The Mesozoic Iberia-Eurasia diffuse plate boundary: A wide domain of distributed transtensional deformation progressively focusing along the North Pyrenean Zone



*Published Version:*
The Mesozoic Iberia-Eurasia diffuse plate boundary: A wide domain of distributed transtensional deformation progressively focusing along the North Pyrenean Zone / Asti, R; Saspiturry, N; Angrand, P. - In: EARTH-SCIENCE REVIEWS. - ISSN 0012-8252. - ELETTRONICO. - 230:104040(2022), pp. 1-31. [10.1016/j.earscirev.2022.104040]

This version is available at: https://hdl.handle.net/11585/943170 since: 2023-10-03

*Published:*

DOI: http://doi.org/10.1016/j.earscirev.2022.104040

EARTH-SCIENCE REVIEWS vol. 230 ISSN 0012-8252

DOI: 10.1016/j.earscirev.2022.104040

**The Mesozoic Iberia-Eurasia diffuse plate boundary: a wide domain of distributed transtensional deformation progressively focusing along the North Pyrenean Zone**

Riccardo Asti[1,2]*, Nicolas Saspiturry[3,4] & Paul Angrand[5]

1) Univ Rennes, CNRS, Géosciences Rennes, UMR 6118, 35000 Rennes, France

2) Université Côte d'Azur, OCA, CNRS, IRD, Géoazur, 250 rue Albert Einstein, 06560 Valbonne, France

3) Université Bordeaux Montaigne / EA 4592 Géoressources & Environnement, 1 allée Fernand Daguin, 33607 Pessac cedex, France

4) Géosciences Montpellier, Université de Montpellier-CNRS, Place Eugène Bataillon, 34095 Montpellier, France

5) Geosciences Environnement Toulouse (GET), Université de Toulouse, UPS, Univ. Paul Sabatier, CNRS, IRD, 14 av. Edouard Belin, F-31400 Toulouse, France

* Corresponding author : riccardo.asti@geoazur.unice.fr

## Abstract

Plate kinematic reconstructions available for the Late Jurassic-Early Cretaceous eastward drift and counterclockwise rotation of the Iberian plate imply a major left-lateral motion of Iberia with respect to Eurasia. According to most authors, this displacement has been accommodated

along the transform North Pyrenean Zone. However, no relevant field evidence exists for the proposed >400 km of horizontal displacement along the North Pyrenean Fault. Several Permian-Mesozoic basins are distributed around the Iberia/Eurasia plate boundary and have been more or less inverted during the Cenozoic Pyrenean Orogeny (i.e. Iberian Chain basins, North and South Pyrenean basins, Basque-Cantabrian Basin, Parentis Basin, Bay of Biscay/Asturian margins). All of these basins experienced a complex kinematic history and shared the same tectono-stratigraphic evolution, with two successive rifting stages: (i) Permian-Triassic rifting following the dismantling of the Variscan belt and recording the early breakup of Pangea and (ii) Late Jurassic-Early Cretaceous rifting developing after a Jurassic post-rift thermal cooling stage. Depending on the different techniques of investigation and on the interpretation of controversial datasets, authors proposed either opening by orthogonal rifting or by transtensional/pull-apart tectonics for these basins.

In this work, we propose a reappraisal of the processes responsible for the Mesozoic Iberia/Eurasia plate boundary compartmentalization by reviewing the tectono-sedimentary history and the kinematic evolution of the sedimentary basins involved in this domain. We shed light on the fact that the Cretaceous left-lateral movement within the plate boundary was not accommodated by localized deformation along the single North Pyrenean Fault wrench structure, but rather by a distributed zone of deformation in which the transtensional regime was recorded by the sedimentary basins therein. We also suggest that other Permian-Mesozoic depocenters located below the Cenozoic foreland basins of the Pyrenean belt (i.e. the Ebro and Aquitaine basins) may have been active segments of this rift system. We then propose that the real extent of the Mesozoic plate boundary is roughly defined by two NW-SE trending lineaments corresponding to the southwestern margin of the Iberian Chain, on the Iberian side, and to the southern Armorican margin and the southwestern border of the French Central Massif, on the Eurasian side. The complex pre-Cretaceous tectono-sedimentary history of this region determined its peculiar pre-rift structure. Such structural inheritance may have favored a distributed rather than a localized mode of

deformation at the Iberia/Eurasia diffuse plate boundary during the Late Jurassic-Early Cretaceous, whilst mechanisms related to the eastward propagation of the Bay of Biscay system might have been responsible for the final localization of the plate boundary along the Basque-Cantabrian/North Pyrenean corridor.

**Key words**

- Iberia/Eurasia plate boundary
- Diffuse plate boundary
- Plate kinematics
- Structural inheritance
- Polyphased rifting
- Orthogonal vs. oblique rifting

## 1. INTRODUCTION

Two of the major assumptions in plate tectonics theory are that tectonic plates are rigid undeformable blocks and that deformation localizes in narrow zones at their edges, known as "plate boundaries" (e.g. Wilson, 1965; McKenzie & Parker, 1967). Since the early formulation of this theory in the 1960s, these assumptions have been questioned by geological and geophysical constraints evidencing (i) that intraplate deformation can occur and (ii) that deformation can be accommodated by wide domains along plate edges known as "diffuse plate boundary zones" (e.g. Gordon & Stein, 1992; Gordon, 1998; Kreemer *et al*., 2003 and references therein). In fact, in the case where a large domain surrounding a plate boundary has experienced a coherent tectonic history, it can be reasonably regarded as a diffuse plate boundary zone. Such fossil analogues are of broad interest since diffuse plate boundaries cover a significant portion of Earth's surface (~15%; Gordon, 1998). Indeed, the identification of such broad deforming domains accommodating relative movement between tectonic plates may provide important constraints to plate kinematic models. This can also help to resolve controversies arising from the discrepancy regarding the amount of displacement postulated by plate kinematic models and the amount of deformation estimated from available geological observations.

The Mesozoic Iberia/Eurasia plate boundary is an excellent example to study the partitioning of deformation at plate boundaries and its implications on kinematic models. Indeed, the plate boundary has classically been identified within the narrow Pyrenean realm as the inverted North Pyrenean Zone (e.g. Le Pichon *et al*., 1970; Choukroune *et al*., 1973; Choukroune & Mattauer, 1978). However, it is worth noting that the Pyrenean domain is surrounded by numerous inverted Permian-Mesozoic rift basins, such as the Iberian Chain System (e.g. Alvaro *et al*., 1979) or the Parentis Basin (e.g. Pinet *et al*., 1987; Bois *et al*., 1990) (Fig. 1). On the Iberian side of the Iberia/Eurasia plate boundary, the tectonic history of these domains has been often considered as related to intraplate deformation (e.g. Salas *et al*., 2001, 2010; Guimerà *et al*., 2004; Guimerà, 2018). Nevertheless, the consistency in the tectonic evolution of these inverted basins, on both sides of the Iberia/Eurasia plate boundary, has seldom been taken into account (e.g. Tugend *et al*., 2015a; Lagabrielle *et al*., 2020; Angrand & Mouthereau, 2021).

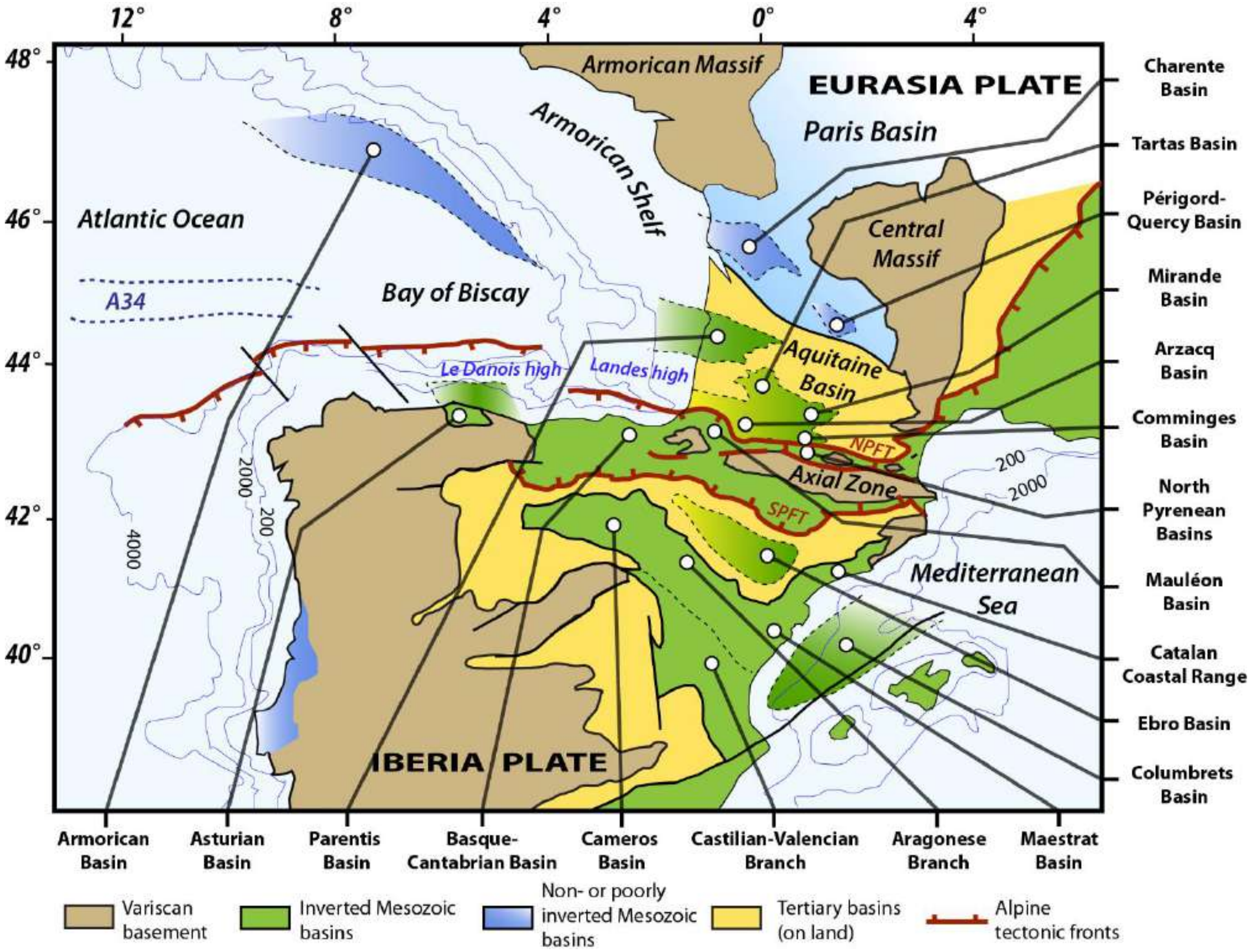


***Fig. 1:*** *Simplified structural map of the Iberia/Eurasia diffuse plate boundary zone, with locations of the basins presented in this work (modified after Lagabrielle et al., 2020). Acronyms: NPFT, North Pyrenean Frontal Thrust; SPFT, South Pyrenean Frontal Thrust.*

Since early studies in the 1970s (e.g. Le Pichon *et al*., 1970; Le Pichon & Sibuet, 1971; Choukroune *et al*., 1973; Sibuet, 1974; Williams, 1975; Choukroune & Mattauer, 1978), the Late Jurassic-Early Cretaceous kinematic evolution of the Iberia/Eurasia plate boundary, which is strictly linked to the coeval northward propagation of the southern North Atlantic and the opening of the V-shaped Bay of Biscay margins, has been widely debated and remains an unsolved issue in the Western European tectonic framework. The main reasons for this long-lasting debate are the contrasting interpretations given to the M0 magnetic anomaly in the Bay of Biscay/North Atlantic margins (e.g. Barnett-Moore *et al.*, 2016 and references therein) and the fact that considerable amounts of displacement between the Iberian and Eurasia plates occurred during the ~40 Myr-long C34 magnetic chron (i.e. Aptian *pp*-Santonian) (Neres *et al.*, 2013). This context implies lots of uncertainties on the kinematics of the Iberian plate during the Late Jurassic-Early Cretaceous interval and has left space for very contrasting plate kinematic models in the last 50 years.

The main plate kinematic models that have been proposed up to now can be subdivided into three groups characterized by differences in chronology and kinematics, with models proposing (Fig. 2): i) an eastward displacement of Iberia during the Albian-Cenomanian accommodated by the opening of sinistral pull-apart (Choukroune & Mattauer, 1978) or transtensional basins (Olivet, 1996) in the ~E-W trending North Pyrenean Zone; ii) a left-lateral transcurrent displacement between Iberia and Eurasia accommodated along the ~E-W trending North Pyrenean Fault between the Late Jurassic and the Aptian, followed by Albian-Cenomanian orthogonal (N-S) extension (e.g. Jammes *et al.*, 2009); iii) a scissor opening of the Bay of Biscay margins during the Albian, implying coeval convergence and subduction of several hundreds of kilometers of oceanic crust in the Pyrenean realm (e.g. Srivastava *et al.*, 1990; Sibuet *et al.*, 2004; Vissers & Meijer, 2012; Vissers *et al.*, 2016). This latter group of models is generally considered to not be supported by geological constraintsdue to the substantial lack of geological evidence for subduction and convergence in the Pyrenean domain prior to the Late Cretaceous and to the fact that these models are based on the restoration of the J series magnetic anomalies. These anomalies have been recently demonstrated to not correspond to oceanic magnetic isochrons and are thus not suitable for plate kinematic reconstructions (Nirrengarten *et al.*, 2017; Szameitat *et al.*, 2020). This implies that the most reliable kinematic models correspond to groups i and ii. Although these models agree on the fact that ~400 km of left-lateral displacement must have been accommodated between Iberia and Eurasia, the precise timing of this movement is not a matter of consensus (i.e. Albian-Cenomanian vs. Late Jurassic-Aptian).

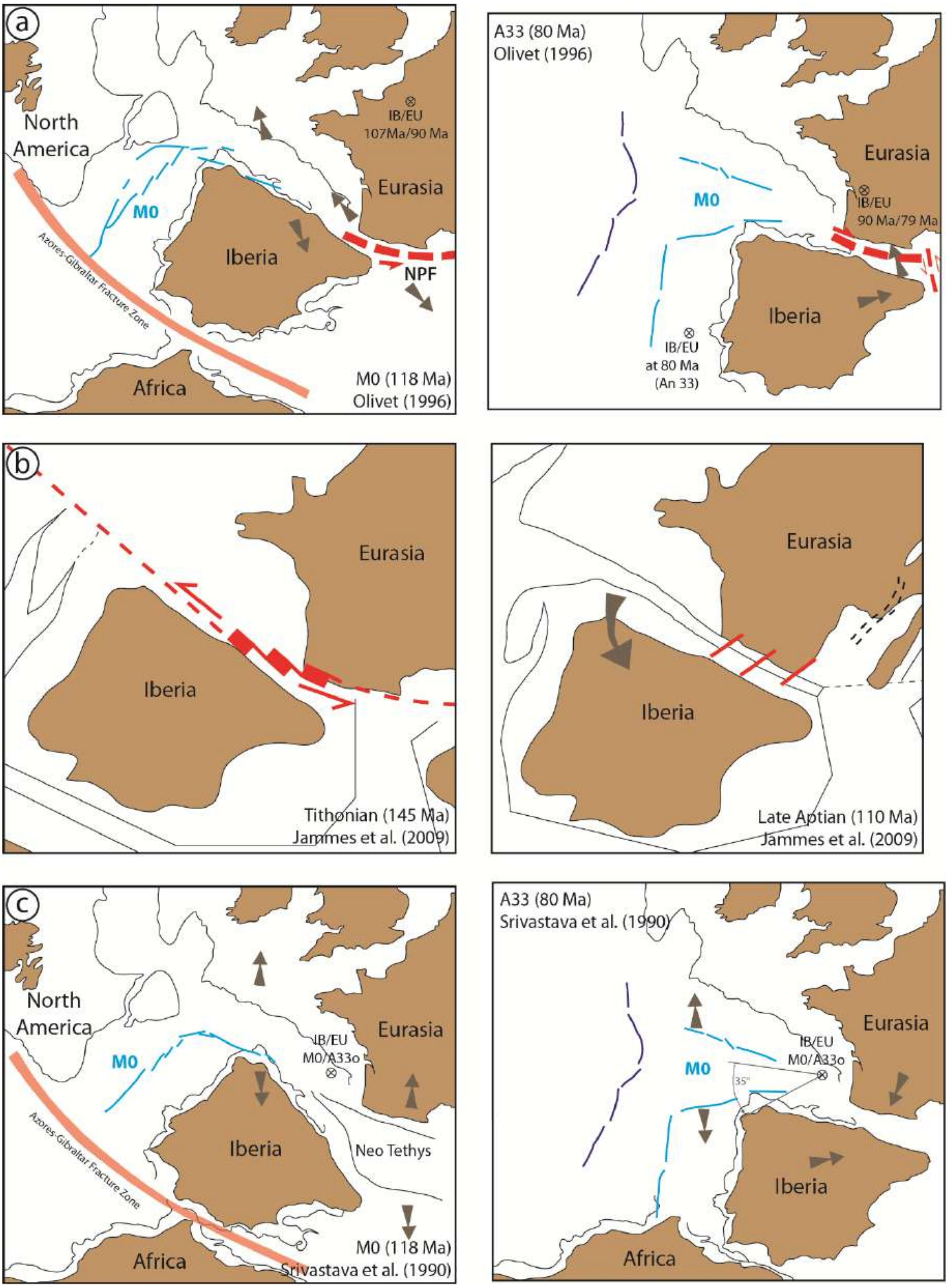


***Fig. 2:** Main plate kinematic models proposing a different Late Jurassic-Cretaceous evolution of the Iberia/Eurasia plate boundary. a) Model by Olivet (1996) proposing an Albian-Cenomanian eastward displacement of the Iberian plate accommodated along the North Pyrenean Fault (as redrawn by Mouthereau et a., 2014). b) Model by Jammes et al. (2009) proposing left-lateral displacement between Iberia and Eurasia accommodated along the North Pyrenean Fault between the Late Jurassic and the Aptian, followed by Albian-Cenomanian orthogonal (N-S) extension. c) Model by Srivastava et al. (2000) and Sibuet et al. (2004) proposing a scissor opening of the Bay of Biscay, implying subduction of a large oceanic domain during the Albian in the Pyrenean realm (as redrawn by Mouthereau et a., 2014).*

In the past, most of these models (i.e. groups i and ii) have postulated that the large-scale sinistral displacement of Iberia relative to Eurasia was accommodated along the North Pyrenean Fault transform system, which has thus been classically considered to represent the plate boundary between the two plates. However, geological evidence from the Pyrenees shows that the left-lateral displacement accommodated by this structure is one order of magnitude smaller (i.e. few tens of kilometers; e.g. Debroas, 1987, 1990, 1995; Canérot, 2016) than what is required by plate kinematic models. More recently, new models have proposed a distribution of the Late Jurassic-Early Cretaceous deformation between the two plates in two (Angrand *et al.*, 2020; Angrand & Mouthereau, 2021; Frasca *et al.*, 2021; King *et al.*, 2021) or three (Tugend *et al.*, 2015a; Nirrengarten *et al.*, 2018) transtensional corridors located in the Iberian Chain Rift System, in the Pyrenees, and in the Parentis Basin (Fig. 3). This partitioning of the deformation in space and time along distinct tectonic corridors better conforms with geological observations (e.g., Angrand et al., 2020; Angrand & Mouthereau, 2021). However, the amount of left-lateral displacement remains larger than what can be inferred from geological observations. Due to the lack of reliable oceanic magnetic anomalies to constrain the Late Jurassic-Early Cretaceous kinematic evolution of the Iberia/Eurasia plate boundary, accurate compilation of the available regional geological constraints is key to resolving this long-lasting debate.

The large study region that includes the Bay of Biscay margins and the numerous surrounding basins, formed during Permian-Cretaceous times (see Section 2) between Iberia and Eurasia, recorded a complex polyphase tectonic history. This domain is characterized by large-scale fault systems, inherited from the Variscan Orogeny (e.g. Arthaud & Matte, 1975; Ziegler, 1988; Matte, 2001). These structures controlled the localization of a large number of rift basins that share the same tectonic history, from the Late Carboniferous-Early Permian collapse of the Variscan belt (e.g. Lago *et al.*, 2004a, b; Saspiturry *et al.*, 2019a), to the Late Permian-Triassic breakup of Pangea (e.g. Sopeña *et al.*, 1988; Frizon de Lamotte *et al.*, 2015), and finally the progressive opening of the North Atlantic-Bay of Biscay oceanic systems from the Jurassic to the Cretaceous (e.g. Vergés &

García-Senz, 2001). Considering the space/time tectonic evolution of this large system of basins as a whole may reveal important constraints on the polyphase evolution of the Iberia/Eurasia plate boundary.

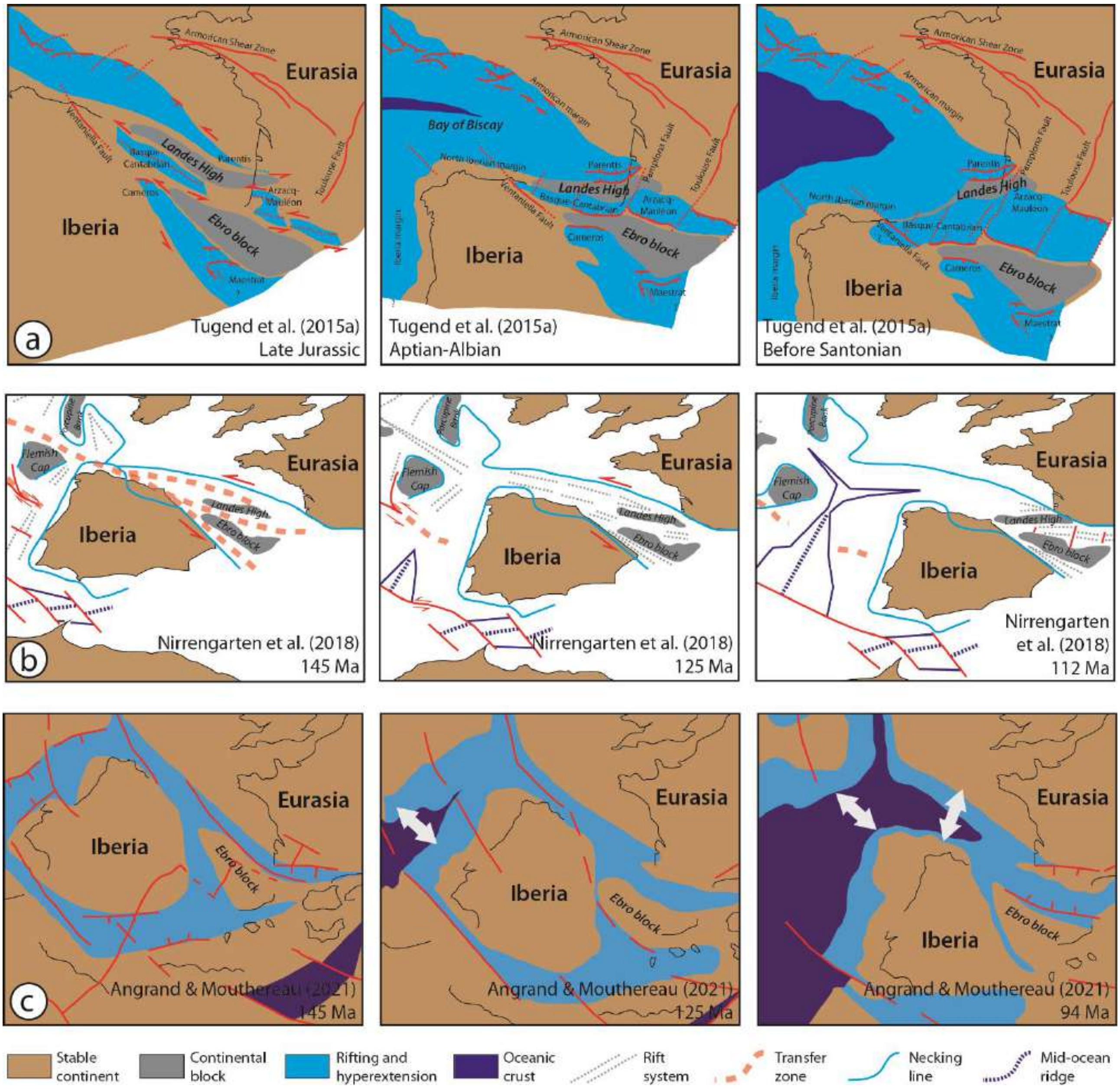


***Fig. 3:*** *Recent plate kinematic models by (a) Tugend et al. (2015a), (b) Nirrengarten et al. (2018), and (c) Angrand & Mouthereau (2021) proposing a partitioning of the Late Jurassic-Early Cretaceous deformation between Iberia and Eurasia in two or three transtensional corridors located in the Iberian Chain Rift System, in the Pyrenees, and in the Bay of Biscay/Parentis system, separated by one or two intervening micro continental blocks (i.e. the Landes High and the Ebro Block).*

In this study, we propose a reappraisal of the Mesozoic tectonic and kinematic evolution of the sedimentary basins across the Iberia/Eurasia plate boundary (Fig. 1). These basins are: (1) the

Bay of Biscay margins, (2) the Asturian Basin, (3) the Iberian Chain basins, (4) the Pre-Ebro Basin, (5) the Basque-Cantabrian Basin, (6) the North Pyrenean Zone basins, (7) the Organyà Basin, (8) the Parentis Basin and (9) the Southern and Northern Aquitaine basins. This review allows for discussion of several key aspects of the Late Jurassic-Early Cretaceous history of this domain, such as the accommodation of the deformation over a large domain at the plate boundary and the parameters that favored distributed rather than localized deformation. This study also allows for inferences to be made about the timing of rotation of the Iberian plate during the Mesozoic and to highlight the contribution to the Mesozoic evolution of the plate boundary of some domains within the Cenozoic foreland basins of the Pyrenees that have been, up to now, disregarded.

## 2. REVIEW OF THE TECTONO-SEDIMENTARY EVOLUTION OF THE IBERIA/EURASIA PLATE BOUNDARY BASINS

The aim of this section is to review the tectono-stratigraphic evolution of the rift basins included in a ~400 km wide region that spans from the Iberian Chain basins (in the southwest) to the Northern Aquitaine Basin (in the northeast) (Fig. 1). This wide domain recorded: i) late-Variscan evolution (Late Carboniferous-Early Permian) as well as Pangea breakup (Late Permian to Triassic-Jurassic boundary); ii) the complex kinematic evolution of these basins during the Late Jurassic-Early Cretaceous rifting in relation to the opening of the V-shaped Bay of Biscay margins, the eastward drift of Iberia, and its coeval counterclockwise rotation. During this latter phase, the Keuper evaporites played an important role as an efficient decoupling layer at the base of the pre-rift sedimentary cover.

### 2.1. Bay of Biscay margins

The Bay of Biscay is a V-shaped E-W trending oceanic basin that opened during the Early Cretaceous between the non-volcanic Western Approaches/Armorican Margin (to the north) and the North Iberian Margin (to the south) (Figs. 1, 2 and 3). Its opening occurred in relation to the northward propagation of the North Atlantic Rift System (e.g. Montadert *et al*., 1974; 1979; Malod & Mauffret, 1990; Barnett-Moore *et al*., 2016 and references therein). This region is characterized by a strong Late Paleozoic tectonic inheritance, mainly consisting of lithospheric scale strike-slip shear zones (e.g. Ziegler, 1988; Burg *et al*., 1994; Matte, 2001; Bourrouilh, 2012 and references therein). The beginning of rifting is constrained to the Early Cretaceous (Berriasian-Late Aptian) (Williams, 1975; Montadert *et al*., 1979). Oceanic spreading started during the Late Aptian, as indicated by a Middle/Late Aptian breakup unconformity on the margins (Thinon *et al*., 2002; Roca *et al*., 2011; Cadenas & Fernández-Viejo, 2017), and ceased before Chron 33 (i.e. Santonian-Campanian boundary) (Williams, 1975). During this period, the northern and southern margins of the Bay of Biscay underwent post-rift thermal subsidence (Thinon *et al*., 2002; Cadenas & Fernández-Viejo, 2017). Despite general consensus that oceanic spreading occurred during magnetic Chron C34 (i.e. Late Aptian-Santonian) (e.g. Williams, 1975; Sibuet *et al*., 2004), the timing of lithospheric breakup and of the formation of the first oceanic crust in the Bay of Biscay domain have been widely debated over the last decades. The debate is mainly due to contrasting interpretations of the M-series magnetic anomalies (see Nirrengarten *et al*., 2017 for an exhaustive review), which in the Bay of Biscay system developed in the distal part of the ocean-continent transition, rather than in the true oceanic domain (Thinon *et al*., 2003; Tugend *et al*., 2014). Even though there is general agreement on the fact that the Late Jurassic-Early Cretaceous Bay of Biscay margins opened in the general context of left-lateral transtension, the relative chronology of the transtensional vs. orthogonal rifting phases and the spatial distribution of the deformation are still widely debated (e.g. Choukroune & Mattauer, 1978; Olivet, 1996; Jammes *et al*., 2009; Tugend *et al*., 2015a; Barnett-Moore *et al*., 2016; Nirrengarten *et al*., 2018; Peace *et al*., 2019; Angrand *et al*., 2020; Frasca *et al*., 2021; King *et al*., 2021).

