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.
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 transient 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; Moutherau 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).
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; Stampfl 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; Denèl 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; Denèl 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 Betic (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
the entire stratigraphy are corrected based on the oldest well of the region. We then calculated the mean crustal stretching ($\beta$ 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
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).
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).
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).
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.

Author contributions. This article was mostly written by P. Angrand and F. Mouthereau. P. Angrand has carried out the compilation of data, interpretation and kinematic model and figures, in tight collaboration with F. Mouthereau. The text benefits from the expertise and contribution of E. Masini and R. Asti.

Competing interests. No competing interests are present.

Acknowledgements. This study is part of the OROGEN scientific project (Total/CNRS-INSU/BRGM) as a post-doctoral grant of P. Angrand. We acknowledge the members of the OROGEN scientific project for support and discussions, in particular S. Calassou, O. Vidal, I. Thinon, L. Moen-Maurel, M. Ford, L. Jolivet, G. Manatschal and G. Frasca.
References

Aldega, L., Viola, G., Casas-Sainz, A., Marcén, M., Román-Berdiel, T., and van der Lelij, R.: Unraveling Multiple Thermotectonic Events Accommodated by Crustal-Scale Faults in Northern Iberia, Spain: Insights From K-Ar Dating of Clay Gouges, Tectonics, 38, 3629–3651, https://doi.org/10.1029/2019TC005585, 2019.

Arche, A. and López Gómez, J.: Origin of the Permian-Triassic Iberian basin, central-eastern Spain, Tectonophysics, 266, 443–464, 1996.

Aurell, M., Fregenal-Martínez, M., Badingas, B., Muñoz-García, M. B., Élez, J., Meléndez, N., and de Santisteban, C.: Middle Jurassic–Early Cretaceous tectono-sedimentary evolution of the southwestern Iberian Basin (central Spain): Major palaeogeographical changes in the geotectonic framework of the Western Tethys, Earth-Science Reviews, 199, 102983, https://doi.org/10.1016/j.earscirev.2019.102983, https://doi.org/10.1016/j.earscirev.2019.102983, 2019.

Avedik, F.: Seismic Structure of the Western Approaches and the South Armorican Continental Shelf and Its Geological Interpretation., Geol, 1, 29–43, 1975.

Azambre, B., Rossy, M., and Lago, M.: Caractéristiques pétrologiques des dolérites tholéitiques d’ âge triasique ( ophites ) du domaine pyrénéen, Bulletin de Minéralogie, 110, 379–396, 1987.

Balkwill, H. R. and Legall, F. D.: Whale Basin, Offshore Newfoundland: Extension and Salt Diapirism: Chapter 15: North American Margins, 1989.

Barnett-Moore, N., Hosseinpour, M., and Maus, S.: Assessing discrepancies between previous plate kinematic models of Mesozoic Iberia and their constraints, Tectonics, 35, 1843–1862, https://doi.org/10.1002/2015TC004019, 2016.

Bestani, L., Espurt, N., Lamarche, J., Bellier, O., and Hollender, F.: Reconstruction of the Provence Chain evolution, southeastern France, Tectonics, 35, 1506–1525, https://doi.org/10.1002/2016TC004115, 2016.

Bill, M., O’Dogherty, L., Guex, J., Baumgartner, P. O., and Masson, H.: Radiolarite ages in Alpine-Mediterranean ophiolites: Constraints on the oceanic spreading and the Tethys-Atlantic connection, Bulletin of the Geological Society of America, 113, 129–143, https://doi.org/10.1130/0016-7606(2001)113<0129:RAIAMO>2.0.CO;2, 2001.

Cámara, P. and Flinch, J.: The Southern Pyrenees: A Salt-Based Fold-and-Thrust Belt., Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins, pp. 395–415, https://doi.org/10.1016/B978-0-12-809417-4.00019-7, https://www.sciencedirect.com/science/article/pii/B9780128094174000197, 2017.

Canérot, J.: The Iberian plate: Myth or reality?, Boletín Geológico y Minero, 127, 563–574, 2016.

Cerbiá, J. M., López-Ruiz, J., Doblas, M., Martins, L. T., and Munha, J.: Geochemistry of the Early Jurassic Messejana-Plasencia dyke (Portugal-Spain): Implications on the Origin of the Central Atlantic Magmatic Province, Journal of Petrology, 44, 547–568, https://doi.org/10.1093/petrology/44.3.547, https://academic.oup.com/petrology/article-lookup/doi/10.1093/petrology/44.3.547, 2003.

Channell, J. E. and Kozur, H. W.: How many oceans? Meliata, Vardar, Pindos oceanic basins in Mesozoic Alpine paleogeography, Geology, 25, 183–186, https://doi.org/10.1130/0091-7613(1997)025<0183:HMOMVA>2.3.CO;2, 1997.

Chevrot, S., Sylvander, M., Diaz, J., Martin, R., Mouthereau, F., Manatschal, G., Masini, E., Calassou, S., Grimaud, F., Pauchet, H., and Ruiz, M.: The non-cylindrical crustal architecture of the Pyrenees, Scientific Reports, 8, 1–8, https://doi.org/10.1038/s41598-018-27889-x, 2018.

