike-slip movement between Iberia and Europe, rather than a full-fit in the Southwest Iberia that leads to significant overlapping between the Flemish Cap and Galicia.

Our kinematic model is based on the following constraints (Table 1): (1) geological constraints on the timing of deformation and subsidence during late Permian-Triassic time in the intra- and peri-Iberian basins mentioned above (Fig. 3); (2) age of rifting, mantle exhumation, onset of oceanic spreading in the Atlantic; (3) the present-day position of ophiolites bodies and the timing of the rifting, oceanic spreading and subduction for the Tethyan-related oceanic domains (Paleotethys, Neotethys, Pindos, Meliata, Vardar); (4) at 100 Ma, Iberia should be close to its present-day along-strike position relative to Europe, so that the orthogonal Pyrenean shortening is accommodated in the late Mesozoic-Cenozoic times.

We then integrate kinematic evolution for published models in both the Atlantic and the Tethys according to the following workflow: 1) the reconstruction of the western Tethys prior to the Late Jurassic is based on the kinematic evolution of the Mediterranean region since the Triassic from Van Hinsbergen et al. (2019) that we corrected for overlap over the western France, Iberian and Adriatic domains; 2) for the Late Jurassic and Cretaceous times, we compiled rotation poles for Adria and Africa from Handy et al. (2010) and for the North America-Europe system from Barnett-Moore et al. (2016); 3) Adria and Africa were then corrected for the position of Africa according to Heine et al. (2013).

4.1 Permian-Late Triassic (270-200 Ma)

The Neotethys Ocean opening initiated in the early Permian in the northern Gondwana margin, resulting in the northward drift of the Cimmerian terrane and the subduction of the Paleozoic Paleotethys Ocean (Stampfli et al., 2001; Stampfli and Borel, 2002). This occurred contemporaneously with the establishment of the Carboniferous-Permian magmatic activity in the North Sea rift and Midland Valley rift areas (Evans et al., 2003; Heeremans et al., 2004; Upton et al., 2004).

As the Neotethys rift propagated westwards, diffuse continental rifting took place in whole Western Europe defined by the position of the Paleozoic Variscan and Caledonian orogenic belts in the West, the Tornquist suture in the East and a diffuse transtensional transfer zone along the Africa-Iberia-Adria boundary (Fig. 4A). This is recorded by several late Permian rift domains located in the southern North Atlantic (Rasmussen et al., 1998; Leleu et al., 2016), in the Adriatic (Scisciani and Esestime, 2017) in the North Sea (Hassaan et al., 2020), in the Germanic rift basins, including the Zechstein basin (Evans, 1990; Van Wees et al., 2000; Jackson et al., 2019) and in Iberia (Figs. 2, 3 and 4A). Back-arc extension associated with the subduction of the Paleotethys (Van Hinsbergen et al., 2019) (Fig. 4B) triggered extension and formation of oceanic basins in the Pindos and Meliata domains during the Early (250 Ma) and Late Triassic (Carnian, 220 Ma), respectively (Channell and Kozur, 1997; Stampfli et al., 2001). As proposed by Schmid et al. (2008), the Pindos ocean was probably a western branch of the Neotethys rather than a unique ocean. The strike-slip reactivation of the Tornquist Zone could also be a far-field effect of Paleotethys closure (e.g., Phillips et al., 2018).

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During the Late Triassic-Early Jurassic (Fig. 4C-D) the opening of the Ionian basin (Tugend et al., 2019) triggers northward displacement of Adria relative to Iberia and Africa and induced trans-tension between Adria and Iberia. This is consistent with Triassic basins of eastern Betics and Catalonia that developed at the emplacement of the future Alpine Tethys, which rifting started from the Late Triassic (220 Ma) (Stampfli and Borel, 2002; Schmid et al., 2008). The large rift-related subsidence in the Iberian basins (Fig. 3B) is kinematically consistent with the stretching lineations documented from Triassic strata (Soto et al., 2019). Ebro is already individualized from Iberia and moved eastwards relative to Iberia and Europe through right-lateral and left-lateral strike-slip movements, respectively.

