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Dear Editor, dear Reviewers,

Thank you very much for the time you have dedicated to review and comment our manuscript. We believe that your comments have helped us to improve significantly the quality of the work. Please find below the responses to the Referees.

The response is organized with responses to the Referees' major points, structured as follow: (1) comments from Referees (italicized text), (2) authors' response, (3) authors' changes in manuscript, and responses to the Referees' minor points. For minor changes (e.g., spelling, word substitution), we indicate if we applied the changes but not systematically write the modified text in the response (if we simply apply, we indicate by "done").

In addition, please find a marked-up manuscript version showing the changes made (red, small size = removed, blue = modifications; made with latexdiff in LaTeX, as suggested).

Significant changes have been made to the manuscript. Main changes include a new dedicated section about the methodology we use for the reconstruction and a subsection in the discussion to better discuss geological implications of our reconstruction.

Yours sincerely,
Paul Angrand
On the behalf of co-authors Frédéric Mouthereau, Emmanuel Masini and Riccardo Asti.

1 Response to interactive comment of Referee #1 (Anonymous)

1.1 Response to the major point

General comment *This is a short paper dealing with the long lasting problem of the Mesozoic kinematics of Iberia. Here the authors revise the the Permo-Triassic rifting stage in Iberia and surrounding regions, and propose that including this stage into the puzzle may help in reconciling geological evidence and plate kinematic models. In detail, the authors suggest that Iberia cannot be considered an integer plate but, rather, it must be separated into the Ebro and Western Iberia blocks, which is in agreement with most of the recently published works on this topic/area. The work is well written and well illustrated. There are some minor points that should be addressed and a major issue.*

Authors' response We acknowledge the constructive review done by an anonymous referee about our manuscript. This review helped us to improve our manuscript, by better discussing the geological implications of our reconstruction.

Referee's comment *Hundreds of km of Mesozoic sinistral movements between Iberia and Europe have been postulated in several plate kinematic reconstructions since the 70's. The North Pyrenean Fault has been indicated as the Iberia-Europe Mesozoic plate boundary that should have accommodated such a huge amount of strike- slip/transtensive motion. As reported by the authors, there are currently no firm geological constraints supporting significant sinistral deformation during the Jurassic or the Cretaceous along this fault. The authors thus propose that the Mesozoic strike-slip movement could have partly occurred along the Ebro-W Iberia boundary. In detail, they propose that along this boundary, the Asturian, Maestrat, Cameros, and Columbretes basins formed/were reactivated as pull apart basins within a lithospheric Mesozoic sinistral strike-slip shear zone, where hundreds of km of sinistral motion would have occurred. The authors do not individuate and describe the lithospheric fault(s) border- ing the pull apart system and ensuring the connection of the sinistral shear zone with the Bay of Biscay and the north Atlantic. As far I know, the only candidate is the 400 km long Ventaniella Fault. Thus, it is mandatory to describe and discuss the nature and kinematics of this fault. Apart from this, my impression is that using Ventaniella + North Pyrenean faults instead of the North Pyrenean fault along, is jumping out of the frying pan into the fire: The Ventaniella fault is well exposed and only gently affected by Cenozoic deformation. Paleozoic markers across it are presently offsetted in a dextral sense of less than 5 km (see Alvarez-Marro´n, 1995. Journal of Structural Geology or any published geological map of the Cantabrian region). The dextral movement for the Ventaniella fault is generally attributed to a Cenozoic stage. One may argue that the amount of this Cenozoic displacement could be not well constrained (Mesozoic sinistral + cenozoic dextral). However, you can use the Cenozoic dextral displacement of the 100 km long Ubierna fault, which significantly overlaps the Ventaniella fault at its SE tip, to get an idea of the order of magnitude. For the Ubierna fault, the Cenozoic dextral displacement proposed by different authors ranges from 10 km (see Tavani et al., 2011, Tectonophysics) to almost nothing (see Quintana et al., 2015, Tectonophysics). Thus, if we remove 0 to 10 km of Cenozoic dextral displacement for the Ventaniella fault, we end up with Paleozoic markers displaced in a sinistral sense - during the Mesozoic - of less than 5 km. This issue should be addressed.*

Authors' response This comment raises a major issue about a geological implication of our model that needs to be clarified. This is about the role of the Ventaniella Fault as a good candidate to accommodate the Iberia-Ebro relative motion.

This point is critical as most of the recent models accounting for a segmented Iberian plate invoke the Ventaniella Fault as a main boundary fault accommodating a large amount of Iberia-Ebro movement (Tugend et al., 2015; Nirrengarten et al., 2018). As pointed out by the referee, the estimated left-lateral displacement along the Ventaniella Fault (after correction of the right-lateral Cenozoic displacement) is expected to be in the order a some kilometers during late Paleozoic-middle Cretaceous (Tavani et al., 2011).

We actually do not propose that the Ventaniella Fault accommodates in our reconstruction the large displacement between the Ebro block and Europe. We made this point clearer by reorganizing the discussion.

Changes in the manuscript

"Discussion: Implications for strike-slip movements and the Europe-Iberia boundary 1. Amount of strike-slip displacement # former discussion section

2. Strike-slip structures in the intra-Iberian basins # new section

Despite the requirement of 245 km left-lateral strike-slip displacement along the Iberia-Ebro boundary from 160 to 100 Ma, there is no simple geological evidence in support of a unique major crustal-scale fault in the Iberian Range-Basque Cantabrian Basin system.

Several studies have suggested that a left-lateral shear zone can be recognized along the Iberian Range and the Basque-Cantabrian rifts system. Geological evidence includes the High Tagus Fault in the Iberian Range (Aldega et al., 2019; Aurell et al., 2019) and the Ventaniella Fault in the Basque-Cantabrian region (e.g., Tavani et al., 2011). The latter fault is often considered in recent reconstructions to accommodate alone the Iberia-Ebro movement (Tugend et al., 2015; Nirrengarten et al., 2018). However, the estimated left-lateral displacement along the Ventaniella Fault is only in the order of magnitude of a few kilometers (Tavani et al., 2011) and therefore cannot be used as a North Pyrenean Fault equivalent.

In the Basque Cantabrian Basin, the Ventaniella Fault is part of a NW-SE fault system that acted as left-lateral shear zone during the Late Jurassic-Early Cretaceous and has been subsequently inverted with a right-lateral kinematic during the Cenozoic (De Vicente et al., 2011; Tavani et al., 2011; Cámara and Flinch, 2017). These faults have a Triassic origin (Tavani and Granado, 2015). Tectonic activity along these faults gets younger NE-ward (Ubierna fault: Late Jurassic-Early Cretaceous; Zamanza-Oña fault: Early-Middle Cretaceous; salt tectonics in the center of the basin, Cámara and Flinch, 2017). We suggest the Iberia-Ebro displacement have possibly been distributed along these structures.

The role of the weak Triassic evaporites in efficiently decoupling deformation in the pre-salt basement from the thin-skinned extension in sedimentary cover has been emphasized largely in the Pyrenees (e.g., Grool et al., 2019; Duretz et al., 2019; Jourdon et al., 2020; Lagabrielle et al., 2020). Salt tectonics has also been suggested to have been particularly significant from the Jurassic through the Early Cretaceous in Mesozoic basins that shaped NW-directed boundary between Ebro and Iberia, including the Basque-Cantabrian Basin (Cámara and Flinch, 2017), Parentis Basin (Ferrer et al., 2012), Cameros Basin (Rat et al., 2019) and Maestrat Basin (Vergés et al., 2020). The surface expression of the crustal strike-slip movements is inferred to have been limited in supra-salt layers."

1.2 Responses to minor points

Comments from Referees are in italicized text.

L2: *well registered* > "well recorded"

L3: *a key* > done

L4: *The Late Permian-Triassic Iberian rift basins have accommodated...* > we shortened this sentence: « The Late Permian-Triassic Iberian rift basins have accommodated extension, but... »

L8: *reconstruction. We* > done

L19-21: *and orogens. However, the required.....often uncertain.* > "and orogens (e.g., Handy et al., 2010). However, ..."