Choukroune, P. and Mattauer, M.: Tectonique des plaques et Pyrenees; sur le fonctionnement de la faille transformante nord-pyreneenne; comparaisons avec des modes actuels, Bulletin de la Société géologique de France, 7, 689–700, 1978.
Coltice, N., Bertrand, H., Rey, P., Jourdan, F., Phillips, B. R., and Ricard, Y.: Global warming of the mantle beneath continents back to the Archaean, Gondwana Research, 15, 254–266, https://doi.org/10.1016/j.gr.2008.10.001, http://dx.doi.org/10.1016/j.gr.2008.10.001, 2009.

de Saint Blanquat, M.: La faille normale ductile du massif du Saint Barthélémy. Evolution hercynienne des massifs nord-pyrénéens cata- zonaux considérée du point de vue de leur histoire thermique, Geodinamica Acta, 6, 59–77, 1993.

De Saint Blanquat, M., Lardeaux, J. M., and Brunel, M.: Petrological arguments for high-temperature extensional deformation in the Pyrenean Variscan crust (Saint Barthélémy Massif, Ariège, France), Tectonophysics, 177, 245–262, 1990.

Debroas, E. J.: Modèle de bassin triangulaire à l’intersection de décrochements divergents pour le fossé albo-cénomanien de la Ballongue (Zone Nord-Pyrénéenne, France), Bulletin de la Societe Géologique de France, 8, 887–898, 1987.

Debroas, E. J.: Le Flysch noir albo-cénomanien témoin de la structuration albienne à sénonienne de la Zone nord-pyrénéenne en Bigorre (Hautes-Pyrénées, France), Bull. Soc. géol. France, 8, 273–285, 1990.

Denèle, Y., Paquette, J. L., Olivier, P., and Barbey, P.: Permian granites in the Pyrenees: The Aya pluton (Basque Country), Terra Nova, 24, 105–113, https://doi.org/10.1111/j.1365-3121.2011.01043.x, 2012.

Denèle, Y., Laumonier, B., Paquette, J. L., Olivier, P., Gleizes, G., and Barbey, P.: Timing of granite emplacement, crustal flow and gneiss dome formation in the Variscan segment of the Pyrenees, Geological Society Special Publication, 405, 265–287, https://doi.org/10.1144/SP405.5, 2014.

Deptuck, M. E. and Kendell, K. L.: A review of Mesozoic-Cenozoic salt tectonics along the Scotian margin, eastern Canada, in: Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins, pp. 287–312, Elsevier, 2017.

Doré, A. G.: The structural foundation and evolution of Mesozoic seaways between Europe and the Arctic, Palaeogeography, Palaeoclimatology, Palaeoecology, 87, 441–492, 1991.

Doré, A. G., Lundin, E. R., Jensen, L. N., Birkeland, Ø., Eliassen, P. E., and Fichler, C.: Principal tectonic events in the evolution of the northwest European Atlantic margin, in: Geological society, London, petroleum geology conference series, vol. 5, pp. 41–61, Geological Society of London, 1999.

Duretz, T., Asti, R., Lagabrielle, Y., Brun, J. P., Jourdon, A., Clerc, C., and Corre, B.: Numerical modelling of Cretaceous Pyrenean Rifting: The interaction between mantle exhumation and syn-rift salt tectonics, Basin Research, pp. 1–16, https://doi.org/10.1111/bre.12389, 2019.

Espurt, N., Angrand, P., Teixell, A., Labaume, P., Ford, M., De Saint Blanquat, M., and Chevrot, S.: Crustal-scale balanced cross-section and restorations of the Central Pyrenean belt (Nestes-Cinca transect): Highlighting the structural control of Variscan belt and Permian-Mesozoic rift systems on mountain building, Tectonophysics, 764, 25–45, https://doi.org/10.1016/j.tecto.2019.04.026, https://doi.org/10.1016/j.tecto.2019.04.026, 2019.

Etheve, N., Mohn, G., Frizon de Lamotte, D., Roca, E., Tugend, J., and Gómez-Romeu, J.: Extreme Mesozoic Crustal Thinning in the Eastern Iberia Margin: The Example of the Columbrets Basin (Valencia Trough), Tectonics, 37, 636–662, https://doi.org/10.1002/2017TC004613, 2018.

Evans, C. D. R.: United Kingdom offshore regional report: the geology of the western English Channel and its western approaches, Tech. rep., 1990.

Evans, D., of London, G. S., Petroleumsforening, N., and geologiske Undersøgelse, D. o. G.: The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea, Geological Society of London, https://books.google.co.uk/books?id=sR50QgAACAAJ, 2003.

Fabriès, J., Lorand, J. P., Bodinier, J. L., and Dupuy, C.: Evolution of the upper mantle beneath the pyrenees: Evidence from orogenic spinel lherzolite massifs, Journal of Petrology, Special-Vo, 55–76, https://doi.org/10.1093/petrology/Special_Volume.2.55, 1991.
Fabriès, J., Lorand, J. P., and Bodinier, J. L.: Petrogenetic evolution of orogenic lherzolite massifs in the central and western Pyrenees, Tectonophysics, 292, 145–167, https://doi.org/10.1016/S0040-1951(98)00055-9, 1998.