4.2 Early Jurassic (200-160 Ma)

This period marks a gradual change from Tethyan-dominated to Atlantic-dominated tectonism in Iberia. As the Neotethys propagated in the Vardar Ocean, the Pindos and Meliata oceans started to close (Fig. 4C) (Channell and Kozur, 1997). Major dynamic changes occurred with the CAMP event (Olsen, 1997; Marzoli et al., 1999; McHone, 2000; Leleu et al., 2016; Peace et al., 2019) that led to breakup in the Central Atlantic Ocean during the 190-175 Ma interval (Pliensbachian-Toarcian) (Fig. 4C-D) according to Labails et al. (2010) and Olyphant et al. (2017), respectively. The propagation of the Central Atlantic rift northwards caused extension to propagate in the southern North Atlantic (Murillas et al., 1990; Leleu et al., 2016) and laterally, eastward in the Alpine Tethys (Schmid et al., 2008; Marroni et al., 2017) by some reactivation of Triassic Neotethyan rift structures. Evidence for nearly synchronous intrusions of MORB-type gabbro, in a western branch of the Alpine Tethys, is described at 180 Ma in the internal zones of eastern Betics (Puga et al., 2011), associated with the rapid subsidence in the Betics (Fig. 3B). However, whether this is related to incipient oceanic spreading or magmatism in hyper-extended margin is controversial. By contrast, both the thermal and stratigraphic evolutions (also Fig. 2) suggest that central Iberia remained little affected by the propagation of the Early Jurassic Atlantic rift Iberian basins (Aurell et al., 2019; Rat et al., 2019). A kinematic change from oblique to orthogonal E-W extension in the Alpine Tethys is marked by the onset of oceanic spreading between the Bajocian-Bathonian (170-166 Ma) and the Oxfordian (161 Ma) as suggested by the ages of MORB magmatism in the Alps (Schaltegger et al., 2002) and first post-rift sediments (Bill et al., 2001). As such the Jurassic Alpine Tethys has temporal and genetic affinities with the Atlantic Ocean evolution, rather than the Neotethys. The required differential movement between the opening the Alpine oceanic domains, the central Atlantic and the closure of the Neotethys and Vardar Oceans at 160 Ma induced the reactivation of the former diffuse transfer zone between Iberia and Africa into a localized transform plate boundary (Fig. 5A).

4.3 Late Jurassic-Early Cretaceous (160-100 Ma)

A major tectonic change occurred in the Late Jurassic-Early Cretaceous when the North Central Atlantic successfully rifted the continental domain located offshore Southwest Iberia in present-day coordinates (between 160 and 100 Ma, Fig. 5), as recorded by mantle exhumation and subsequent oceanic spreading at 150 Ma (e.g., Murillas et al., 1990; Mohn et al., 2015; Barnett-Moore et al., 2016) (Fig. 5B). At that time, the east-directed movement of Iberia relative to Ebro induced left-lateral trans-tensional faulting in a corridor shaped by the Iberian basins (Tugend et al., 2015; Aurell et al., 2019; Rat et al., 2019).

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We further infer a residual strike-slip movement between Ebro and Europe until the Mid-Cretaceous (118 Ma) when the Bay of Biscay opened and rotation of Iberia occurred (Sibuet et al., 2004; Barnett-Moore et al., 2016). The eastwards motion of Iberia relative to Adria resulted in the closure of the southern Alpine Tethys (Fig. 5C). Eastward rotation of Africa induces subduction along the northern Neotethyan margin (Schmid et al., 2008) (Fig. 5B-D).

Until 120 Ma (Early Cretaceous) eastward accommodation space is constantly created by the formation of rift segments in the Southwest Alpine domain (Valaisan domain and Southeast basins of France) and then Provence domains (Tavani et al., 2018). In the southern part of the Western Alps, reactivation of Tethyan normal faults are shown to be Late Jurassic-Early Cretaceous in age (Tavani et al., 2018). At 110 Ma, deformation migrates in the South Provence Basin making a straighter continuity of the Pyrenean system toward the East (Tavani et al., 2018).