### ***2.1.1.*** *The Northern Margin*

The Armorican Basin, located at the foot of the Armorican continental slope (Fig. 1), developed during the opening of the Bay of Biscay margins and is filled with up to 7 km of sediments (Bacon *et al*., 1969; Avedik & Howard, 1979; Thinon *et al*., 2002, 2003). It lies on the extremely thinned (<4 km) continental crust (Avedik & Howard, 1979; Montadert *et al*., 1979; Le Pichon & Sibuet, 1981) of an ~80 km wide ocean-continent transition (Thinon *et al*., 2003), which also includes a domain of possibly exhumed sub-continental mantle (Tugend *et al*., 2014). In general, the Armorican Margin (to the east) seems to be characterized by a wider ocean-continent transition and by fewer tilted crustal blocks compared to the Western Approaches Margin (to the west) (Thinon *et al*., 2003). The pre-rift series consist of Late Jurassic (Kimmeridgian-Tithonian) platform carbonates (Thinon *et al*., 2002, 2003). The extensional history of the basin is marked by a rapid pre-Berriasian compartmentalization into horsts and grabens, followed by a significant Berriasian-Aptian subsidence phase which culminated in an abrupt Late Aptian collapse of the transitional domain (Thinon *et al*., 2002). Tectonic inversion related to the Pyrenean convergence phase is very limited on the Armorican side of the Bay of Biscay margins (Thinon *et al*., 2001).

### ***2.1.2.*** *The Southern Margin*

The North Iberian Margin displays much evidence for significant tectonic inversion related to the Late Cretaceous-Cenozoic Pyrenean compression, with incipient southward subduction of the oceanic domain below the continental margin (Boillot *et al*., 1979; Malod *et al*., 1982; Pulgar *et al*., 1996; Alvarez-Marrón *et al*., 1997; Fernández-Viejo *et al*., 1998, 2011; Roca *et al*., 2011). In the eastern (Cantabrian) part of the North Iberian Margin continental shelf, the E-W trending structural high of the Landes Plateau separates the Late Jurassic-Early Cretaceous Parentis Basin (to the north) from the Basque-Cantabrian Basin (to the south) (e.g. Pinet *et al*., 1987; Roca *et al*., 2011) (Fig. 1). In the central (Asturian) part of the continental shelf, the E-W trending structural high of the Le Danois Bank separates the southern ocean-continent transition of the Bay of Biscay margins (to the north) from the Late Jurassic-Early Cretaceous Le Danois Basin (to the south), which represents the offshore part of the Asturian Basin (see Section 2.2. Asturian Basin) (e.g. Pulgar *et al*., 1996; Fernández-Viejo *et al*., 1998; Roca *et al*., 2011; Cadenas & Fernández-Viejo, 2017; Cadenas et al., 2018, 2020) (Figs. 1 and 4a). Apatite fission track ages support exhumation of the lower granulitic crust on the continental slope to the north of the Le Danois Bank during the Berriasian-Early Aptian interval (Fügenschuh *et al*., 2003).

A notable difference between the northern and southern Bay of Biscay margins is the record of the Permian-Triassic rifting phase and its subsequent impact. Indeed, on the Armorican side of the Bay of Biscay system, the sedimentary record of this rifting event seems to be absent (Thinon *et al*., 2002), which implies lack of deposition of the Late Triassic Keuper evaporites in this sector. By contrast, along the North Iberian Margin, the Permian-Triassic rifting is well developed as indicated by the deposition of thick Late Triassic evaporitic deposits at the base of the Jurassic post-rift series (e.g. Lepvrier & Martínez-García, 1990; Espina *et al*., 2004; Cadenas & Fernández-Viejo, 2017; Zamora *et al*., 2017 and references therein). The Keuper evaporites played a fundamental decoupling role during the Late Jurassic-Early Cretaceous evolution of the North Iberian Margin (e.g. Boillot *et al*., 1979; Ferrer *et al*., 2012, 2014; Cadenas & Fernández-Viejo, 2017; Zamora *et al*., 2017; Lagabrielle *et al*., 2020). This configuration is similar to the situation for the easterly Aquitaine Basin, where the Celtaquitaine Flexure, which aligns to the NW with the Armorican continental slope, marks the northern limit of the distribution of the Keuper evaporites in the region (e.g. BRGM *et al*., 1974; see Section 2.8. Aquitaine Basin).

## 2.2. Asturian Basin

The Asturian Basin is an onshore/offshore partially inverted Permian-Mesozoic basin localized on the northern Iberian margin, at the transition between the continental Iberian plate and the oceanic Bay of Biscay system (Lepvrier and Martínez-García, 1990; Cadenas & Fernández-

Viejo, 2017) (Figs. 1 and 4a). In the literature, the offshore part of this basin is also referred to as the Le Danois Basin (e.g. Roca *et al*., 2011) (Fig. 4a). This basin experienced a polyphase rifting history, with an initial Permian-Triassic rifting phase related to Pangea breakup, and a second Middle(?)/Late Jurassic-Early Cretaceous rifting phase resulting from the opening of the Bay of Biscay margins (López-Gómez *et al*., 2019a and references therein). The maximum thickness of its sedimentary fill may reach 10 km (Cadenas & Fernández-Viejo, 2017; López-Gómez *et al*., 2019a). The Upper Triassic sediments consist of Keuper facies evaporitic deposits (Suárez-Rodríguez, 1988; Pieren *et al*., 1995; Cadenas & Fernández-Viejo, 2017). Early/Middle Jurassic carbonate sediments are transgressive over the Permian-Triassic deposits and are overlain by Late Jurassic (Kimmeridgian) syn-rift siliciclastic sequences (Valenzuela *et al*., 1986; Cadenas & Fernández-Viejo, 2017; García-Senz *et al*., 2019a). After a phase of erosion/non deposition between the latest Tithonian and the earliest Barremian (at least in the onshore part of the basin), these deposits are covered by a Barremian to Santonian Cretaceous succession (e.g. González-Fernández *et al*., 2004, 2014). Aptian post-rift limestones unconformably overlie both the Paleozoic and the Jurassic successions on blocks separated by NE-SW trending faults that previously controlled uplift and erosion (Lepvrier and Martínez-García, 1990; González-Fernández *et al*., 2004, 2014; Cadenas & Fernández-Viejo, 2017). However, García-Senz *et al*. (2019a) proposed that the Aptian-Albian series should be considered as syn-rift deposits due to significant thickness variations in these deposits and by analogy with the successions of the Basque-Cantabrian Basin. In the offshore part of the basin, the Neocomian phase of erosion/non deposition is not reported by Cadenas *et al*. (2018, 2020), who rather propose a unique Late Jurassic to Barremian rifting phase. The sag-shaped geometry of the syn-rift infill evidenced by seismic reflection profiles (e.g. Cadenas & Fernández-Viejo, 2017; Cadenas *et al*. 2018; Martín-Chivelet *et al*. 2019) might be related to the presence of a salt decoupling layer at the base of the sedimentary cover, as in other salt-controlled smooth-slope basins of the region (see review in Lagabrielle *et al*., 2020). In addition, Keuper-related syn-rift halokinetic features have been recognized elsewhere in the basin (Boillot *et al*., 1979; Cadenas & Fernández-Viejo, 2017).

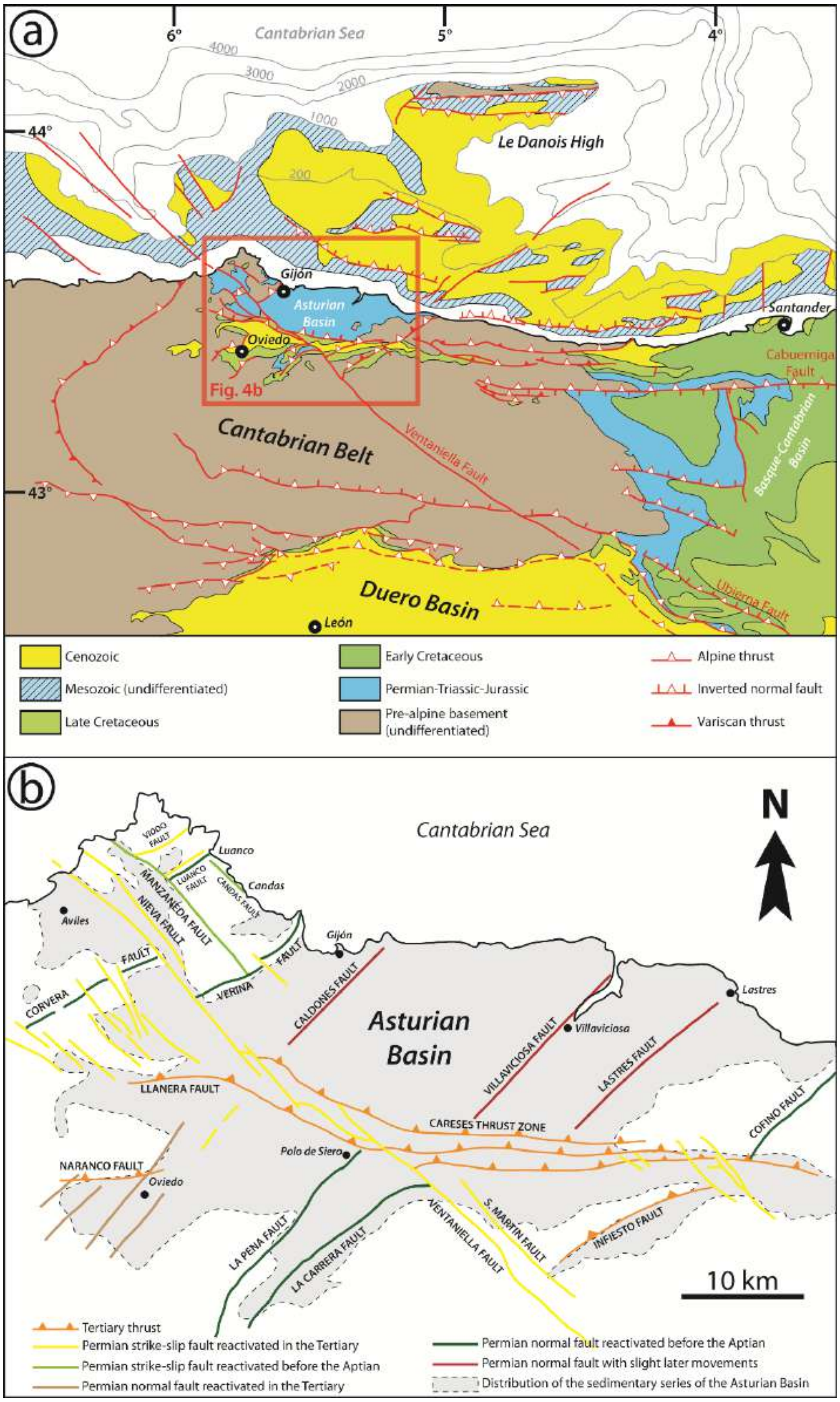


***Fig. 4:*** *Geological map and structural pattern of the Asturian Basin. a) Geological map of the Asturian Basin (including the offshore Le Danois sub-basin) and of the surrounding Cantabrian region (redrawn and modified after Pulgar et al., 1999). b) Simplified structural map of the onshore Asturian Basin with age of (re)activation of the main structures (redrawn and modified after Lepvrier & Martínez-García, 1990).*

The Meso-Cenozoic fault pattern of the basin is inherited from the late Variscan (Permian) period (Lepvrier and Martínez-García, 1990) and includes three sets of fault groups oriented NW-SE, NE-SW and E-W (Juliver *et al.*, 1971; Lepvrier and Martínez-García, 1990; Uzkeda *et al*., 2016; Granado *et al*., 2018) (Fig. 4b). Even though the Mesozoic directions of extension are difficult to estimate, the Late Jurassic-Aptian reactivation of NW-SE trending Permian strike-slip faults and NE-SW trending Permian normal faults (Fig. 4b; Lepvrier and Martínez-García, 1990) may suggest a NW-SE direction of stretching for the Late Jurassic-Early Cretaceous rifting phase. This interpretation is consistent with structural studies showing the influence of NE-SW trending normal faults on the Late Jurassic syn-rift sedimentay profile (Uzkeda *et al*., 2013, 2016). However, these same studies document the coeval Late Jurassic activity of E-W and NW-SE trending sets of normal faults (Uzkeda *et al*., 2016), thus revealing complex syn-rift kinematics. In this context, Granado *et al*. (2018) proposed a NNE-SSW direction of extension based on interpretation of joint set directions. This is consistent with the preponderance of E-W trending normal faults controlling E-W oriented depocentres during rifting in the offshore part of the Asturian Basin, as evidenced by Cadenas & Fernández-Viejo (2017). Moreover, recent studies on the offshore part of the basin proposed a tectonic regime of left-lateral transtension for the Late Jurassic to Barremian rifting phase (Cadenas *et al*., 2020).

### 2.3. The Iberian Chain basins system

The Iberian Chain is a NW-SE trending intraplate belt, which results from the Late Cretaceous-Cenozoic inversion of former Permian-Mesozoic sedimentary basins (e.g. Alvaro *et al*., 1979; Guimerà & Alvaro, 1990; Casas & Faccenna, 2001; Salas *et al*., 2001; Guimerà, 2018 and references therein) (Figs. 1 and 5a). It is composed of two sub-parallel sedimentary troughs separated by the Cenozoic Almazan Basin and that merge in the SE in the Teruel region (Fig. 5a). This latter area corresponds to a significant gravimetric minimum indicating a higher crustal thickness (Salas *et al*., 2001). The southwesterly Castillan-Valencian Branch terminates with the southeasterly South Iberian Basin (and possibly the offshore Columbrets Basin). The northeasterly Aragonese Branch includes the northwesterly Cameros Basin, the Central Iberian Basin and the southeasterly Maestrat (or Maestrazgo) Basin (e.g. Capote *et al*., 2002; Martín-Chivelet *et al*., 2019). To first order, all these basins experienced the same tectono-stratigraphic evolution, with an initial Permian-Triassic rifting and a subsequent Late Jurassic-Early Cretaceous rifting (e.g. Alvaro *et al*., 1979; Salas & Casas, 1993; Van Wees *et al*., 1998; Salas *et al*., 2001; Martín-Chivelet *et al*., 2019). In the following section, we will describe separately the Cameros Basin and the rest of the Iberian Chain basins.

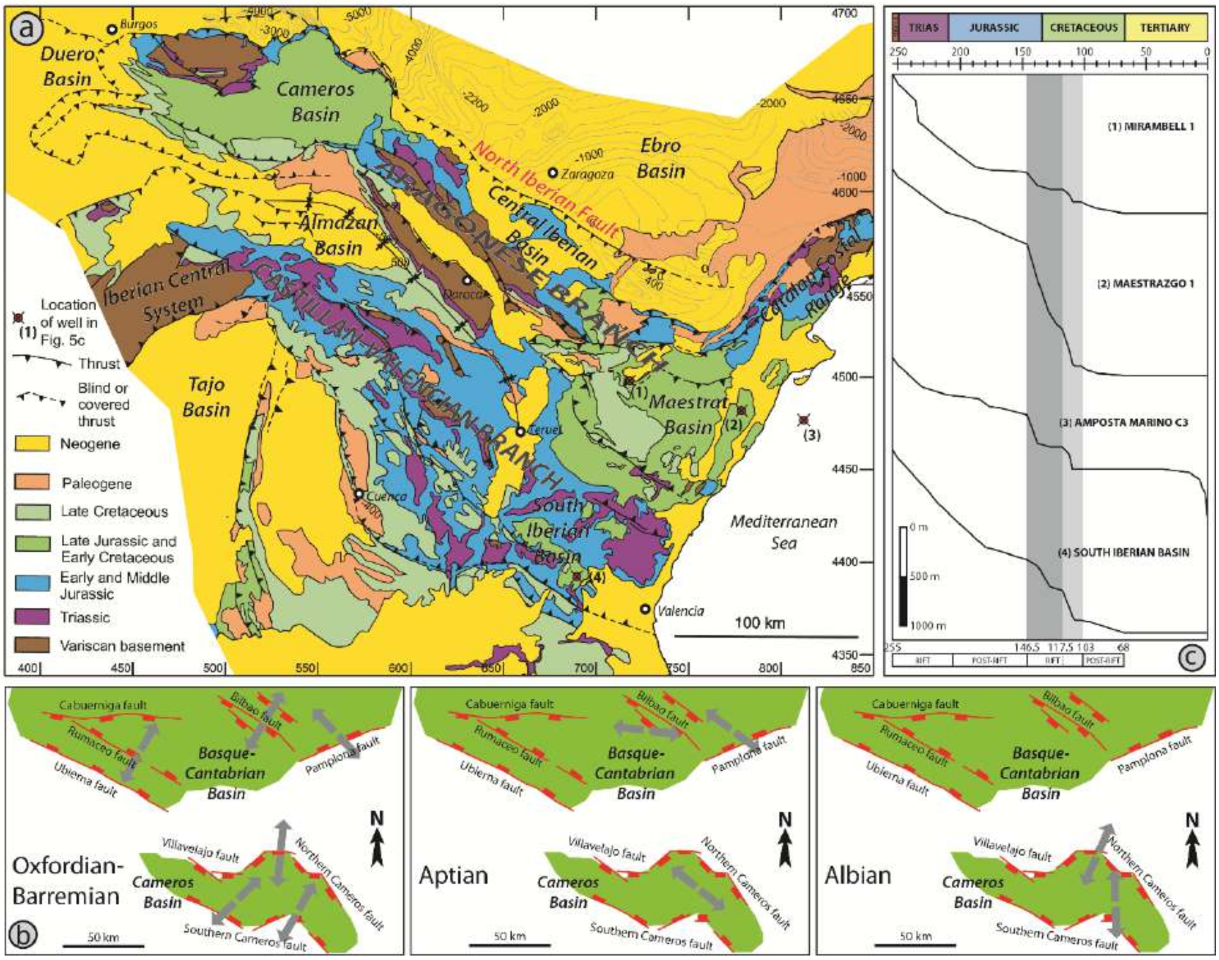


*Fig. 5: a) Simplified geological map of the Iberian Chain System with locations of the main Permian-Mesozoic rift basins (modified after Guimerà, 2018); isolines in the Ebro Basin refer to base of the Cenozoic series. b) Evolution of extension directions (gray arrows) between the Late Jurassic and the Albian in the Cameros and in the Basque-Cantabrian basins as retrieved by anisotropy of magnetic susceptibility (AMS) analysis (modified after Soto et al., 2008). c) Backstripped tectonic subsidence curves for the southeastern part of the Iberian Chain System (Maestrat and South Iberian basins); see (a) for location of the wells (redrawn and modified after Salas et al., 2001). Note that during the Late Jurassic-Early*

*Cretaceous rifting, tectonic subsidence curves are steeper for the Early Cretaceous interval than for the Late Jurassic one.*

### ***2.3.1.*** *Cameros Basin*

The Cameros Basin is an inverted sedimentary basin settled in the northwestern part of the Iberian Chain, which experienced polyphased rifting between the Permian and the Early Cretaceous (e.g. Salas & Casas, 1993; Salas *et al*., 2001). It consists of a ~120 km long and ~80 km wide WNW-ESE trending sedimentary basin, which was compartmentalized during the Late Jurassic-Early Cretaceous rifting stage that affected the Iberian Basin Rift System (Platt, 1990; Martín-Chivelet *et al*., 2019 and references therein) (Fig. 5a). The basin experienced an initial Permian-Triassic rifting episode (Alvaro *et al*., 1979; Salas *et al*., 2001), which culminated with the deposition of a ~500 m thick series of Keuper evaporitic deposits that decouple the overlying Mesozoic cover from its basement (Guiraud and Séguret, 1985; Casas-Sainz, 1993; Casas-Sainz and Gil-Imaz, 1998; Casas *et al*., 2009; Rat *et al*., 2019). This stage was followed by a Jurassic phase of thermal subsidence, which resulted in the deposition of unconformable carbonate platform sequences reaching up to ~800 m in thickness (Platt, 1990; Aurell and Meléndez, 1993; Aurell *et al*., 2003). A second rifting phase took place in the Late Jurassic (Tithonian)-Early Cretaceous (Early Albian) with the deposition of a thick syn-rift sedimentary pile reaching a maximum thickness of ~6500 m to 9000 m (Platt, 1990; Mas *et al*., 1993, 2011; Casas-Sainz and Gil-Imaz, 1998; Salas *et al*., 2001; Omodeo Salè *et al*., 2014; García-Lasanta *et al*., 2017; Martín-Chivelet *et al*., 2019; Rat *et al*., 2019). This phase includes a Late Berriasian–Early Barremian interval of reduced subsidence (Omodeo-Salé *et al*., 2017). The Late Jurassic-Early Cretaceous Cameros Basin has been interpreted by several authors as a ramp-syncline basin developed over a buried S-dipping detachment fault resulting from regional N-S to NNE-SSW extension (Mas *et al*., 1993, 2011; Guimerà *et al*., 1995; Salas *et al*., 2001; Omodeo-Salé *et al*., 2014). Recent interpretations have proposed that the syncline shape of the basin was accentuated by homogeneous ductile thinning of the basement below the Keuper evaporites décollement layer (Lagabrielle *et al*., 2020; Saspiturry *et* *al*., 2021). The lower portion of the sedimentary fill of the basin experienced HT/LP metamorphism due to severe lithosphere thinning and significant sedimentary burial during the Early Cretaceous rifting (e.g. Guiraud & Séguret, 1985; Golberg *et al*., 1988; Mata *et al*., 2001; Rat *et al*., 2019; Saspiturry *et al*., 2021).

Field studies have shown that relevant thickness variations in the Late Jurassic-Early Cretaceous sequences are controlled by both NW-SE and NE-SW trending faults (Platt, 1990). Despite important thickness variations observed across NE-SW trending faults, Platt (1990) interpreted this set of faults as transverse faults (*sensu* Gibbs, 1984) and the NW-SE trending faults as normal faults. Even though most authors agree that the main direction of extension during the Late Jurassic-Early Cretaceous rifting is ~NE-SW, anisotropy of magnetic susceptibility (AMS) studies highlighted a phase of NW-SE stretching recorded in the basin between the Barremian and the Aptian (Soto *et al*., 2008; García-Lasanta *et al*., 2014) (Fig. 5b). This phase seems to coincide also with an increase in tectonic subsidence (e.g. Mas *et al*., 1993; Omodeo-Salé *et al*., 2017; Angrand *et al*., 2020). These observations are consistent with K-Ar dating, documenting an Early Cretaceous phase of left-lateral transtensional displacement along the Río Grío Fault, which bounds the northeastern margin of the transition between the Cameros Basin and the Central Iberian Chain Basin and is part of the larger North Iberian Fault system (Aldega *et al*., 2019).

#### ***2.3.2.*** *The Central and Southern part of the Iberian Chain basins*

This part of the Iberian Chain is composed of several inverted Permian-Mesozoic rift basins, which span from the Cameros Basin (in the NW) to the Mediterranean coastline of the Valencia trough (Figs. 1 and 5a). During the Permian-Triassic rifting, subsidence was controlled by late- to post-Variscan normal and sinistral strike-slip faults (e.g. Alvaro *et al*., 1979; Arche & López-Gómez, 1996; Antolín-Tomás *et al*., 2007). This phase culminated with the deposition of thick Keuper evaporitic series (e.g. Canérot, 1991; Arche & López-Gómez, 1996; Salas *et al*., 2001; Ortí *et al*., 2017; Vergés *et al*., 2020) and was followed by an Early/Middle Jurassic phase of post-rift thermal subsidence resulting in the formation of stable carbonate platforms (e.g. Canérot, 1991; Aurell *et al*., 2003, 2019 and references therein).

Rifting reactivation started during the latest Oxfordian and lasted until the Early Albian (Salas and Casas, 1993; Van Wees *et al*., 1998; Salas *et al*., 2001; Martín-Chivelet *et al*., 2019). This Late Jurassic-Early Cretaceous rifting phase includes two main subsidence phases (latest Oxfordian-Berriasian and Late Hauterivian-Early Albian) separated by a Valanginian-Early Hauterivian phase of reduced subsidence (e.g. Salas and Casas, 1993; Salas *et al*., 2001), whose base is marked by an angular unconformity (Martín-Chivelet *et al*., 2019 and references therein). However, these two phases are not exactly synchronous at the scale of the whole Iberian Chain system. For example, rifting started in the latest Oxfordian in the Maestrat Basin and in the Early Tithonian in the southern part of the Castillan-Valencian Branch (Salas & Casas, 1993; Salas *et al*., 2001). Moreover, the Aragonese Branch recorded a more continuous sedimentary history than the Castillan-Valencian Branch, which is characterized by non-deposition during the Valanginian-Early Hauterivian phase (Martín-Chivelet *et al*., 2019). It is worth noting that in each of the two branches the thickness of the Late Jurassic-Early Cretaceous deposits increases towards the southeast (Martín-Chivelet *et al*., 2019 and references therein).

The structural evolution of the Late Jurassic-Early Cretaceous rifting phase of the Iberian Chain basins is rather complex. It is mainly controlled by NW-SE and NE-SW trending faults (e.g. the High Tagus and Rio Grio faults; Roca *et al*., 1994; Antolín-Tomás *et al*., 2007; Liesa, 2011; Aldega *et al*., 2019; Aurell *et al*., 2019; Martín-Chivelet *et al*., 2019), which were also strongly conditioned by pre-existing structures (e.g. Alvaro *et al*., 1979; Roca *et al*., 1994; Salas *et al*., 2001). Faults and fractures with a NW-SE orientation dominate in the western part of the Maestrat Basin while E-W and NE-SW directions, respectively, prevail in the central and eastern portions of the basin. This pattern has been related to radial extension (i.e. vertical $\sigma_1 >> \sigma_2 \sim \sigma_3$) during the Early Cretaceous (Aranda & Simón, 1993; Antolín-Tomás *et al*., 2007; Martín-Chivelet *et al*., 2019 and references therein). Accordingly, magnetic fabric distribution reflecting the extension directions during the Early Cretaceous reveals two main perpendicular stretching directions, with mainly NE-SW extension directions characteristic of the northwestern part of the basin, while NW-SE directions of stretching prevail in the southeastern domain (García-Lasanta *et al*., 2015). More generally, the southeastern termination of the Iberian Chain basins system shows an overall NW-SE direction of extension during the Late Jurassic-Early Cretaceous rifting, as indicated by extensional fault patterns and associated salt tectonics (mainly trending NE-SW) in the southeastern Maestrat Basin (Roca *et al*., 1994; Vergés *et al*., 2020) and by the opening direction of the Columbrets Basin in the Valencia trough (Etheve *et al*., 2018). The Columbrets Basin consists of an 8-9 km thick Mesozoic sequence that was initiatied in the Triassic (Roca, 1994) and experienced hyper-extension during the Albian (Etheve *et al*., 2018). This same Early Cretaceous extensional pattern is also reported for the Garraf Basin of the Catalan Coastal Range (to the east of the Ebro Basin), which also experienced the same Permian-Mesozoic tectonic evolution (Anadón *et al*., 1979; Salas *et al*., 2001; López-Gómez *et al*., 2019b; Martín-Chivelet *et al*., 2019). From a kinematic perspective, Martín-Chivelet *et al*. (2019) suggest that the distribution of accelerated subsidence in small depocenters during the Late Hauterivian-Early Albian phase could be explained by strike-slip transtensional tectonics related to left-lateral displacement between Iberia and Eurasia.