Fernández, O.: The Jurassic evolution of the Africa-Iberia conjugate margin and its implications on the evolution of the Atlantic-Tethys triple junction, Tectonophysics, 750, 379–393, https://doi.org/10.1016/j.tecto.2018.12.006, https://doi.org/10.1016/j.tecto.2018.12.006, 2019.

Ganne, J., Feng, X., Rey, P., and De Andrade, V.: Statistical petrology reveals a link between supercontinents cycle and mantle global climate, American Mineralogist, 101, 2768–2773, https://doi.org/10.2138/am-2016-5868, https://pubs.geoscienceworld.org/ammin/article/101/12/2768-2773/298173, 2016.

Glennie, K. W., Higham, J., and Stemmerik, L.: Permian, in: The millennium atlas; petroleum geology of the central and northern North Sea, edited by Evans, D., Graham, C., Armour, A., and Bathurst, P., chap. 8, pp. 91–103, Geological Society of London, London, 2003.

Goldsmith, P. J., Hudson, G., and Van Veen, P.: Triassic, in: The millennium atlas; petroleum geology of the central and northern North Sea, edited by Evans, D., Graham, C., Armour, A., and Bathurst, P., pp. 105–127, Geological Society of London, London, 2003.

Grool, A. R., Huismans, R. S., and Ford, M.: Salt décollement and rift inheritance controls on crustal deformation in orogens, Terra Nova, 31, 562–568, https://doi.org/10.1111/ter.12428, 2019.

Hafid, M.: Triassic-early Liassic extensional systems and their Tertiary inversion, Essaouira Basin (Morocco), Marine and Petroleum Geology, 17, 409–429, https://doi.org/10.1016/S0264-8172(98)00081-6, 2000.

Handy, M. R., Schmid, S., Bousquet, R., Kissling, E., and Bernoulli, D.: Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological-geophysical record of spreading and subduction in the Alps, Earth-Science Reviews, 102, 121–158, https://doi.org/10.1016/j.earscirev.2010.06.002, http://dx.doi.org/10.1016/j.earscirev.2010.06.002, 2010.

Hanne, D., White, N., and Lonergan, L.: Subsidence analyses from the Betic Cordillera, southeast Spain, Basin Research, 15, 1–21, https://doi.org/10.1046/j.1365-2117.2003.00192.x, 2003.

Hassaan, M., Inge, J., Helge, R., and Tsikalas, F.: Carboniferous graben structures, evaporite accumulations and tectonic inversion in the southeastern Norwegian Barents Sea, Marine and Petroleum Geology, 112, 104 038, https://doi.org/10.1016/j.marpetgeo.2019.104038, https://doi.org/10.1016/j.marpetgeo.2019.104038, 2020.

Heine, C., Zoethout, J., and Müller, R. D.: Kinematics of the South Atlantic rift, Solid Earth, 4, 215–253, https://doi.org/10.5194/se-4-215-2013, 2013.

Jackson, C. A., Gawthorpe, R. L., Elliott, G. M., and Rogers, E. R.: Salt thickness and composition influence rift structural style, northern North Sea, offshore Norway, pp. 514–538, https://doi.org/10.1111/jre.12332, 2019.

Jammes, S., Manatschal, G., Lavier, L., and Masini, E.: Tectonosedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees, Tectonics, 28, 1–24, https://doi.org/10.1029/2008TC002406, 2009.

Jourdon, A., Mouthereau, F., Pourhiet, L. L., and Callot, J. P.: Topographic and Tectonic Evolution of Mountain Belts Controlled by Salt Thickness and Rift Architecture, pp. 1–14, https://doi.org/10.1002/2019TC005903, 2020.

Labails, C., Olivet, J. L., Aslaman, D., and Roest, W. R.: An alternative early opening scenario for the Central Atlantic Ocean, Earth and Planetary Science Letters, 297, 355–368, https://doi.org/10.1016/j.epsl.2010.06.024, http://dx.doi.org/10.1016/j.epsl.2010.06.024, 2010.

Lagabrielle, Y., Labaume, P., and De Saint Blanquat, M.: Mantle exhumation, crustal denudation, and gravity tectonics during Cretaceous rifting in the Pyrenean realm (SW Europe): Insights from the geological setting of the lherzolite bodies, Tectonics, 29, 1–26, https://doi.org/10.1029/2009TC002588, 2010.
Lagabrielle, Y., Asti, R., Duretz, T., Clerc, C., Fourcade, S., Teixell, A., Labaume, P., Corre, B., and Saspiturry, N.: A review of cretaceous smooth-slopes extensional basins along the Iberia-Eurasia plate boundary: How pre-rift salt controls the modes of continental rifting and mantle exhumation, Earth-Science Reviews, 201, 103 071, https://doi.org/10.1016/j.earscirev.2019.103071, https://doi.org/10.1016/j.earscirev.2019.103071, 2020.

Lago, M., Arranz, E., Pocoví, A., Galé, C., and Gil-Imaz, A.: Lower Permian magmatism of the Iberian Chain, Central Spain, and its relationship to extensional tectonics, Geological Society, London, Special Publications, 223, 465–490, https://doi.org/10.1144/GSL.SP.2004.223.01.20, http://sp.lyellcollection.org/lookup/doi/10.1144/GSL.SP.2004.223.01.20, 2004a.