5 Implications for strike-slip movements and the Europe-Iberia plate boundary

Table 2 summarizes the timing, amounts and sense of strike-slip component of the Ebro kinematics relative to Europe and Iberia inferred from our model. Our reconstructions suggest a total left-lateral strike-slip movement of 278 km between Europe and Ebro. 90 km were accommodated during the late Permian-Triassic period (Fig. 4A-C, 270-200 Ma). 86 km were accommodated during the Jurassic (Figs. 4C-D and 5A-B, 200-140 Ma). We quantify 99 km and 19 km for the 140-120 and 120-100 Ma time intervals, respectively, leading to a total of 128 km of strike-slip movement during the Lower Cretaceous, in the range of amounts deduced from offshore and onshore geological observations (Olivet, 1996; Canérot, 2016). By 118 Ma, most of the strike-slip faulting is terminated as extension became orthogonal and Ebro is close to its present-day position (Jammes et al., 2009; Mouthereau et al., 2014). The maximum strain rate of 5 km.Myr^{-1} is obtained for the 140-120 Ma time interval, revealing progressive strain localization in the Pyrenean basins before mantle exhumation (Jammes et al., 2009; Lagabrielle et al., 2010; Mouthereau et al., 2014; Tugend et al., 2014).

The Iberia-Ebro boundary has a more complex tectonic history than the Europe-Ebro boundary. The rapid eastward displacement of Ebro during the late Permian to Late Jurassic period (Figs. 4 and 5) induces a total of 67 km (12, 33, 17, and 5 km during the 270-250, 250-200, 200-180, and 180-160 Ma time interval, respectively) right-lateral strike-slip between Ebro and Iberia (i.e., Galicia). This displacement has been partitioned with extension within the Iberian basins along a NW-directed intra-continental deformation corridor. This is consistent with stretching markers in Triassic rocks in this area (Soto et al., 2019). From 160 to 100 Ma, the northward propagation of the Central Atlantic spreading ridge into the southern North Atlantic resulted in a net left-lateral slip of 245 km and increasing strain rates of up to 9 km.Myr^{-1}, indicating the southern Ebro boundary became the main tectonic boundary in Iberia, accommodating eastwards displacement of Iberia into the Alpine Tethys region. Despite the requirement of such large movements in the Iberian Range geological evidence are lacking. This likely reflect the role played by the Triassic evaporites that decouples the large extension in the pre-salt basement from thin-skinned extension in sedimentary cover as shown around Iberia by numerical studies (e.g., Grool et al., 2019; Duretz et al., 2019; Jourdon et al., 2020; Lagabrielle et al., 2020).

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The cumulated left-lateral displacement from both rift system, corrected for the right-lateral displacement in the Iberian basins, is 456 km, consistent with the absolute 400-500 km required from the closure of the Atlantic between Iberia and Newfoundland.

6 Conclusions

We show that kinematic reconstruction of Iberia accounting for the late Permian-Triassic basins evolution and further consideration of the role of Ebro and larger-scale plate reconstruction in the Atlantic and Tethys allows revolving several issues: 1) left-lateral strike-slip movement did occur in the Pyrenees from the late Permian to the Early Cretaceous but ended as the Bay of Biscay opened, 2) late Permian-Triassic extension in the Atlantic and Iberia (including Ebro) is key to quantify the strike-slip movement in Iberia that is otherwise not well resolved from the geological constraints in Iberian basins and from full-fit reconstructions in the Jurassic. Salt tectonics that decouples syn-rift Iberian basins evolution from their basement likely explains the lack of geological constraints.