### 2.4. Pre-Ebro Basin

The Ebro Basin represents the pro-foreland basin of the Pyrenean Belt that developed during the Late Cretaceous-Cenozoic inversion of the Pyrenean rift system (e.g. Puigdefàbregas *et al*., 1986; Gaspar-Escribano *et al*., 2001; Vergés *et al*., 2002). It is delimited to the north by the South Pyrenean Frontal Thrust, to the east by the Catalan Coastal Range and to the south by the Iberian Chain (Figs. 1 and 5a). As with most of the domains included between the Iberian Chain and the Aquitaine Basin, the Pre-Ebro Basin recorded a phase of Permian-Early Lias rifting which culminated in the deposition of thick Keuper evaporites (Deselgaux & Moretti, 1988; Arche & López-Gómez, 1996; Arche *et al*., 2004, 2007; Vargas *et al*., 2009; De la Horra *et al*., 2013; Ortí *et al*., 2017). During this phase, a structural high, characterized by no sedimentation, was probably located in the northeastern sector of the present-day Ebro Basin. This high has been previously referred to in the literature as the Ebro High (e.g. Vergés *et al*., 1998; Arche *et al*., 2004; Vargas *et al*., 2009; Ortí *et al*., 2017). In general, the Permian-Early Lias rifting was strongly influenced by structures inherited from the Variscan period (e.g. Arche & López-Gómez, 1996; Arche *et al*., 2004). Since the Middle Lias, the Pre-Ebro Basin was characterized by post-rift thermal subsidence that allowed the development of stable Jurassic carbonate platforms (Deselgaux & Moretti, 1988; Filleaudeau, 2011). Traces of the Late Jurassic-Early Cretaceous rifting phase are hardly perceptible in the present-day Ebro Basin. Indeed, these have been overprinted by the Pyrenean compression and the post-compressive sedimentary fill (Fig. 5a). This led most authors to suggest that the Late Jurassic-Early Cretaceous rifting did not affect this domain (e.g. Deselgaux & Moretti, 1988; Gaspar-Escribano *et al*., 2001). Such an interpretation implies that the Ebro realm behaved as an undeforming continental block between the Iberian Chain and the Pyrenean rift corridors during the opening of the Bay of Biscay margins (e.g. Gaspar-Escribano *et al*., 2001; Tugend *et al*., 2015a; Nirrengarten *et al*., 2018; Angrand *et al*., 2020; Lagabrielle *et al*., 2020; Angrand & Mouthereau, 2021; Frasca *et al*., 2021; King *et al*., 2021) (Fig. 3). However, there are observations consistent with the occurence of a Late Jurassic-Early Cretaceous rifting phase in this domain. Indeed, tectonic subsidence analyses performed on the Bujaraloz-1 well (located ~50 km to the ESE of the town of Zaragoza; Fig. 6a), show two intervals of increasing subsidence rates (Vargas *et al*., 2009; Fig. 6b). The first subsidence phase is recorded during the Kimmeridgian-Tithonian(?), followed by a second and more pronounced subsidence phase during the Barremian-Aptian(?) (Vargas *et al*., 2009; Fig. 6b). A map of the Mesozoic substratum of the Cenozoic deposits of the Ebro Basin, constructed by interpolating well log data, shows that Early Cretaceous sediments are locally preserved below the foreland basin cover (Fig. 6a), particularly to the east of Zaragoza and in the northwestern corner of the basin between the Basque-Cantabrian and Cameros basins (Filleaudeau, 2011). Finally, modeling of gravimetric data suggests the presence of up to ~4000 m of Mesozoic sediments preserved in the northwestern part of the Ebro Basin below the Cenozoic cover (Wehr *et al*., 2018; see their Fig. 14a), even though this interpretation contrasts with interpretation of seismic data proposing the presence of only few hundred meters of Mesozoic sediments (Casas-Sainz *et al*., 2000). These reconstructions suggest significant E-W variations in the distribution (preservation?) of the Mesozoic sediments. During the Late Cretaceous (Campanian?), in response to the onset of Iberia/Eurasia N-S convergence, the Pre-Ebro Basin realm underwent emersion and erosion before the development of the Cenozoic foreland basin sedimentation (e.g. Puigdefàbregas & Souquet, 1986; Gaspar-Escribano *et al*., 2001). This evolution is consistent with a tectonic context of syn-convergence flexural bulging of the subducting plate. This is probably one of the main reasons why evidence of the Late Jurassic-Early Cretaceous rifting phase is so poorly preserved below the Cenozoic cover.

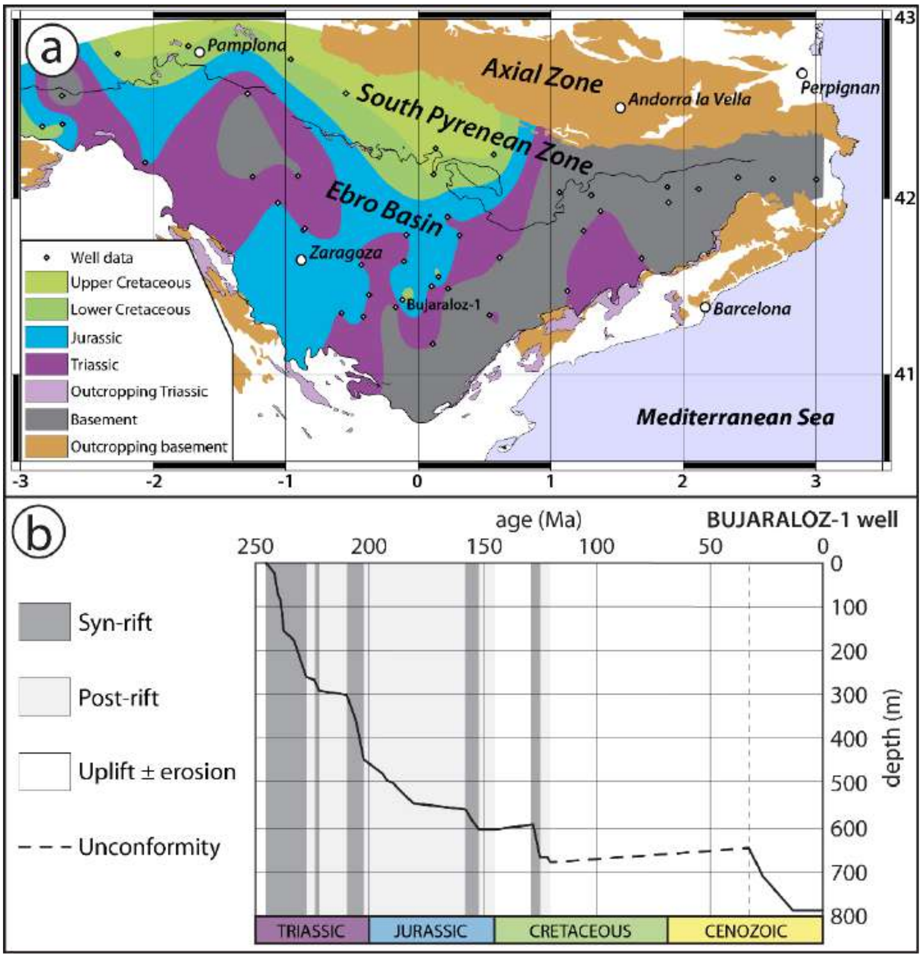


***Fig. 6:*** *a) Age map of the sedimentary series underlain below the Cenozoic cover of the Ebro Basin as derived from interpolation of well log data (modified after Filleaudeau, 2011). b) Tectonic subsidence curve for the Bujaraloz-1 well (see location in (a); modified after Vargas et al., 2009).*

## 2.5. Basque-Cantabrian Basin

The Basque-Cantabrian Basin is a mildly inverted Permian-Mesozoic basin localized at the transition between the Basque Pyrenees of France (Mauléon Basin) and the Cantabrian Range (Rat, 1988; García-Mondéjar *et al*., 1996; Carola *et al*., 2013; Pedrera *et al*., 2017; Teixell *et al*., 2018) (Figs. 1 and 7). After an initial Permian-Triassic rifting phase, which included the deposition of a thick pile of evaporitic Keuper sequences (Rat, 1988; Espina *et al*., 2004; Serrano and Martínez del Olmo, 2004), a subsequent Late Jurassic (Tithonian)-Early Cretaceous rifting phase took place (Rat, 1988; García-Mondéjar *et al*., 1996; 2004; Cámara, 2017; Pedrera *et al*., 2017 and references therein). The thickness of the sedimentary fill in the basin may reach 12,5 km (Rat, 1988; García-

Mondéjar *et al*., 1996; 2004). The latter extensional phase also included a Valanginian-Barremian generalized regression (e.g. Cámara, 2020 and references therein), and eventually resulted in severe crustal thinning leading to subcontinental mantle exhumation below the Cretaceous basin during the Late Albian-Early Cenomanian interval (Mendia and Gil-Ibarguchi, 1991; Roca *et al*., 2011; DeFelipe *et al*., 2017; Pedrera *et al*., 2017). During this phase, pre- and syn-rift sedimentary series exposed in the eastern part of the basin (Nappe des Marbres Unit) recorded HT-LP metamorphism in relationship with mantle exhumation (e.g. Ducoux *et al*., 2019 and references therein) (Fig. 7). The crucial role of the decoupling level represented by the Keuper evaporites during the Late Jurassic-Early Cretaceous rifting has been evidenced by several studies in the region (e.g. Serrano and Martínez del Olmo, 2004; Tavani *et al*., 2013; Cámara, 2017; DeFelipe *et al*., 2017; Pedrera *et al*., 2017; Bodego *et al*., 2018; Lescoutre, 2019; Cámara, 2020; Lagabrielle *et al*., 2020; Lescoutre & Manatschal, 2020).

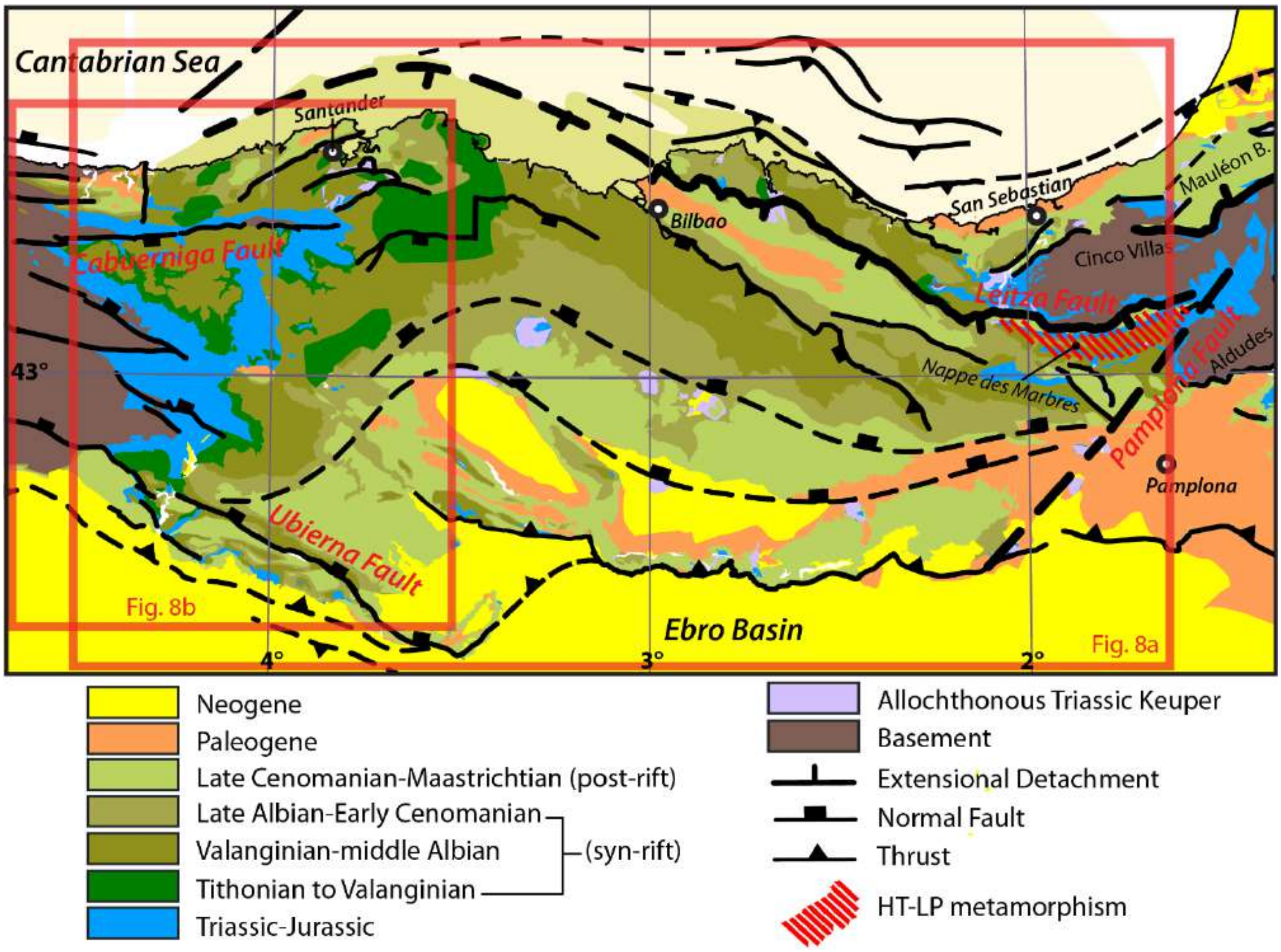


***Fig. 7:*** *Geological map of the Basque-Cantabrian Basin with locations of the structural maps presented in Fig. 8 outlined in red boxes (modified after Pedrera et al., 2017).*

From a kinematic perspective, a lateral component of displacement has been proposed during this last extensional event (Rat, 1988; García-Mondéjar, 1989; García-Mondéjar *et al*., 1996 and references therein). Even though a complex fault pattern was recorded during the Aptian-Albian (Urgonian) rifting phase, which was potentially related to a strong Permian-Triassic inheritance (García-Mondéjar, 1989; García-Mondéjar *et al*., 1996 and references therein), evidence for sinistral strike-slip activity on NW-SE trending faults suggests a transtensional regime during this phase rather than a purely orthogonal rifting mode (García-Mondéjar, 1989; García-Mondéjar *et al*., 1996; Agirrezabala & Dinares-Turell, 2013; Cámara, 2017) (Fig. 8). Accordingly, meso-structural data (Soto *et al*., 2007; Tavani & Muñoz, 2012) and AMS studies (Soto *et al*., 2007, 2008; Oliva-Urcia *et al*., 2013) highlight a complex pattern of extension directions during the Late Jurassic-Early Cretaceous, with dominant NE-SW and subordinate NW-SE directions of extension. This complex pattern of extension directions may have resulted from variations in the orientation of the stress regime during rifting, with a pre-Aptian NE-SW direction of extension (related to orthogonal rifting) and a NW-SE direction of stretching during Aptian/Albian times (Soto *et al*., 2007 and references therein). This scenario is consistent with minor mid-Cretaceous (Aptian/Albian) inversion on N-S trending structures in relation to sinistral strike-slip movement along en-echelon NW-SE oriented faults in the western Basque-Cantabrian Basin (Soto *et al*., 2011) (Fig. 8b). In contrast, other authors have argued for a strictly NE-SW orthogonal direction of extension associated with folding of the supra-salt sedimentary cover during the entire Late Jurassic-Albian rifting stage, based on structural analyses (e.g. Tavani & Muñoz, 2012; Tavani *et al*., 2013). Accordingly, the same authors attribute the sinistral strike-slip movement recorded along NW-SE structures to the Late Cretaceous-Cenozoic convergence (e.g. Tavani, 2012; Tavani *et al*., 2013). However, this interpretation disagrees with paleomagnetic studies showing a Late Albian anticlockwise rotation of syn-rift deposits in the northern part of the Basque-Cantabrian Basin, with that rotation interpreted as being related to ESE-trending sinistral wrench faulting (Agirrezabala & Dinares-Turell, 2013).

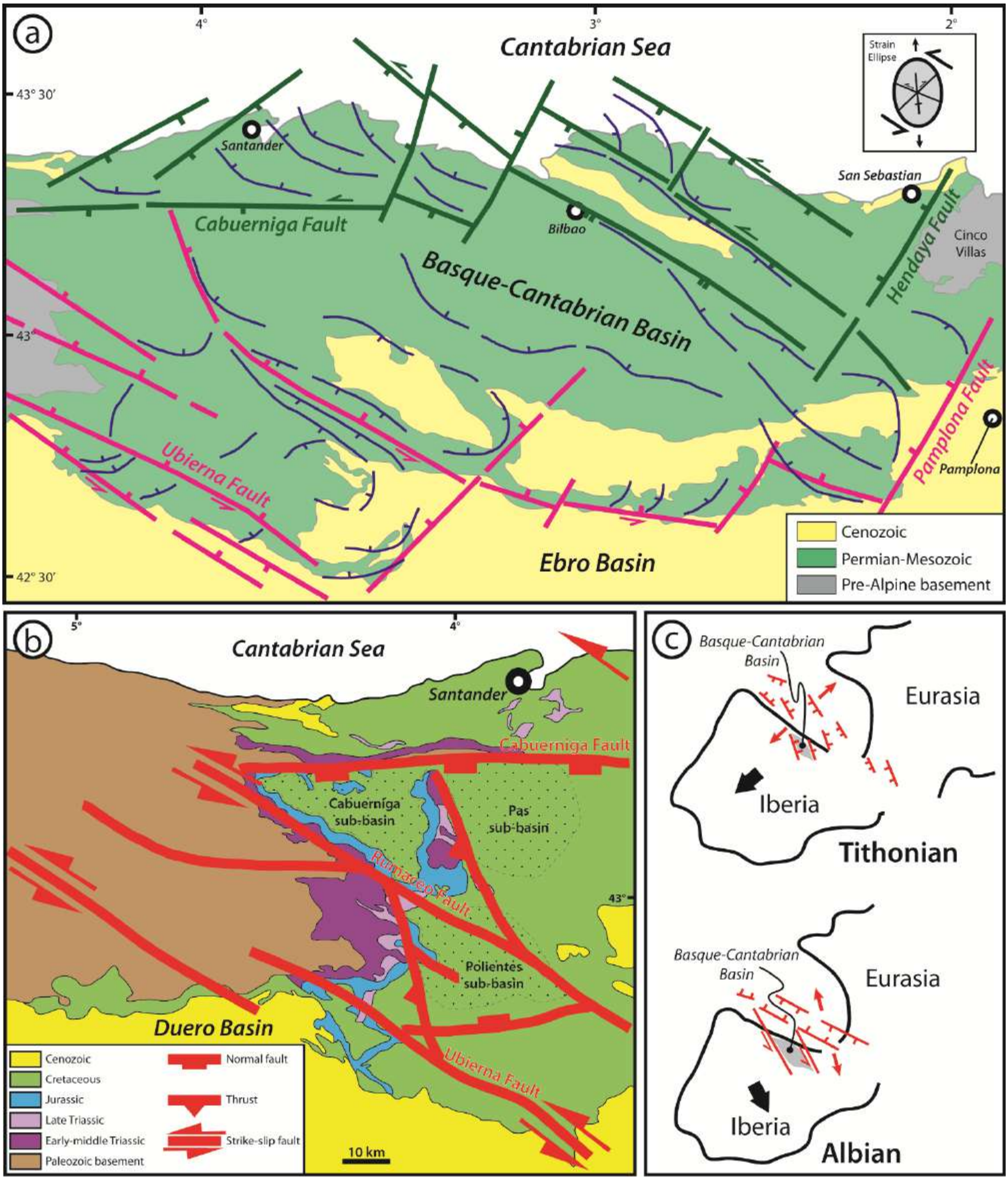


***Fig. 8:*** *a) Simplified geological map of the Basque-Cantabrian Basin with structural patterns related to the Late Jurassic-Early Cretaceous rifting phase and with the strain ellipse (in the inset) related to the inferred tectonic regime (redrawn and modified after Cámara, 2017). In green: Northern rift fault system; in magenta: southern rift fault system; in blue: listric faults and salt-related structures. b) Geological map of the western Basque-Cantabrian Basin showing the structural pattern of the main faults controlling the mid-Cretaceous transtensional phase (modified after Soto et al., 2011). c) Schematic reconstruction of the relative position of Iberia and Eurasia between the Late Jurassic and the Early Cretaceous with the location of the Basque-Cantabrian Basin in the frame of the plate kinematic context; this model proposes an initial Tithonian phase of orthogonal rifting followed by a subsequent phase of left-lateral transtensional extension during the Albian (redrawn and modified after Soto et al., 2007).*

## 2.6. The Pyrenean belt and its Mesozoic basins

The Pyrenean belt is an E-W trending alpine orogen marking the border between France and Spain. It resulted from the Late Cretaceous-Cenozoic convergence and collision between Iberia and Eurasia, which induced the tectonic inversion of an Early Cretaceous hyperextended rift system (e.g. Choukroune & ECORS Team, 1989; Roure *et al.*, 1989; Muñoz, 1992; Teixell, 1998; Vergés *et al.*, 2002; Teixell *et al.*, 2018; Espurt *et al.*, 2019; Saspiturry *et al.*, 2020a; Angrand *et al.*, 2021). Between the northerly Aquitaine retro-foreland basin and the southerly Ebro pro-foreland basin, the Pyrenees are classically subdivided into three different E-W trending structural domains (from north to south) (Fig. 9): i) the North Pyrenean Zone, ii) the Axial Zone and iii) the South Pyrenean Zone (e.g. Mattauer, 1968; Choukroune & Séguret, 1973; Choukroune, 1992). The North Pyrenean Zone is bounded to the north by the North Pyrenean Frontal Thrust and to the south by the North Pyrenean Fault, which has often been considered to mark the limit between the Iberian and Eurasian plates (e.g. Mattauer, 1968; Choukroune & Mattauer, 1978; Choukroune & ECORS Team, 1989; see Section 2.6.2 for details on the controversies regarding this latter structure). This structural domain is the one that best preserves traces of the Early Cretaceous rifting phase, whose main expression corresponds to the North Pyrenean basins (see Section 2.6.1). It also includes a series of amygdaloidal Paleozoic massifs, 10s of kilometres wide, known as North Pyrenean massifs (see Section 2.6.3). The pre- and syn-rift sedimentary fill of the southern North Pyrenean basins, enclosed between the North Pyrenean massifs and the North Pyrenean Fault, recorded widespread syn- to post-rift (~110-85 Ma) HT/LP metamorphism (the Internal Metamorphic Zone, e.g. Ravier, 1959; Azambre & Rossy, 1976; Albarède & Michard-Vitrac, 1978; Montigny *et al.*, 1986; Golberg *et al.*, 1986; Golberg & Maluski, 1988; Golberg & Leyreloup, 1990; Clerc *et al.*, 2015) related to severe crustal thinning and mantle exhumation during the Cretaceous (e.g. Vielzeuf & Kornprobst, 1984; Golberg & Maluski, 1988; Dauteuil & Ricou, 1989; Golberg & Leyreloup, 1990; Clerc &

Lagabrielle, 2014 ; Clerc *et al*., 2015; Lagabrielle *et al*., 2016) (Fig. 9). The Axial Zone represents the Paleozoic basement of the Pyrenean belt and lies between the North and South Pyrenean zones. Traces of the Cretaceous rifting are substantially lacking in the Axial Zone. The South Pyrenean Zone is bounded to the south by the South Pyrenean Frontal Thrust and is mainly composed of Mesozoic series covered by syn- to post-orogenic Cenozoic deposits. In the central part of this domain, the South Pyrenean Central Unit exposes several allochthonous Cretaceous basins (such as the Organyà and Cotiella basins), which are decoupled at their base at the level of the Triassic evaporites and thrusted southward onto the Cenozoic foreland (see Section 2.6.4).

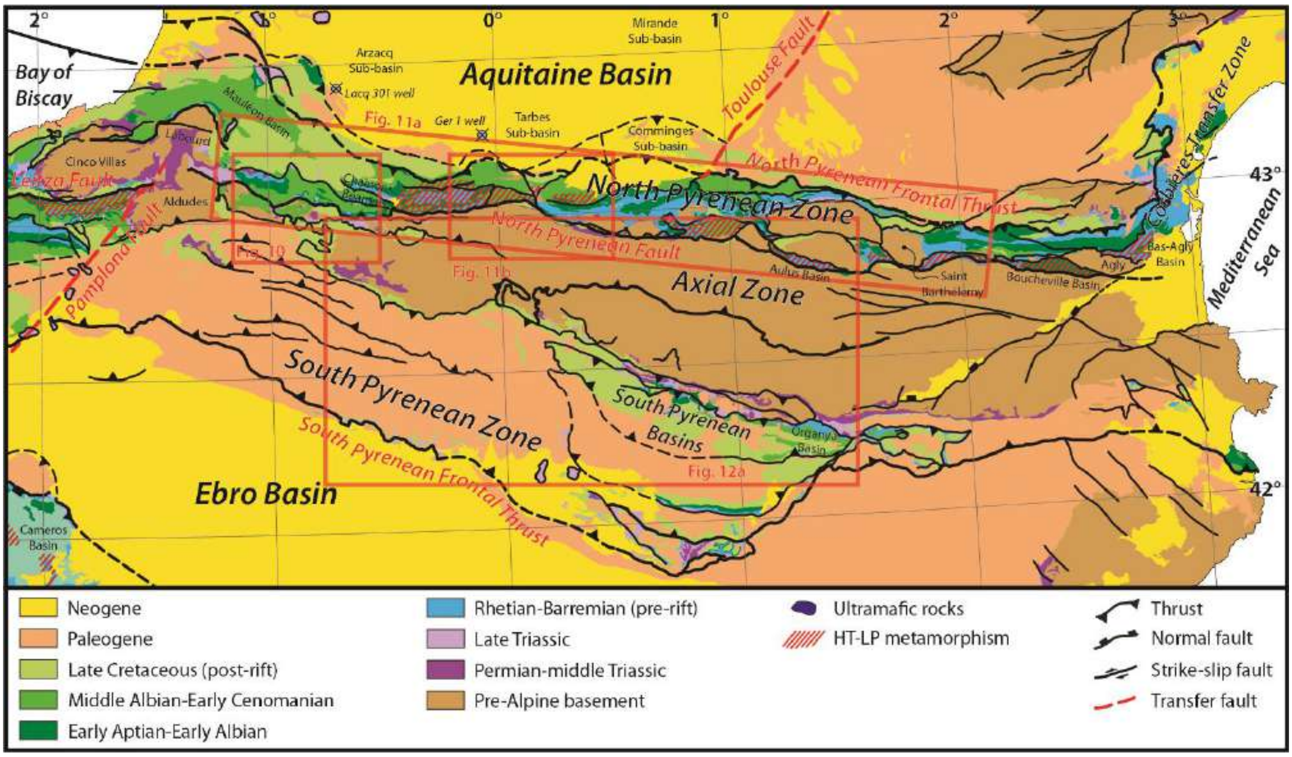


***Fig. 9:*** *Geological map of the Pyrenean Belt with locations of the structural maps and schematic reconstructions presented in Figs. 10, 11 and 12 as the boxes outlined in red and of the wells from the Southern Aquitaine basins presented in Fig. 14 (modified after Ducoux et al., 2019).*

***2.6.1.*** *North Pyrenean basins*

The North Pyrenean basins consist of a series of inverted Cretaceous sedimentary basins developed along an E-W trend, from the westerly Mauléon Basin to the easterly Boucheville/Bas-Agly basins (Fig. 9). Extension and crustal thinning in the North Pyrenean basins started during the latest Carboniferous-Early Permian, related to the late- to post-orogenic evolution of the Variscan

Belt (e.g. Lucas, 1985; Bixel and Lucas, 1987; de Saint Blanquat *et al*., 1990; Bouhallier *et al*., 1991; de Saint Blanquat, 1993; Cochelin *et al*., 2017; Saspiturry *et al*., 2019a; Asti *et al*., 2021). This initial phase of thinning was followed by a Late Permian-Triassic rifting phase culminating in the deposition of ~1-2 km thick Keuper evaporitic series (e.g. Curnelle, 1983; Calvet & Lucas, 1995; Canérot *et al*., 2005; Biteau *et al*., 2006; Saspiturry *et al*., 2019a). These first episodes of crustal stretching resulted in a significant thinning of the continental crust prior to the Early Cretaceous hyperextensional stage (Espurt *et al*., 2019; Asti *et al*., 2021). Subsequently, a quiet period of thermal subsidence led to the development of stable transgressive carbonate platforms and to the deposition of up to ~2000 m thick post-rift Jurassic sediments (e.g. Delfaud and Henry, 1967; Delfaud and Villanova, 1967; Arnaud-Vanneau *et al*., 1979; Canérot, 1991; Lenoble, 1992; James, 1998; Debrand-Passard *et al*., 1995 and references therein). The late period of this phase is marked by a generalized emersion of the carbonate platforms, with local development of bauxites, between the Late Jurassic and the earliest Barremian (e.g. Souquet *et al*., 1995; Combes *et al*., 1998; James, 1998; Canérot *et al*., 1999; Saspiturry *et al*., 2019b). A subsequent generalized transgression allowed the deposition of Barremian-Aptian carbonate platform sediments above the Neocomian erosional surface (Delfaud & Villanova, 1967; Arnaud-Vanneau *et al*., 1979; Souquet *et al*., 1995 and references therein). These deposits onlapped on a syncline-shaped Jurassic substratum, which probably acquired this geometry during the Neocomian emersion phase (Saspiturry *et al*., 2019b). This might indicate that the onset of Cretaceous extension in the North Pyrenean realm occurred at some time during the Neocomian emersion, leading to the formation of a syncline-shaped basin like in early phases of other smooth-slope basins across the Iberia-Eurasia transition (see Lagabrielle *et al*., 2020; Saspiturry *et al*., 2021), but without the deposition of proper syn-rift deposits due to intense bauxitization of the Jurassic substratum. However, the main rifting phase in the North Pyrenean Zone is considered to have occurred during the Early Albian-Early Cenomanian period and led to the deposition of 4000-5000 m thick syn-rift turbiditic series (Souquet *et al*., 1985, 1995; Debroas, 1990; Debroas *et al*., 2010). This phase culminated in crustal breakup resulting in lithospheric mantle exhumation below the Cretaceous basins (e.g. Vielzeuf & Kornprobst, 1984; Fabriès *et al*., 1991, 1998; Jammes *et al*., 2009; Lagabrielle *et al*., 2010; Teixell *et al*., 2016; Espurt *et al*., 2019; Garcia-Senz *et al*., 2019b; Labaume & Teixell, 2020; Saspiturry *et al*., 2020a, 2021b; Angrand *et al*., 2021). Syn-rift series are covered by Middle Cenomanian-Santonian post-rift calci-turbidites, which predate the onset of the Late Santonian to Eocene convergence phase (e.g. Puigdefàbregas & Souquet., 1986; Razin, 1989; Puigdefàbregas *et al*., 1992; Debrand-Passard *et al*., 1995 and references therein). During the Cretaceous rifting phase, the thick Keuper evaporites at the base of the pre-rift stratigraphic pile played a fundamental decoupling role and strongly controlled the architecture and the thermal regime of the Cretaceous basins (Canérot, 1988; Jammes *et al*., 2009, 2010a; Lagabrielle *et al*., 2010, 2020; Corre *et al*., 2018; Duretz *et al*., 2019; Saspiturry *et al*., 2021). From the beginning of the Albian extension to the Santonian onset of rift inversion, the pre-rift and syn-rift series recorded a significant thermal anomaly which resulted in HT-LP metamorphism (Albarède and Michard-Vitrac, 1978; Montigny *et al*., 1986; Golberg *et al*., 1986; Golberg and Maluski, 1988; Clerc *et al*., 2015; Lescoutre *et al.*, 2019; Saspiturry *et al.*, 2020b) controlled by an abnormally elevated thermal gradient, i.e. ~60-80°C/Km (Vacherat *et al*., 2014; Corre, 2017; Hart *et al*., 2017; Asti *et al*., 2021; Saspiturry *et al*., 2020b).