Lago, M., Arranz, E., Pocoví, A., Galé, C., and Gil-Imaz, A.: Permian magmatism and basin dynamics in the southern Pyrenees: a record of the transition from late Variscan transtension to early Alpine extension, Geological Society, London, Special Publications, 223, 439–464, 2004b.

Leleu, S., Hartley, A. J., van Oosterhout, C., Kenann, L., Ruckwied, K., and Gerdes, K.: Structural, stratigraphic and sedimentological characterisation of a wide rift system: The Triassic rift system of the Central Atlantic Domain, Earth-Science Reviews, 158, 89–124, https://doi.org/10.1016/j.earscirev.2016.03.008, http://dx.doi.org/10.1016/j.earscirev.2016.03.008, 2016.

Lucas, C.: Le grès rouge du versant nord des Pyrénées: essai sur la géodynamique de dépôts continentaux du Permien et du Trias, Ph.D. thesis, Université de Toulouse, 1985.

Malavieille, J., Guihot, P., Costa, S., Lardeaux, J. M., and Gardien, V.: Collapse of the thickened Variscan crust in the French Massif Central: Mont Pilat extensional shear zone and St. Etienne Late Carboniferous basin, Tectonophysics, 177, 139–149, 1990.

Marroni, M., Meneghini, F., and Pandolfi, L.: A Revised Subduction Inception Model to Explain the Late Cretaceous, Double-Vergent Orogen in the Precollisional Western Tethys: Evidence From the Northern Apennines, Tectonics, 36, 2227–2249, https://doi.org/10.1002/2017TC004627, 2017.

Marzoli, A., Renne, P. R., Piccirillo, E. M., Ernesto, M., Bellieni, G., and De Min, A.: Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province, Science, 284, 616–618, https://doi.org/10.1126/science.284.5414.616, 1999.

Masini, E., Manatschal, G., Tugend, J., Mohn, G., and Flamant, J. M.: The tectono-sedimentary evolution of a hyper-extended rift basin: The example of the Arzacq-Mauléon rift system (Western Pyrenees, SW France), International Journal of Earth Sciences, 103, 1569–1596, https://doi.org/10.1007/s00531-014-1023-8, 2014.

McHone, J. G.: Non-plume magmatism and rifting during the opening of the central Atlantic Ocean, Tectonophysics, 316, 287–296, https://doi.org/10.1016/S0040-1951(99)00260-7, 2000.

McKenzie, D.: Some remarks on the development of sedimentary basins, Earth and Planetary Science Letters, 40, 25–32, https://doi.org/10.1016/0012-821X(78)90071-7, 1978.

McKenzie, D., Daly, M. C., and Priestley, K.: The lithospheric structure of Pangea, Geology, 43, 783–786, https://doi.org/10.1130/G36819.1, 2015.

McKie, T.: Paleogeographic evolution of latest Permian and Triassic salt basins in Northwest Europe, in: Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins, pp. 159–173, Elsevier, 2017.

Mohn, G., Karner, G. D., Manatschal, G., and Johnson, C. A.: Structural and stratigraphic evolution of the Iberia-Newfoundland hyper-extended rifted margin: A quantitative modelling approach, Geological Society Special Publication, 413, 53–89, https://doi.org/10.1144/SP413.9, 2015.
Mouthereau, F., Filleaudeau, P. Y., Vacherat, A., Pik, R., Lacombe, O., Fellin, M. G., Castelltort, S., Christophoul, F., and Masini, E.: Placing limits to shortening evolution in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe convergence, Tectonics, 33, 2283–2314, https://doi.org/10.1002/2014TC003663, 2014.

Müller, R. D., Seton, M., Zahirovic, S., Williams, S. E., Matthews, K. J., Wright, N. M., Shephard, G. E., Maloney, K. T., Barnett-Moore, N., Hosseinpour, M., Bower, D. J., and Cannon, J.: Ocean Basin Evolution and Global-Scale Plate Reorganization Events Since Pangea Breakup, Annual Review of Earth and Planetary Sciences, 44, 107–138, https://doi.org/10.1146/annurev-earth-060115-012211, 2016.

Müller, R. D., Cannon, J., Qin, X., Watson, R. J., Gurnis, M., Williams, S., Pfaffelmoser, T., Seton, M., Russell, S. H., and Zahirovic, S.: GPlates: Building a Virtual Earth Through Deep Time, Geochemistry, Geophysics, Geosystems, 19, 2243–2261, https://doi.org/10.1029/2018GC007584, 2018.

Murillas, J., Mougenot, D., Boillot, G., Comas, M. C., Banda, E., and Mauffret, A.: Structure and evolution of the Galicia Interior Basin (Atlantic western Iberian continental margin), Tectonophysics, 184, 297–319, 1990.

Nirrengarten, M., Manatschal, G., Tugend, J., Kusznir, N. J., and Sauter, D.: Kinematic Evolution of the Southern North Atlantic: Implications for the Formation of Hyperextended Rift Systems, Tectonics, 37, 89–118, https://doi.org/10.1002/2017TC004495, 2018.

Olivet, J. L.: La cinématique de la plaque ibérique, Tech. Rep. 1, 1996.