The diffuse deformation across the Iberia-Europe plate boundary prior to oceanic spreading in the Bay of Biscay and hyper-extension in the Pyrenees appears to result mainly from transcurrent deformation partitioned with subordinate fault-perpendicular extension. The major intra-Iberia NW-trending strike-slip fault system outlined by spatially disconnected rift basins (Basque-Cantabrian, Cameros, Maestrat, and Columbrets basins) played a significant role in the Late Jurassic-Early Cretaceous, in addition to the North Pyrenean rift system.

By integrating the position of Iberia in the Tethyan and Atlantic evolution and propagating the effect of the eastward movement of Iberia into the Alpine Tethys, our reconstructions further implies that: 1) Ebro was part of Adria before the onset of the Alpine Tethys opening, 2) the southern Alpine Tethys started to close between 150 Ma and 100 Ma, 3) the boundary between Iberia and Africa localized as a transform plate boundary at 160 Ma, connecting the Alpine oceanic domains with the Central Atlantic.

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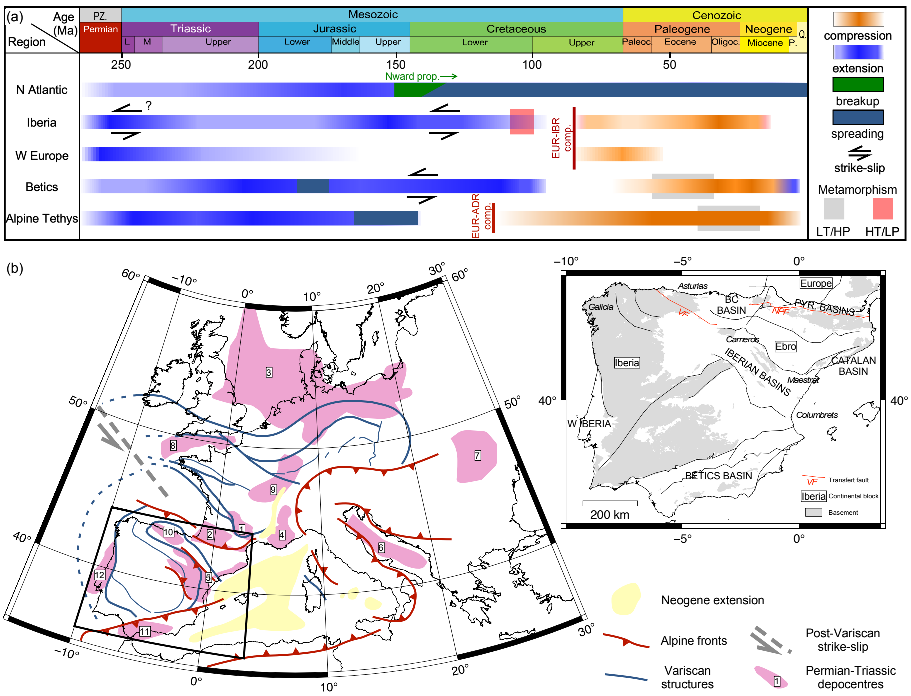

Figure 1. Geodynamic chart and localization of the study area. (a): Geodynamic chart of the main structural areas of the Iberian domain. BCB: Basque-Cantabrian basin. (b) Localization map of West Europe, showing the areas that are deformed in compression and extension and Permian-Triassic depocenters. 1: French Massif Central; 2: Aquitaine Basin and Pyrenees; 3: Germanic Basin; 4: South East France; 5: Iberian Basin; 6: Italy; 7: Central Europe; 8: English Channel; 9: North East France; 10: Basque-Cantabrian Basin; 11: Betics; 12: West Iberia. Inset: Map of the Iberian sedimentary basins and structures. BC: Basque-Cantabrian; PYR: Pyrenean.