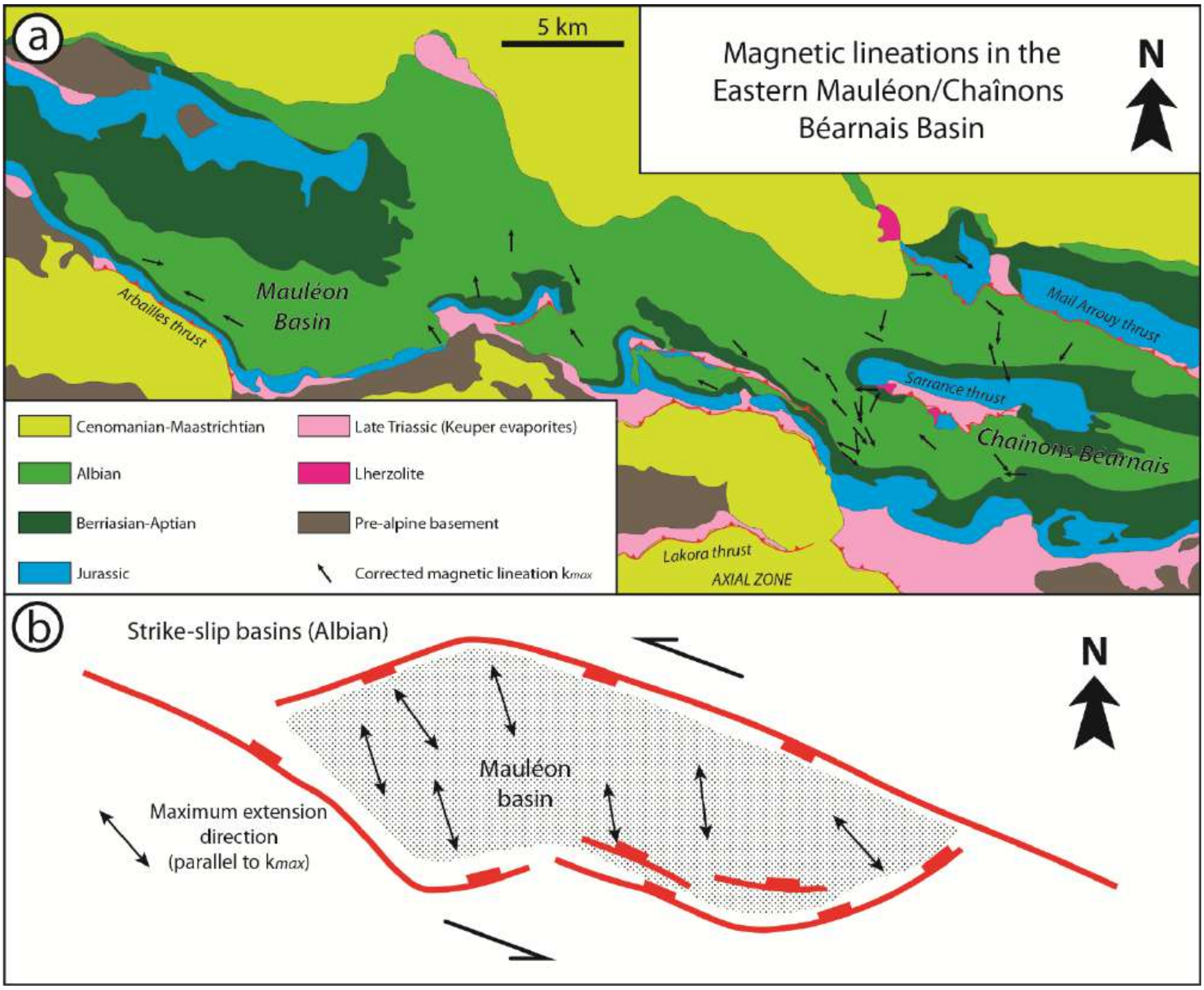


***Fig. 10:*** *a) Geological map of the Eastern Mauléon/Chaînons Béarnais Basin with orientations of the magnetic lineations after bedding correction retrieved by AMS studies. b) Schematic model proposing the development of the Albian rifting phase in the Mauléon Basin under a sinistral strike-slip regime and illustrating the possible orientation of the magnetic lineations before the Cenozoic compression. Both images are modified after Oliva-Urcia et al., 2010.*

The kinematic evolution of the North Pyrenean rift system has been debated for a long time and remains a very controversial subject. No consensus exists on the stretching direction among the different North Pyrenean basins. The main consequence has been the proposal of different kinematic models explaining their formation, spanning from pull-apart transtensional tectonics (e.g. Choukroune et Mattauer., 1978; Debroas, 1978, 1987) to orthogonal rifting (e.g. Jammes *et al*., 2009; Masini *et al*., 2014). While in the western Pyrenees the Mauléon Basin mainly shows evidence for a NNE-SSW trending direction of extension during its mid-Cretaceous opening (e.g. Jammes *et al*., 2009; Masini *et al*., 2014; Lescoutre, 2019; Saspiturry *et al*., 2019b), the rest of the North Pyrenean basins display compelling evidence for a NW-SE trending transtensional opening.

Several studies have proposed that the North Pyrenean Zone would have accommodated the sinistral movement of the Iberian plate with respect to Europe as a transtensional corridor where pull-apart basins developed (e.g. Le Pichon *et al*., 1970; Choukroune *et al*., 1973; Choukroune, 1976, 1992; Choukroune & Mattauer, 1978; Peybernès et Souquet, 1984; Debroas, 1990, 1995). In the Chaînons Béarnais region, immediately to the east of the Mauléon Basin, AMS studies have revealed a main N-S to NW-SE direction of stretching during the Albian rifting resulting from left-lateral transtension (Oliva-Urcia *et al*., 2010) (Fig. 10). Accordingly, Canérot (2017) proposed that the transitional domain between the Mauléon and Chaînons Béarnais basins opened as a pull-apart basin between the latest Aptian and the Early Cenomanian, controlled by sinistral displacement along its northern and southern margins. In the central North Pyrenean Zone, studies on the tectono-stratigraphic evolution of the sedimentary basins have proposed a pull-apart mechanism with a NW-SE trending direction of stretching (Debroas, 1987, 1990, 1995, 2003) (Fig. 11). From the Baronnies Basin (to the west) to the Bessède-de-Sault region (to the east), most of the stretching lineations developed in the sedimentary cover, in relation to the syn-rift HT-LP metamorphism, point to a NW-SE direction of stretching, consistent with a transtensional opening of the Pyrenean rift system (Clerc, 2012; Clerc *et al*., 2015; Ducoux, 2017). A notable exception is represented by the eastern termination of the North Pyrenean basins (i.e. Boucheville Basin and Bas-Agly syncline), where stretching lineation directions are more scattered and trend NNE-SSW, E-W and N-S (e.g. Clerc, 2012; Vauchez *et al*., 2013; Clerc *et al*., 2015, 2016; Chelalou *et al*., 2016; Ducoux, 2017). To sum up, evidence for NW-SE trending oblique extension is rare in the western (i.e. Mauléon Basin) and easternmost (i.e. Boucheville Basin and Bas-Agly syncline) Pyrenees, where a NNE-SSW direction of extension is documented (e.g. Vauchez *et al*., 2013; Clerc *et al*., 2015, 2016; Ducoux, 2017; Lescoutre, 2019; Saspiturry *et al*., 2019b), but is widespread all along the central and eastern parts of the North Pyrenean Rift System (e.g. Clerc *et al*., 2015; Ducoux, 2017).

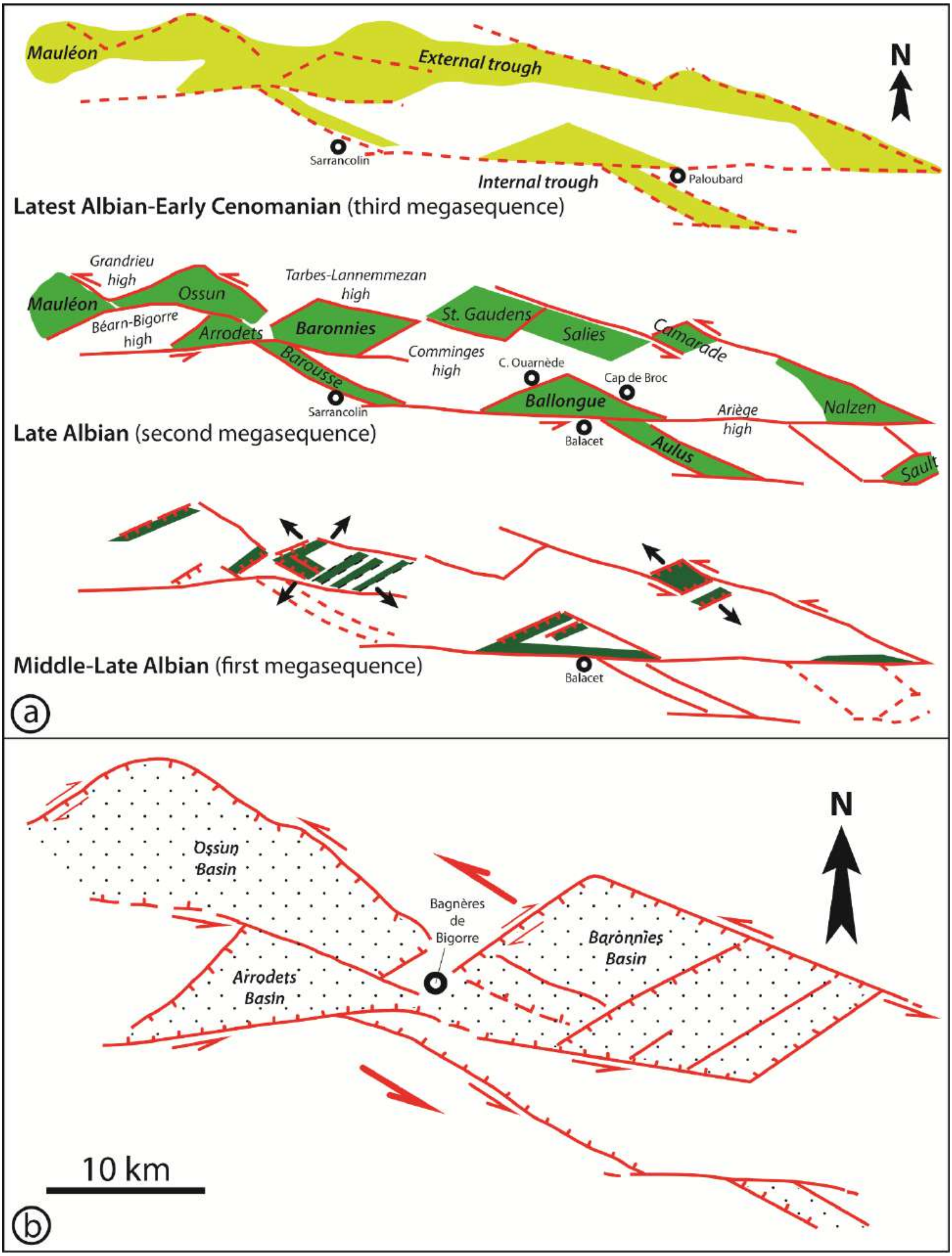


***Fig. 11:*** *a) Schematic representation of the progressive development of the North Pyrenean basins between the Middle Albian and the Early Cenomanian by gradual connection of isolated pull-apart basins to form a single sedimentary trough in a left-lateral transtensional regime (modified after Debroas, 1995, 2003). b) Schematic structural model illustrating the opening of the rift basins exposed in the Bigorre region as sinistral pull-apart basins during the Albian-Cenomanian (modified after Debroas, 1990).*

### ***2.6.2.*** *The North Pyrenean Fault*

The North Pyrenean Fault is a nearly E-W trending, ~300 km long, sub-vertical strike-slip structure which was inherited from late-Variscan times and has classically been considered to represent the limit between the Iberian and Eurasian plates (e.g. Mattauer, 1968; Choukroune, 1976; Choukroune & Mattauer, 1978; Choukroune & ECORS Team, 1989) (Figs. 1 and 9). Its formation has been related to a series of strike-slip shear zones that accommodated the dextral displacement between Iberia and Eurasia during the late-Variscan period (e.g. Arthaud & Matte, 1975; Matte 2001). Afterwards, it was characterized by left-lateral kinematics during the Early Cretaceous (e.g. Choukroune, 1976; Choukroune & Mattauer, 1978).

Often presented in the literature as a single and continuous structure, the North Pyrenean Fault is indeed a strike-slip fault system consisting of several subparallel segments (see historical review in Souquet *et al.*, 1977). This system is more or less continuously exposed between the easternmost Pyrenees and the Chaînons Béarnais region (to the west), but its trace fades away to the west between the Chaînons Béarnais and the Labourd Paleozoic Massif (e.g. Hall & Johnson, 1986). Further west, it aligns with the strike-slip Leitza Fault of the eastern Basque-Cantabrian Basin, separating the Cinco Villas Paleozoic Massif and the Nappe des Marbres metamorphic unit (Figs. 7 and 9). This structure has often been considered as the western prolongation of the North Pyrenean Fault (e.g. Choukroune, 1976; Rat, 1988; Mendia & Ibarguchi, 1991; Combes *et al.*, 1998). The transition zone between these two domains consists of a complex corridor of en-echelon strike-slip faults (Canérot *et al.*, 2004; Canérot, 2016 and references therein). However, recent publications have proposed that the Leitza Fault actually corresponds to a former syn-rift detachment fault which was subsequently reactivated during the convergence (see DeFelipe *et al.*, 2018; Ducoux *et al.*, 2019; Lescoutre, 2019; Lescoutre & Manatschal, 2020; Manatschal et al., 2021) such that the strike-slip component is only minor.

Several plate kinematic models have considered that the North Pyrenean Fault accommodated ~400-500 km of left-lateral displacement between Iberia and Eurasia during the Late Jurassic-Early Cretaceous (e.g. Le Pichon *et al.*, 1970; Choukroune & Mattauer, 1978; Olivet, 1996; Jammes *et al.*, 2009) (Fig. 2). However, despite widespread evidence for a NW-SE transtensional component during the opening of the Pyrenean rift system, the maximum sinistral displacement observed on the North Pyrenean Fault is on the order of ~20 km (Debroas, 1987). The minor contribution of this fault to the Late Jurassic-Early Cretaceous eastward displacement of Iberia is also suggested by the insignificant displacement of the previous paleogeographic markers (e.g. Peybernès, 1978; Canérot, 2016). Some authors have also suggested that the deformation between the Iberian and Eurasian plates was not accommodated strictly by the North Pyrenean Fault, but rather by the diffused continental transtensional system of pull-apart basins represented by the North Pyrenean Zone during the Late Jurassic, which later stretched under ~NNE-SSW orthogonal extension during the Aptian-Cenomanian (e.g. Jammes *et al.*, 2009; Tugend *et al.*, 2015a).

#### ***2.6.3.*** *North Pyrenean Basement*

The Pyrenees were mainly affected by Carboniferous to Permian metamorphism due to crustal thinning and lithospheric mantle delamination (Denèle *et al.*, 2014; Cochelin *et al.*, 2017; Lemirre *et al.*, 2019 and references therein), resulting in the partial melting of the middle/lower crust, which then intruded into the base of the upper crust of the Axial Zone as gneiss domes along major ductile shear zones (Denèle *et al.*, 2007; 2009; Cochelin *et al.*, 2017, 2018a, 2018b). Within the Variscan crust of the Pyrenees, thinning was accommodated by the activation of extensional shear zones at the top of migmatitic gneiss domes (Mezger and Passchier, 2003; Cochelin *et al.*, 2017). The associated direction of stretching was both longitudinal and transverse, illustrating strain partitioning within the partially molten crust (Cochelin *et al.*, 2018b).

Several ductile extensional shear zones are exposed in the Paleozoic basement of the North Pyrenean Zone. Nevertheless, the interpretation of the shear zones exposed in the North Pyrenean massifs is not always straightforward and their periods of activity have been proposed to be either Carboniferous-Permian or Cretaceous in age. However, some ductile extensional structures undoubtedly related to the Cretaceous rifting event exist. In the Urdach Massif of the Chaînons Béarnais (western Pyrenees), crustal rocks associated with the exhumed lithospheric mantle display an ENE-WSW trending stretching lineation, associated with a top-to-the-ENE sense of shear (Asti *et al*., 2019; Lagabrielle *et al*., 2019). This extensional deformation has been constrained to the Late Albian by $^{40}Ar/^{39}Ar$ dating on muscovite (Asti *et al*., 2019). Moreover, in the Turon de la Técouère ultramafic massif (Chaînons Béarnais) stretching lineations trending NW-SE are associated with a top-to-the-NW extensional shear zone developed during the Cretaceous mantle exhumation (Vissers, *et al*., 1997; Newman *et al*., 1999). This direction of extension is also consistent with observations from the Lherz ultramafic massif exposed in the Aulus Basin (e.g. Lagabrielle & Bodinier, 2008).

In the Saint Barthélemy North Pyrenean Massif, a south-verging extensional shear zone is exposed (Passchier, 1982). Even though early studies have considered a Cretaceous age for the formation of this shear zone (e.g. Passchier, 1984; de Saint Blanquat *et al*., 1986), studies on its tectono-metamorphic evolution suggest rather a late/post-Variscan age (Permian) for its activation (de Saint Blanquat *et al*., 1990; de Saint Blanquat, 1993; Delapierre *et al*., 1994; Lemirre, 2018). However, some minor reactivation of this shear zone during the Cretaceous rifting cannot be ruled out (Costa & Maluski, 1988; de Saint Blanquat *et al*., 1990; Odlum & Stockli, 2020). A similar situation is reported for the Agly North Pyrenean Massif (eastern Pyrenees), where a top-to-the-NNE late Variscan extensional shear zone (Bouhallier *et al*., 1991; Olivier *et al*., 2008) has been proposed to also have been reactivated during the Cretaceous rifting event (Vauchez *et al*., 2013; Clerc *et al*., 2016; Odlum & Stockli, 2019).

*__2.6.4.__ Organyà Basin (South Pyrenean Zone)*

The Organyà Basin is a WNW-ESE trending allochthonous Late Jurassic-Early Cretaceous sedimentary basin exposed in the central part of the South Pyrenean Zone (Berástegui *et al*., 1990; Muñoz, 1992; Vergés & García-Senz, 2001) (Figs. 9 and 12). It is thrusted ~100 km southward with respect to its original position and it is decoupled at its base at the level of the Triassic Keuper evaporites (Muñoz, 1992; Puigdefàbregas *et al*., 1992; Mencos *et al*., 2015). In its present-day position, it resides over Permian-Triassic basins, which in turn lie unconformably over the Variscan basement or over Carboniferous-Permian sediments deposited during the collapse of the Variscan belt (Vergés & García-Senz, 2001 and references therein). The total thickness of the sedimentary fill is ~5000-6000 m, including about 4000-5000 m of latest Tithonian-Middle Albian syn-rift deposits (Berástegui *et al*., 1990; Dinarès-Turell & García-Senz, 2000; Vergés & García-Senz, 2001; García-Senz & Muñoz, 2019 and references therein). The rifting phase includes a sedimentary hiatus between the uppermost Valanginian and the Early Barremian (e.g. Dinarès-Turell & García-Senz, 2000), followed by an increase in sedimentation rates during the Aptian-Early Albian, culminating in a Middle Albian-Middle Cenomanian unconformity (Berástegui *et al*., 1990; Dinarès-Turell & García-Senz, 2000; García-Senz & Muñoz, 2019 and references therein). This uppermost unconformity is also coeval with rifting and mantle exhumation in the North Pyrenean basins (e.g. Lagabrielle *et al*., 2010). Paleomagnetic studies of the syn-rift sedimentary fill have highlighted a ~35° counter clockwise vertical axis rotation during the Albian, which has been interpreted as reflecting the coeval rotation of the whole Iberian plate (Gong *et al*., 2008). Deposition of Late Cenomanian-Early Santonian post-rift series precedes the onset of tectonic inversion in the Late Santonian (Mencos *et al*., 2015 and references therein).

At present, there is no consensus on the kinematic evolution of the Organyà Basin during the Early Cretaceous rifting phase. AMS studies in the syn-rift series provided scattered directions of the magnetic fabric (Gong *et al*., 2009; Oliva-Urcia *et al*., 2011) (Fig. 12a). In particular, Gong *et* *al*. (2009) proposed that this complex pattern is the result of a N-S direction of extension (in present-day coordinates) during the Early Cretaceous (orthogonal) rifting, partially modified during the following compressional phase. Nevertheless, Oliva-Urcia *et al*. (2011), whose interpretation is strengthened by the presentation of coherent mineralogical and meso-structural data and by a comparison with the adjacent Cotiella Basin, proposed that the AMS pattern resulted from NW-SE oriented extension in a left-lateral transtensional tectonic regime (Fig. 12a). By contrast, Tavani *et al*. (2011a) propose a NNE-SSW direction of extension (i.e. orthogonal rifting) for the opening of the Organyà Basin, based on macro- and meso-structural observations on the southern margin of the basin, although this study also reports the existence of NE-SW trending normal faults and tension gashes developed during the rifting phase (Fig. 12b).

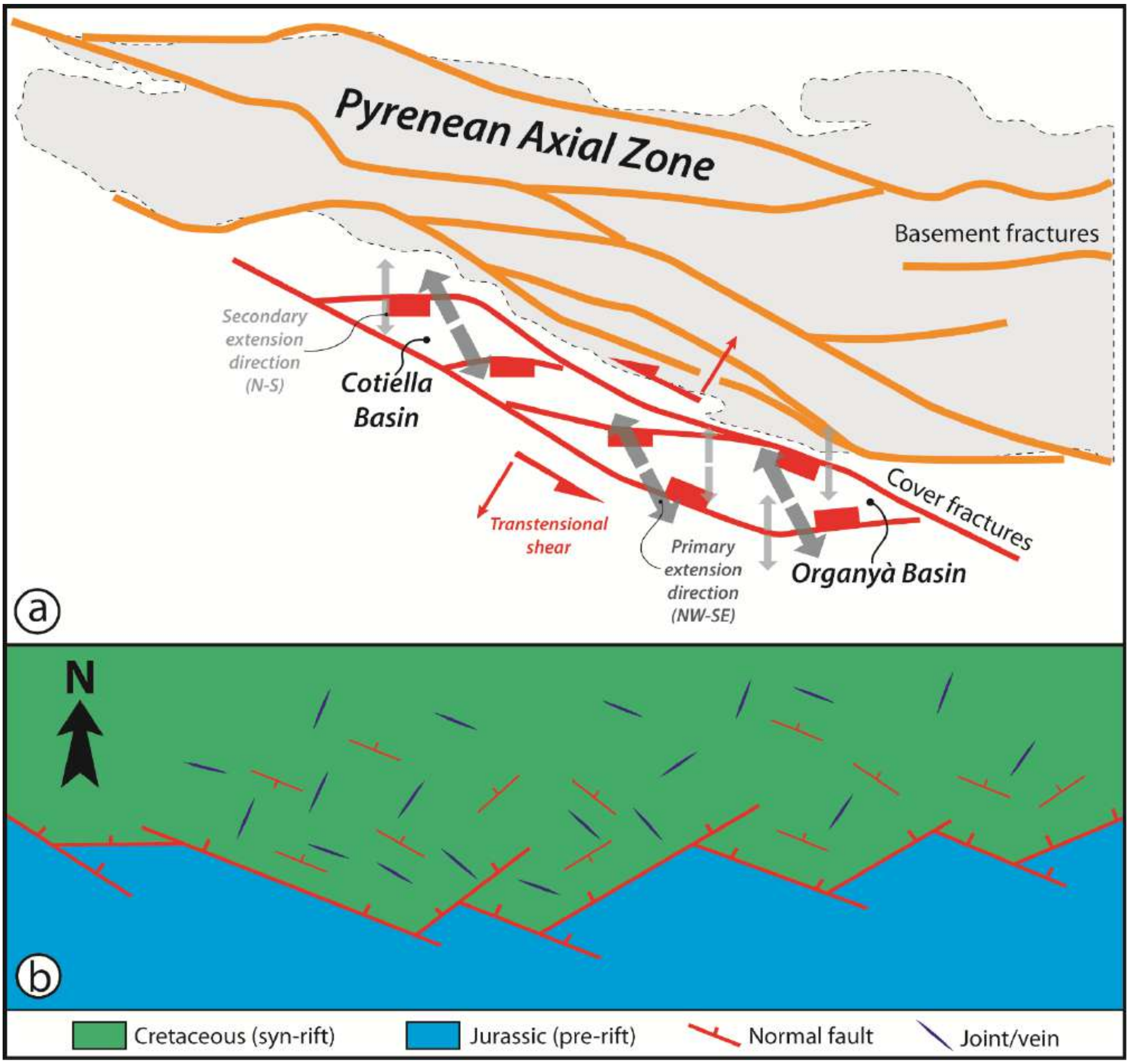


***Fig. 12:*** *a) Schematic representation of faulting relationships in the Pre-Alpine basement of the Pyrenean Axial Zone and in the Mesozoic series of the South Pyrenean basins, with illustration of the extension directions (grey arrows) during the Aptian-Albian transtensional interval retrieved by structural and AMS studies (redrawn and modified after Oliva-Urcia et al., 2011). b) Schematic map view representation of the structural patterns related to the Early Cretaceous extensional phase on the southern margin of the Organyà Basin, showing the general orientation of the main extension-related structures such as normal faults and joints/veins (modified after Tavani et al., 2011a).*

### 2.7. Parentis Basin

The Parentis Basin is a slightly inverted, E-W trending offshore basin. It represents the eastern termination of the V-shaped Bay of Biscay rift system and is located between the Southern Armorican Shelf (to the north) and the Landes Plateau (to the south) (e.g. Bois *et al*., 1997) (Figs. 1, 13a and 14a). It is filled by up to 10-11 km of Permian-Mesozoic sediments accumulated in response to ~40 km of crustal stretching (Brunet, 1994; Bourrouilh *et al.*, 1995; Bois *et al.*, 1997; Vergés & García-Senz, 2001 and references therein). The continental crust has been progressively thinned to a total thickness of only 5-6 km below the base of the basin (e.g. Pinet *et al.*, 1987; Bois *et al.*, 1997) (Figs. 13b and c). An initial phase of Permian-Triassic rifting culminated in the deposition of thick Keuper evaporites and was followed by the deposition of up to ~2 km thick Jurassic post-rift series (e.g. Mathieu, 1986; Desegaulx & Brunet, 1990; Brunet, 1994; Bourrouilh *et al.*, 1995). A subsequent rifting phase took place between the latest Jurassic (Kimmeridgian/Tithonian boundary?) and the Early Cretaceous (Early Albian) resulting in the accumulation of up to ~4-5 km thick syn-rift deposits (e.g. Mathieu, 1986; Brunet, 1984, 1994; Curnelle, 1995). This phase includes a Neocomian interval of reduced subsidence (e.g. Brunet, 1997) and the development of a top-Barremian unconformity (e.g. Ferrer *et al.*, 2012 and references therein). Several studies have highlighted the important decoupling role played by the Keuper evaporites in the lower part of the pre-rift series during the Early Cretaceous rifting phase (e.g. Jammes *et al.*, 2010a, b, c; Ferrer *et al.*, 2012, 2014; Lagabrielle *et al.*, 2020). After the Late Albian, the Parentis Basin underwent post-rift thermal subsidence (e.g. Mathieu, 1986; Roca *et al.*, 2011) and thickness variations observed in the Late Cretaceous deposits are mainly controlled by post-rift salt diapirism (Roca *et al.*, 2011).