Olsén, P. E.: Stratigraphic Record of the Early Mesozoic Breakup of Pangea in the Laurasia-Gondwana Rift System, Annual Review of Earth and Planetary Sciences, 25, 337–401, https://doi.org/10.1146/annurev.earth.25.1.337, 1997.

Olyphant, J. R., Johnson, R. A., and Hughes, A. N.: Evolution of the Southern Guinea Plateau: Implications on Guinea-Demerara Plateau formation using insights from seismic, subsidence, and gravity data, Tectonophysics, 717, 358–371, https://doi.org/10.1016/j.tecto.2017.08.036, 2017.

Ortí, F., Pérez-López, A., and Salvany, J. M.: Triassic evaporites of Iberia: Sedimentological and palaeogeographical implications for the western Neotethys evolution during the Middle Triassic–Earliest Jurassic, Palaeogeography, Palaeoclimatology, Palaeoecology, 471, 157–180, https://doi.org/10.1016/j.palaeo.2017.01.025, 2017.

Peace, A. L., Welford, J. K., Ball, P. J., and Nirrengarten, M.: Deformable plate tectonic models of the southern North Atlantic, Journal of Geodynamics, 128, 11–37, https://doi.org/10.1016/j.jog.2019.05.005, https://doi.org/10.1016/j.jog.2019.05.005, 2019.

Phillips, T. B., Jackson, C. A., Bell, R. E., and Duffy, O. B.: Oblique reactivation of lithosphere-scale lineaments controls rift physiography – the upper-crustal expression of the Sorgenfrei – Tornquist Zone, offshore southern Norway, pp. 403–429, 2018.

Phillips, T. B., Fazliikhani, H., Gawthorpe, R. L., Fossen, H., Jackson, C. A., Bell, R. E., Faleide, J. I., and Rotevatn, A.: The Influence of Structural Inheritance and Multiphase Extension on Rift Development, the Northern North Sea, Tectonics, pp. 4099–4126, https://doi.org/10.1029/2019TC005756, 2019.

Puga, E., Fanning, M., Díaz de Federico, A., Nieto, J. M., Beccaluva, L., Bianchini, G., and Díaz Puga, M. A.: Petrology, geochemistry and U-Pb geochronology of the Betic Ophiolites: Inferences for Pangaea break-up and birth of the westernmost Tethys Ocean, Lithos, 124, 255–272, https://doi.org/10.1016/j.lithos.2011.01.002, http://dx.doi.org/10.1016/j.lithos.2011.01.002, 2011.

Quirk, D. G. and Rüpke, L. H.: Melt-induced buoyancy may explain the elevated rift-rapid sag paradox during breakup of continental plates, Scientific Reports, 8, 1–13, https://doi.org/10.1038/s41598-018-27981-2, 2018.
Ramos, A., Fernández, O., Terrinha, P., and Muñoz, J. A.: Extension and inversion structures in the Tethys–Atlantic linkage zone, Algarve Basin, Portugal, International Journal of Earth Sciences, 105, 1663–1679, https://doi.org/10.1007/s00531-015-1280-1, 2016.

Rasmussen, E. S., Lomholt, S., Andersen, C., and Vejbæk, O. V.: Aspects of the structural evolution of the Lusitanian Basin in Portugal and the shelf and slope area offshore Portugal, Tectonophysics, 300, 199–225, https://doi.org/10.1016/S0040-1951(98)00241-8, 1998.

Rat, J., Moutthereau, F., Brichau, S., Crémades, A., Bernet, M., Balvay, M., Ganne, J., Lahfid, A., and Gautheron, C.: Tectonothermal Evolution of the Cameros Basin: Implications for Tectonics of North Iberia, Tectonics, 38, 440–469, https://doi.org/10.1029/2018TC005294, 2019.

Salas, R. and Casas, A.: Mesozoic extensional tectonics, stratigraphy and crustal evolution during the Alpine cycle of the eastern Iberian basin, Tectonophysics, 228, 33–55, https://doi.org/10.1016/0040-1951(93)90213-4, 1993.

Salas, R., Guimerà, J., Mas, R., Martín-Closas, C., Melendez, A., and Alonso, A.: Evolution of the Mesozoic Central Iberian Rift System and its Cenozoic inversion (Iberian chain), vol. 186, 2001.

Sánchez-Navas, A., García-Casco, A., Mazzoli, S., and Martín-Algarra, A.: Polymetamorphism in the Alpujarride Complex, Betic Cordillera, South Spain, The Journal of Geology, 125, 637–657, https://doi.org/10.1086/693862, https://www.journals.uchicago.edu/doi/10.1086/693862, 2017.

Saspiturry, N., Cochelin, B., Razin, P., Leleu, S., Lemirre, B., Bouscary, C., Issautier, B., Serrano, O., Lasseur, E., and Baudin, T.: Tectono-sedimentary evolution of a rift system controlled by Permian post-orogenic extension and metamorphic core complex formation (Bidarray Basin and Ursuya dome, Western Pyrenees), Tectonophysics, 768, 228–180, 2019.