L42: *Understood by who? Also, here and below it must be clearly differentiated between papers in which the strike-slip motion is postulated/suggested, from those in which evidence of strike-slip tectonics is documented* > We reworked this part in order to better describe the previous models. Now reads as follow: "An alternative scenario has recently emerged (Tugend et al., 2015; Nirrengarten et al., 2018; Tavani et al., 2018), proposing a spatiotemporal partitioning of the deformation in a wider deformation corridor than the single Pyrenean belt. It suggests that the transcurrent deformation that results from the eastwards movement of Iberia occurred mainly during the Late Jurassic-Early Cretaceous in Northern Iberia along a hundred-kilometer scale pull-part or en-echelon rift basins formed by the NW-SE-trending Iberian Massifs. Indeed, along these massifs, several extensional basins recorded major subsidence and strike-slip deformation during the Late Permian to middle Cretaceous time interval (Alvaro et al., 1979; Salas et al., 2001; Aldega et al., 2019; Aurell et al., 2019; Soto et al., 2019). However, no geological evidence for lithosphere-scale strike-slip movements is yet clearly defined in the intra-Iberian basins."

L 46: *list the evidence* > merged with L42.

L 59: *I suggest to briefly mention the permo-triassic stratigraphy of the area.* > We add a sentence about the stratigraphy. "This late Permian-Lower Triassic phase is associated with the deposition of thick detrital non-marine deposits in intra-continental basins. Sedimentation became carbonaceous during the middle Triassic. Finally, the Late Triassic is characterized by a thick evaporitic (mainly salt) sequence (e.g., Ortí et al., 2017)."

L 71: *Remove pre-salt (no salt has been introduced to the reader)* > We keep this as we added informations about the stratigraphy.

L 76-81: *Poorly relevant* > This paragraph is needed to introduce the following paragraph.

L 82-83: *Rephrase it* > We reorganized this paragraph according to RC2's comments.

L 90-93: *Cryptic* and L 93-94:*Expand the concept* > Now reads as follow: "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). Therefore the subsidence appears much lower than that predicted by simple isostatic model of crustal thinning (McKenzie, 1978)."

L 94-104: *This is material for the discussion* > We prefer keeping this paragraph in that position as it supports the extension phase we discuss later in the text.

L 96: *breakup (* > done

L112-115: *Add Alvaro et al '79* > done

L119: *See Gomez et al 2002 for a partial subsidence curve in the Basque-Cantabrian basin. Additional curves can be probably derived from papers published in the book "The Geology of Spain".* > We agree that it would be interesting to add more subsidence data but we chose on purpose to limit the number of curves to not overload the figure. Most importantly, and as reported by the referee, subsidence curves in the proposed source are not covering the all Mesozoic and do not show the Triassic phase.

L 139: *As it stands, it seems that Rat and Aurell have suggested left-lateral tectonics, which is not the case* > we removed « strike slip deformation ».

L 174: *Label them in figure 4* > done

Figs 2&3. *Increase the font size* > done.

2 Response to interactive comment of Referee #2 (A. L. Peace)

2.1 Responses to the major points

General comment *This short paper by Angrand et al. makes some interesting and relevant points regard- ing the evolution of Iberia. The description of geological events that shaped the region is detailed and well organised, needing only minor modifications and clarifications in my opinion. The subject of the paper is very timely and is suitable for Solid Earth. However, I felt that the paper required further work to be suitable for publication. In particular, the description of the methodology, the quality of the figures and some other aspects outlined below need improving. Thus, my overall recommendation is revision of the manuscript as it think it has the potential to make a good contribution to Solid Earth.*

Authors' response We thank Alexander L. Peace for his is a very constructive review that led us to improve the manuscript, in particular the presentation of the methodology. Find below our responses to the major points raised by the reviewer and further minor points.

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1) Description of reconstruction methodologies, workflow and examination of previous reconstructions. *The paper essentially revolves around detailed examination of plate reconstructions to explore specific aspects of Iberia's evolution. This is a combination of previous reconstructions and the authors own work. This is a worthy topic for investigation given that Iberia's kinematics are a source of substantial unknows when conducting reconstructions of this region.*
As such, given that the paper is based on plate reconstructions, my main issue with the paper is that the methods related to plate reconstructions are not currently well described. This is in part because the methods are merged in with the description of the regional evolution. In addition, it was not immediately clear which aspects of the reconstructions are the authors own work and what is from previous reconstructions. I would therefore suggest separating out the workflow and methods into a dedicated section.
I also felt that because multiple reconstructions are referred to further examination of the limitations and inputs of these models is required. For example, many reconstructions have been produced for the region recently (Müller et al., 2016; Barnett-Moore et al., 2018; Nirrengarten et al., 2018; Peace et al., 2019a). Each of these models comes with simplifications and limitations depending on the aspects examined (e.g., local/global models and rigid/deformable models) and I felt that this needed further examining in the manuscript. In addition, given that the rotations for different parts of the model presented are from different previous work I felt that a summary of the poles used would be highly beneficial. This could be simply achieved in a summary table showing pole timing and location with the corresponding reference. Table 1 currently does not adequately display the required information and although the 'motion paths' on Figures 4 and 5 help somewhat they are quite hard to read.

Authors' response Description of the reconstruction method We add a dedicated 'Methodology' section before the section 'Kinematics of Iberia between Atlantic and Tethys'. In this new section we present the published kinematic models used in our reconstruction and the modifications we made. We added a new figure to present the models from the literature and a new table to present the rotation poles of the main plates of our GPlates model.

Changes in the manuscript

"4 Methodology

4.1 Previous kinematic models

We compile and implement previous kinematic models involving Iberia (Fig. 4). The objective is to establish a coherent kinematic model of Iberia that considers both the evolution of the Neotethyan and Atlantic regions. These kinematic models are either global (e.g., Müller et al., 2019), based on the assimilation of geological and geophysical information at large scale to allow a dynamic understanding of Earth's plate tectonics but do not aim to solve regional tectonic issues such as strain partitioning between Iberia and Europe. On the other hand, regional models are focused on the reconstruction of North Atlantic (e.g., Barnett-Moore et al., 2016; Nirrengarten et al., 2018; Peace et al., 2019b) or are interested in the reconstruction of the Alpine orogen with inferences on the kinematics of the Tethys and Adria (Schmid et al., 2008; Handy et al., 2010; Van Hinsbergen et al., 2019).

North Atlantic reconstructions use offshore geophysical constraints from the Northwest Iberian margins and pay relatively little attention to the geological evolution of the Pyrenees and other orogenic domains in Iberia (e.g., Sibuet et al., 2004; Barnett-Moore et al., 2016; Nirrengarten et al., 2018). However, these models give fundamental insights on the geometry of the North Atlantic full-fit reconstruction and the timing of oceanic spreading. The nature of some magnetic anomalies in the southern North Atlantic has been the matter of considerable debate (Olivet, 1996; Sibuet et al., 2004; Vissers and Meijer, 2012; Barnett-Moore et al., 2016). Here, we adopt the reconstruction of Nirrengarten et al. (2018) who propose a model based on the re-evaluation of magnetic anomalies that are considered not oceanic before C34 (83 Ma) and therefore not suitable for kinematic studies (Nirrengarten et al., 2017).

Reconstructions of the Alpine domain (Schmid et al., 2008; Handy et al., 2010) and at a larger scale of the Tethys domain (Van Hinsbergen et al., 2019) are keys to understand the evolution of past oceanic domains now inverted in Alpine orogenic systems (e.g., Paleotethys, Neotethys, Meliata, Pindos and Vardar oceans). These models however do not account for the recent reconstruction of the southern North Atlantic presented above that have impact on the movement of Iberia of interest for our study.

4.2 Reconstruction workflow

A plate reconstruction from late Permian to middle Cretaceous is presented in Figs. 5 and 6, based on a kinematic modelling using GPlates version 2.1 (Müller et al., 2018). The rotation poles of the main plates are summarized in Table 1 (see also Supplementary Material for GPlates files).

Our compilation is as follow: (1) the reconstruction of the western Tethys prior to the Late Jurassic is constrained by the kinematic evolution of the Mediterranean region since the Triassic from Van Hinsbergen et al. (2019) that we corrected for overlap of Iberia over western France; (2) the kinematics of Africa follows Müller et al. (2019), based on Heine et al. (2013); (3) for the Late Jurassic and Cretaceous times, we compiled rotation poles of the North America-Europe system from Barnett-Moore et al. (2016), updated from Peace et al. (2019) for North Atlantic continental blocks (Flemish Cap, Orphan Knoll, and Porcupine Bank); (4) our reconstruction of Adria follows the model from Müller et al. (2019) that was modified to account for the possible younger opening of the Ionian basin (Tugend et al., 2019).

Because there is no motion during the 270-250 Ma interval for the North America and Africa plates relative to Europe (Domeier and Torsvik, 2014), we extended the full-fit of these models to 270 Ma.