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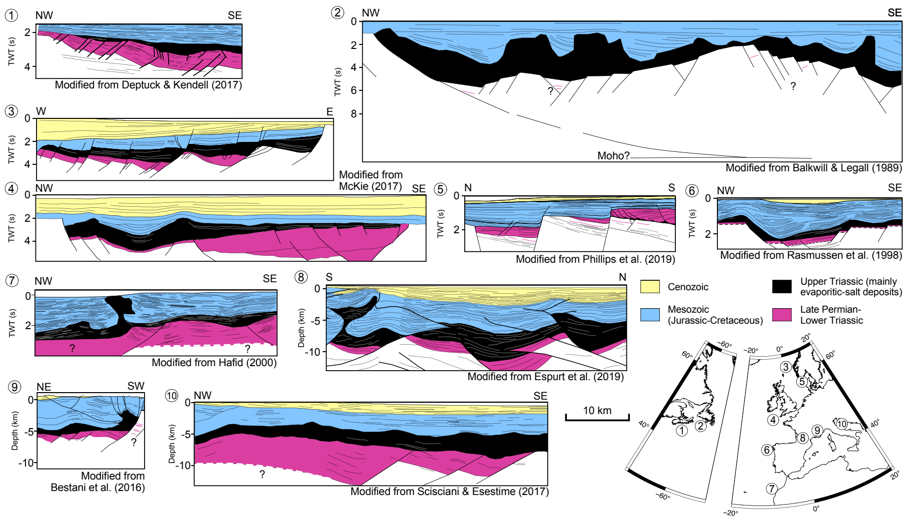

Figure 2. Compilation of interpreted seismic profiles along the North Atlantic margins and in West Europe. 1: Deptuck and Kendell (2017); 2: Balkwill and Legall (1989); 3-4: McKie (2017); 5: Philipps et al. (2019); 6: Rasmussen et al. (1996); 7: Hafid (2000); 8: Espurt et al. (2019); 9: Bestani et al. (2016); 10: Scisciani and Esestime (2017).

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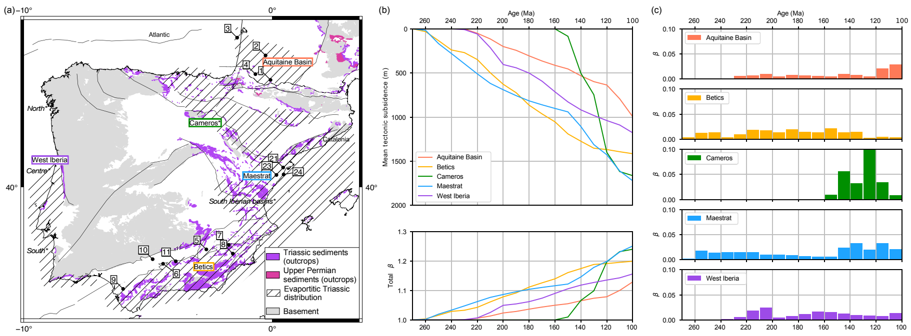

Figure 3. Late Permian-Triassic deposits and subsidence analyses. (a) Map of the Upper Permian-Triassic sediment outcrops, main depocenters, and distribution of the Upper Triassic evaporitic sequence in Iberia and southwest France. (b) Top: Mean tectonic subsidence curves in the Aquitaine Basin (Brunet, 1984), Betics (Hanne et al., 2003), Cameros basin (Salas and Casas, 1993; Salas et al., 2001; Omodeo-Sale et al., 2017), Maestrat basin (Salas and Casas, 1993; Salas et al., 2001) and West Iberia (Spooner et al., 2018). See Supplementary Material for individual tectonic subsidence curves in each region. 1: Ger1; 2: Lacquy1; 3: Sextant1; 4: Lacq301; 5: Santiago de la Espada; 6: Nueva Carteya1; 7: Rio Segura G1; 8: Espugna; 9: Betica 18-1; 10: Rio Guadalquivir; 11: Fusanta; 12: Lazaro; 13: Fuentatoba*; 14: Poveda*; 15: Cameros2*; 16: Enciso*; 17: Rollamentia*; 18: Castellijo*; 19: Molino*; 20: Yanguas*; 21: Mirambell; 22; Amposta Marino C3; 23: Salzedella; 24: Maestrazgo; 25: South Iberian Basin; 26: W-Iberia S; 27: W-Iberia C; 28: W-Iberia N. Synthetic well (shown by *) are not represented on the map. Bottom: Total stretching factor (β) (isostatic calculation, Watts, 2001) calculated from the mean tectonic subsidence of each region. (c) Incremental stretching factor (β) with a 10 Myr time step.