Schaltegger, U., Desmurs, L., Manatschal, G., Möntener, O., Meier, M., Frank, M., and Bernoulli, D.: The transition from rifting to sea-floor spreading within a magma-poor rifted margin: Field and isotopic constraints, Terra Nova, 14, 156–162, 2002.

Schettino, A. and Turco, E.: Tectonic history of the Western Tethys since the Late Triassic, Bulletin of the Geological Society of America, 123, 89–105, https://doi.org/10.1130/B30064.1, 2011.

Schmid, S. M., Bernoulli, D., Fügenschuh, B., Matenco, L., Scherfer, S., Schuster, R., Tischler, M., and Ustaszewski, K.: The Alpine-Carpathian-Dinaridic orogenic system: Correlation and evolution of tectonic units, Swiss Journal of Geosciences, 101, 139–183, https://doi.org/10.1007/s00015-008-1247-3, 2008.

Scisciani, V. and Esestime, P.: The Triassic evaporites in the evolution of the Adriatic Basin, in: Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins, pp. 499–516, Elsevier, 2017.

Seton, M., Müller, R. D., Zahirovic, S., Gaina, C., Torsvik, T. H., Shephard, G. E., Talsma, A., Gurnis, M., Turner, M., Maus, S., and Chandler, M.: Global continental and ocean basin reconstructions since 200Ma, Earth-Science Reviews, 113, 212–270, https://doi.org/10.1016/j.earscirev.2012.03.002, http://dx.doi.org/10.1016/j.earscirev.2012.03.002https://linkinghub.elsevier.com/retrieve/pii/S0012825212000311, 2012.

Sibuet, J. C., Srivastava, S. P., and Spakman, W.: Pyrenean orogeny and plate kinematics, Journal of Geophysical Research: Solid Earth, 109, 1–18, https://doi.org/10.1029/2003JB002514, 2004.

Simon, N. S. and Podladchikov, Y. Y.: The effect of mantle composition on density in the extending lithosphere, Earth and Planetary Science Letters, 272, 148–157, https://doi.org/10.1016/j.epsl.2008.04.027, 2008.

Solé, J., Cosca, M., Sharp, Z., and Enrique, P.: 40 Ar/ 39 Ar Geochronology and stable isotope geochemistry of Late-Hercynian intrusions from north-eastern Iberia with implications for argon loss in K-feldspar, International Journal of Earth Sciences, 91, 865–881, https://doi.org/10.1007/s00531-001-0251-x, http://link.springer.com/10.1007/s00531-001-0251-x, 2002.
Sopeña, A., López, J., Arche, A., Pérez-Arlucea, M., Ramos, A., Virgili, C., and Hernando, S.: Permian and Triassic rift basins of the Iberian Peninsula, in: Developments in Geotectonics, vol. 22, pp. 757–786, https://doi.org/10.1016/B978-0-444-42903-2.50036-1, https://linkinghub.elsevier.com/retrieve/pii/B9780444429032500361, 1988.

Soto, R., Casas-Sainz, A. M., Oliva-Urcia, B., García-Lasanta, C., Izquierdo-Llavall, E., Moussaid, B., Kullberg, J. C., Román-Berdiel, T., Sánchez-Moya, Y., Sopeña, A., Torres-López, S., Villalaín, J. J., El-Ouardi, H., Gil-Peña, I., and Hirt, A. M.: Triassic stretching directions in Iberia and North Africa inferred from magnetic fabrics, Terra Nova, 31, 465–478, https://doi.org/10.1111/ter.12416, 2019.

Spooner, C., Stephenson, R., and Butler, R. W.: Pooled subsidence records from numerous wells reveal variations in pre-breakup rifting along the proximal domains of the Iberia-Newfoundland continental margins, Geological Magazine, 156, 1323–1333, https://doi.org/10.1017/S0016756818000651, 2019.

Stampfli, G. M. and Borel, G. D.: A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons, Earth and Planetary Science Letters, 196, 17–33, https://doi.org/10.1016/S0012-821X(01)00588-X, 2002.

Stampfli, G. M., Mosar, J., Favre, P., Pillevuit, A., and Vannay, J.-C.: Permo-Mesozoic evolution of the western Tethyan realm: the Neotethys/East-Mediterranean connection, in: Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins, edited by Ziegler, P. A., Cavazza, W., Robertson, A. H. F., and Crasquin-Soleau, S., vol. 186, pp. 51–108, Mémoirs du Muséum d’Histoire Naturelle, Paris, 2001.

Štolfová, K. and Shannon, P. M.: Permo-Triassic development from Ireland to Norway: basin architecture and regional controls, Geological Journal, 44, 652–676, 2009.

Tankard, A. J. and Welsink, H. J.: Extensional tectonics and stratigraphy of Hibernia oil field, Grand Banks, Newfoundland, AAPG Bulletin, 71, 1210–1232, 1987.

Tavani, S., Bertok, C., Granado, P., Piana, F., Salas, R., Vigna, B., and Muñoz, J. A.: The Iberia-Eurasia plate boundary east of the Pyrenees, Earth-Science Reviews, 187, 314–337, https://doi.org/10.1016/j.earscirev.2018.10.008, 2018.