These input models were then updated according to the following constraints (Tab. 2): (1) age of rifting, mantle exhumation, onset of oceanic spreading in the Atlantic; (2) the present-day position of ophiolites bodies and the timing of rifting, oceanic spreading and subduction for the Tethyan-related oceanic domains (Paleotethys, Neotethys, Pindos, Meliata, Vardar); (3) at 100 Ma, Iberia is close to the present-day position relative to Europe, so that the late Mesozoic-Cenozoic Pyrenean shortening is essentially orthogonal.

4.3 Implementations of the pre-existing models

A critical step in determining the pre-rifting configuration is the restoration of rifted margins. Here, we adopted the reconstructed continental crust geometry of Nirrengarten et al. (2018). Polygons from the model of Nirrengarten et al. (2018) that are based on Seton et al. (2012), were re-defined such that they include new smaller polygons (continental micro-blocks) separated by deformed areas in Iberia and Adria to account for internal deformation (Fig. 1b).

The kinematics of these continental blocks (e.g., the Ebro block) has been reconstructed using geological constraints inferred from the tectono-sedimentary evolution of intra- and peri-Iberian basins (see Section 3 and Fig. 3) that allows defining periods of deformation and subsidence related to extension or transcurrent deformation.

Because a full-fit reconstruction in the Southwest Iberia leads to significant overlapping between the Flemish Cap and Galicia, we use the Nazaré Fault (Pereira et al., 2017) to segment West Iberia. This allows us to minimize the overlap of Northwest Iberia (Galicia) over Flemish Cap, or to have a gap between Southwest Iberia and Newfoundland."

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2) Kinematics of minor plates. *Related to the previous point, the concussion of the paper that previous work has neglected the need for a Ebro microcontinent/plate/block seems reasonable and adds of a growing bank of work demonstrating that such smaller blocks play a crucial role in such rift systems. Separating Iberia into smaller 'plates' seems reasonable given the information presented. However, it is apparent that even within relatively coherent plates/blocks there is some deformation but at what point is such an entity an independent plate? This is particularly pertinent as the boundaries between the plates are described in the manuscript 'diffuse'. The nature of diffuse deformation has been the focus of recent deformable modelling of the region which might be of use to the authors (Peace et al., 2019a). One of the problems encountered in Peace et al. (2019a) is the over thickening of crust related to strike slip deformation. Perhaps the authors could shed some insights here.*

Also, I felt that description of how the kinematics of such blocks are defined requires further clarification and description.

By this I mean that the large-scale kinematics of the major plates can be reconstructed from the oceanic isochrons for the Mesozoic, but this is not the case for the minor plates. The minor plates instead rely on much poorer constraints, such as timing of syn-rift sedimentation and faulting styles (as used by the authors). As such, I felt that further information on how the kinematics of Iberia's constituent plates were reconstructed is required. In addition, I felt that this aspect could have been better reconciled with the geological observations. This point may in part be rectified by addressing the point above regarding the methods.

One of the main conclusions of the work presented in the manuscript is that breaking Iberia into smaller blocks in plate tectonic models might result in more realistic re- constructions (i.e. emphasis on the Ebro block). This is in line with a number of recent studies in the region that also use smaller blocks (e.g., Nirrengarten et al., 2018). Thus, I think it should be more clearly outlined that the conclusion of the present paper sup- ports those of the previous work. Moreover, breaking plates into smaller plates/blocks with independent kinematics presents several issues that need considering further. For example, the requirement of substantial amounts of strike slip deformation for the authors model would benefit from further examination of the geological evidence. I acknowledge that this is examined by in the manuscript somewhat but I think it could be clearer.

My final point regarding minor plates is that the authors focus on minor plates in Iberia appears to not extend to the other parts of the modelled region which I think likely over simplifies the region and perhaps the interpretation. This is demonstrated in Figures 4 and 5 where the separate Ebro and West Iberia blocks are clearly visible but not the separate blocks included in the recent models such as the Flemish Cap, Orphan Knoll, Porcupine Bank etc. (e.g., Nirrengarten et al., 2018). The importance of including these blocks is shown in Peace and Welford (2020). Essentially, these blocks play an important kinematic role and I do not think that Iberia can be accurately reconstructed without including these blocks. I suggest that the authors try to include these blocks or discuss why they are not included.

Authors' responses

Definition of an independent plate A very interesting point raised in this comment is about the definition of what is an individual plate. We define Ebro as a continental block rather than an independent plate. We think that this definition is better appropriate than 'plate', as its motion cannot be simply related to the forces typically driving lithospheric plates such as mantle convection, slab pull, ridge push etc. No localized plate boundaries can be defined such as spreading centers or subduction zones. Rather, the Ebro block represents a rigid continental body surrounded by deformed areas moving independently between 'plates'. Further study is required to fully understand the origin, nature and evolution of the Ebro block and we cannot answer to these questions in the present manuscript.

In the light of recent publications (e.g., Nirrengarten et al., 2018; Peace et al., 2019b), which show the importance of intra-plate deformation in plate kinematic models, the definition of what is a tectonic plate needs to be thought not only in term of continental region bounded by oceanic crust. In our manuscript, we have adopted the terminology "block" to Ebro whereas Europe, Africa and Western Iberia, all bordered by spreading centers, are plates.

Strike-slip deformation Concerning the crustal thickening related to the strike-slip deformation, we also experienced difficulties to accurately represent the strike-slip deformed areas using the GPlates topological network over such large distances (200 km). This results in inappropriate mesh and local high strain (both compressive or extensive). The precise study of these deformed areas is out of the scope of this paper. However, this is something we are working on. We would be very interested to discuss this further in order to establish a proper methodology that would apply to strike-slip settings.

Breaking Iberia into small blocks Recent works that separate the Ebro continental block from Iberia (Tugend et al., 2015; Nirrengarten et al., 2018) are presented in the Introduction. We add a sentence in the discussion to better say that the conclusion about breaking Iberia into smaller blocks supports previous works. According to Referee #1 comments, we also better discuss the nature of the Iberia-Ebro tectonic boundary.

Changes in the manuscript

'Our results support recent studies (e.g., Tugend et al., 2015; Nirrengarten et al., 2018) that postulate that breaking Iberia into smaller blocks results in more realistic models.'

N Atlantic blocks The N Atlantic blocks (Flemish Cap, Orphan Knoll, Porcupine) are included in our GPlates model. These blocks follow the kinematics of Peace et al. (2019b) although they are not distinctly represented (they are delimited by the background diffuse area and the fault features), nor studied with the same intention, in our study. In the revised manuscript we make an effort to better represent these blocks in the figures but we do not want to overload the figure too much.

2.2 Responses to the minor points

Comments from Referees are in italicized text.

L 3: *'rift systems'. Consider adding 'spreading' to this sentence as breakup has actually occurred in the region* > We replaced 'rift systems' by 'oceanic systems'

L 4: *'significant'. Is it possible to quantify how significant?* > we shortened this sentence: « The Late Permian-Triassic Iberian rift basins have accommodated extension, but… »

Introduction: *The opening paragraph has no citations despite containing several state- ments that require citations. I suggest adding relevant citations to the opening para- graph.* > We added references. Now reads as follow: "Global plate tectonic reconstructions are mostly based on the knowledge and reliability of magnetic anomalies that record age, rate and direction of sea-floor spreading (Stampfli and Borel, 2002; Müller et al., 2008; Seton et al., 2012). 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 (e.g., Handy et al., 2010; McQuarrie and Van Hinsbergen, 2013). However, the required quantification and distribution of finite strain into deformed continents remain often uncertain due to the poor preservation of pre-kinematic markers."

L 17: *'plate tectonic reconstructions'. As you have shown not all reconstructions are necessarily based on oceanic magnetic isochrons. I think this should be clarified.* > cf Introduction.

L 20: *I suggest adding relevant citations after 'boundaries'.* > cf Introduction.

L27-29: *This sentence doesn't make complete sense to me. Perhaps 'if' should be replaced with 'although'?* > done

L 29-30: *This sentence is confusing. I suggest rewording.* > Now reads as follow: 'Because of the lack of geological constraints about the timing and localization, this displacement has been supposedly exported along the North Pyrenean Fault.'

L 46: *'evidence'. What sort of evidence. I suggest providing further details of this 'evidence'.* > Reworked based on Referee #1's comments.

Section 2: *I found this whole section quite wordy and hard to follow. I suggest refining it down to just the most essential details.* > we reworked this section based on both referees' comments.

L 60: *'Iberian Buffer'. If this is a quote perhaps it should have a reference?* > This is not a quote. This not a standard way to name Iberia, so we prefer to use quote marks here.