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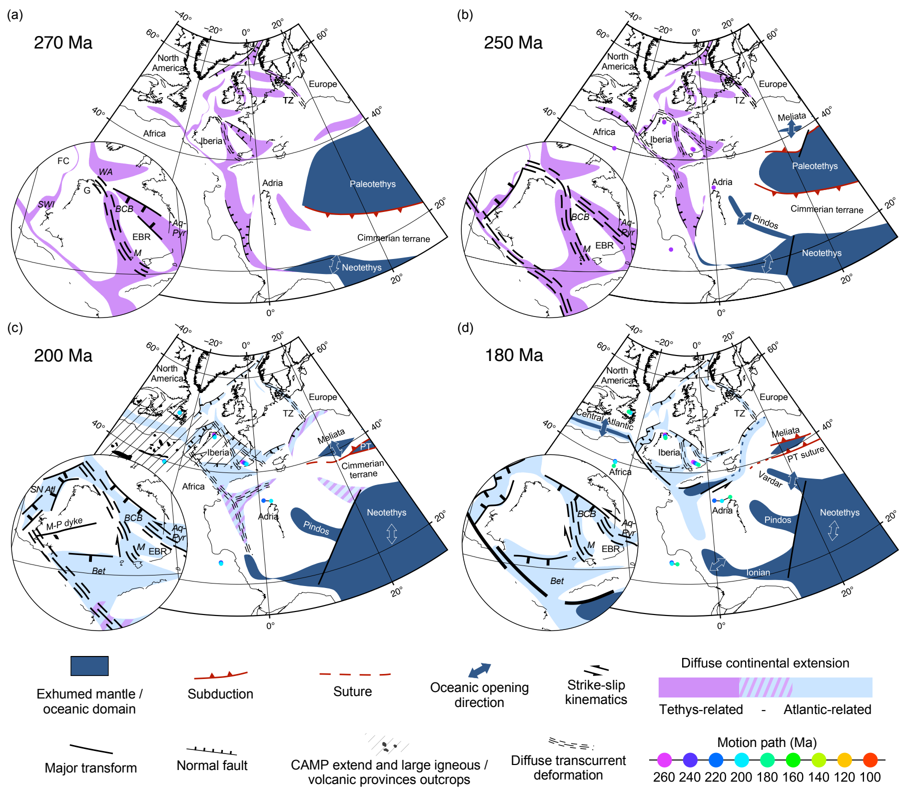

Figure 4. Large-scale reconstruction of the Tethys-Atlantic area for the 270 Ma (a), 250 Ma (b), 200 Ma (c), and 180 Ma (d) periods. Maps are in orthographic projection. Aq-Pyr: Aquitain-Pyrenean basin; BCB: Basque-Cantabrian basin; Bet: Betics basin; EBR: Ebro; FC: Flemish Cap; G: Galicia; M: Maestrat; M-P: Messejaña-Plascencia; PT: Paleotethys; SN Atl: southern North Atlantic; SWI: Southwest Iberia; TZ: Tornquist Zone; WA: Western Approaches.