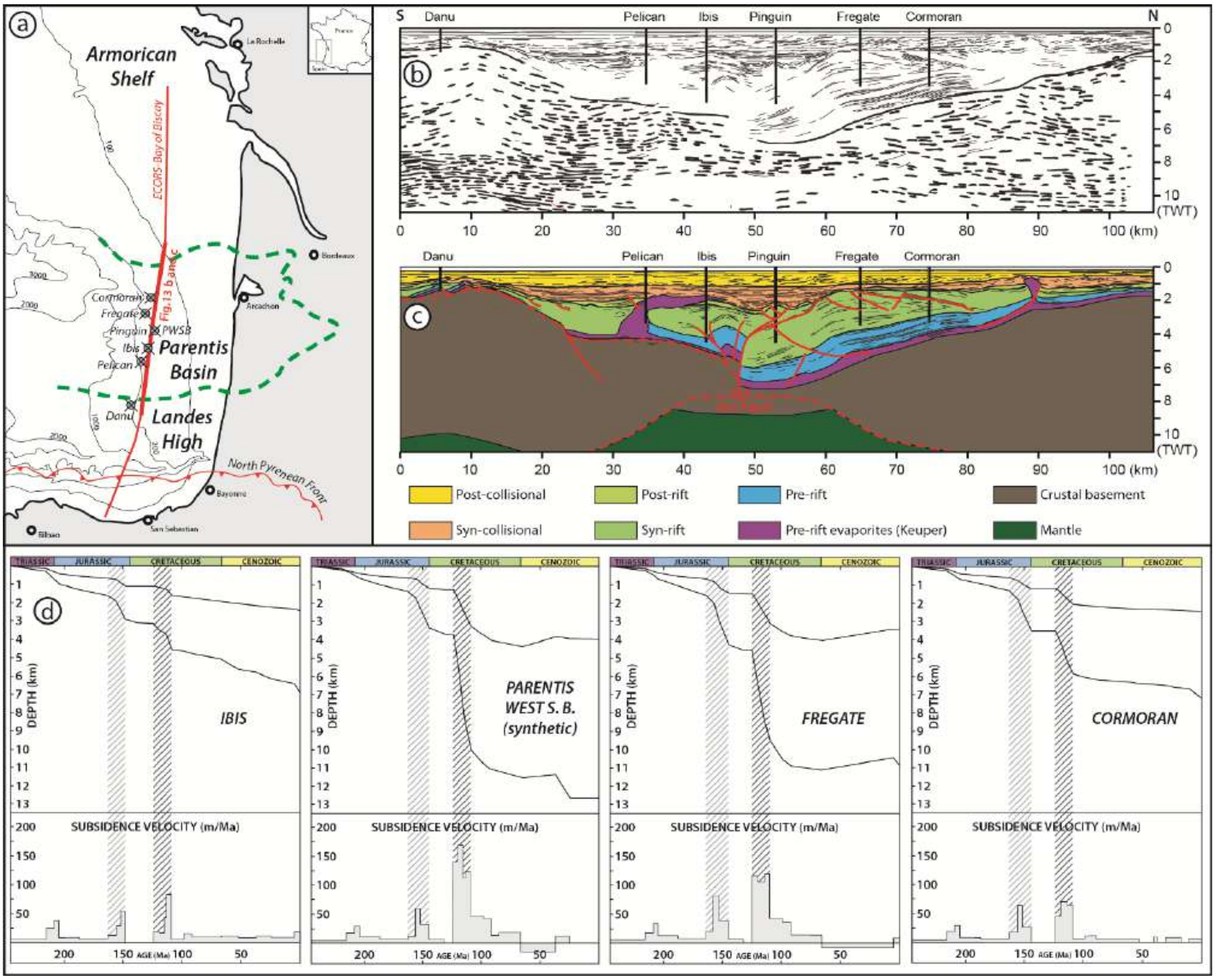


***Fig. 13:*** *a) Locations of the ECORS-Bay of Biscay seismic reflection profile across the Parentis Basin and of the boreholes used for its calibration (redrawn and modified after Bois et al., 1997). b) Line drawing and c) interpretation of the central portion of the ECORS-Bay of Biscay seismic reflection profile (modified after Jammes, 2009). Note the overall flower structure of the Parentis Basin in cross section, with most of the (reactivated) extensional structures converging towards the Ibis Fault. d) Tectonic subsidence curves and tectonic subsidence velocities corrected for sea-level and water depth variations for three oil wells (Ibis, Fregate and Cormoran) and one synthetic well (Parentis West S. B.; see Brunet, 1991) (redrawn and modified after Brunet, 1997). Upper curves represent tectonic subsidence under water with local isostatic compensation, while lower curves represent basement deepening curves with decompacted sediments (see Brunet, 1997 for details on applied corrections). Note that during the Late Jurassic-Early Cretaceous rifting, tectonic subsidence is noticeably faster in the Early Cretaceous interval than in the Late Jurassic interval.*

Even though sinistral strike-slip pull-apart mechanisms have been proposed for the Cretaceous rifting phase (e.g. Choukroune & Mattauer, 1978; Mathieu, 1986; Biteau *et al*., 2006; Jammes *et al*., 2010a, b, c), deep seismic investigations did not provide irrefutable evidence for such a tectonic scenario (e.g. Bois *et al*., 1997). In particular, Mathieu (1986) proposes a first phase of N-S extension during the Late Jurassic-Aptian and a second Late Aptian-Early Albian phase controlled by left-lateral transtension. In agreement with this interpretation, Biteau *et al*. (2006)

suggest a NW-SE direction of extension during the main Aptian-Albian phase of development of the Parentis depocenter, after a first Late Jurassic phase of NE-SW trending extension. By contrast, Jammes *et al*. (2010a, b, c) propose rather an initial Late Jurassic-Early Aptian phase of sinistral transtension, accommodated by the strike-slip Ibis Fault below the Parentis Basin (Fig. 13c), and a subsequent Late Aptian-Early Albian phase of orthogonal rifting. However, it is not clear which geological data support this scenario, which also seems to contrast with interpretations of the ECORS Parentis seismic reflection profile proposed by Tugend *et al*. (2015b). On this section, a major variation in the Neocomian sediments is described either side of the Ibis Fault, which is not the case for the Albian deposits. Whatever the kinematic interpretation, it is worth noting that these two phases are characterized by substantial differences in subsidence rates, with the Aptian-Albian phase showing the highest subsidence rates (Brunet, 1983, 1984, 1994). Such an evolution of the subsidence rates might be more in agreement with a tectonic evolution from orthogonal rifting to sinistral transtension.

**2.8. Aquitaine Basin**

The Aquitaine Basin is a wide Late Cretaceous-Cenozoic retro-foreland basin developed during the Pyrenean Orogeny (e.g. BRGM *et al*., 1974; Désegaulx & Brunet, 1990; Christophoul *et al*., 2003; Ford *et al*., 2016; Rougier *et al*., 2016; Angrand *et al*., 2018; Espurt *et al*., 2019; Ortiz *et al*., 2020). It is bounded to the south by the North Pyrenean Frontal Thrust, to the west by the Bay of Biscay passive margins, to the east by the French Central Massif and to the north by the Armorican Massif (Figs. 1 and 14a). While the Late Cretaceous-Cenozoic flexural sequences are deposited in a vast single basin, below the syn-orogenic Cenozoic cover several Late Paleozoic-Mesozoic basins are preserved (e.g. BRGM *et al*., 1974; Curnelle *et al*., 1982; Brunet, 1984; Biteau *et al*., 2006; Serrano *et al*., 2006; Angrand *et al*., 2018; Issautier *et al*., 2020) (Figs. 1 and 14a). The evolution of these basins was strongly influenced by Variscan inheritance (e.g. Autran & Cogné, 1980; Debelmas, 1986; Bourrouilh *et al*., 1995). The pre-orogenic basement of the Aquitaine Basin is divided in a southern and a northern domain by the WNW-ESE trending Celtaquitaine Flexure (BRGM *et al*., 1974) (Fig. 14a). This inherited Variscan structural lineament marks a significant paleogeographic limit, representing the northern boundary of the depositional environment of the Late Triassic-Early Lias Keuper evaporites around the Iberia/Eurasia plate boundary (e.g. BRGM *et al*., 1974; Biteau *et al*., 2006; Serrano *et al*., 2006). To the NW, this structure aligns with the steep scarp between the South Armorican shelf and the Bay of Biscay abyssal plain. The southern Aquitaine domain includes the mildly inverted ~WNW-ESE trending Arzacq, Tartas, Tarbes, Comminges and Mirande basins, while the northern domain includes the NW-SE trending Charente and Périgord-Quercy basins (Figs. 1 and 14a). In the northern domain the Mesozoic sedimentary fill does not exceed 2000 m, while in the southern domain it can locally be thicker than 5000 m (BRGM *et al*., 1974; Serrano *et al*., 2006; Issautier *et al*., 2020). Nevertheless, Late Cretaceous uplift of the northern Aquitaine domain resulted in southward tilting of the Aquitaine platform and subsequent erosion of the older deposits, thus contributing to the relative erosional thinning of the sedimentary cover preserved in the northern domain (Platel, 1987, 1996).

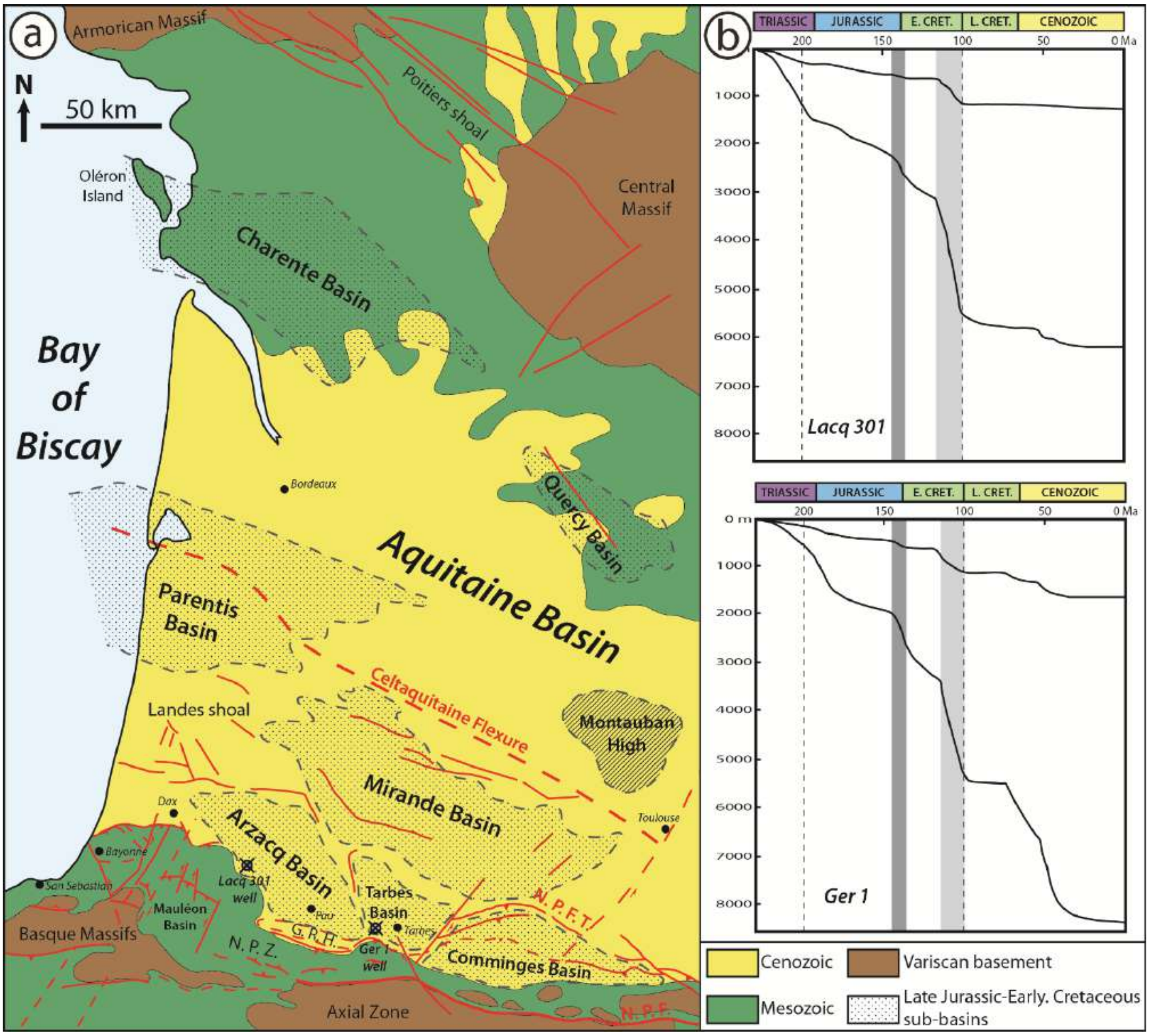


*Fig. 14: a) Simplified geological map of the Aquitaine Basin with locations of the main Late Jurassic-Early Cretaceous sub-basins reviewed in this study and of the wells presented in (b) (redrawn and modified after Bourrouilh et al., 1995). Abbreviations: G.R.H. = Grand-Rieu High; N.P.F. = North Pyrenean Fault; N.P.F.T. = North Pyrenean Frontal Thrust; N.P.Z. = North Pyrenean Zone. b) Subsidence curves for the Lacq 1 (Arzacq Basin) and Ger 1 (Tarbes Basin) wells from the Southern Aquitaine Basin (redrawn and modified after Brunet, 1984; see Fig. 9 for location). Upper curves are tectonic subsidence curves with local isostatic compensation; lower curves represent progressive deepening of the Paleozoic basement with decompacted sediments (see Brunet, 1984 for details on the applied corrections). Note that during the Late Jurassic-Early Cretaceous rifting, tectonic subsidence curves are steeper for the Early Cretaceous interval than for the Late Jurassic one.*

### **2.8.1.** Southern Aquitaine basins

Sedimentary basins in the southwestern domain are separated by two major WNW-ESE trending Variscan inherited structures, namely (from south to north) the Grand-Rieu High and Audignon-Pécorade-Antin Maubourguet ridges (Fig. 14a). The former separates the North Pyrenean basins (e.g. Mauléon Basin) from the Arzacq Basin; the latter isolates the Arzacq Basin to the south from the Tartas/Mirande Basin to the north (Serrano *et al*., 2006; Issautier *et al*.; 2020). This domain of the Aquitaine Basin recorded an initial phase of Permian-Early Lias rifting, which culminated in the Late Triassic-Hettangian deposition of up to ~1 km thick Keuper evaporites (e.g. Curnelle *et al*., 1982; Curnelle, 1983, 1995; Biteau *et al*., 2006; Serrano *et al*., 2006) in a likely transtensional pull-apart setting related to the early breakup of Pangea (e.g. Issautier *et al*., 2020). This phase was followed by an Early-Middle Jurassic phase of post-rift thermal subsidence which led to the development of stable carbonate platforms across the whole Aquitaine Basin realm, resulting in the accumulation of up to ~2 km thick post-rift series (e.g. Curnelle *et al*., 1982; Brunet, 1984; Biteau *et al*., 2006; Serrano *et al*., 2006). Rifting resumed in the Late Jurassic-Early Cretaceous interval with a complex topographic pattern (e.g. Brunet, 1984). This resulted in a patchwork of structural highs (e.g. Grand Rieu and Audignon-Pécorade-Antin Maubourguet highs), which underwent erosion and/or non-deposition between the Kimmeridgian/Tithonian and the Neocomian (i.e. Berriasian-Hauterivian), and localized subsiding domains allowing a sedimentary record of this tectonic event (e.g. Bourrouilh *et al*., 1995; Issautier *et al*., 2020). This phase was followed by a progressive transgression of Barremian-Aptian sedimentation over the structural highs (Issautier *et al*., 2020), connecting both Arzacq and Tartas basins into a single and vast Early Aptian basin. Then, sedimentation rates increased in the Late Aptian-Albian interval (e.g. Brunet, 1983, 1984; Désegaulx & Brunet, 1990; Fig. 14b), with an extensional tectonic regime strongly influenced by the decoupling layer at the base of the pre-rift series represented by the Keuper evaporites (e.g. Curnelle *et al*., 1982; Bourrouilh *et al*., 1995; Issautier *et al*., 2020; Saspiturry *et al*., 2021). The onset of this latter increase in the sedimentation rate seems to be slightly diachronous between these different basins, starting in the Barremian in the Mirande Basin (as in the Parentis Basin) and in the Aptian in the Arzacq and Tartas basins (Brunet, 1983; Issautier *et al*., 2020). Finally, since the Cenomanian, the southern domain of the Aquitaine Basin underwent post-rift thermal subsidence (e.g. Brunet, 1983; Fig. 14b), which continued during the early orogenic phase (Desegaulx *et al*., 1991; Angrand *et al*., 2018). Thick-skinned deformation related to the Pyrenean compression started during the latest Santonian-Campanian (e.g. Désegaulx & Brunet, 1990; Christophoul *et al.*, 2003; Biteau *et al.*, 2006; Ford *et al.*, 2016; Rougier *et al.*, 2016; Espurt *et al.*, 2019).

Since the Mesozoic deposits are buried beneath thick Cenozoic series, there are not many firm constraints on the kinematic evolution of the southern Aquitaine sub-basins during the Late Jurassic-Early Cretaceous rifting phase. However, several authors have suggested that this domain accommodated part of the deformation related to the left-lateral displacement between Iberia and Eurasia (e.g. Choukroune & Mattauer, 1978; Curnelle *et al.*, 1982; Boillot, 1984; Biteau *et al.*, 2006). In particular, most of them proposed an initial Late Jurassic-Neocomian phase of orthogonal rifting under ~NNE-SSW stretching followed by a subsequent phase of Aptian-Albian sinistral transtension resulting in ~NW-SE extension (Boillot, 1984; Bourrouilh *et al.*, 1995; Biteau *et al.*, 2006; Serrano *et al.*, 2006). Nonetheless, other studies based on the Arzacq Basin have rather suggested orthogonal (NNE-SSW) extension during the Aptian-Albian (e.g. Masini et al., 2014; Tugend et al., 2015a; Issautier et al., 2020). However, as discussed above, the Aptian-Albian phase interestingly corresponds to an increase in sedimentation rates (Fig. 14b; Brunet, 1983, 1984; Désegaulx & Brunet, 1990). This is more consistent with a kinematic scenario where the Late Jurassic-Neocomian phase is dominated by orthogonal rifting, whereas the Aptian-Albian phase is dominated by sinistral transtension. In fact, transtensional pull-apart systems typically show higher sedimentation rates than orthogonal rift systems (e.g. Mann *et al.*, 1983; Hempton & Dunne, 1984; Gürbüz, 2014 and references therein).

***2.8.2.*** *Northern Aquitaine basins*

The Charente and Périgord-Quercy basins of the northern Aquitaine domain (Fig. 14a) accumulated only a few tens of meters of sediments during the Permian-Early Lias phase (in contrast with the ~2000 m thick pile of sediments locally deposited in the southern domain; BRGM *et al.*, 1974). After an Early-Middle Jurassic tectonic quiescence, these two basins recorded localized subsidence starting in the Kimmeridgian, allowing the deposition of Late Jurassic evaporite-bearing series (BRGM *et al*., 1974; Cubaynes *et al*., 1989; Pélissié & Astruc, 1995). During the Early Cretaceous, the whole northern Aquitaine domain underwent emersion and erosion (e.g. BRGM *et al*., 1974; Cubaynes *et al*., 1989; Combes *et al*., 1998; James, 1998; Canérot *et al*., 1999; Serrano *et al*., 2006; Husson *et al*., 2015), erasing most of the sedimentary record of any tectonic event during this period. However, some Early Cretaceous continental deposits are described in the Charente Basin, aligned along a NW-SE axis (e.g. Platel, 1987; Néraudeau *et al*., 2012; Husson *et al*., 2015 and references therein). The Cenomanian transgressive deposits unconformably overlie the Jurassic series (BRGM *et al*., 1974; Moreau, 1995).

Due to the Early Cretaceous erosion and to major uncertainties on the architecture of these basins, very little is known about what controlled the localization of subsidence during the Late Jurassic. However, Delfaud *et al*. (1995) proposed that this phase could be related to the activation of transtensional systems. Moreover, considering the distribution of the Early Cretaceous continental deposits in very narrow and relatively deep depocenters in Charente, Husson *et al*. (2015) suggested that this could be the result of a tectonically controlled paleogeography, structured in narrow horsts and grabens or in pull-apart basins. In this framework, it is worth noting that the Northern Aquitaine basins are aligned along a NW-SE trend, which is parallel to the Variscan strike-slip structures of the Southern Armorican Massif (e.g. Matte, 1986; Ballèvre *et al*., 2009; Fig. 14a). This trend also continues more to the NW, with major strike-slip structures on the South-Armorican continental shelf (e.g. Thinon, 1999; Barrier *et al*., 2004; Thinon *et al*., 2008, 2018; Lemaire et al., 2021).

## 3. DISCUSSION: THE MESOZOIC IBERIA/EURASIA PLATE BOUNDARY: A WIDE DOMAIN OF TRANSTENSION PROGRESSIVELY LOCALIZING THE PLATE DISPLACEMENT

The review of the tectono-stratigraphic history of the basins presented in this work has major implications on the timing and distribution of the deformation in the wide transform domain forming the Iberia/Eurasia plate boundary (Fig. 15). Our compilation of basin histories shows that, along both sides of their theoretical limits, the Iberia and Eurasia plates are not rigid but fractured into multiple pieces that may deform independently. Therefore, the displacement of the Iberian plate related to the northward propagation of the Southern North Atlantic and to the opening of the V-shaped Bay of Biscay margins is accommodated within a ~400 km wide NW-SE trending corridor, spanning from the Asturian/Iberian Chain (in the SW) to the Armorican Shelf/Northern Aquitaine domains (in the NE).

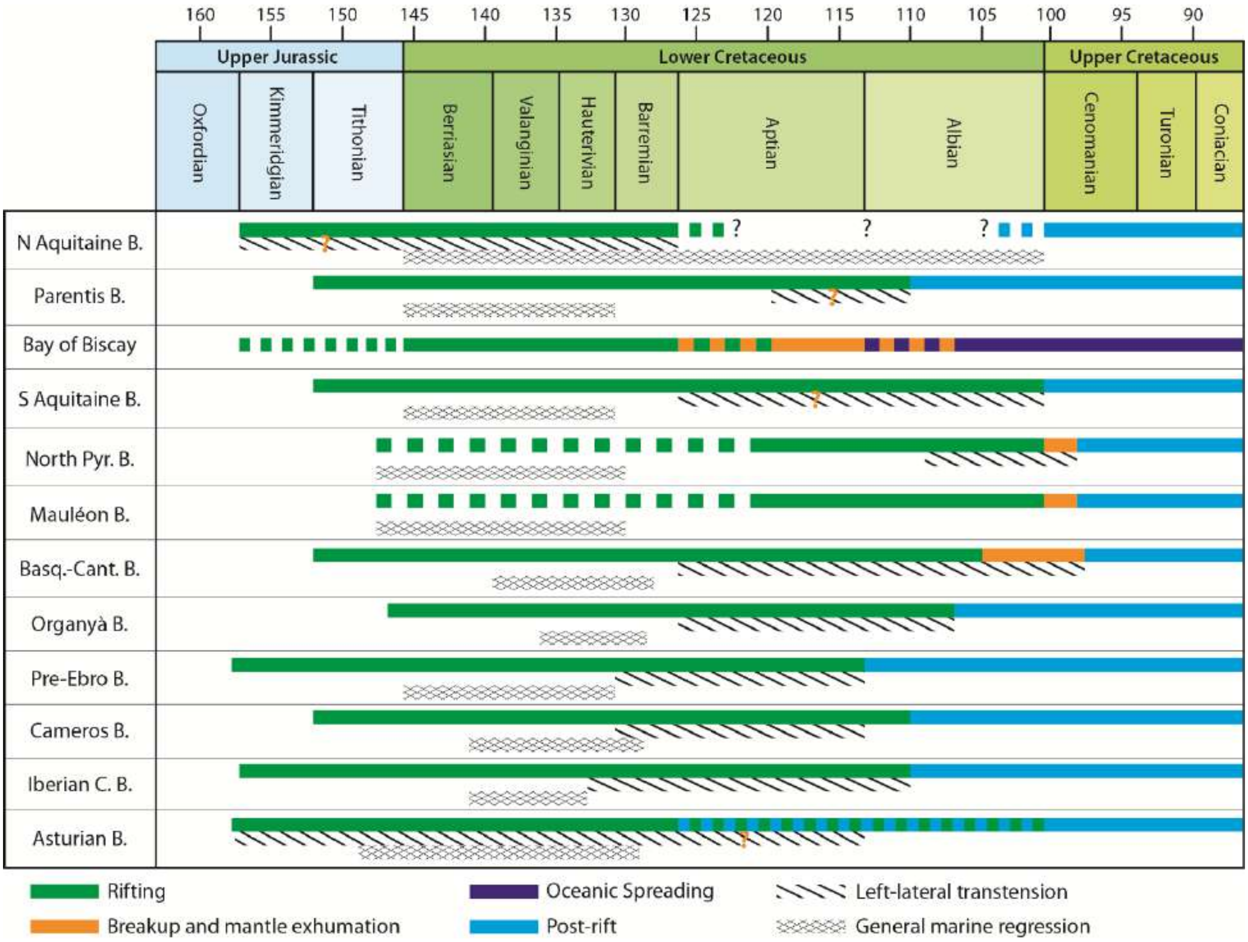


*__Fig. 15:__ Schematic diagram showing the main tectonic phases affecting the basins reviewed in this work during the Late Jurassic-Early Cretaceous interval. During the Late Jurassic, extension seems to have initially affected the most external parts of the system and then progressively affected the inner portions. During this phase, the Northern Aquitaine basins and the Asturian Basin, located at the boundaries of the system, underwent oblique rifting, while the rest of the system underwent orthogonal rifting. All the basins were affected by an episode of emersion and/or reduced subsidence during the Neocomian (~145 to 130 Ma). After the Neocomian, most of the rift basins experienced a phase of renewed subsidence controlled by oblique transtensional rifting, with the notable exception of the North*

*Pyrenean basins. This phase coincided with crustal breakup in the inner Bay of Biscay margins. When oceanic spreading affected the Bay of Biscay domain during the Albian, most of the rift basins became inactive and transtensional rifting accommodating the displacement between Iberia and Eurasia localized along the Basque-Cantabrian and North Pyrenean systems. Rifting finally terminated during the Cenomanian.*

### 3.1. Distribution and timing of deformation along the diffuse plate boundary

To first order, all of the reviewed Mesozoic sedimentary basins recorded the same tectonic phases. However, the identified geodynamic stages are slightly diachronous and get younger from the edges of the system towards its central part (Fig. 15). In the following section, we examine how such differences reveal the behavior and evolution of the Iberia/Eurasia plate boundary.

In particular, most of these basins seem to have experienced two distinct tectonic/kinematic phases, the first one during the Late Jurassic-Berriasian and the second one during the Barremian-Early Cenomanian. These two parts of their tectonic history are separated by a generally Neocomian (~Valanginian-Hauterivian) interval of emersion and/or reduced subsidence, which does not necessarily correspond to a quiet tectonic phase (for example, the Basque-Cantabrian Basin is tectonically active during this phase, but the Valanginian-Barremian syn-rift series are essentially continental; e.g. Camara [2020] and references therein). During the initial stages of plate reorganization, the deformation seems to affect the system edges simultaneously at first, and then progressively migrates towards the central part of the system. In fact, the first basins that started to develop are the Northern Aquitaine basins (in the NE; aligned with the Armorican Shelf) and the Asturian and Central and Southern Iberian Chain basins (in the SW), which underwent rifting since the latest Oxfordian/earliest Kimmeridgian (Fig. 15). The deformation then stepped inward with the activation, since the Tithonian, of the Cameros, Basque-Cantabrian, Southern Aquitaine and Parentis basins. Between the latest Tithonian and the Barremian, rift activation progressivelly reached the inner Bay of Biscay margins (Armorican Basin), the South Pyrenean Rift System (Organyà Basin) and finally the North Pyrenean basins. Indeed, rifting is recorded in the North Pyrenean Zone since the Aptian or even earlier, if the creation of a synform-shaped basin during the Neocomian emersion is considered as the onset of the rifting (e.g. Saspiturry *et al.*, 2019b; see

Section 2.6.1). From a kinematic point of view, it is worth noting that this first phase of rifting is characterized by geological evidence suggesting a left-lateral transtensional regime in the Northern Aquitaine and Asturian basins at the edges of the system, while all of the other basins seem to be affected by orthogonal rifting (Figs. 15 and 16). Thus, during this event, the plate boundary behaves as a wide extending domain accommodating the onset of left-lateral displacement of Iberia at its external edges and undergoing orthogonal extension in its interior (Fig. 16a). From a geodynamic point of view, this phase is coeval with rifting along the West Iberian Margin of the Southern North Atlantic (e.g. Alves *et al*., 2002, 2006, 2009).