L 66: *'Atlantic province and Northwest Europe'. I feel like these locations and citations could be better organised. I suggest separating out the regions better and adding the citations that are appropriate for the specific region. Also see Sandoval et al. (2019) and Yang et al. (2020) for very recent southern North Atlantic margins work.* > We reworked this part and included more references. Now reads as follows: "Crustal thinning, attested by thick late Permian-Triassic detrital rift-basins deposited above an erosive surface, is well documented on seismic lines along the Atlantic margins (Fig. 2): Nova Scotia-Moroccan basins (Welsink et al., 1989; Deptuck and Kendell, 2017; Hafid, 2000); Iberia-Grand Banks (Balkwill and Legall, 1989; Leleu et al., 2016; Spooner et al., 2019); southern North Atlantic (Tankard and Welsink, 1987; Doré, 1991; Doré et al., 1999; Štolfová and Shannon, 2009; Peace et al., 2019b; Sandoval et al., 2019); North Western Approaches (Avedik, 1975; Evans, 1990; McKie, 2017); North Sea (McKie, 2017; Jackson et al., 2019; Hassaan et al., 2020; Phillips et al., 2019). Onshore Iberia (Arche and López Gómez, 1996; Soto et al., 2019) and in the Pyrenean-Provence domains (Lucas, 1985; Espurt et al., 2019; Cámara and Flinch, 2017; Bestani et al., 2016) (Fig. 1b), an angular unconformity is observed between the Paleozoic and the Permian-Triassic strata (Fig. 2)."

L 83; L 87: *'abnormally high heat flow'. Abnormally high compared to what value? What is normal heat flow anyway?* AND *I feel that this sentence overly simplifies the relationship between CAMP and the breakup. I suggest seeing Peace et al. (2019b) for a detailed review of this.* > We reworked this part, as we agree that it was unclear. As suggested by the referee, it is difficult to define a 'abnormally high heat flow'. Now reads as follows: "An expression of the continued lithospheric thinning and thermal instability associated with high heat flow during the Permian (McKenzie et al., 2015) and the Triassic (Peace et al., 2019a, and references therein). Lithospheric extension prior (or associated with the premises of the subsequent) Early Jurassic continental breakup in the Central Atlantic then favored drainage of mantle melt reservoir (Silver et al., 2006; Peace et al., 2019a), attested by the very rapid 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). 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)."

L 94-95: *I found this sentence quite awkward to follow and suggest rewording it.* > Now reads as follows: "Two hypotheses may be invoked to explain the difference with the McKenzie model. (1) Reduction of mantle density during lithospheric thinning, due to mantle phase transitions to lighter mineral phases because of crustal attenuation (Simon and Podladchikov, 2008) and/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. (2) Another possible hypothesis for the Permian-Triassic topographic evolution..."

L 96: *A space is missing before the citation.* > done

L 99: *'the' is possibly missing before 'Pangea'?* > done

L 99-100: *A review of insulation beneath Pangea is undertaken in Peace et al. (2019b).* > We modified this section to better consider the review in (Peace et al., 2019a). Now reads as follows: "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). This thermal insulation would be responsible for the accumulation of magmatic material of the CAMP (see Peace et al., 2019a, and references therein). Such mantle thermal anomaly could have further inhibited lithospheric mantle re-equilibration after late-Variscan mantle delamination over a long-time span. This model requires a strong impermeability of the overlying lithosphere (Silver et al., 2006). 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."

L 110-115: *I felt that this paragraph would benefit from several references.* > This part is mostly a description of our figures. We however added some references.

L 121-122: *Are you talking about Beta factor or stretching factor here? Please clarify.* > We calculated the stretching factor (so called beta factor) from from the tectonic subsidence, as defined in Watts (2001).

L 153: *Were the same blocks used here as those from Nirrengarten et al. (2018) and subsequently Peace et al. (2019a)? Or are they different? I suggest clarifying either way.* > cf Methodology section

L 155: *I suggest expanding upon why a 'full fit' reconstruction of Iberia is not possible? I suspect that some of the troubles are stemming from the inclusion on the Flemish Cap as part of the North American plate rather than an independent plate. Also a brief discussion of breakup anomalies offshore Iberia might be useful here.* > cf Methodology section

L 165: *'workflow'. I think a dedicated workflow section would be beneficial.* > cf Methodology section

L 220: *I think it would be useful to summarise the rotations described in the text as a table.* > cf Methodology section. We added a new table with rotation poles of the main plates.

L 239: *Why does the Iberia-Ebro boundary have a more complex tectonic history than the Europe-Ebro boundary? I suggest explaining this further.* > "More complex" was ambiguous we changes with: "The Iberia-Ebro boundary has played as right-lateral and left-lateral kinematics."

L 256: *Awkward wording. I suggest editing this phrase.* > Now reads as follows: "To revolve several long-lasting problems of the Mesozoic kinematics of Iberia, we propose to better consider: the late Permian-Triassic basins evolution in Iberian kinematic reconstructions, the role of the Ebro continental block in the partitionning of the deformation, and to replace Iberia in a larger-scale plate reconstruction of the Atlantic and Tethys domains. We show that: (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."

Figures: *The text is too small to read on the geological time scale.* AND *Details and text are too small to read on all parts of these figures. I would also suggest more clearly labelling the subfigures and describing them more fully in the captions.* > We increased font size and generally better described the figures and subfigures in the captions.

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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 recorded the propagation of these two rift oceanic systems and is therefore a 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 have accommodated 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 kinematic model of Iberia that considers accounts for 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 micro-continentthe Ebro block. 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 Neotethys Ocean and their control on localization the development of the Atlantic rift.

1 Introduction

Plate Global plate tectonic reconstructions are mostly based on the knowledge and reliability of magnetic anomalies that record age, rate and direction of sea-floor spreading (Stampfli and Borel, 2002; Müller et al., 2008; Seton et al., 2012). 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(e.g., Handy et al., 2010; McQuarrie and Van Hinsbergen, 2013). 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 Although 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 geological constraints, such a large strike-slip displacement has been supposedly exported along the North Pyrenean Fault (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 (Tugend et al., 2015; Nirrengarten et al., 2018; Tavani et al., 2018), 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 transcurrent deformation that results from the eastwards movement of Iberia first occurred occurred mainly during the Late Jurassic-Early Cretaceous in northern Iberia along Northern Iberia along a hundred-kilometer scale pull-part or en-echelon rift basins formed by the NW-SE-trending Iberian massifs (Tugend et al., 2015; Nirrengarten et al., 2018)Massifs. Indeed, along these massifs, 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. recorded major subsidence and strike-slip deformation during the Late Permian to middle Cretaceous time interval (Alvaro et al., 1979; Salas et al., 2001; Aldega et al., 2019; Aurell et al., 2019; Soto et al., 2019). However, no geological evidence for lithosphere-scale strike-slip movements is yet clearly defined in the intra-Iberian basins.

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. 31a) (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; Stampfli and Borel, 2002; Ziegler, 1989, 1990). This late Permian-Lower Triassic phase is associated with the deposition of thick detrital non-marine deposits in intra-continental basins. Sedimentation became carbonaceous during the middle Triassic. Finally, the Late Triassic is characterized by a thick evaporitic (mainly salt) sequence (e.g., Ortí et al., 2017). 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

Crustal thinning, attested by thick late Permian-Triassic detrital rift-basins deposited above an erosive surface, is well documented in the Atlantic province and Northwest Europe continental shelves on seismic lines along the Atlantic margins (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., 2019b) 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 2): Nova Scotia-Moroccan basins (Welsink et al., 1989; Deptuck and Kendell, 2017; Hafid, 2000); Iberia-Grand Banks (Balkwill and Legall, 1989; Leleu et al., 2016; Spooner et al., 2019); southern North Atlantic (Tankard and Welsink, 1987; Doré, 1991; Doré et al., 1999; Štolfová and Shannon, 2009; Peace et al., 2019b; Sandoval et al., 2019); North Western Approaches (Avedik, 1975; Evans, 1990; McKie, 2017); North Sea (McKie, 2017; Jackson et al., 2019; Hassaan et al., 2020; Phillips et al., 2019). Onshore Iberia (Arche and López Gómez, 1996; Soto et al., 2019) and in the Pyrenean-Provence domains (Lucas, 1985; Espurt et al., 2019; Cámara and Flinch, 2017; Bestani et al., 2016) (Fig. 2). An 1b), 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). (Fig. 2).