Tugend, J., Manatschal, G., Kusznir, N. J., Masini, E., Mohn, G., and Thinon, I.: Formation and deformation of hyperextended rift systems: Insights from rift domain mapping in the Bay of Biscay-Pyrenees, Tectonics, 33, 1239–1276, https://doi.org/10.1002/2014TC003529, http://doi.wiley.com/10.1002/2014TC003529, 2014.

Tugend, J., Manatschal, G., and Kusznir, N. J.: Spatial and temporal evolution of hyperextended rift systems: Implication for the nature, kinematics, and timing of the Iberian-European plate boundary, Geology, 43, 15–18, https://doi.org/10.1130/G36072.1, 2015.

Tugend, J., Chamot-Rooke, N., Arsenikos, S., Blanpied, C., and Frizon de Lamotte, D.: Geology of the Ionian Basin and Margins: A Key to the East Mediterranean Geodynamics, Tectonics, 38, 2668–2702, https://doi.org/10.1029/2018TC005472, 2019.

Upton, B. G. J., Stephenson, D., Smedley, P. M., Wallis, S. M., and Fitton, J. G.: Carboniferous and Permian magmatism in Scotland, Geological Society, London, Special Publications, 223, 195–218, 2004.

Vacherat, A., Moutherneau, F., Pik, R., Huyghe, D., Paquette, J. L., Christophoul, F., Loget, N., and Tibari, B.: Rift-to-collision sediment routing in the Pyrenees: A synthesis from sedimentological, geochronological and kinematic constraints, Earth-Science Reviews, 172, 43–74, https://doi.org/10.1016/j.earscirev.2017.07.004, http://dx.doi.org/10.1016/j.earscirev.2017.07.004, 2017.

Van Hinsbergen, D. J. J., Torsvik, T. H., Schmid, S. M., Matenco, L. C., Maffione, M., Vissers, R., Gürrer, D., and Spakman, W.: Orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic, 2019.
Van Wees, J. D., Arche, A., Beijdorff, C. G., López-Gómez, J., and Cloetingh, S. A.: Temporal and spatial variations in tectonic subsidence in the Iberian Basin (eastern Spain): Inferences from automated forward modelling of high-resolution stratigraphy (Permian-Mesozoic), Tectonophysics, 300, 285–310, https://doi.org/10.1016/S0040-1951(98)00244-3, 1998.

Van Wees, J. D., Stephenson, R., Ziegler, P. A., Bayer, U., McCann, T., Dadlez, R., Gaupp, R., Narkiewicz, M., Bitzer, F., and Scheck, M.: On the origin of the southern Permian Basin, Central Europe, Marine and Petroleum Geology, 17, 43–59, 2000.

Vissers, R.: Variscan extension in the Pyrenees, Tectonics, 11, 1369–1384, 1992.

Vissers, R. and Meijer, P.: Mesozoic rotation of Iberia: Subduction in the Pyrenees?, Earth-Science Reviews, 110, 93–110, https://doi.org/10.1016/j.earscirev.2011.11.001, http://dx.doi.org/10.1016/j.earscirev.2011.11.001https://linkinghub.elsevier.com/retrieve/pii/S0012825211001644, 2012.

Watts, A. B.: Isostasy and Flexure of the Lithosphere, Cambridge University Press, 2001.

Welsink, H. J., Dwyer, J. D., and Knight, R. J.: Tectono-Stratigraphy of the Passive Margin Off Nova Scotia: Chapter 14: North American Margins, 1989.

Ziegler, P. A.: Geodynamic model for Alpine intra-plate compressional deformation in Western and Central Europe, in: Inversion Tectonics, edited by Cooper, M. A. and Williams, G. D., vol. 3, pp. 63–85, Geological Society Special Publication, 1989.

Ziegler, P. A.: Collision related intra-plate compression deformations in Western and Central Europe, Journal of Geodynamics, 11, 357–388, 1990.

Ziegler, P. A. and Dézes, P.: Crustal evolution of Western and Central Europe, Geological Society Memoir, 32, 43–56, https://doi.org/10.1144/GSL.MEM.2006.032.01.03, 2006.