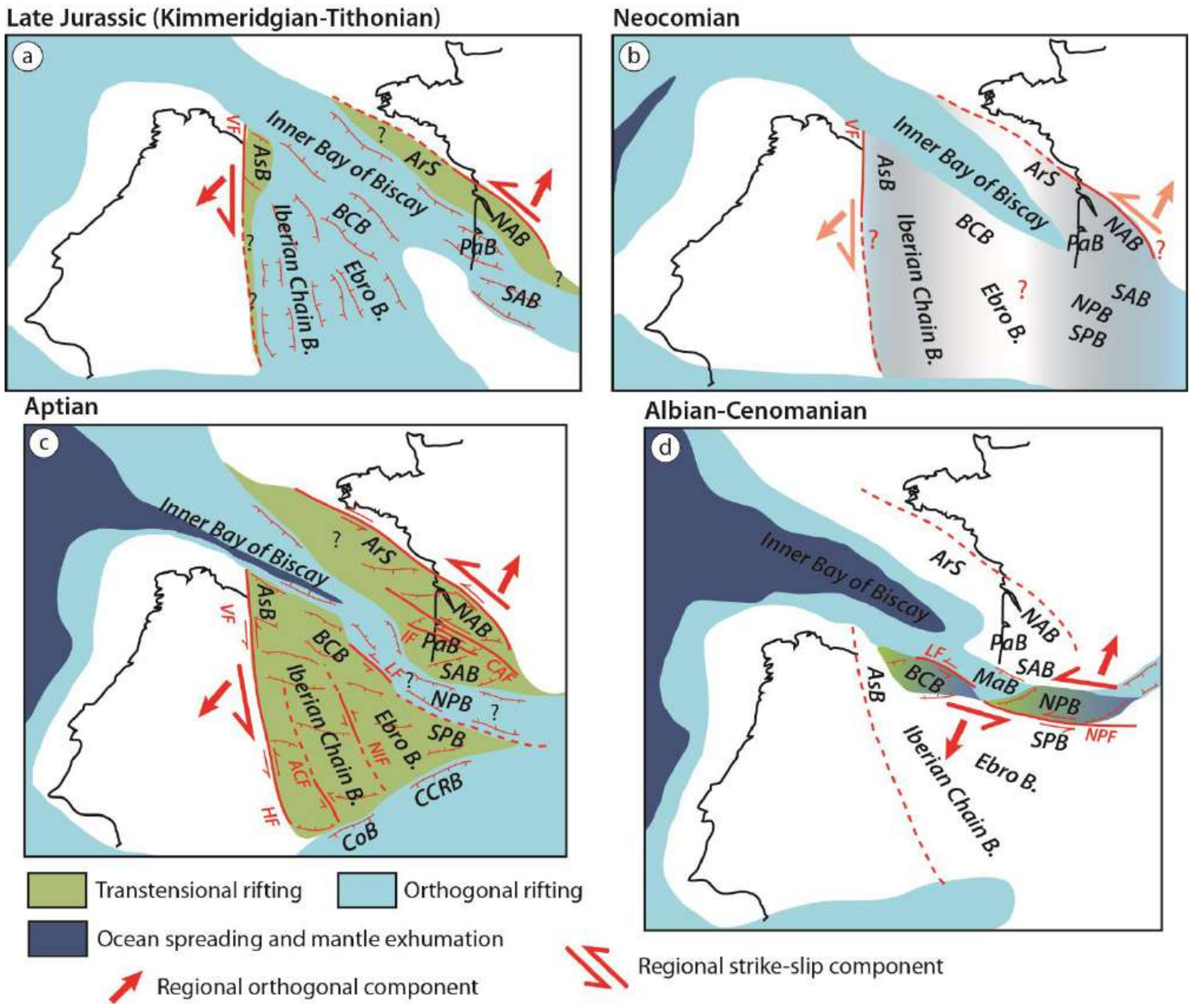


*Fig. 16: Kinematic reconstruction of the Iberia/Eurasia diffuse plate boundary between the Late Jurassic and the Early Cretaceous, with representation of the rift domains reviewed in this study and their kinematic evolution through time. During the Late Jurassic (a) left-lateral displacement between the two plates concentrates on the edges of the system, while the rest of the plate boundary undergoes mainly orthogonal rifting. During the Neocomian (b) the whole plate*

*boundary experiences a phase of reduced subsidence with localized exhumation events, while lithospheric breakup propagates northward on the Western Iberian margin. During the Aptian (c) most of the rift basins within the plate boundary zone are affected by left-lateral transtension controlling a phase of increased subsidence, with the notable exception of the North Pyrenean Rift System. During the Albian-Cenomanian (d) the Bay of Biscay realm undergoes oceanic accretion and the transtensional deformation localizes along the Basque-Cantabrian/North Pyrenean Rift System, which remains the only active domain while the rest of the sedimentary basins attain the post-rift stage. Plate kinematic model modified after Angrand et al. (2020). Acronyms: ACF, Ateca-Castellon Fault; AsB, Asturian Basin; ArS, Armorican Shelf; BCB, Basque-Cantabrian Basin; CAF, Celtaquitaine Flexure; CCRB, Catalan Coastal Range Basin; CoB, Columbrets Basin; HF, Hesperian Fault; IF, Ibis Fault; LF, Leitza Fault; MaB, Mauléon Basin; NAB, North Aquitaine basins; NIF, North Iberian Fault; NPB, North Pyrenean basins; PaB, Parentis Basin; SAB, South Aquitaine basins; SPB, South Pyrenean basins; VF, Ventaniella Fault.*

The final part of this first rifting phase is characterized by a generalized emersion/regression that affected all of the sedimentary basins within the Iberia/Eurasia plate boundary zone during the Late Tithonian-Neocomian interval (Figs. 15 and 16b). This phase is slightly diachronous between the different basins, but its onset seems to be geographically scattered and thus did not follow the same edges-to-center trend of the onset of rifting. Indeed, the emersion/regression started in the Late Tithonian in the Asturian and North Pyrenean basins while the other reviewed basins were affected between the Berriasian and the Valanginian. The end of this phase coincides globally with the end of the Neocomian, spanning between the Late Hauterivian and the Early Barremian, with the notable exception of the Northern Aquitaine basins, which remained emerged until the Cenomanian (Fig. 15). From a geodynamic perspective, this phase of generalized regression is coeval with northward propagation of crustal necking and mantle exhumation along the West Iberian Margin (e.g. Soares *et al*., 2012; Mohn *et al*., 2015; Jeanniot *et al*., 2016; Alvès & Cunha, 2018; Nirrengarten *et al*., 2018).

The second phase of rift-related subsidence generally started after the Neocomian (Fig. 15). The boundaries of the system (Asturian and North Aquitaine basins) are less kinematically constrained than the rest of the plate boundary zone, where evidence suggesting a progressive migration of left-lateral transtension towards the center (Pyrenees) is observed. In fact, left-lateral transtension first affected the Iberian Chain and the Pre-Ebro basins from the Late Hauterivian-Early Barremian, then activated in the Basque-Cantabrian, South Pyrenean, Southern Aquitaine and Parentis domains in the Aptian (Fig. 16c). Transtension finally reached the North Pyrenean basins during the Albian (Fig. 16d). The end of rifting followed the same geographic trend from the Aptian-Albian boundary to the Early Cenomanian and was coeval with the breakup phase of the inner Bay of Biscay (Thinon *et al*., 2002; Roca *et al*., 2011) (Figs. 15 and 16) and NW Iberia margins (Soares *et al*., 2012; Alvès & Cunha, 2018; Alvès *et al*., 2020). As oceanic spreading began along these margins, the transtensional deformation finally reached the North Pyrenean Rift System, which became, together with the Basque-Cantabrian Basin, the locus of new crustal breakup and lithospheric mantle exhumation (Figs. 15 and 16d). On a larger scale, this phase coincides with continental breakup and progressive onset of oceanic accretion in the Southern Nord Atlantic (e.g. Jagoutz *et al*., 2007; Tucholke *et al*., 2007; Alvès & Cunha., 2018).

While the entire system underwent extension since at least the Late Jurassic, it is noteworthly that only the North Pyrenean/Basque-Cantabrian system localized the plate boundary (Fig. 16) and reached mantle exhumation in Albian-Cenomanian times. This observation is consistent with several analogue and numerical oblique rifting models which show that at the onset of stretching the deformation is accommodated over a more or less large region and then progressively localizes in a narrower domain at the center of the extending region (e.g. Autin *et al*., 2010; Brune, 2014; Duclaux *et al*., 2020). Onset and localization of rifting in the North Pyrenean/Basque-Cantabrian domain might represent an oblique continental breakup propagation resulting from the eastward propagation of the Bay of Biscay oceanic basin, as suggested by recent numerical models of crustal breakup propagation (see Jourdon *et al*., 2020). Such a process could have favored the sudden localization of the plate boundary along the North-Pyrenean/Basque-Cantabrian corridor. In fact, in almost all of the basins reviewed in this work, rifting stopped as soon as the Basque-Cantabrian/North Pyrenean corridor underwent crustal breakup (Figs. 15 and 16). The orthogonal component of extension across this trough has likely been important. Indeed, 2D crustal balanced cross-section restorations, across the Pyrenees, show: 1) a pre-orogenic width of exhumed mantle domain ranging from ~10-20 km (Lagabrielle *et al*., 2010; Teixell *et al*., 2016, 2018; Espurt *et al*., 2019; Ternois *et al*., 2019; Angrand *et al*., 2021), to ~50/70 km (Mouthereau *et* *al*., 2014; Grool *et al*., 2018; Jourdon *et al*., 2019), and 2) a N-S width of the synrift turbiditic basins spanning between ~60/90 km (Mouthereau *et al*., 2014; Clerc *et al*., 2016; Ternois *et al*., 2019; Saspiturry *et al*., 2020a) and ~145 km (Espurt *et al*., 2019).

To sum up, the Early Cretaceous transtensional deformation at the plate boundary was first distributed and accommodated over a large domain and then localized in a narrower corridor in the central part of the system during the Albian-Early Cenomanian, following lithospheric breakup in the Bay of Biscay (Fig. 16). This episode marks the progressive focusing of the plate boundary along the narrower North Pyrenean rift system. This is thus a good example of progressive localization of deformation, from a wide and distributed plate boundary to a narrow tectonic corridor.

### 3.2. Timing of the counterclockwise rotation of Iberia

One of the main ongoing debates on the Mesozoic kinematic evolution of Iberia concerns the timing of its counterclockwise rotation in relation to the opening of the North Atlantic and of the Bay of Biscay margins. Despite most authors agreeing on the fact that a rotation of about 35°-40° must have occurred, no consensus exists on its timing (e.g. Van der Voo, 1969; Galdeano *et al*., 1989; García-Mondéjar, 1996; Gong *et al*., 2008; Barnett-Moore *et al*., 2016 and references therein). The most solid reconstructions suggest that this rotation must have taken place sometime between the Triassic and the Late Cretaceous (Van der Voo, 1969). However, it has not yet been clarified if this rotation occurred as a single tectonic event or if it was polyphase and distributed in time. Gong *et al*. (2008), on the basis of paleomagnetic data from the Early Cretaceous sediments of the Organyà Basin, argued for an Aptian 35° counterclockwise rotation. These authors used this argument to state that the rotation of Iberia occurred in a single Aptian event. However, as we have suggested in Section 2.6.4, the Aptian represents a phase of left-lateral transtension within the Organyà Basin. Moreover, the pre- and syn-rift sedimentary cover are strongly decoupled from their basement due to the thick Keuper evaporites at their base and this may have favored the cover mobility. Thus, it is likely that the rotation evidenced by Gong *et al*. (2008) is, at least partially, related to local rotations in the Organyà Basin due to the transtensional tectonic regime and to the strong basement/cover decoupling, rather than to the rotation of the whole Iberian plate. This is also consistent with local rotations observed during the Early Cretaceous rifting phase of the Organyà Basin by Dinarès-Turell & García-Senz (2000). The reliability of Gong *et al*. (2008)'s hypothesis had already been recently questioned by Barnett-Moore *et al*. (2016). Indeed, these latter studies highlight the difficulty in reconciling the idea of a rotation of Iberia limited to a single Aptian event and the evidence for northward propagation of rifting along the Iberia-Newfoundland margins since the Late Triassic–Early Jurassic (Tucholke *et al*., 2007; Alvès *et al*., 2009).

Based on the spatial correlation of the Armorican and the North Iberian margins across the restored Bay of Biscay system, García-Mondéjar (1996) argued for a counterclockwise rotation of about 37° of the Iberian plate and proposed that it took place during the Aptian-Albian interval. However, the review presented in this work shows that the opening of the Bay of Biscay margins was polyphased and occurred over a long time between the Late Jurassic (Kimmeridgian) and the Albian/Cenomanian. Recent works have also shown that displacement of Iberia with respect to North America and Eurasia also occurred during the Permian-Triassic period (Angrand *et al*., 2020 and references therein). Moreover, paleomagnetic data from the Lisbon region (Portugal; Galdeano *et al*., 1989) suggest that most of the counterclockwise rotation of Iberia took place since the Barremian, with a larger amount (~27°) between 125 and 110 Ma, and a smaller amount (~14°) after ~110 Ma. This could be compatible with a model implying widespread left-lateral transtension at the scale of the whole plate boundary zone during the Barremian-Early Albian (Figs. 15 and 16c), and a more localized transtension in the Basque-Cantabrian/North Pyrenean corridor during the Albian-Early Cenomanian interval (Figs. 15 and 16d). These arguments thus favor the hypothesis that the counterclockwise rotation of Iberia was polyphase and occurred in response to a series of rifting events at the northern and western plate margins distributed throughout the whole Mesozoic.

### 3.3. Questioning the existence of the Ebro Block

As discussed above in Section 2.4, several studies concerning the Late Jurassic-Early Cretaceous kinematic evolution of the Iberia-Eurasia plate boundary have postulated that the Ebro realm behaved as a rigid, undeforming continental ribbon while rifting was occurring along the Iberian Chain and the Pyrenean basins at its boundaries (e.g. Tugend *et al*., 2015a; Nirrengarten *et al*., 2018; Tavani *et al*., 2018; Angrand *et al*., 2020; Angrand & Mouthereau, 2021; Frasca *et al*., 2021; King *et al*., 2021) (Fig. 3). However, the review presented in this work shows that some traces of the Late Jurassic-Early Cretaceous rifting exist below the Cenozoic Ebro Basin (Fig. 6). Interestingly, the few existing data on the Mesozoic subsidence of the Ebro domain show that this region, like the other rift basins within the broad Iberia/Eurasia plate boundary zone, recorded two distinct subsidence phases during the Kimmeridgian-Tithonian(?) interval and during the Barremian-Aptian(?), which are separated by a Neocomian interval of reduced subsidence (Vargas *et al*., 2009). The Barremian-Aptian rifting phase shows a higher subsidence rate than the Kimmeridgian-Tithonian one. This could be due to kinematic differences between an initial Late Jurassic phase of orthogonal rifting and a subsequent Early Cretaceous phase of sinistral transtension, as suggested for other sedimentary basins within the plate boundary zone (e.g. Mathieu, 1986; Serrano *et al*., 2006; Martín-Chivelet *et al*., 2019). In light of these considerations, the existence of the Ebro Block as an undeforming continental ribbon during the opening of the Bay of Biscay should be questioned. In our opinion, it is much more likely that the Ebro realm behaved as a deforming domain undergoing rifting during at least the Late Jurassic-Early Cretaceous and accommodating a certain amount of left-lateral displacement between Iberia and Eurasia, as suggested for the other rift basins in its surroundings (Figs. 15 and 16).

### 3.4. A conceptual model for the Mesozoic Iberia/Eurasia plate boundary zone

In this work we show that the deformation related to the left-lateral displacement between Iberia and Eurasia is accommodated over a large domain (~400 km wide). The transtensional corridors therein did not react synchronously and each of them accommodated a portion of the deformation between the Late-Jurassic and the Early Cretaceous. Most of the plate kinematic reconstructions agree on the fact that during this period the Iberian plate should have moved several hundreds (~400) of kilometers eastward (e.g. Olivet, 1996; Jammes *et al*., 2009; Nirrengarten *et al*., 2018) (Figs. 2 and 3). However, there has always been an inconsistency between these kinematic models and the lack of a single wrench structure accommodating the displacement between the two plates. This paradox can thus be resolved by looking to the wider domain that accommodated this displacement (Fig. 16).

Some strike-slip faults involved in the transtensional phases of some sedimentary basins within this domain (such as the North Pyrenean Fault, the Leitza Fault, the Ventaniella/Ubierna Fault system, the Hesperian Fault, the North Iberian Fault, the Ibis Fault) accommodated strike-slip displacement on the order of a few tens of kilometers (e.g. Souquet *et al*., 1977; Peybernès, 1978; Debroas, 1987; Canérot, 2016). It is worth noting that, during the transtensional phases, the basins described in this work likely developed as negative flower structures (e.g. Jammes *et al*., 2010c) (see the example of the Parentis Basin in Fig. 13c). This implies that the emerging strike-slip structures that may be observed at the boundaries of these basins (such as the North Pyrenean Fault for example) accommodated only a portion of the total strike-slip displacement accounted for by each flower structure. Hence, amounts of horizontal displacement quantified on oblique/strike-slip structures bounding these basins likely represent a substantial underestimation of the whole horizontal displacement accommodated by each transtensional basin. If we assume that each transitional corridor reviewed in this work (about ten in total) accommodated the same order of magnitude of left-lateral displacement (few tens of kilometers) during the Late Jurassic-Early Cretaceous, then this would imply that the whole domain enclosed between the Iberian Chain and the Armorican Shelf could have accommodated the several hundreds of kilometers of left lateral displacement between Iberia and Eurasia proposed by the plate kinematic models (Fig. 17). It does not strictly mean that each one these rift systems accommodated exactly the same amount of left-lateral displacement, but at least that this component of the deformation has been distributed over a wide region. This scenario could resolve a long-lasting paradox in Western European Mesozoic tectonics.

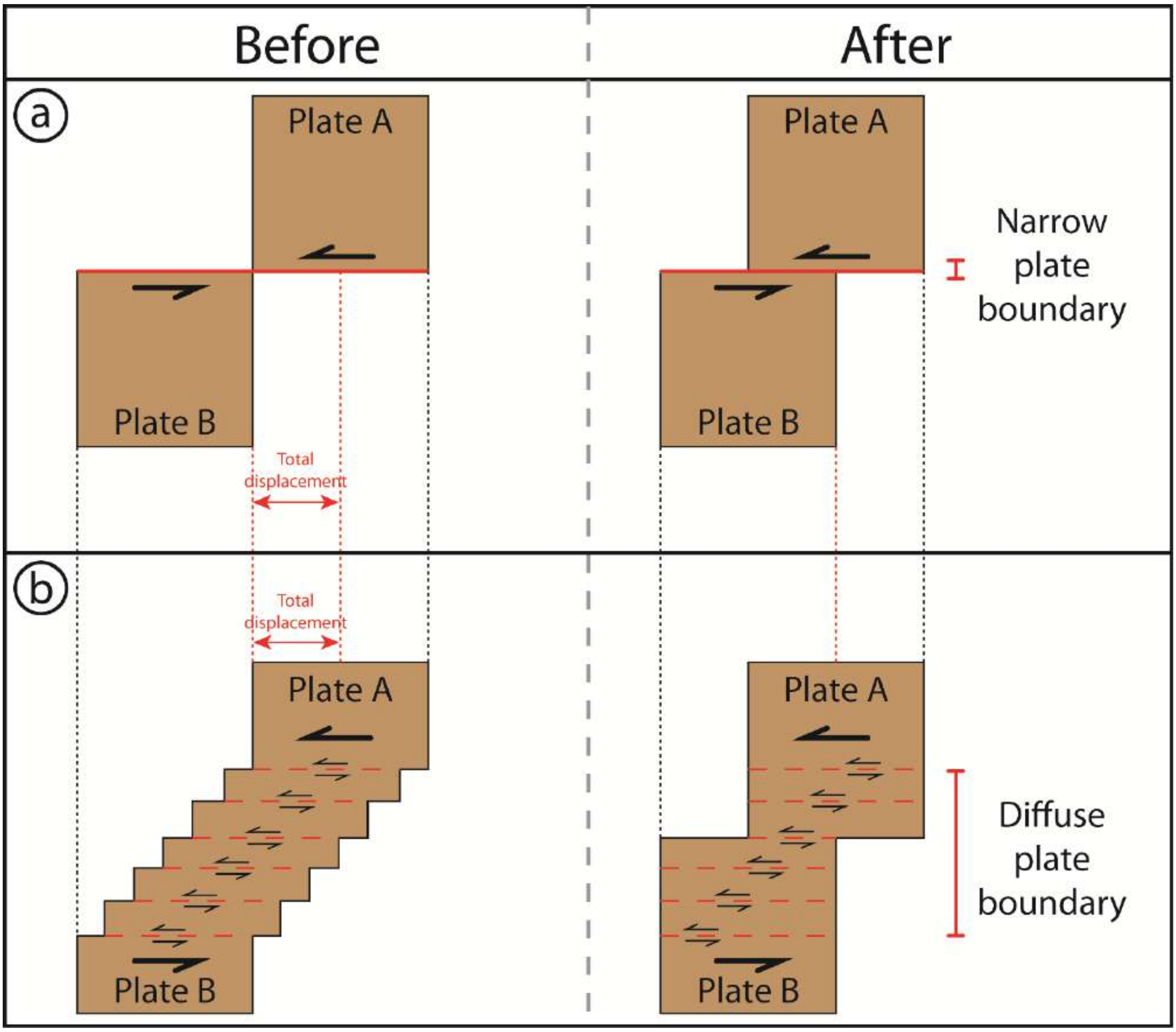


***Fig. 17:*** *Schematic representation of (a) a narrow transform plate boundary and of (b) a diffuse transform plate boundary. In (a) the total left-lateral displacement between the two plates is accommodated by a single wrench structure. In (b) the very same amount of total displacement is partitioned between a series of sub-parallel strike-slip structures, each of which accommodates a portion of the total left-lateral displacement between the stable parts of the plates.*

### 3.5. What causes the kinematic ambiguity?

The Late Jurassic-Early Cretaceous kinematic evolution of the different rift basins within the Iberia/Eurasia plate boundary zone and their role in the overall plate kinematic context have been largely debated over the last decades. Several reasons might be behind this long lasting controversy.

Particularly, some authors have put forward models arguing for a dominantly orthogonal rifting at the scale of the plate boundary (e.g. Manatschal & Müntener, 2009; Tavani *et al*., 2018), while others have supported models in favor of dominantly left-lateral transtensional mechanisms (e.g. Choukroune & Mattauer, 1978; Olivet, 1996; Stampfli & Borel, 2002). The review of the kinematic evolution of all of the rift domains presented in this paper shows indeed that both tectonic regimes affected these sedimentary basins, but during distinct time intervals. In fact, most of the sedimentary basins in the inner domain of the plate boundary zone were affected by an initial orthogonal rifting phase (generally during the Late Jurassic-Early Neocomian, with ~N-S to ~NE-SW directions of extension), but also by a subsequent sinistral transtensional rifting event (generally between the Barremian and the Albian, with a ~NW-SE direction of extension), although with a potentially significant orthogonal component. Thus, in order to correctly interpret the extension directions recorded in these sedimentary basins in the frame of the overall plate kinematics, one should be careful and properly identify to which tectonic phase the observed geological markers are related. In other words, since both orthogonal and transtensional regimes affected the rift basins within the Iberia/Eurasia plate boundary zone during the Late Jurassic-Early Cretaceous rifting, with more or less pronounced diachronicity between the different basins, the timing and the kinematics of a tectonic event described in a single rift basin cannot be extrapolated to the whole plate boundary domain.

As already pointed out by Oliva-Urcia *et al*. (2011), another possible cause of the controversy regarding the kinematic evolution of the rift basins reviewed in this work is the coexistence of different stretching directions during the transtensional phases, and the confusion that may arise between regional and local extension directions. In fact, in transtensional tectonic settings the deformation is often partitioned between a strike-slip component and an extensional component (e.g. Sanderson & Marchini, 1984; Umhoefer & Dorsey, 1997; Dewey *et al*., 1998; Dewey, 2002; Wilson *et al*., 2006; Autin *et al*., 2010; Brune, 2014). In the reviewed basins, the relative importance of these two components is highly difficult to quantify. In some cases, such as for the Pyrenean realm (e.g. Oliva-Urcia *et al*., 2010; Tavani *et al*., 2011; Mouthereau *et al*., 2014; Espurt *et al*., 2019; Saspiturry *et al*., 2019b), the orthogonal component of extension might have been important during the transtensional phase. This may increase the complexity of the relative extension directions and of the resulting overall tectonic pattern. Moreover, it has been largely illustrated that, close to major strike-slip faults, stress deflection may cause local deviations of the extension direction (e.g. Casas *et al*., 1992; Simón *et al*., 1999; Homberg *et al*., 2004; Nüchter & Ellis, 2011). This may thus lead to misinterpretations between the regional far-field extension direction and the locally deflected ones. For this reason, the most reliable studies to unravel the kinematic evolution of the basins within the Iberia-Eurasia plate boundary zone are those that consider the overall structural and/or AMS patterns at the scale of entire basins (e.g. Pulgar *et al*., 1999; Soto *et al*., 2007, 2008, 2011; Oliva-Urcia *et al*., 2010, 2011; Camara, 2017), rather than those based on local observations at particular sites within the basins. Moreover, analogue and numerical modeling studies have shown that in transtensional tectonic settings the directions of extension may be scattered and vary though time (e.g. Withjack & Jamison, 1986; Autin *et al*., 2010; Brune, 2014; Duclaux *et al*., 2020; Jourdon *et al*., 2020).

### 3.6. What favors the distribution of deformation?

As we have discussed above, the deformation related to the left-lateral displacement between Iberia and Eurasia during the Late-Jurassic-Early Cretaceous is distributed over a ~400 km wide region, rather than localized on a single wrench structure. The main reason is probably that this domain was already deformed and strongly fragmented as a consequence of the rift events that preceded the Late Jurassic-Early Cretaceous phase, such the Late Carboniferous-Early Permian extension during the early dismantling of the Variscan belt and the Late Permian-Triassic rifting related to the breakup of the Pangea supercontinent (e.g. Arthaud & Matte, 1975; Autran & Cogné, 1980; Ziegler, 1988; Matte, 2001; Ziegler & Dèzes, 2006; Ziegler *et al*., 2006). These events strongly influenced the transition between Iberia and Eurasia with the formation of large scale strike-slip faults and shear zones, such as the Ventaniella/Ubierna fault system (e.g. Tavani *et al*., 2011b; Fernández-Viejo *et al*., 2014), the North Pyrenean Fault (e.g. Mattauer, 1968; Choukroune, 1976), the Celtaquitaine Flexure (e.g. BRGM *et al*., 1974) and the South Armorican Shear Zone (e.g. Jégouzo, 1980). Moreover, most of the sedimentary basins in this domain also experienced an important Permian-Triassic rifting phase (e.g. Sopeña *et al*., 1988; Doblas *et al*., 1994; Serrano *et al*., 2006). This could imply that part of the left-lateral motion between the Iberian and Eurasian plates had already been achieved before the Jurassic and not only during the opening of the North Atlantic and Bay of Biscay oceanic basins (Angrand *et al*., 2020; Angrand & Mouthereau, 2021). Therefore, this strong compartmentalization of the wide domain at the transition between the two plates favored the reactivation of all of these systems during the Late Jurassic-Early Cretaceous rifting phase, rather than the localization of the strain along a single narrow plate boundary.

## 4. CONCLUSION

The review presented in this work proposes a coherent tectonic Mesozoic framework of the wide domain accommodating the deformation between the Iberian and Eurasian plates. The main conclusions can be summarized as follows:

- The Mesozoic deformation at the Iberia/Eurasia plate boundary, related to the opening of the southern North Atlantic and the Bay of Biscay margins, was accommodated across a ~400 km wide region spanning from the Iberian Chain System (in the SW) to the Armorican Shelf/Northern Aquitaine systems (in the NE). Thus, this region should be considered as a diffuse plate boundary zone (*sensu* Gordon, 1998) as opposed to previous interpretations considering a narrow plate boundary along the North Pyrenean Fault only.
- During the Late Jurassic-Early Cretaceous interval, some domains that have been previously overlooked, such as the Pre-Ebro Basin and the Northern Aquitaine basins, have likely accommodated a certain amount of the deformation between Iberia and Eurasia.