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 and thermal instability associated with high heat flow during the Permian (McKenzie et al., 2015) and the Triassic and abnormally high heat flow is recorded by the (Peace et al., 2019a, and references therein). Lithospheric extension prior (or associated with the premises of the subsequent) Early Jurassic continental breakup in the Central Atlantic then favored drainage of mantle melt reservoir (Silver et al., 2006; Peace et al., 2019a), attested by the very rapid 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 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)Therefore the subsidence appears much lower than that predicted by simple isostatic model of crustal thinning (McKenzie, 1978).

Two hypotheses may be invoked to explain the difference with the McKenzie model. (1) Reduction of mantle density during lithospheric thinning, due to mantle phase transitions to lighter mineral phases because of crustal attenuation (Simon and Podladchikov, 2008) and/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. (2) 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). This thermal insulation would be responsible for the accumulation of magmatic material of the CAMP (see Peace et al., 2019a, and references therein). Such mantle thermal anomaly could have further inhibited lithospheric mantle re-equilibration after late-Variscan mantle delamination over a long-time span. This model requires a strong impermeability of the overlying lithosphere (Silver et al., 2006). 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.

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 ($\sim$300 to $\sim$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 $\sim$100 Myr (late Carboniferous to Late Triassic) of continental lithosphere thinning and magmatism prior to Jurassic Early Cretaceous 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 (Alvaro et al., 1979; Lagabrielle et al., 2020) (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 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 This phase is contemporaneous with 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 Methodology

A plate reconstruction from late Permian to Cretaceous is presented in Fig. 5 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

4.1 Previous kinematic models

We compile and implement previous kinematic models involving Iberia (Fig. 4). The objective is to establish a coherent kinematic model of Iberia that considers both the evolution of the Neotethyan and Atlantic regions. These kinematic models are either global (e.g., Müller et al., 2019), based on the assimilation of geological and geophysical information at large scale to allow a dynamic understanding of Earth's plate tectonics but do not aim to solve regional tectonic issues such as strain partitioning between Iberia and Europe. On the other hand, regional models are focused on the reconstruction of North Atlantic (e.g., Barnett-Moore et al., 2016; Nirrengarten et al., 2018; Peace et al., 2019b) or are interested in the reconstruction of the Alpine orogen with inferences on the kinematics 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 Adria (Schmid et al., 2008; Handy et al., 2010; Van Hinsbergen et al., 2019).

North Atlantic reconstructions use offshore geophysical constraints from the Northwest Iberian margins and pay relatively little attention to the geological evolution of the Pyrenees and other orogenic domains in Iberia (e.g., Sibuet et al., 2004; Barnett-Moore et al., 2016; Nirrengarten et al., 2018). However, these models give fundamental insights on the geometry of the North Atlantic full-fit reconstruction and the timing of oceanic spreading. The nature of some magnetic anomalies in the southern North Atlantic has been the matter of considerable debate (Olivet, 1996; Sibuet et al., 2004; Vissers and Meijer, 2012; Barnett-Moore et al., 2016). Here, we adopt the reconstruction of Nirrengarten et al. (2018) who propose a model based on the re-evaluation of magnetic anomalies that are considered not oceanic before C34 (83 Ma) and therefore not suitable for kinematic studies (Nirrengarten et al., 2017).

Reconstructions of the Alpine domain (Schmid et al., 2008; Handy et al., 2010) and at a larger scale of the Tethys domain (Van Hinsbergen et al., 2019) are keys to understand the evolution of past oceanic domains now inverted in Alpine orogenic systems (e.g., Paleotethys, Neotethys, Meliata, Pindos and Vardar oceans). These models however do not account for the recent reconstruction of the southern North Atlantic presented above that have impact on the movement of Iberia of interest for our study.

4.2 Reconstruction workflow

A plate reconstruction from late Permian to middle Cretaceous is presented in Figs. 5 and 6, based on a kinematic modelling using GPlates version 2.1 (Müller et al., 2018). The rotation poles of the main plates are summarized in Table 1 (see also Supplementary Material for GPlates files).

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 Our compilation is as follow: (1) the reconstruction of the western Tethys prior to the Late Jurassic is constrained by the kinematic evolution of the Mediterranean region since the Triassic from Van Hinsbergen et al. (2019) that we corrected for overlap of Iberia over western France; (2) the kinematics of Africa follows Müller et al. (2019), based on Heine et al. (2013); (3) for the Late Jurassic and Cretaceous times, we compiled rotation poles of the North America-Europe system from Barnett-Moore et al. (2016), updated from Peace et al. (2019) for North Atlantic continental blocks (Flemish Cap, Orphan Knoll, and Porcupine Bank); (4) our reconstruction of Adria follows the model from Müller et al. (2019) that was modified to account for the possible younger opening of the Ionian basin (Tugend et al., 2019).

Because there is no motion during the 270-250 Ma interval for the North America and Africa plates relative to Europe (Domeier and Torsvik, 2014), we extended the full-fit cannot be reconstructed along the whole Iberia margin (Fig.

5a), 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 Galiciaof these models to 270 Ma.

Our kinematic model is based on These input models were then updated according to the following constraints (Tab. 2): (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; (32) 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); (43) at 100 Ma, Iberia should be close to its is close to the present-day along-strike position relative to Europe, so that the orthogonal late Mesozoic-Cenozoic Pyrenean shortening is accommodated in the late Mesozoic-Cenozoic timesessentially orthogonal.

We then integrate kinematic evolution for published models in both the Atlantic and the Tethys according to the following workflow: 1) the reconstruction of

4.3 Implementations of the pre-existing models

A critical step in determining the pre-rifting configuration is the restoration of rifted margins. Here, we adopted the reconstructed continental crust geometry of Nirrengarten et al. (2018). Polygons from the model of Nirrengarten et al. (2018) that are based on Seton et al. (2012), were re-defined such that they include new smaller polygons (continental micro-blocks) separated by deformed areas in Iberia and Adria to account for internal deformation (Fig. 1b).

The kinematics of these continental blocks (e.g., the Ebro block) has been reconstructed using geological constraints inferred from 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); tectono-sedimentary evolution of intra- and peri-Iberian basins (see Section 3) Adria and Africa were then corrected for the position of Africa according to Heine et al. (2013)and Fig. 3) that allows defining periods of deformation and subsidence related to extension or transcurrent deformation.

Because a full-fit reconstruction in the Southwest Iberia leads to significant overlapping between the Flemish Cap and Galicia, we use the Nazaré Fault (Pereira et al., 2017) to segment West Iberia. This allows us to minimize the overlap of Northwest Iberia (Galicia) over Flemish Cap, or to have a gap between Southwest Iberia and Newfoundland.

5 Kinematics of Iberia between Atlantic and Tethys

5.1 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. 5a). 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 5a). Recent study (Sandoval et al., 2019) also showed a high pre-Early Jurassic thinning in North Atlantic basins (e.g., Galicia Interior, Porcupine, and Orphan basins).

Back-arc extension associated with the subduction of the Paleotethys (Van Hinsbergen et al., 2019) (Fig. 5b) 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), as suggested by Phillips et al. (2018).

During the Late Triassic-Early Jurassic (Fig. 5c-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.

5.2 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. 5c) (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., 2019b) that led to breakup in the Central Atlantic Ocean during the 190-175 Ma interval (Pliensbachian-Toarcian) (Fig. 5c-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 short-lived Vardar Oceans from 160 Ma onward induced the reactivation of the former diffuse transfer zone between Iberia and Africa into a localized transform plate boundary (Fig. 6a).

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

A major tectonic change occurred in the Late Jurassic-Early Cretaceous when the North Central southernmost North Atlantic successfully rifted the continental domain located offshore Southwest Iberia in present-day coordinates (between 160 and 100 Ma, Fig. 6), 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) 147 Ma and 135-133 Ma, respectively, in Gorringe bank (Sallarès et al., 2013). Oceanic opening then migrated northward, attested by mantle exhumation and oceanic offshore southwest Galicia between 139.8 and 129.4 Ma (Mohn et al., 2015) and 121-112 Ma (Bronner et al., 2011; Vissers and Meijer, 2012), respectively (Fig. 6b). 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 in the Pyrenean basins 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. 6c). Eastward rotation of Africa induces subduction along the northern Neotethyan margin (Schmid et al., 2008) (Fig. 6b-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).

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

6.1 Amount of strike-slip displacement

Table 3 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. 5a-c, 270-200 Ma). 86 km were accommodated during the Jurassic (Figs. 5c-d and 6a-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 boundaryplayed as right-lateral and left-lateral kinematics. The rapid eastward displacement of Ebro during the late Permian to Late Jurassic period (Figs. 5 and 6) 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.