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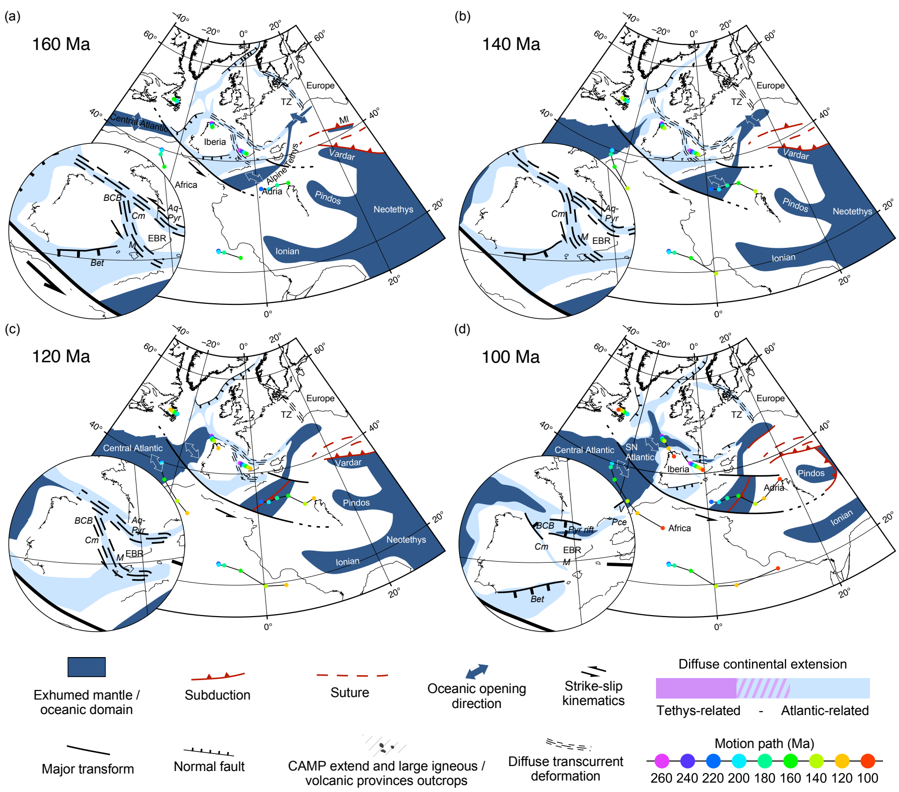

Figure 5. Large-scale reconstruction of the Tethys-Atlantic area for the 160 Ma (a), 140 Ma (b), 120 Ma (c), and 100 Ma (d) periods. Maps are in orthographic projection. Aq-Pyr: Aquitain-Pyrenean basin; BCB: Basque-Cantabrian basin; Bet: Betics basin; Cm: Cameros; EBR: Ebro; M: Maestrat; Ml: Meliata; Pce: Provence basin; V: Valaisan basin; TZ: Tornquist Zone.

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Table 1. Geodynamic and timing constrains used in the kinematic reconstruction model