- To first order, the rift basins within the diffuse plate boundary zone experienced the same Late Jurassic-Early Cretaceous tectonic history, but with: (i) slight diacronicities between the different systems and (ii) two main subsidence phases characterized either by orthogonal or transtensional rifting.
- The Late Jurassic-Early Cretaceous evolution of the Iberia/Eurasia diffuse plate boundary zone can be summarized in four steps: (i) a Late Jurassic phase of transtensional rifting localized at the northeastern and southwestern margins of the system, while the rest of the sedimentary basins underwent orthogonal rifting; (ii) a Neocomian phase of generalized regression, with emersion of several domains within the diffuse plate boundary zone; (iii) a Barremian-Aptian phase of distributed transtensional rifting, with the notable exception of the North Pyrenean System which was undergoing orthogonal rifting; (iv) an Albian-Cenomanian phase of localization of the transtensional deformation along the Basque-Cantabrian/North Pyrenean corridor after the onset of oceanic spreading in the Bay of Biscay margins, while the rest of the rift basins became tectonically inactive.
- The distribution of the deformation over the wide Iberia/Eurasia diffuse plate boundary zone is favored by the structural pre-rift inheritance, as this region has a strong late/post-Variscan pre-rift heterogeneity.
- The regional tectonic template developed during the Late Jurassic-Early Cretaceous phase represents a fundamental structural inheritance for the subsequent Late Cretaceous-Cenozoic convergence phase, since most of the reviewed rift basins have been more or less inverted during the Pyrenean Orogeny and thus accommodated parts of the Iberia-Eurasia convergence.

More generally, this review has major implications for future plate kinematic reconstructions of Iberia during the Mesozoic. Indeed, we show that the limits of the stable plates should be placed to the SW of the Iberian Chain System (on the Iberian side) and along the

Armorican Shelf/Northeastern Aquitaine boundary (on the Eurasian side). The deforming domain between these two boundaries should be represented as a fuzzy region where exact locations of the different tectonic structures and rift basins therein are uncertain. The inconsistency between the deformation inferred from plate kinematic models of the Iberia/Eurasia plate boundary and geological observations in the Pyrenees has been highlighted for a long time (e.g. Souquet *et al*., 1977). However, kinematic models published in the last four decades have never quite satisfied constraints derived from field observations. Going beyond the assumption that plate boundaries are necessarily narrow and determining the real width of the domains that may accommodate the deformation between moving plates may resolve controversies that often arise between plate kinematic models and geological constraints.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**ACKNOWLEDGEMENTS**

This project has been supported by the Orogen Project (BRGM + Total + CNRS-INSU; https://convergent-margins.com/orogen/) by providing post-doc grants to RA and PA and a PhD scholarship to NS. This work benefitted from precious suggestions and interesting discussions with Benoit Issautier, Frederic Mouthereau and Isabelle Thinon. The authors wish to express their gratitude to Yves Lagabrielle for his continuous and unselfish support. The manuscript benefitted from insightful comments and reviews by J. Kim Welford, Miguel Garces and an anonymous reviewer. Thanks to Editor Carlo Doglioni for editorial handling.

This work would never have been possible without the fruitful discussions that flourished in the frame of the Orogen Project, which also favored transmission of knowledge between different generations of Earth scientists. Most importantly, this research program naturally gave birth to a dynamic and highly motivated community of young researchers that were very prone to cooperate and develop multidisciplinary research projects. Unfortunately, most of this freshly built scientific community has been already hopelessly dismembered by the scarcity of opportunities in Academia, particularly due to the increasing difficulty in finding permanent positions. This paper is dedicated to all those passionate young scientists that after PhD and post-doc contracts are still struggling in finding their way in this life.

**REFERENCES**


Agirrezabala LM, Dinarès-Turell J. 2013. Albian syndepositional block rotation and its geological consequences, Basque–Cantabrian Basin (western Pyrenees). *Geol. Mag.* 150(6):986–1001. http://dx.doi.org/10.1017/S0016756813000149.

Albarede F, Michard-Vitrac A. 1978. Age and significance of the North Pyrenean metamorphism. *Earth Planet. Sci. Lett.* 40:327–332.

Aldega L, Viola G, Casas-Sainz A, Marcén M, Román-Berdiel T, van der Lelij R. 2019. Unraveling multiple thermotectonic events accommodated by crustal-scale faults in northern Iberia, Spain: Insights from K-Ar dating of clay gouges. *Tectonics* 38:3629–3651. https://doi.org/10.1029/2019TC005585

Alvarez-Marrón J, Rubio E, Torné M. 1997. Subduction-related structures in the North Iberian Margin. *J. Geophys. Res.* 102:497–511, doi:10.1029/97JB01425.

Alvaro M, del Villar RC, Vegas R. 1979. Un modelo de evolución geotectónica para la Cadena Celtibérica. *Acta Geológica Hispánica* 14:172–177.

Alves TM, Cunha TA. 2018. A phase of transient subsidence, sediment bypass and deposition of regressive–transgressive cycles during the breakup of Iberia and Newfoundland. *Earth Planet Sci. Lett.* 484:168–183. https://doi.org/10.1016/j.epsl.2017.11.054.

Alves TM, Gawthorpe RL, Hunt DH, Monteiro JH. 2002. Jurassic tectono-sedimentary evolution of the Northern Lusitanian Basin (offshore Portugal). *Mar. Pet. Geol.* 19:727–754. doi:10.1016/S0264-8172(02)00036-3.

Alves TM, Moita C, Sandnes F, Cunha T, Monteiro JH, Pinheiro LM. 2006. Mesozoic – Cenozoic evolution of North Atlantic continental slope basins: The Peniche basin, western Iberian margin. *AAPG Bull.* 90:31–60. doi:10.1306/08110504138.

Alves TM, Moita C, Cunha T, Ullnaess M, Myklebust R, Monteiro JH, Manuppella G. 2009. Diachronous evolution of Late Jurassic–Cretaceous continental rifting in the northeast Atlantic (west Iberian margin). *Tectonics* 28:TC4003. https://doi.org/10.1029/2008TC002337

Alves TM, Fetter M, Busby C, Gontijo R, Cunha T, Mattos NH. 2020. A tectono-stratigraphic review of continental breakup on intraplate continental margins and its impact on resultant hydrocarbon systems. *Marine and Petroleum Geology* 117. https://doi.org/10.1016/j.marpetgeo.2020.104341

Anadón P, Colombo F, Esteban M, Marzo M, Robles S, Santanach P, Solé Sugrañés YL. 1979. Evolución tectonoestratigráfica de los Catalánides. *Acta Geol. Hispànica* 242–270.

Angrand P, Ford M, Ducoux M, De Saint Blanquat M. 2022. Extension and early orogenic inversion along the basal detachment of a hyper-extended rifted margin: an example from the Central Pyrenees (France). *Journal of the Geological Society*, 179(1).

Angrand P, Ford M, Watts AB. 2018. Lateral variations in foreland flexure of a rifted continental margin: the Aquitaine Basin (SW France). *Tectonics* 37. https://doi.org/10.1002/2017TC004670.

Angrand P, Mouthereau F, Masini E, Asti R. 2020. A reconstruction of Iberia accounting for W-Tethys/N-Atlantic kinematics since the late Permian-Triassic. *Solid Earth*, https://doi.org/10.5194/se-2020-24.

Angrand P, Mouthereau F. 2021. Evolution of the Alpine orogenic belts in the Western Mediterranean region as resolved by the kinematics of the Europe-Africa diffuse plate boundary. *BSGF-Earth Sciences Bulletin*, 192(1), 42.

Antolín-Tomás B, Liesa CL, Casas AM, Gil-Peña I. 2007. Geometry of fracturing linked to extensión and basin formation in the Maestrazgo Basin (Eastern Iberian Chain, Spain). *Revista de la Sociedad Geológica de España* 20(3–4):351–365.

Aranda M, Simón JL. 1993. Aspectos de la tectónica cretácica y terciaria en la Cuenca de Utrillas (Teruel) a partir de los datos de minería del interior. *Revista de la Sociedad Geológica de España* 6(1–2):123–129.

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

Arche A, López-Gómez J, Marzo M, Vargas H. 2004. The siliciclastics Permian–Triassic deposits in Central and Northeastern Iberian Peninsula (Iberian, Ebro and Catalan Basins): a proposal for correlation. *Geologica Acta* 2:305–320.

Arche A, Diez JB, López-Gómez J. 2007. Identification of the Early Permian (Autunian) in the subsurface of the Ebro Basin, NE Spain, and its paleogeographic consequences. *Journal of Iberian Geology* 33(1):125–133.

Arnaud-Vanneau A, Arnaud H, Charollais J, Conrad MA, Cotillon P, Ferry S, Masse JP, Peybernès B. 1979. Paléogéographie des calcaires urgoniens du sud de la France. *Géobios* 3:363–383.

Arthaud F, Matte P. 1975. Les decrochements tardi-hercyniens du sud-ouest de l'europe. Geometrie et essai de reconstitution des conditions de la deformation. *Tectonophysics* 25:139–171. doi:10.1016/0040-1951(75)90014-1

Asti R, Lagabrielle Y, Fourcade S, Corre B, Monié P. 2019. How Do Continents Deform During Mantle Exhumation? Insights From the Northern Iberia Inverted Paleopassive Margin, Western Pyrenees (France). *Tectonics* 2018TC005428, doi:10.1029/2018TC005428.

Asti R, Rossetti F, Lucci F, Poujol M, Lagabrielle Y. 2021. Polyphase post- Variscan thinning of the North Pyrenean crust: Constraints from the P-T-t-deformation history of the exhumed Variscan lower crust (Saleix Massif, France). *Tectonophysics* 820, 229122. https://doi.org/10.1016/j.tecto.2021.229122

Aurell M, Meléndez A. 1993. Sedimentary evolution and sequence stratigraphy of the Upper Jurassic in the central Iberian Chain, northeast Spain. *Spec. Publ. Int. Ass. Sediment.*

Aurell M, Robles S, Bádenas B, Rosales I, Quesada S, Meléndez G, García-Ramos J. 2003. Transgressive–regressive cycles and Jurassic palaeogeography of northeast *Iberia. Sediment. Geol.* 162:239–271. https://doi.org/10.1016/S0037-0738(03)00154-4

Aurell M, Fregenal-Martínez M, Bádenas B, Muñoz-García MB, Élez J, Meléndez N, de Santisteban C. 2019. Middle Jurassic–Early Cretaceous tectono-sedimentary evolution of the southwestern Iberian Basin (central Spain): Major palaeogeographical changes in the geotectonic framework of the Western Tethys. *Earth-Science Reviews* 199:102983.

Autin J, Bellahsen N, Husson L, Beslier M-O, Leroy S, d'Acremont E. 2010. Analog models of oblique rifting in a cold lithosphere. *Tectonics* 29(6):TC6016. doi:10.1029/2010TC002671.

Autran A, Cogné EJ. 1980. La zone interne de l'orogéne varisque dans l'Ouest de la France et sa place dans le développement de la chaine hercynienne. In: Cogné, J., Slansky, M. (Eds.), Géologie de l'Europe, Mémoires du BRGM 108, pp. 90-111.

Avedik F, Howard D. 1979. Preliminary results of a seismic refraction study in the Meriadzek-Trevelyan area, Bay of Biscay. In : L. Montadert, D.G. Roberts *et al.*, Eds., Init. Rep. Deep Sea Drill. Proj. 48. – Washington, U.S. Govt. Print. Off., 1015-1023.

Azambre B, Rossy M. 1976. Le magmatisme alcalin d'age cretace, dans les Pyrenees occidentales et l'Arc basque; ses relations avec le metamorphisme et la tectonique. *Bull. Soc. Geol. Fr.* S7–XVIII:1725–1728. doi:10.2113/gssgfbull.S7-XVIII.6.1725

Azambre B, Guitard G. 2001. Disthène et staurotide reliques dans les métapelites du Canigou (Pyrénées orientales). Relations avec les épisodes hercyniens de basse et moyenne pressions. *Comptes Rendus de l'Academie de Sciences - Serie IIa: Sciences de la Terre et des Planetes* 333:601–609, https://doi.org/10.1016/S1251-8050(01)01670-6.

Bacon M, Gray F, Matthews T. 1969. Crustal structure studies in the Bay of Biscay. *Earth Planet. Sci. Lett.* 6:101–105.

Ballèvre M, Bosse V, Ducassou C, Pitra P. 2009. Palaeozoic history of the Armorican Massif: models for the tectonic evolution of the suture zones. *C. R. Geosci.* 341:174–201.

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

Barrier E, Chamot-Rooke N, Giordano G. 2004. Geodynamic Maps of the Mediterranean. Sheet 1, Commission for the Geological Map of the World (CGMW), map at 1:13 000 000 scale.

Berástegui X, García-Senz J, Losantos M. 1990. Tecto-sedimentary evolution of the Organyà extensional basin (central south Pyrenean unit, Spain) during the Lower Cretaceous. *Bull. Soc. Géol. Fr.* 8:251–264.

Biteau JJ, Marrec AL, Vot ML, Masset JM. 2006. The aquitaine basin. *Petroleum Geoscience* 12:247–273. https ://doi.org/10.1144/1354-079305-674

Bixel F, Lucas C. 1987. Approche Géodynamique du Permien et du Trias des Pyrénées dans le cadre du sud-ouest européen. *Cuad. Geol. Iber.* 11:57–81.

Bodego A, Iriarte E, López-Horgue MA, Álvarez I. 2018. Rift-margin extensional forced folds and salt tectonics in the eastern Basque-Cantabrian rift basin (western Pyrenees). *Marine and Petroleum Geology*. 91:667-682.

Boillot G, Dupeuble PA, Malod J. 1979. Subduction and tectonics on the continental margin off northern Spain. *Mar. Geol.* 32:53–70.

Boillot G. 1984. Le Golfe de Gascogne et les Pyrénées. In, Boillot, G., Montadert, M., Lemoine, M., and Biju-Duval, B., eds, Les marges continentales actuelles et fossiles autour de la France, Masson, Paris, p.5–81.

Bois C, Pinet B, Gariel O. 1997. The sedimentary cover along the ECORS Bay of Biscay deep seismic reflection profile: a comparison between the Parentis Basin and other European rifts and basins. *Soc. Géol. Fr. Mém.* 171:143–165.

Bouhallier H, Choukroune P, Ballèvre M. 1991. Evolution structurale de la croute profonde hercynienne; exemple du massif de l'Agly (Pyrénées orientales, France). *Comptes rendus de l'Académie des sciences Série 2* 312:647–654.

Bourrouilh R, Richter JP, Zolnaï G. 1995. The North Pyrenean Aquitaine Basin (France): evolution and hydrocarbons. *AAPG Bull.* 79:831–853.

Bourrouilh R. 2012. The Aquitaine Basin and the Pyrenees: geodynamical evolution and hydrocarbons. In: Regional Geology and Tectonics: Phanerozoic Passive Margins, Cratonic Basins and Global Tectonic Maps, 802–866. doi:10.1016/b978-0-444-56357-6.00021-4

BRGM, Elf, Esso, SNPA. 1974. Géologie du Bassin d’aquitaine (BRGM Ed). Paris: BRGM Editions.

Brun JP. 1999. Narrow rifts versus wide rifts: Inferences for the mechanics of rifting from laboratory experiments. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 357:695–712. https://doi.org/10.1098/rsta.1999.0349.

Brune S. 2014. Evolution of stress and fault patterns in oblique rift systems: 3-D numerical lithospheric-scale experiments from rift to breakup. *Geochem. Geophys. Geosyst.* 15(8):3392–3415. doi:10.1002/2014GC005446.

Brunet MF. 1983. La subsidence du Bassin d'Aquitaine au Mesozoi'que et au Cenozoi'que. *Comptes Rendus des Seances hebdomadaires de l'Academie des Sciences Paris* II 297:599-602.

Brunet MF. 1984. Subsidence history of the Aquitaine Basin determined from subsidence curves. *Geological Magazine* 121:421–428.

Brunet MF. 1994. Subsidence in the Parentis Basin (Aquitaine, France): Implications of the thermal evolution. In Hydrocarbon Exploration and Underground Gas Storage in France, vol. 4, edited by A. Mascle, pp. 187–198, Springer, Paris.

Buck WR. 1991. Modes of continental lithospheric extension. *J. Geophys. Res.* 96:20161–20178.

Burg JP, Van Den Driessche J, Brun JP. 1994. Syn- to post-thickening extension in the Variscan Belt of Western Europe: modes and structural consequences. *Géologie de la France* 3:33–51.

Cadenas P, Fernández-Viejo G. 2017. The Asturian Basin within the North Iberian margin (Bay of Biscay): Seismic characterization of its geometry and its Mesozoic and Cenozoic cover. *Basin Research* 29:521–541. https://doi.org/10.1111/bre.12187

Cadenas P, Fernández-Viejo G, Pulgar J A, Tugend J, Manatschal G, Minshull T A. 2018. Constraints imposed by rift inheritance on the compressional reactivation of a hyperextended margin: Mapping rift domains in the North Iberian Margin and in the Cantabrian Mountains. *Tectonics* 37:758–785. https://doi.org/10.1002/2016TC004454

Cadenas P, Manatschal G, Fernández-Viejo G. 2020. Unravelling the architecture and evolution of the inverted multi-stage North Iberian-Bay of Biscay rift. *Gondwana Research* 88:67–87. https://doi.org/10.1016/j.gr.2020.06.026

Calvet F, Lucas C. (coord.) *et al*. (1995). Trias. In Barnolas A., Chiron J.C. : "Synthèse géologique et géophysique des Pyrénées". Édition BRGM - ITGE, vol. 2, pp. 22-73.

Cámara P. 2017. Salt and Strike-Slip Tectonics as Main Drivers in the Structural Evolution of the Basque-Cantabrian Basin, Spain. In: Soto JI, Flinch JF, Tari G (eds), Permo-Triassic Salt Provinces of Europe, North Africa and the Atlantic Margins Tectonics and Hydrocarbon Potential, Elsevier, Amsterdam, Netherlands, p 371–393

Cámara P. 2020. Inverted turtle salt anticlines in the Eastern Basque-Cantabrian basin, Spain. *Marine and Petroleum Geology* 117. https://doi.org/10.1016/j.marpetgeo.2020.104358

Canérot J. 1988. Manifestations de l'halocinèse dans les Chaînons Béarnais (Zone Nord-Pyrénéenne) au Crétacé inférieur. *Comptes Rendus De L'académie Des Sciences Paris* 306:1099–1102.

Canérot J. 1991. Comparative study of the Eastern Iberides (spain) and the Western Pyrenees (France) Mesozoic basins. *Palaeogeography, Palaeoclimatology, Palaeoecology* 87:1–28. https://doi.org/10.1016/0031-0182(91)90128-E

Canérot J. 2016. The Iberian Plate: myth or reality? *Bol. Geológico Min.* 127, 563–574.

Canérot J. 2017. The pull apart-type Tardets-Mauléon Basin, a key to understand the formation of the Pyrenees. *Bull. Soc. Geol. Fr.* 188(6):35. https://doi.org/10.1051/bsgf/2017198.

Canérot J, Majesté-Menjoulas C, Ternet Y. 1999. Le cadre stratigraphique et géodynamique des altérites et des bauxites sur la marge ibérique des Pyrénées occidentales (France). *Comptes Rendus de l'Académie des Sciences-Series II. Earth and Planetary Science* 328 (7):451–456.

Canérot J, Majesté-Menjoulas C, Ternet Y. 2004. Nouvelle interprétation structurale de la « faille Nord- Pyrénéenne » en vallée d’Aspe (Pyrénées-Atlantiques). Remise en question d’un plutonisme ophitique danien dans le secteur de Bedous. *Comptes Rendus Geosci.* 336:135–142. doi:10.1016/j.crte.2003.11.004

Canérot J, Hudec MR, Rockenbauch K. 2005. Mesozoic diapirism in the Pyrenean orogen: Salt tectonics on a transform plate boundary. *AAPG Bull.* 89:211–229. https://doi.org/10.1306/09170404007

Capote R, Muñoz JA, Simón JL, Liesa CL, Arlegui LE. 2002. Alpine tectonics I: the Alpine system north of the Betic cordillera. In: Gibbons W, Moreno T (eds), The Geology of Spain. The Geological Society, London, pp 367–400.

Carola E, Tavani S, Ferrer O, Granado P, Quintà A, Butillé M, Muñoz JA. 2013. Along-strike extrusion at the transition between thin- and thick-skinned domains in the Pyrenean Orogen (northern Spain). Geological Society, London, Special Publications. 377(1):119–140. https://doi.org/10.1144/SP377.3

Casas AM, Faccenna C. 2001. Tertiary compressional deformation of the Iberian plate. *Terra Nova* 13:281–288.

Casas AM, Simón JL, Serón FJ. 1992. Stress deflection in a tectonic compressional field: a model for the North-Western Iberian chain (Spain). *J. geophys. Res*. 97:7183–7192.

Casas AM, Villalaín JJ, Soto R, Gil-Imaz A, Del Río P, Fernández G. 2009. Multidisciplinary approach to an extensional syncline model for the Mesozoic Cameros Basin (N Spain). *Tectonophysics* 470:3–20.

Casas-Sainz AM. 1993. Oblique tectonic inversion and basement thrusting in the Cameros Massif (Northern Spain). *Geodin. Acta* 6:202–216. https://doi.org/10.1080/09853111.1993.11105248

Casas-Sainz AM, Gil-Imaz A. 1998. Extensional subsidence, contractional folding and thrust inversion of the eastern Cameros basin, northern Spain. *Geol. Rundsch.* 86:802–818. https://doi.org/10.1007/s005310050178

Casas-Sainz AM, Cortés AL, Maestro A. 2000. Intra-plate deformation and basin formation during the Tertiary at the Northern Iberian Plate: Origin and evolution of the Almazán Basin. *Tectonics* 19:258–289.

Chelalou R, Nalpas T, Bousquet R, Prevost M, Lahfid A, Ringenbach JC, Ballard JF. 2016. New sedimentological, structural and paleo-thermicity data on the Boucheville basin (eastern north Pyrenean zone, France). *Compte Rendu Géoscience*. doi:10.1016/j.crte.2015.11.008

Choukroune P. 1976. Structure et évolution tectonique de la zone nord-pyrénéenne: analyse de la déformation dans une portion de chaîne à schistosité sub-verticale. Société géologique de France, Paris.

Choukroune P. 1992. Tectonic Evolution of the Pyrenees. *Annu. Rev. Earth Planet. Sci.* 20:143–158. doi:10.1146/annurev.ea.20.050192.001043

Choukroune P, Seguret M, Galdeano A. 1973. Caracteristiques et evolution structurale des Pyrenees; un modele de relations entre zone orogenique et mouvement des plaques. *Bull. Société Géologique Fr.* S7–XV:600–611. doi:10.2113/gssgfbull.S7-XV.5-6.600

Choukroune P, ECORS Team. 1989. The Ecors Pyrenean deep seismic profile reflection data and the overall structure of an orogenic belt. *Tectonics* 8:23–39. http://dx.doi.org/10.1029/TC008i001p00023.

Choukroune P, Séguret M. 1973. Carte structurale des Pyrénées. ELF-ERAP.

Choukroune P, Mattauer M. 1978. Tectonique des plaques et Pyrénées: Sur le fonctionnement de la faille transformante nord-Pyrénéenne; comparaisons avec les modèles actuels. *Bulletin de la Societe Geologique de France* 20:689–700.

Christophoul F, Soula JC, Brusset S, Elibana B, Roddaz M, Bessiere G, Déramond J. 2003. Time, place and mode of propagation of foreland basin systems as recorded by the sedimentary fill: Examples of the Late Cretaceous and Eocene retro-foreland basins of the north-eastern Pyrenees.

*Geological Society, London, Special Publications* 208(1):229–252. https://doi.org/10.1144/GSL.SP.2003.208.01.11

Clerc C. 2012. Evolution du domaine nord-pyreneen au Crétacé. Amincissement crustal extreme et thermicité élevée: un analogue pour les marges passives (PhD thesis). Université Pierre et Marie Curie - Paris VI.

Clerc C, Lagabrielle Y. 2014. Thermal control on the modes of crustal thinning leading to mantle exhumation: Insights from the Cretaceous Pyrenean hot paleomargins. *Tectonics* 33:2013TC003471. doi:10.1002/2013TC003471

Clerc C, Lahfid A, Monie P, Lagabrielle Y, Chopin C, Poujol M, Boulvais P, Ringenbach JC, Masini, E, de St Blanquat M. 2015. High-temperature metamorphism during extreme thinning of the continental crust: a reappraisal of the North Pyrenean passive paleomargin. *Solid Earth* 6:643–668. doi:10.5194/se-6-643-2015

Clerc C, Lagabrielle Y, Labaume P, Ringenbach JC, Vauchez A, Nalpas T, Bousquet R, Ballard JF, Lahfid A, Fourcade S. 2016. Basement – Cover decoupling and progressive exhumation of metamorphic sediments at hot rifted margin. Insights from the Northeastern Pyrenean analog. *Tectonophysics* 686:82–97. https://doi.org/10.1016/j.tecto.2016.07.022

Cochelin B, Chardon D, Denèle Y, Gumiaux C, Le Bayon B. 2017. Vertical strain partitioning in hot Variscan crust: Syn-convergence escape of the Pyrenees in the Iberian-Armorican syntax. *Bulletin de la Société Géologique de France* 188(6):39. doi:10.1051/bsgf/2017206

Cochelin B, Lemirre B, Denèle Y, de Saint Blanquat M, Lahfid A, Duchêne S. 2018a. Structural inheritance in the central Pyrenees: the variscan to Alpine tectonometamorphic evolution of the axial zone. *J. Geol. Soc.* 175:336–351. doi:10.1144/jgs2017-066.

Cochelin B, Gumiaux C, Chardon D, Denèle Y, Le Bayon B. 2018b. Multi-scale strainfield analysis using geostatistics: Investigating the rheological behavior of the hot Variscan crust of the Pyrenees (Axial Zone). *J. Struct. Geol.* 116:114–130. doi:10.1016/j.jsg.2018.07.024

Coltice N, Bertrand H, Rey P, Jourdan F, Phillips BR, Ricard, Y. 2009. Global warming of the mantle beneath continents back to the Archaean. *Gondwana Research* 15:254–266, https://doi.org/10.1016/j.gr.2008.10.001, http://dx.doi.org/10.1016/j.gr.2008.10.001.

Combes PJ, Peybernès B, Leyreloup AF.,1998. Altérites et bauxites, témoins des marges européenne et ibérique des Pyrénées occidentales au Jurassique supérieur—crétacé inférieur, à l'ouest de la vallée d'Ossau (Pyrénées-Atlantiques, France). *Comptes Rendus de l'Académie des Sciences-Series II. Earth and Planetary Science* 327 (4):271–278.

Corre B. 2017. La bordure nord de la plaque ibérique à l'Albo-Cénomanien: architecture d'une marge passive de type ductile (Chaînons Béarnais, Pyrénées Occidentales) (PhD Thesis). Rennes 1.

Corre B, Boulvais P, Boiron MC, Lagabrielle Y, Marasi L, Clerc C. 2018. Fluid circulations in response to mantle exhumation at the passive margin setting in the north Pyrenean zone, France. *Mineralogy and Petrology*, 1–24.

Costa S, Maluski H. 1988. Use of the 40Ar-39Ar stepwise heating method for dating mylonite zones: An example from the St. Barthélémy massif (Northern Pyrenees, France). *Chem. Geol. Isot. Geosci. Sect.* 72:127–144. doi:10.1016/0168-9622(88)90061-9

Cubaynes R, Faure P, Hantzpergue P, Pélissié T, Rey J. 1989. Le Jurassique du Quercy - unités lithostratigraphiques, stratigraphie et organisation séquentielle, évolution sédimentaire. *Géologie de la France* 3:33-62.

Curnelle R. 1983. Evolution structuro-sédimentaire du Trias et de l'Infra-Lias d'Aquitaine. *Bull. Cent. Rech. Explor. Prod. Elf-Aquitaine* 7(1):69–99.

Curnelle R. 1995. Evoution mesozoique du bassin d’Aquitaine. Séance spécialisée de la Soc. géol. France “ Le Bassin d’Aquitaine, évolution sédimentaire et structurale”, Toulouse, 18 Septembre 1995 - *Strata*, Toulouse, sér. 1, 7:12-20

Curnelle R, Dubois P, Seguin JC. 1982. The Mesozoic-Tertiary evolution of the Aquitaine Basin. *Philosophical Transactions of the Royal Society of London* A 305:63-84.

Dauteuil O, Ricou LE. 1989. Une circulation de fluides de haute-temperature a l’origine du metamorphisme cretace nord-pyreneen. Circ. High-Temp. Fluids Orig. North Pyrenean Cretac. Metamorph. 3:237–250.

de Hoÿm de Marien L, Le Bayon B, Pitra P, Van Den Driessche J, Poujol M, Cagnard F. 2019. Two-stage Variscan metamorphism in the Canigou massif: Evidence for crustal thickening in the Pyrenees. *Journal of Metamorphic Geology* 37:863–888. https://doi.org/10.1111/jmg.12487.