6.2 Strike-slip structures in the intra-Iberian basins

Despite the requirement of 245 km left-lateral strike-slip displacement along the Iberia-Ebro boundary from 160 to 100 Ma, there is no simple geological evidence in support of a unique major crustal-scale fault in the Iberian Range-Basque Cantabrian Basin system.

Several studies have suggested that a left-lateral shear zone can be recognized along the Iberian Range and the Basque-Cantabrian rifts system. Geological evidence includes the High Tagus Fault in the Iberian Range (Aldega et al., 2019; Aurell et al., 2019) and the Ventaniella Fault in the Basque-Cantabrian region (e.g., Tavani et al., 2011). The latter fault is often considered in recent reconstructions to accommodate alone the Iberia-Ebro movement (Tugend et al., 2015; Nirrengarten et al., 2018). However, the estimated left-lateral displacement along the Ventaniella Fault is only in the order of magnitude of a few kilometers (Tavani et al., 2011) and therefore cannot be used as a North Pyrenean Fault equivalent.

In the Basque Cantabrian Basin, the Ventaniella Fault is part of a NW-SE fault system that acted as left-lateral shear zone during the Late Jurassic-Early Cretaceous and has been subsequently inverted with a right-lateral kinematic during the Cenozoic (De Vicente et al., 2011; Tavani et al., 2011; Cámara and Flinch, 2017). These faults have a Triassic origin (Tavani and Granado, 2015). Tectonic activity along these faults gets younger NE-ward (Ubierna fault: Late Jurassic-Early Cretaceous; Zamanza-Oña fault: Early-Middle Cretaceous; salt tectonics in the center of the basin, Cámara and Flinch, 2017). We suggest the Iberia-Ebro displacement have possibly been distributed along these structures.

The role of the weak Triassic evaporites in efficiently decoupling deformation in the pre-salt basement from the thin-skinned extension in sedimentary cover has been emphasized largely in the Pyrenees (e.g., Grool et al., 2019; Duretz et al., 2019; Jourdon et al., 2020; Lagabrielle et al., 2020). Salt tectonics has also been suggested to have been particularly significant from the Jurassic through the Early Cretaceous in Mesozoic basins that shaped NW-directed boundary between Ebro and Iberia, including the Basque-Cantabrian Basin (Cámara and Flinch, 2017), Parentis Basin (Ferrer et al., 2012), Cameros Basin (Rat et al., 2019) and Maestrat Basin (Vergés et al., 2020). The surface expression of the crustal strike-slip movements is inferred to have been limited in supra-salt layers.

The mechanism responsible for the independent movement of Ebro relative to Europe and Iberia prior to the opening of the southern North Atlantic remains unclear. The most likely hypothesis is that before the opening of the Alpine Tethys, the Ebro continental block was related to the regional eastward rotation of the Africa-Adria system. This rotation caused Ebro to move eastward, accommodating left-lateral and right-lateral strike-slip kinematics in the Pyrenean and Iberian basins, respectively.

7 Conclusions

We show that kinematic reconstruction of Iberia accounting for the late To revolve several long-lasting problems of the Mesozoic kinematics of Iberia, we propose to better account for deformation associated with late Permian-Triassic basins evolution and further consideration of the role of Ebro and larger-scale plate reconstruction in rifting, the role of the Ebro continental block in accommodating complex strain partitioning along the Iberia-Europe plate boundary, and replace Iberia in a refined plate reconstruction between the Atlantic and Tethys allows revolving several issues: domains. We show that: (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 closed in the Early Cretaceous (145 to 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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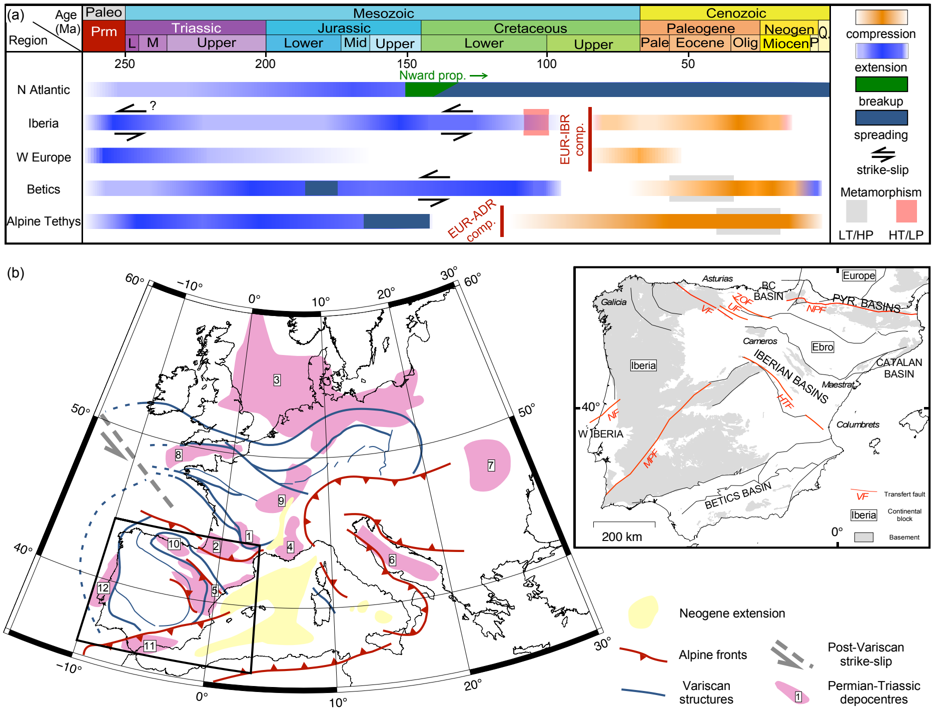

Figure 1. Geodynamic chart and localization of the study area. (a): Geodynamic chart of the main structural areas of the Iberian domain. BCB: Basque-Cantabrian basin. (b) Localization Location map of West Europe, showing the areas that are deformed in compression and extension and Permian-Triassic depocenters. 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 Iberia showing the Iberian main structures and transforms (red) and sedimentary basins (capitalized and structuresitalicized text) and sub-basins (italicized text). BC: Basque-Cantabrian; HTF: High tagus Fault; MPF: Messejana-Plasencia Fault; NF: Nazaré Fault; NPF: North Pyrenean Fault; PYR: Pyrenean; UF: Ubierna Fault; VF: Ventaniella Fault; ZOF: Zamanza-Oña Fault.

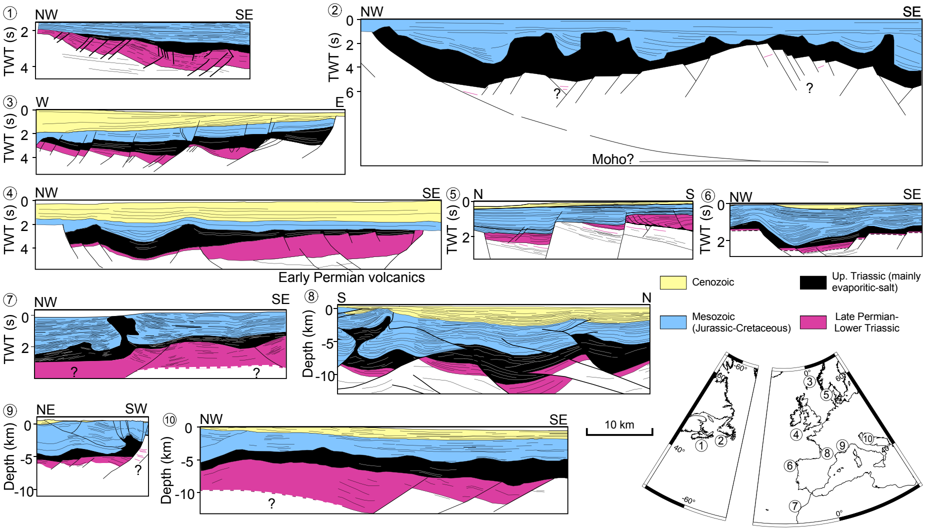

Figure 2. Compilation of interpreted seismic profiles along the North Atlantic margins and in West Europe. 1: Deptuck and Kendell (2017); 2: Balkwill and Legall (1989); 3-4: McKie (2017); 5: Philipps et al. (2019); 6: Rasmussen et al. (1996); 7: Hafid (2000); 8: Espurt et al. (2019); 9: Bestani et al.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