Domain	Area	Event/kinematics	Age (Ma)	References
Central Europe	Germanic/Polish Basin	Continental rifting	270 (?) to 250	Evan et al., 1990; Van Wees et al., 2000; Evans et al., 2003; Jackson et al., 2019
	Tornquist Zone	Right-lateral	Carboniferous to 250 (?)	Phillips et al., 2019
		Left-lateral	170	Phillips et al., 2019
		Right-lateral	145 to 125	Hippolyte, 2002; Phillips et al., 2019
West Europe (France)	Aquitaine Basin	Continental rifting	270 (?) to 145 ; 125 to 94	Curnelle, 1983; Brunet, 1984; Biteau et al., 2006; Serrano et al., 2006
	Pyrenees	Continental rifting - left lateral	270 (?) to 145	Curnelle, 1983; Lucas, 1995
		Hyper-extended rifting - left-lateral	125 to 94	Vielzeuf and Kornprobst, 1984; Golberg and Leyreloup, 1990; Lagabrielle et al., 2010
Iberia	Basque-Cantabrian Basin	Left-lateral	140 to 120	Quintana et al., 2015; Zamora et al., 2017; Nirrengarten et al., 2018
	Ebro Basin	Continental rifting	270 (?) to 145	Vargas et al., 2009
	Iberian Range	Continental rifting - left lateral	270 (?) to 145	Salas and Casas, 1993
		Hyper-extended rifting	150 to 120	Salas and Casas, 1993; Arche and Gomez, 1996; Salas et al., 2001; Omodeo-Sale et al., 2017; Rat et al., 2019
Southern North Atlantic	W Galicia	Continental rifting	200 to 145	Murillas et al., 1990
		Lithospheric mantle exhumation	135-115	Mohn et al., 2015
		Initiation of oceanic spreading	133-100	Olivet, 1996; Strivastava et al., 2000; Schettino & Turco, 2009; Whitmarsh and Manatschal, 2012
	Bay of Biscay	Mantle exhumation	160 to 130	Thinon et al., 2001; Tugend et al., 2014
		Oceanic spreading	124-112 to 83	Thinon, 2002; Sibuet et al., 2004; Tugend et al., 2015
	Gorringe Bank	Continental rifting	200 to 161	Murillas et al., 1990
		Mantle exhumation	150-133	Mohn et al., 2015
		Initiation of oceanic spreading	125-112	Olivet, 1996; Srivastava et al., 2000; Schettino and Turco, 2009; Fernandez, 2019
North Sea	Artic rift system	Continental rifting	290 (?) to 200	Evans et al., 2003
	Rockall/Porcupine	Continental rifting	230 (?) to 112	Evans et al., 2003
	Orphan	Continental rifting	270to 112	Nirrengarten et al., 2018; Hassan et al., 2019; Sandoval et al., 2019
Tethys & peri-Tethys	S Alpine Tethys	Continental rifting	270 to 220	Stampfli and Borel, 2002; Schmid et al., 2008; Scisciani and Esestime, 2017
		Breakup	180	Schmid et al., 2008; Puga et al., 2011; Marroni et al., 2017
	N Alpine Tethys	Oceanic spreading	170-161	Bill et al., 2001; Schaltegger et al., 2002
	Paleotethys	Subduction	early Carboniferous to 200	Stampfli et al., 2001; Stampfli and Borel, 2002; Evans et al., 2003
	Neotethys sensu stricto	Oceanic spreading	Early Permian (?)-	Van Hinsbergen et al., 2019
		Subduction	from 156	Schmid et al., 2008; Van Hinsbergen et al., 2019
	Ionian	Continental rifting	270 to 200 (?)	Muttoni et al., 2001; Tugend et al., 2019
		Oceanic spreading	onset at 180 ?	Tugend et al., 2019
	Vardar	Oceanic spreading	180 to 160 (?)	Channell & Kozur, 1997
		Subduction	145 to 110	Channell and Kozur, 1997
	Pindos	Oceanic spreading	250 to 200	Channel and Kozur, 1997; Stampfli et al., 2001; Schmid et al., 2008
		Subduction	from Late Cretaceous	Channell and Kozur, 1997
	Meliata	Oceanic spreading	220 to 200	Channel and Kozur, 1997; Stampfli et al., 2001; Schmid et al., 2008
		Subduction	180 to 160 (?)	Channell and Kozur, 1997
Central Atlantic		Continental rifting	250 to 200	Kneller et al., 2012
		Oceanic spreading	190 to 175	Labails et al., 2010; Olyphant et al., 2017

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Table 2. Quantification of strike-slip displacement between the European and Ebro and between the Iberia (Galicia) and Ebro.

	IBERIA-EBRO			EUROPE-EBRO		
Age (Ma)	Amount (km)	Rate (km.Ma^{-1})	Direction	Amount (km)	Rate (km.Ma^{-1})	Direction
270-250	12	0.6	right-lateral	16	0.8	left-lateral
250-200	33	0.7	right-lateral	74	1.5	left-lateral
200-180	17	0.9	right-lateral	19	1.0	left-lateral
180-160	5	0.3	right-lateral	24	1.2	left-lateral
160-140	4	0.2	left-lateral	43	2.2	left-lateral
140-120	62	3.1	left-lateral	99	5.0	left-lateral
120-100	179	9.0	left-lateral	19	1.0	left-lateral
TOTAL	67 km (right-lateral)					
	245 km (left-lateral)			278 km (left-lateral)		