Ziegler, P. A., Schumacher, M. E., Dézes, P., van Wees, J. D., and Cloetingh, S. A.: Post-Variscan evolution of the lithosphere in the Rhine Graben area: Constraints from subsidence modelling, Geological Society Special Publication, 223, 289–317, https://doi.org/10.1144/GSL.SP.2004.223.01.13, 2004.
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.
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).
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: Castellijos*; 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 ($\beta$) (isostatic calculation, Watts, 2001) calculated from the mean tectonic subsidence of each region. (c) Incremental stretching factor ($\beta$) with a 10 Myr time step.
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: Messejana-Plascencia; PT: Paleotethys; SN Atl: southern North Atlantic; SWI: Southwest Iberia; TZ: Tornquist Zone; WA: Western Approaches.
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.
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                         | 180                       | Phillips et al., 2010                                                      |
|                         |                           | Left-lateral                          | 150 to 125                | Phillips et al., 2019                                                      |
|                         |                           | Right-lateral                         | 145 to 125                | Høppesyde, 2002; Phillips et al., 2019                                    |
| West Europe (France)    | Aquitaine Basin           | Continental rifting                   | 270 (?) to 145; 125 to 94 | Curnelle, 1983; Brunet, 1984; Betou et al., 2000; Schaltegger et al., 2006; Serrano et al., 2006 |
|                         | Pyrenees                  | Continental rifting - left-lateral    | 270 (?) to 145            | Curnelle, 1983; Lucas, 1995                                                |
|                         |                           | Continental rifting - left-lateral    | 125 to 94                 | Verleirung and Koczenová, 1984; Gelberg and Lercari, 1990; Lagabrielle et al., 2010 |
|                         | Basque-Cantabrian Basin   | Hyper-extended rifting - left-lateral | 150 to 120                | Salas and Casas, 1993; Arduv and Gomez, 1996; Salas et al., 2001; Omores-Sala et al., 2017; Rat et al., 2019 |
|                         | Ebro Basin                | Continental rifting                   | 270 (?) to 145            | Quintana et al., 2015; Zamoros et al., 2017; Nirrengarten et al., 2018       |
|                         |                           | Hyper-extended rifting                | 125 to 94                 | Salas and Casas, 1993; Arduv and Gomez, 1996; Salas et al., 2001; Omores-Sala et al., 2017; Rat et al., 2019 |
|                         | Iberian Range             | Continental rifting                   | 270 (?) to 145            | Quintana et al., 2015; Zamoros et al., 2017; Nirrengarten et al., 2018       |
|                         |                           | Hyper-extended rifting                | 150 to 120                | Salas and Casas, 1993; Arduv and Gomez, 1996; Salas et al., 2001; Omores-Sala et al., 2017; Rat et al., 2019 |
| Southern North Atlantic | W Galicia                 | Continental rifting                   | 200 to 145                | Merillas et al., 1990                                                      |
|                         |                           | Lithospheric mantle exhumation        | 135-115                   | Mohr et al., 2015                                                          |
|                         |                           | Initiation of oceanic spreading       | 135-115                   | Olivier, 1996; Sroboj et al., 2001; Sibuet & Tocquet, 2000; Whitmarsh and Martinot, 2012 |
|                         | Bay of Biscay             | Mantle exhumation                     | 160 to 130                | Thuo et al., 2001; Tugend et al., 2014                                     |
|                         | Gorringe Bank             | Oceanic spreading                     | 124-112 to 83             | Thuo, 2002; Siboit et al., 2014; Tugend et al., 2015                       |
|                         |                           | Continental rifting                   | 200 to 161                | Merillas et al., 1990                                                      |
|                         |                           | Mantle exhumation                     | 150 to 135                | Mohr et al., 2015                                                          |
|                         |                           | Initiation of oceanic spreading       | 125-112                   | Olivier, 1996; Sroboj et al., 2001; Sibuet & Tocquet, 2001; Fernandez, 2019 |
| North Sea               | Artic rift system         | Continental rifting                   | 290 (?) to 200            | Evans et al., 2015                                                         |
|                         | Red Sea/Poro-Prince       | Continental rifting                   | 290 (?) to 112            | Evans et al., 2015                                                         |
|                         | Orphan                    | Continental rifting                   | 230 (?)                   | Nirrengarten et al., 2018; Hanard et al., 2019; Sadrieh et al., 2019         |
| Tethys & peri-Tethys    | S Alpine Tethys           | Continental rifting                   | 250 to 220                | Stampfli and Borel, 2002; Schmid et al., 2008; Scisciani and Lascarena, 2017 |
|                         | N Alpine Tethys           | Subduction                            | 176-161                   | Schmid et al., 2008; Puga et al., 2011; Marion et al., 2017                |
|                         | Palaeotethys              | Subduction                            | Early Permian (?)          | Bil et al., 2001; Schaltegger et al., 2002                                |
|                         | Nortetethys s.s. scitwm   | Subduction                            | Early Permian (?)          | Stampfli et al., 2001; Stampfli and Borel, 2002; Evans et al., 2003        |
|                         | Seriens                  | Subduction                            | Early Permian (?)          | Van Hinsbergen et al., 2019                                               |
|                         | Vardar                    | Oceanic spreading                     | Early Permian (?)          | Schmid et al., 2000; Van Hinsbergen et al., 2019                         |
|                         |                          | Subduction                            | from 196                   | Schmid et al., 2001; Marion et al., 2017; Tugendt et al., 2019             |
|                         | Pandos                   | Oceanic spreading                     | from Cretaceous           | Schmid et al., 2000; Van Hinsbergen et al., 2019                         |
|                         |                          | Subduction                            | 180 to 160 (?)            | Schmid and Krueger, 1997                                                   |
|                         | Mellistas                | Oceanic spreading                     | 180 to 160 (?)            | Schmid and Krueger, 1997                                                   |
|                         |                          | Subduction                            | 145 to 110                | Schmid and Krueger, 1997                                                   |
|                          | Central Atlantic         | Continental rifting                   | 250 to 200                | Schmid and Krueger, 1997                                                   |
|                          |                          | Oceanic spreading                     | 190 to 175                | Schmid and Krueger, 1997                                                   |
Table 2. Quantification of strike-slip displacement between the European and Ebro and between the Iberia (Galicia) and Ebro.

| Age (Ma) | IBERIA-EBRO | EUROPE-EBRO |
|----------|-------------|-------------|
|          | 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) | | |

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