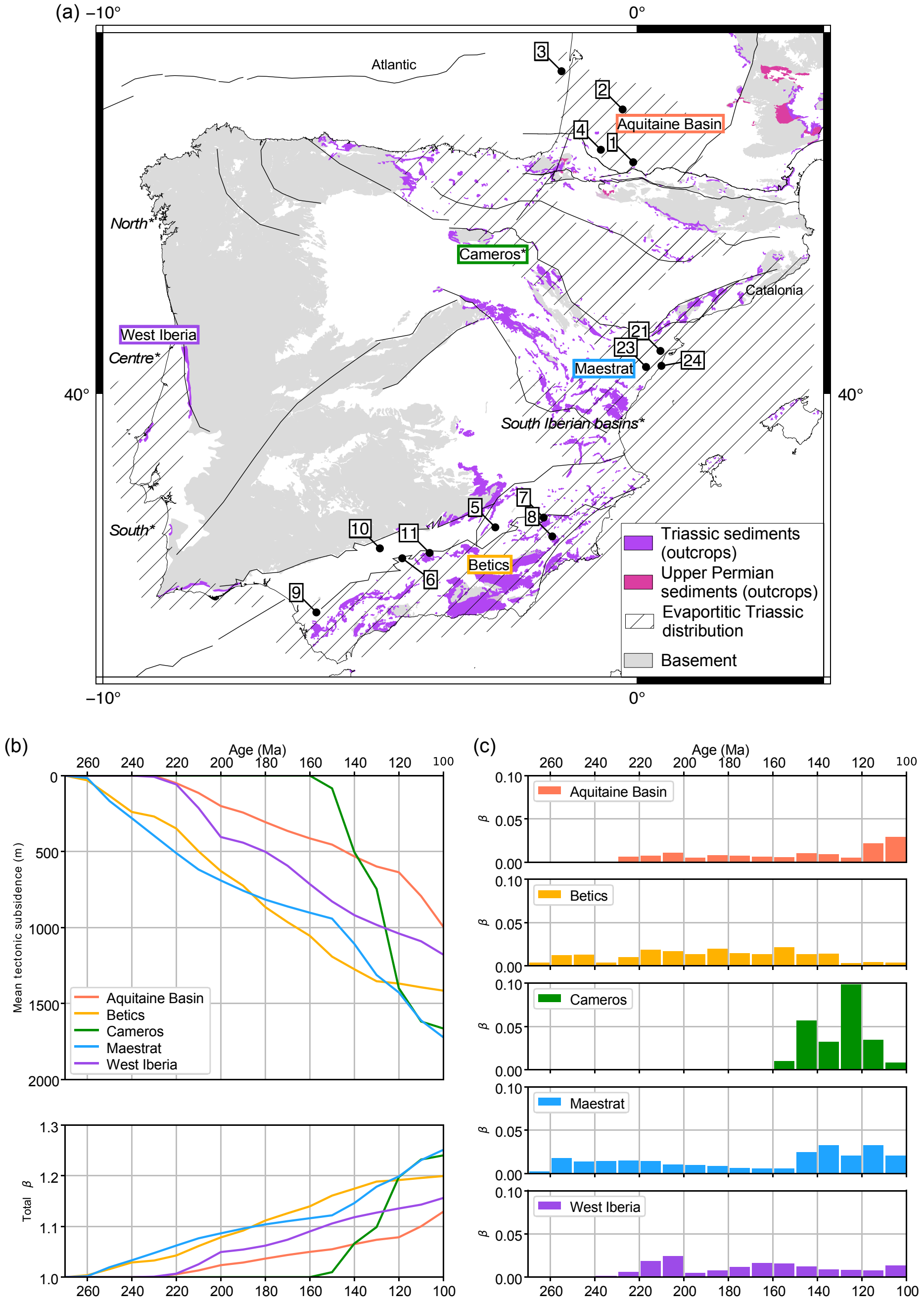

Figure 3. Late Permian-Triassic deposits and subsidence analyses. (a) Map of the Upper Permian-Triassic sediment outcrops, main depocenters, and distribution of the Upper Triassic evaporitic sequence in Iberia and southwest France. (b) Top: Mean tectonic subsidence curves in the Aquitaine Basin (Brunet, 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: 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

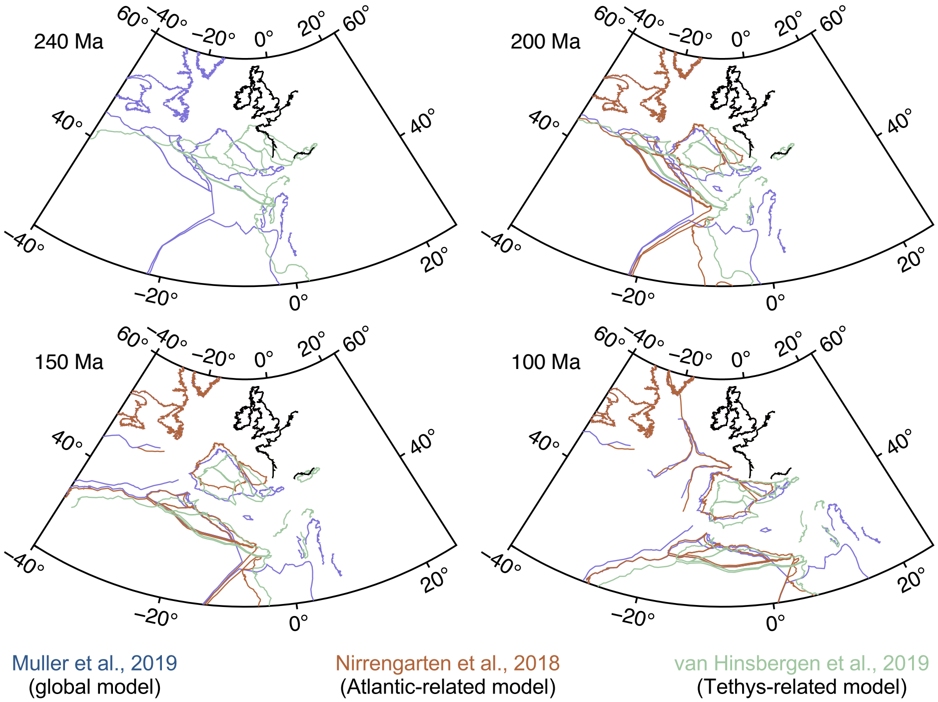

Figure 4. Large-scale reconstruction Compilation of the Tethys-Atlantic area for the 270 previous global (Müller et al., 2018), Atlantic-related (Nirrengarten et al., 2018), or Tethys-related (Van Hinsbergen et al., 2019) kinematics reconstructions used in our reconstruction, at 240 Ma (a), 250 200 Ma (b), 200 150 Ma (c), and 180 100 Ma (d)periods. Maps are Note that the Nirrengarten et al. (2018) reconstruction is not shown at 240 Ma as represented in orthographic projectiontheir model.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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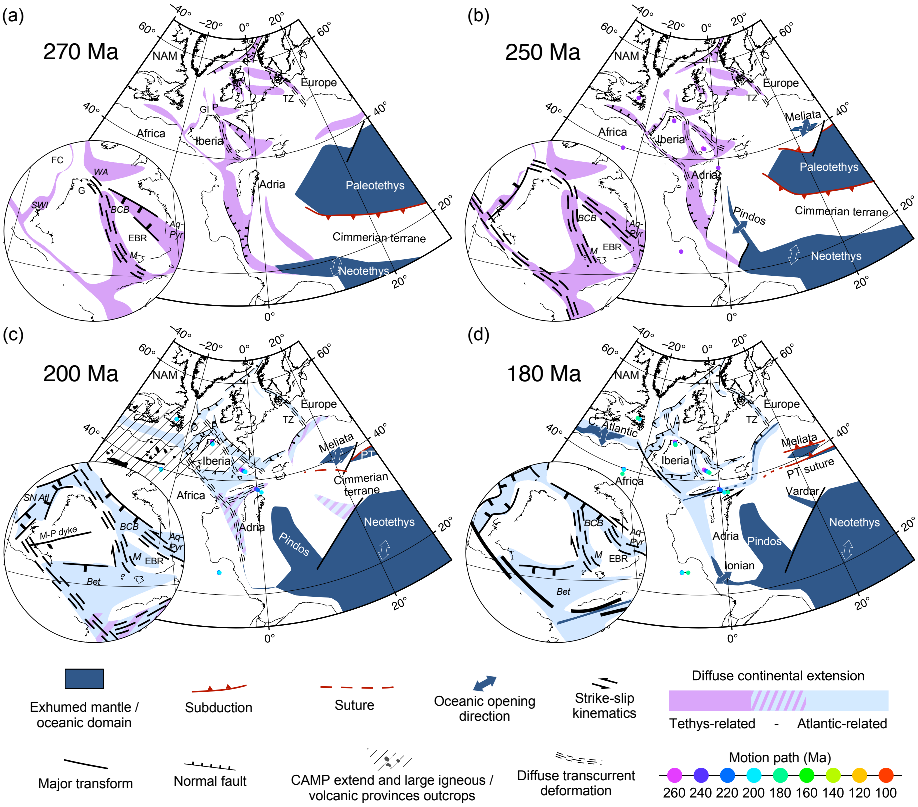

Figure 5. Large-scale reconstruction of the Tethys-Atlantic area for the 270 Ma (a), 250 Ma (b), 200 Ma (c), and 180 Ma (d) periods. Maps are in orthographic projection. Close up shows on the evolution of the Iberia plate and the Ebro continental block. Colored background shows diffuse or ill-defined deformation (extension or transtension) in the continents, associated with the evolution of the Tethys (Paleo- and Neotethys, purple) or the Atlantic (blue). At 200 Ma, the hatched area represents the CAMP extend. Aq-Pyr: Aquitain-Pyrenean basin; BCB: Basque-Cantabrian basin; Bet: Betics basin; EBR: Ebro; FC: Flemish Cap; G: Galicia; GI: Galicia Interior basin; M: Maestrat; M-P: Messejaña-Plascencia; MV: Midland Valley rift; NS: North Sea rift; O: Orphan basin; P: Porcupine basin; PT: Paleotethys; SN Atl: southern North Atlantic; SWI: Southwest Iberia; TZ: Tornquist Zone; WA: Western Approaches.

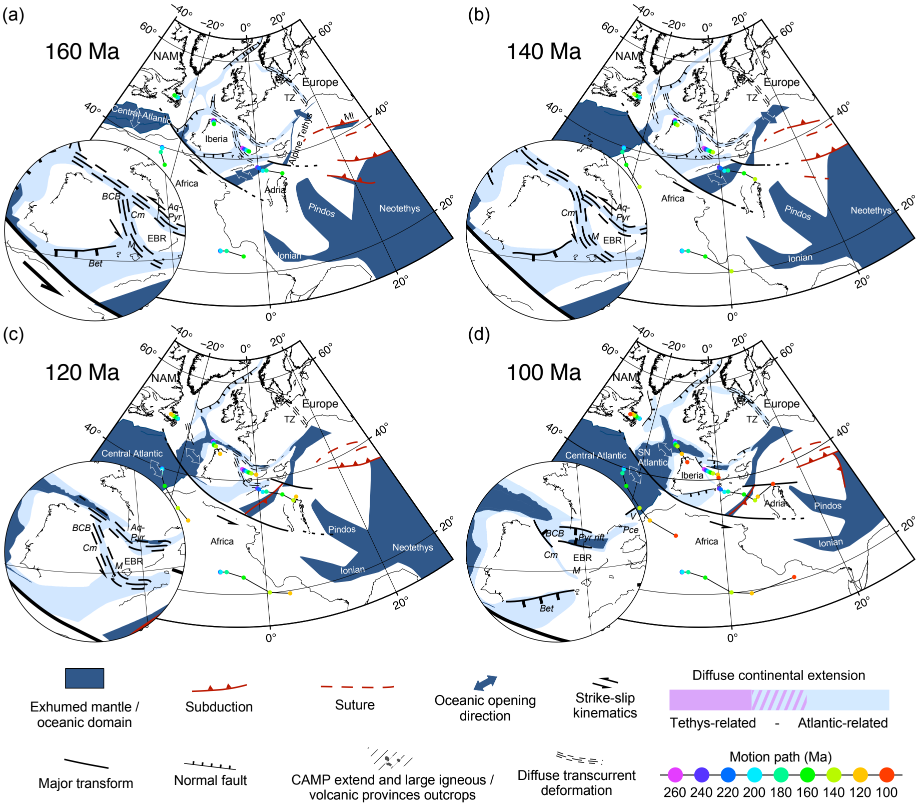

Figure 6. Large-scale reconstruction of the Tethys-Atlantic area for the 160 Ma (a), 140 Ma (b), 120 Ma (c), and 100 Ma (d) periods. Maps are in orthographic projection. Close up shows on the evolution of the Iberia plate and the Ebro continental block. Colored background shows diffuse or ill-defined deformation (extension or transtension) in the continents, associated with the evolution of the Tethys (Paleo- and Neotethys, purple) or the Atlantic (blue). 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 Rotation poles of the main plates or continental blocks used in the kinematic reconstruction modelstudy. Poles with no references are from this study. See the complete list in the GPlates rotation file in Supplementary Materials. References: a: Nirrengarten et al. (2018); b: Müller et al. (2019); c: Heine et al. (2013).

Age (Ma)	Latitude	Longitude	Angle	Fixed plate	Ref	Age (Ma)	Latitude	Longitude	Angle	Fixed plate	Ref
North America						Ebro block					
83.0	76.81	-20.59	29.51	NW AFR	a	0.0	90.0	0.0	0.0	EUR	
120.4	66.28	-19.82	54.44	NW AFR	a	20.0	90.0	0.0	0.0	EUR	
126.7	66.11	-18.95	56.48	NW AFR	a	66.0	40.1807	8.7194	5.606	EUR	
131.9	65.95	-18.5	57.45	NW AFR	a	84.0	-41.0445	136.3388	2.8866	EUR	
139.6	66.12	-18.38	59.9	NW AFR	a	94.0	-41.0445	136.3388	2.8866	EUR	
147.7	66.54	-17.98	62.08	NW AFR	a	118.0	-45.8785	165.4893	4.2288	EUR	
154.3	67.15	-15.98	64.75	NW AFR	a	145.0	-62.2857	170.8607	4.5896	EUR	
170.0	67.09	-13.86	70.55	NW AFR	a	270.0	-58.2298	-176.5352	11.1943	EUR	
190.0	64.31	-15.19	77.09	NW AFR	a	Southwest Iberia					
203.0	64.28	-14.74	78.05	NW AFR	a	84.0	-28.0047	-158.3184	-0.9344		
270.0	64.28	-14.74	78.05	NW AFR		100.0	-36.5872	156.7264	0.6206	WIB	
Flemish Cap						120.0	29.0472	91.4916	-0.257	WIB	
112.0	90.0	0.0	0.0	NAM	a	130.0	-43.3609	171.3962	10.9309	WIB	
140.0	45.28	-53.47	20.03	NAM	a	145.0	-45.4085	167.4179	8.8479	WIB	
160.0	44.65	-54.79	18.83	NAM	a	150.0	47.1092	-9.648	-7.8087	WIB	
200.0	42.8694	-54.8782	17.7035	NAM	a	270.0	45.8739	-8.1058	-9.9091	WIB	
270.0	42.8694	-54.8782	17.7035	NAM		Adria					
Europe						100.0	-26.5	-166.58	7.73	APU	b
79.1	63.4	147.75	-18.48	NAM	a	120.0	-26.5	-166.58	7.73	APU	b
120.0	68.01	153.59	-21.01	NAM	a	250.0	-26.5	-166.58	7.73	APU	b
200.0	71.41	152.6	-23.68	NAM	a	270.0	-26.5	-166.58	7.73	APU	
270.0	71.41	152.6	-23.68	NAM		Northwest Africa					
West Iberia (Galicia)						0.0	90.0	0.0	0.0	NE AFR	c
86.0	-40.18	170.57	10.07	EUR		110.0	90.0	0.0	0.0	NE AFR	c
120.0	-47.9216	179.85	22.8717	EUR		145.0	25.21	5.47	2.87	NE AFR	c
135.0	-49.5226	-177.8405	27.0209	EUR		231.0	25.21	5.47	2.87	NE AFR	c
140.0	-49.695	-177.3636	27.3079	EUR		270.0	25.21	5.47	2.87	NE AFR	
150.0	-50.3915	-177.3963	27.8356	EUR							
270.0	50.9548	5.1656	-28.4002	EUR							

Table 2. 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 Southwest Iberia	Continental rifting	200 to 161	Murillas et al., 1990
		Mantle exhumation	150-133 145	Mohn Sallàres et al., 2015 2013
		Initiation of oceanic spreading	125-112 135-133 (Gorringe Bank)	Olivet, 1996; Srivastava Sallàres et al., 2000; Schettino and Turco, 2009; Fernandez, 2019 2013
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

Table 3. 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)		