De la Horra R, López-Gómez J, Arche A, Escudero-Mozo MJ, Galán-Abellán B, Barrenechea JF, Martín-Chivelet J, Borruel V. 2013. The Permian-Triassic rocks of the Eastern Iberian Ranges: a general approach in the context of the first stages of the break-up of Pangea. Pan-European Correlation of the Triassic. In: 10th International Field Workshop

de Saint Blanquat M. 1993. La faille normale ductile du massif du Saint Barthélémy: Evolution hercynienne des massifs nord-pyrénéens catazonaux considérée du point de vue de leur histoire thermique. *Geodinamica Acta* 6(1):59–77. https://doi.org/10.1080/09853111.1993.11105239

de Saint Blanquat M, Brunel M, Mattauer M. 1986. Les zones de cisaillements du massif nord Pyrénéen du Saint-Bartelemy, témoins probables del'extension crustale d'âge crétacé. *Acad. Sci. Comp. Rend.* 303:1339–1344.

de Saint Blanquat M, Lardeaux JM, Brunel M. 1990. Petrological arguments for high-temperature extensional deformation in the Pyrenean Variscan crust (Saint Barthélémy Massif, Ariège, France). *Tectonophysics* 177(1–3):245–262. https://doi.org/10.1016/0040-1951(90)90284-F

Debelmas J. 1986. L'héritage hercynien à l'origine des grands bassins sédimentaires français. *Bulletin des Centres de Recherche d'Exploration-Production Elf-Aquitaine* 10:151-161.

Debrand-Passard (coord.) *et al*. 1995. Jurassique. In Barnolas A., Chiron J.C. : "Synthèse géologique et géophysique des Pyrénées". Édition BRGM - ITGE, vol. 2, pp. 22-73.

Debroas EJ. 1978. Evolution de la fosse du flysch ardoisier de l'Albien superieur au Senonien inferieur (zone interne metamorphique des Pyrenees navarro-languedociennes). *Bull. Société Géologique Fr.* 7:639–648.

Debroas EJ. 1987. Modèle de basin triangulaire à l'intersection de décrochements divergents pour le fossé albo-cénomanien de la Ballongue (Zone Nord-pyrénéenne, France). *Bull. Soc. Géol. France* 8(III):887-898

Debroas EJ. 1990. Le Flysch noir albo-cénomanien témoin de la structuration albienne à sénonienne de la zone nord-pyrénéenne en Bigorre (Hautes-Pyrénées, France). *Bull. Soc. Géol. France* 8(VI):273-285.

Debroas EJ. 1995. Flysch noir et rifting oblique albo-cénomanien sur la marge aquitaine du sillon nord-pyrénéen - Séance spécialisée de la Soc. géol. France " Le Bassin d'Aquitaine, évolution sédimentaire et structurale", Toulouse, 18 Septembre 1995 - *Strata*, Toulouse, sér. 1, 7:21-23

Debroas EJ. 2003. Le bassin du Flysch noir albo-cénomanien dans les Pyrénées centrales : un rift à ouverture triphasée, en transtension senestre, d'extension décroissante vers l'Est et d'amplitude pluridécakilomé-trique - "Bassins crétacés de France et d'Europe occidentale", séance spéc. SGF, AGBP, APF, ASF, CFS, Paris 6-7 Novembre 2003.

Debroas EJ, Canérot J, Bilotte M. 2010. Les brèches d'Urdach, témoins de l'exhumation du manteau pyrénéen dans un escarpement de faille vraconnien-cénomanien inférieur (Zone nord-pyrénéenne, Pyrénées-Atlantiques, France). *Géologie de la France* 2:53–63.

DeFelipe I, Pedreira D, Pulgar JA, Iriarte E, Mendia M. 2017. Mantle exhumation and metamorphism in the Basque-Cantabrian Basin (N Spain): Stable and clumped isotope analysis in carbonates and comparison with ophicalcites in the North-Pyrenean Zone (Urdach and Lherz). *Geochem. Geophys. Geosystems* 18:631–652. https://doi.org/10.1002/2016GC006690

Delaperriere E, de Saint Blanquat M, Brunel M, Lancelot JR. 1994. Geochronologie U-Pb sur zircons et monazites dans le massif du Saint Barthelemy (Pyrenees, France); discussion des ages des evenements varisques et pre-varisques. *Bull. Société Géologique Fr.* 165:101–112.

Delfaud J, Henry J. 1967. Evolution des bassins jurassiques dans la zone nord-pyrénéenne occidentale. 64ème congrès AFAS Bordeaux, p. 75–80.

Delfaud J, Villanova M. 1967. Evolution des bassins pendant le Crétacé inférieur dans les Pyrénees occidentales et la bordure de l'Aquitaine. 64ème congrès AFAS Bordeaux, p. 87–92.

Delfaud J, Permanyer A, Lacrampe G, Revert J, Sabrier R, Thomas G. 1995. Le contexte dynamique du dépôt de la matière organique dans le Kimméridgien nord-aquitain - Séance spécialisée de la Soc. géol. France " Le Bassin d'Aquitaine, évolution sédimentaire et structurale", Toulouse, 18 Septembre 1995 - *Strata*, Toulouse, sér. 1, 7:24-26.

Denèle Y, Olivier P, Gleizes G, Barbey P. 2007. The Hospitalet gneiss dome (Pyrenees) revisited: lateral flow during Variscan transpression in the middle crust. *Terra Nova* 19:445–453. doi:10.1111/j.1365-3121.2007.00770.x

Denèle Y, Olivier P, Gleizes G, Barbey P. 2009. Decoupling between the middle and upper crust during transpression-related lateral flow: Variscan evolution of the Aston gneiss dome (Pyrenees, France). *Tectonophysics*, 477:244–261. doi:10.1016/j.tecto.2009.04.033

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

Desegaulx P, Moretti I. 1988. Subsidence history of the Ebro Basin. *J. Geodyn.* 10:9–24.

Desegaulx P, Brunet MF. 1990. Tectonic subsidence of the Aquitaine basin since Cretaceous times. *Bulletin de la Société géologique de France* 6:295–305.

Dewey JF. 2002. Transtension in arcs and orogens. *Int. Geol. Rev.* 44:402 – 439.

Dewey JF, Holdsworth RE, Strachan RA. 1998. Transpression and transtension zones. In: Holdsworth, R. E., Strachan, R. A. & Dewey, J. E (eds) 1998. Continental Transpressional and Transtensional Tectonics. Geological Society, London, Special Publications, 135, 1-14.

Dinarès-Turell J, García-Senz J. 2000. Remagnetization of Lower Cretaceous limestones from the southern Pyrenees and relation to the Iberian plate geodynamic evolution *J. geophys. Res*. 105, B8: 405–418.

Doblas M, Oyarzun R, Sopeña A, López Ruiz J, Capote R, Hernández Enrile JL, Hoyos M, Lunar R, Sánchez-Moya Y. 1994. Variscan–Late Variscan–Early Alpine progressive extensional collapse of central Spain. *Geodinamica Acta* 7:1– 14.

Duclaux G, Huismans RS, May DA. 2020. Rotation, narrowing, and preferential reactivation of brittle structures during oblique rifting. *Earth Planet. Sci. Lett.* 531:12.

Ducoux M. 2017. Structure, thermicité et évolution géodynamique de la Zone Interne Métamorphique des Pyrénées. PhD thesis, University of Orléans, France, 646 pp.

Ducoux M, Jolivet L, Callot JP, Aubourg C, Masini E, Lahfid A, . . . Baudin T. 2019. The Nappe des Marbres unit of the Basque-Cantabrian Basin: the tectono-thermal evolution of a fossil hyperextended rift basin. *Tectonics* 2018TC005348. https://doi.org/10.1029/2018TC005348

Duretz T, Asti R, Lagabrielle Y, Brun JP, Jourdon A, Clerc C, Corre B. 2019. Numerical modelling of syn-rift salt tectonics during Cretaceous Pyrenean Rifting. *Basin Res* 1–16. https://doi.org/10.1111/bre.12389.

Espina R, Alonso JL, Pulgar JA. 2004. Extensión Triásica en la Cuenca Vasco-Cantábrica. In J. A. Vera (Ed.), Geología de España (pp. 338–339). Madrid: SGEIGME.

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

Etheve N, Mohn G, Frizon de Lamotte D, Roca E, Tugend J, Gómez-Romeu J. 2018. Extreme Mesozoic crustal thinning in the eastern Iberia margin: The example of the Columbrets Basin (Valencia Trough). *Tectonics* 37:636–662. https://doi.org/10.1002/2017TC004613

Fabries J, Lorand JP, Bodinier JL, Dupuy C. 1991. Evolution of the upper mantle beneath the pyrenees: Evidence from orogenic spinel lherzolite massifs. *Journal of Petrology*, Special-Vo, 55–76. https://doi.org/10.1093/petrology/Special_Volume.2.55.

Fabriès J, Lorand JP, Bodinier JL. 1998. Petrogenetic evolution of orogenic lherzolite massifs in the central and western Pyrenees. *Tectonophysics* 292:145–167. https://doi.org/10.1016/S0040-1951(98)00055-9.

Fernández-Viejo G, Gallart J, Pulgar JA, Gallastegui J, Dañobeitia JJ, Córdoba D. 1998. Crustal transition between continental and oceanic domains along the North Iberian margin from wide angle seismic and gravity data. *Geophysical Research Letters* 25:4249–4252. https://doi.org/10.1029/1998GL900149

Fernández-Viejo G, Gallastegui J, Pulgar JA, Gallart J. 2011. The MARCONI reflection seismic data: A view into the eastern part of the Bay of Biscay. *Tectonophysics* 508:34–41. https://doi.org/10.1016/j.tecto.2010.06.020

Fernández-Viejo G, López Fernández C, Domínguez-Cuesta MJ, Cadenas P. 2014._How much confidence can be conferred on tectonic maps of continental shelves? The Cantabrian-Fault case. *Sci. Rep*. 4, 3661. doi: 10.1038/srep03661.

Ferrer O, Jackson MPA, Roca E, Rubinat M. 2012. Evolution of Salt Structures During Extension and Inversion of the Offshore Parentis Basin (Eastern Bay of Biscay). In: Alsop, G.I., Archer, S.G., Hartley, A.J., Grant, N.T., Hodgkinson, R. (Eds.), Salt Tectonics, Sediments and Prospectivity. Geological Society of London, Special Publications 363, 361–379.

Ferrer O, Roca E, Vendeville BC. 2014. The role of salt layers in the hangingwall deformation of kinked-planar extensional faults: Insights from 3D analogue models and comparison with the Parentis Basin. *Tectonophysics* 636:338–350.

Filleaudeau PY. 2011. Croissance et dénudation des Pyrénées du Crétacé Supérieur au Paléogène: Apports de l'analyse de bassin et thermochronométrie détritique. Ph.D. thesis. Université Pierre et Marie Curie, Paris VI.

Ford M, Hemmer L, Vacherat A, Gallagher K, Christophoul F. 2016. Retro-wedge foreland basin evolution along the ECORS line, eastern Pyrenees, France. *J. Geol. Soc.* 173(3):419–437. https://doi.org/10.1144/jgs2015-129.

Franke W. 2000. The mid-European segment of the Variscides: Tectonostratigraphic units, terrane boundaries and plate tectonic evolution. *Geological Society Special Publication* 179:35–56, https://doi.org/10.1144/GSL.SP.2000.179.01.05.

Franke W. 2006. The Variscan orogen in Central Europe: Construction and collapse. *Geological Society Memoir* 32:333–343. https://doi.org/10.1144/GSL.MEM.2006.032.01.20.

Frasca G, Manatschal G, Cadenas P, Miró J, Lescoutre R. 2021. A kinematic reconstruction of Iberia using intracontinental strike-slip corridors. *Terra Nova* 00:1–9. https://doi.org/10.1111/ter.12549

Fügenschuh B, Froitzheim N, Capdevila R, Boillot G. 2003. Offshore granulites from the Bay of Biscay margins: fission tracks constrain a Proterozoic to Tertiary thermal history. *Terra Nova* 15(5):337–343.

Galdeano A, Moreau MG, Pozzi JP, Berthou PY, Malod JA. 1989. New paleomagnetic results from Cretaceous sediments near Lisboa (Portugal) and implications for the rotation of Iberia. *Earth Planet. Sci. Lett.* 92:95–106. doi:10.1016/0012- 821X(89)90024-1

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

García-Lasanta C, Oliva-Urcia B, Román-Berdiel T, Casas AM, Hirt AM. 2014. Understanding the Mesozoic kinematic evolution in the Cameros basin (Iberian Range, NE Spain) from magnetic subfabrics and mesostructures. *J. Struct. Geol.* 66:84–101.

García-Lasanta C, Román-Berdiel T, Oliva-Urcia B, Casas AM, Gil-Peña I, Speranza F, Mochales T. 2015. Tethyan versus Iberian extension during the Cretaceous period in the eastern Iberian Peninsula: insights from magnetic fabrics. *Journal of the Geological Society* 173(1):137–141.

García-Lasanta C, Casas-Sainz A, Villalaín JJ, Oliva-Urcia B, Mochales T, Speranza F. 2017. Remagnetizations used to unravel large-scale fold kinematics: A case study in the Cameros Basin (Northern Spain): Unfolding in Basin Inversion. *Tectonics* 36:714–729. https://doi.org/10.1002/2016TC004459

García-Mondéjar J. 1989. Strike-slip subsidence of the Basque-Cantabrian Basin of Northern Spain and its relationships to Aptian-Albian opening of Bay of Biscay. In: Extensional Tectonics and Stratigraphy of the North Atlantic Margins, AAPG Mem., vol. 46, edited by A. J. Tankard and H. R. Balkwill, pp. 395–409, Am. Assoc. of Pet. Geol., Tulsa, Okla.

García-Mondéjar J. 1996. Plate reconstruction of the Bay of Biscay. *Geology* 24(7):635–638.

García-Mondéjar J, Agirrezabala LM, Aranburu A, Fernández-Mendiola PA, Gómez-Pérez I, López-Horgue M, Rosales I. 1996. Aptian–Albian tectonic pattern of the Basque–Cantabrian Basin (Northern Spain). *Geol J* 31(1):13–45

García-Mondéjar J, Fernàndez-Mendiola PA, Agirrezabala LM, Aranburu A, López-Horgue MA, Iriarte E, Martinez de Rituerto S. 2004. Extensón del Aptiense-Albiense en la Cuenca Vasco-Cantábrica. SGEIGME, Madrid. *Geological Society, London, Special Publications* 282:111-138. https://doi.org/10.1144/SP282.6

García-Senz J, Muñoz JA. 2019. South Central Pyrenees: The Organyà Rift Basin. In: Quesada, C. & Oliveira, J.T. (eds), Vergés, J. & Kullberg, J.C. (coord.), The Geology of Iberia: A Geodynamic Approach, Volume 3: The Alpine Cycle. Springer, 182-190.

García-Senz J, Rosales I, Robador A & Pedrera A, 2019a. The Basque-Cantabrian Rift Basin. In: Quesada, C. & Oliveira, J.T. (eds), Vergés, J. & Kullberg, J.C. (coord.), The Geology of Iberia: A Geodynamic Approach, Volume 3: The Alpine Cycle. Springer, 171-182.

Garcia-Senz J, Pedrera A, Ayala C, Ruiz-Constán A, Robador Moreno A, Rodríguez-Fernández R. 2019b. Inversion of the North-Iberian hyperextended margin: the role of exhumed mantle indentation during continental collision. *Geological Society, London, Special Publications* 490. doi:

Gardner RL, Piazolo S, Daczko NR, Evans L. 2019. Ductile deformation without localization: Insights from numerical modeling. *Geochemistry, Geophysics, Geosystems* 20:5710–5726. https://doi.org/10.1029/2019GC008633

Gaspar-Escribano JM, Van Wees JD, Ter Voorde M, Cloetingh S, Roca E, Cabrera L, Muñoz JA, Ziegler PA, Garcia-Castellanos D. 2001. Three-dimensional flex-ural modelling of the Ebro Basin (NE Iberia). *Geophys. J. Int.*145 (2):349–367.

Gibbs AD. 1984. Structural evolution of extensional basin margins. *Journal of the Geological Society, London* 141:609-620.

Golberg JM, Maluski H, Leyreloup AF. 1986. Petrological and age relationship between emplacement of magmatic breccia, alkaline magmatism, and static metamorphism in the North Pyrenean Zone. *Tectonophysics* 129:275–290. doi:10.1016/0040-1951(86)90256-8

Golberg JM, Guiraud M, Maluski H, Séguret M. 1988. Caractères pétrologiques et âge du métamorphisme en contexte distensif du bassin sur décrochement de Soria (Crétacé inférieur, Nord Espagne). *Comptes Rendus Académie Sci. Sér. 2 Mécanique Phys. Chim. Sci. Univers Sci. Terre* 307:521–527.

Golberg JM, Maluski H. 1988. Donnees nouvelles et mise au point sur l'age du metamorphisme pyreneen. New Data Discuss. Age Pyrenean Metamorph. 306, 429–435.

Golberg JM, Leyreloup AF. 1990. High temperature-low pressure Cretaceous metamorphism related to crustal thinning (Eastern North Pyrenean Zone, France). *Contrib. Mineral. Petrol.* 104:194–207. doi:10.1007/BF00306443

Gómez JJ, Aguado R, Azerêdo AC, Cortés JE, Duarte LV, O'Dogherty L, da Rocha RB, Sandoval J. 2019. The Late Triassic–Middle Jurassic Passive Margin Stage. In: Quesada, C. & Oliveira, J.T. (eds), Vergés, J. & Kullberg, J.C. (coord.), The Geology of Iberia: A Geodynamic Approach, Volume 3: The Alpine Cycle. Springer, 55 pp.

Gong Z, Langereis CG, Mullender TAT. 2008. The rotation of Iberia during the Aptian and the opening of the Bay of Biscay. *Earth planet. Sci. Lett.* 273:80–93.

Gong Z, van Hinsbergen DJJ, Vissers RLM, Dekkers MJ. 2009. Early Cretaceous syn-rotational extension in the Organyà basin - New constrains on the palinspastic position of Iberia during its rotation. *Tectonophysics* 473:312–323.

González-Fernández B, Menéndez-Casares E, Gutiérrez-Claverol M, García-Ramos JC. 2004. Litoestratigrafía del sector occidental de la cuenca cretácica de Asturias. *Trabajos de Geologia* 24, 43–80.

González-Fernández B, Menéndez-Casares E, Vicedo V, Aramburu C, Caus E. 2014. New insights about the Upper Jurassic-Lower Cretaceous sedimentary succesions from Asturias (NW Iberian Peninsula). *Journal of Iberian Geology* 40(3):409–430.

Gordon RG. 1998. The plate tectonic approximation: plate nonrigidity, diffuse plate boundaries, and global plate reconstructions. *Ann. Rev. Earth Planet Sci.* 26:615–642.

Gordon RG, Stein S. 1992. Global tectonics and space geodesy. *Science* 256:333–342.

Granado P, Tavani S, Carrera N, Muñoz JA. 2018. Deformation pattern around the Conejera Fault blocks (Asturian Basin, North Iberian Margin). *Geol. Acta* 16 (3):1–17.

Grool AR, Ford M, Vergés J, Huismans RS, Christophoul F, Dielforder A. 2018. Insights into the crustal-scale dynamics of a doubly vergent orogen from a quantitative analysis of its forelands: A case study of the eastern Pyrenees. *Tectonics* 37:450–476. https://doi.org/10.1002/2017TC004731

Guimerà J. 2018. Structure of an intraplate fold-and-thrust belt: The Iberian Chain. A synthesis. *Geologica Acta* 16(4):427-438. DOI: 10.1344/GeologicaActa2018.16.4.6

Guimerà J, Álvaro M. 1990. Structure et évolution de la compression alpine dans la Chaîne Ibérique et la Chaîne Côtière Catalane (Espagne). *Bulletin de la Société Géologique de France* 8(2):339–340.

Guimerà J, Alonso Á, Mas JR. 1995. Inversion of an extensional-ramp basin by a newly formed thrust: the Cameros basin (N. Spain). *Geol. Soc. Lond. Spec. Publ.* 88:433–453. https://doi.org/10.1144/GSL.SP.1995.088.01.23

Guimerà J, Mas R, Alonso A. 2004. Intraplate deformation in the NW Iberian Chain: Mesozoic extension and Tertiary contractional inversion. *Journal of the Geological Society of London* 161(2):291-303.

Guiraud M, Séguret M. 1985. A releasing solitary overstep model for the late Jurassic–early Cretaceous (Wealdian) Soria strike-slip basin (Northern Spain). In: Biddle KT, Christie-Blick N (eds) Strike slip deformation, basin formation and sedimentation, vol 37., SEPM Special PublicationSociety of Economic Paleontologists and Mineralogists, Tulsa, pp 159–175.

Gürbüz A. 2014. Pull-Apart Basin. In: Harff J., Meschede M., Petersen S., Thiede J. (eds) *Encyclopedia of Marine Geosciences*. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-6644-0_116-1

Hall CA, Johnson JA. 1986. Apparent western termination of the North Pyrenean fault and tectonostratigraphic units of the western north Pyrenees, France and Spain. *Tectonics* 5 (4):607–627.

Hempton MR, Dunne LA. 1984. Sedimentation in pull-apart basins. Active example in eastern Turkey. *The Journal of Geology* 92:513–530.

Hart NR, Stockli DF, Lavier LL, Hayman NW. 2017. Thermal evolution of a hyperextended rift basin, Mauléon basin, western Pyrenees: Thermal evolution of hyperextended rift. *Tectonics* doi:10.1002/2016TC004365.

Homberg C, Angelier J, Bergerat F, Lacombe O. 2004. Using stress deflection to identify slip events in fault systems. *Earth and Planetary Science Letters* 217(3-4):409-424

Hopper J, Buck WR. 1996. Effects of lower crustal flow on continental extension and passive margin formation. *Journal of Geophysical Research* 101, 20175–94.

Husson E, Gutierrez T, Camus H, Astruc JC, Cabaret O, Galaup S, Coueffé R. 2015. Origine, caractérisation et distridution prédictive du Karst sur la bordure Nord-Aquitaine – Synthèse bibliographique & rapport d’avancement. BRGM (Ed), Orléans, 146 pp.

Issautier B, Saspiturry N, Serrano O. 2020. Role of structural inheritance and salt tectonics in the formation of pseudosymmetric continental rifts on the european margin of the hyperextended

Mauléon basin (Early Cretaceous Arzacq and Tartas Basins). *Basin Research.* https://doi.org/10.1016/j.marpetgeo.2020.104395

Jagoutz O, Müntener O, Manatschal G, Rubatto D, Péron-Pinvidic G, Turrin BD, Villa IM. 2007. The rift-to-drift transition in the North Altantic: A stuttering start of the MORB machine? *Geology* 35(12):1087–1090. https://doi.org/10.1130/G23613A.1

James V. 1998. La plate-forme carbonatée ouest-pyrénéenne au jurassique moyen et supérieur stratigraphie séquentielle, stades d'évolution, relations avec la subsurface en aquitaine méridionale. Toulouse, Université Paul Sabatier (Sciences), 351 pp.

Jammes S. 2009. Processus d'amincissement crustal en contexte transtensif : l'exemple du golfe de Gascogne et des Pyrénées basques. Université de Strasbourg, France, 280 pp.

Jammes S, Manatschal G, Lavier L, Masini E. 2009. Tectonosedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees. *Tectonics* 28:TC4012. https ://doi.org/10.1029/2008T C002406

Jammes S, Manatschal G, Lavier L. 2010a. Interaction between prerift salt and detachment faulting in hyperextended rift systems: The example of the Parentis and Mauléon basins (Bay of Biscay and western Pyrenees). *AAPG Bull.* 94:957–975. https ://doi.org/10.1306/12090 909116

Jammes S, Tiberi C, Manatschal G. 2010b. 3D architecture of a complex transcurrent rift system: the example of the Bay of Biscay-Western Pyrenees. *Tectonophysics* 489:210–226.

Jammes S, Lavier L, Manatschal G. 2010c. Extreme crustal thinning in the Bay of Biscay and the Western Pyrenees: from observations to modeling. *Geochemistry, Geophysics, Geosystems* 11:Q10016, http://dx.doi.org/10.1029/2010GC003218

Jeanniot L, Kusznir N, Mohn G, Manatschal G, Cowie L. 2016. Constraining lithosphere deformation modes during continental breakup for the Iberia-Newfoundland conjugate rifted margins. *Tectonophysics* 680:28–49. https://doi.org/10.1016/j.tecto.2016.05.006

Jégouzo P. 1980. The South Armorican Shear Zone. *Journal of Structural Geology* 2(1–2):39-47.

Jourdon A, Le Pourhiet L, Mouthereau F, Masini E. 2019. Role of rift maturity on the architecture and shortening distribution in mountain belts. *Earth and Planetary Science Letters* 512:89–99. https://doi.org/10.1016/j.epsl.2019.01.057

Jourdon A, Le Pourhiet L, Mouthereau F, May D. 2020. Modes of propagation of continental breakup and associated oblique rift structures. *Journal of Geophysical Research: Solid Earth* 125, e2020JB019906. https://doi.org/10.1029/2020JB019906

Julivert M, Ramirez del Pozo J, Truyols J. 1971. Le reseau de failles et la couverture post-hercynienne dam les Asturies. In: Histoire Structurale du Golfe de Gascogne. Technip, Paris, 2, pp. 2.1-V.3.33.

King MT, Welford JK, Cadenas P, Tugend J. 2021. Investigating the plate kinematics of the Bay of Biscay using deformable plate tectonic models. *Tectonics* 40, e2020TC006467. https://doi.org/10.1029/2020TC006467

Kreemer C, Holt WE, Haines AJ. 2003. An integrated global model of present-day plate motions and plate boundary deformation. *Geophysical Journal International* 154(1):8–34.

Labaume P, Teixell A. 2020. Evolution of salt structures of the Pyrenean rift (Chaînons Béarnais, France): From hyper-extension to tectonic inversion. *Tectonophysics*. https://doi.org/10.1016/j.tecto.2020.228451.

Lagabrielle Y, Bodinier JL. 2008. Submarine reworking of exhumed subcontinental mantle rocks: Field evidence from the Lherz peridotites, French Pyrenees. *Terra Nova* 20(1):11–21, doi:10.1111/j.1365-3121.2007.00781.

Lagabrielle Y, Labaume P, de Saint Blanquat M. 2010. Mantle exhumation, crustal denudation, and gravity tectonics during Cretaceous rifting in the Pyrenean realm (SW Europe): Insights from the geological setting of the lherzolite bodies. *Tectonics* 29:1–26. https://doi.org/10.1029/2009TC002588.

Lagabrielle Y, Clerc C, Vauchez A, Lahfid A, Labaume P, Azambre B, Fourcade S, Dautria JM. 2016. Very high geothermal gradient during mantle exhumation recorded in mylonitic marbles and carbonate breccias from a Mesozoic Pyrenean palaeomargin (Lherz area, North Pyrenean Zone, France). *Comptes Rendus Geosci*., From rifting to mountain building: the Pyrenean Belt 348:290–300. doi:10.1016/j.crte.2015.11.004

Lagabrielle Y, Asti R, Fourcade S, Corre B, Poujol M, Uzel J, Labaume P, Clerc C, Lafay R, Picazo S, Maury R. 2019. Mantle exhumation at magma-poor passive continental margins. Part I. 3D architecture and metasomatic evolution of a fossil exhumed mantle domain (Urdach lherzolite, North-Western Pyrenees, France). *BSGF - Earth Sci. Bull.* 190, 8. https://doi.org/10.1051/bsgf/2019007.

Lagabrielle Y, Asti R, Duretz T, Clerc C, Fourcade S, Teixell A, Labaume P, Corre B, Saspiturry N. 2020. A review of cretaceous smooth-slopes extensional basins along the Iberia-Eurasia plate boundary: How pre-rift salt controls the modes of continental rifting and mantle exhumation. *Earth-Science Reviews* 201:103071, https://doi.org/10.1016/j.earscirev.2019.103071.

Lago M, Arranz E, Pocoví A, Galé C, Gil-Imaz A. 2004a. Lower Permian magmatism of the Iberian Chain, Central Spain, and its relationship to extensional tectonics. *Geological Society, London, Special Publications* 223(1):465–490. https://doi.org/10.1144/GSL.SP.2004.223.01.20

Lago M, Arranz E, Pocovi A, Galé C, Gil-Imaz A. 2004b. Permian magmatism and basin dynamics in the southern Pyrenees: A record of the transition from late Variscan transtension to early Alpine extension. *Geological Society, London, Special Publications* 223(1):439–464. https://doi.org/10.1144/GSL.SP.2004.223.01.19

Le Pichon X, Bonnin J, Sibuet JC. 1970. La faille nord-pyrénéenne : faille transformante liée à l'ouverture du golfe de gascogne. *Comptes Rendus Académie Sci. Paris* 271:1941–1944.

Le Pichon X, Sibuet JC. 1971.Western extension of boundary between European and Iberian plates during the Pyrenean orogeny. *Earth planet. Sci. Lett*. 12:83–88.

Le Pichon X, Sibuet JC. 1981. Passive margins: a model of formation. *Journal of Geophysical Research* 86:3708–3720.

Le Maire P, Thinon I, Tugend J, Issautier B, Martelet G, et al. 2021 New Magnetic compilation and interpretation of the Bay of Biscay and surrounding continental shelves. *Bulletin de la Société Géologique de France* 192(58), https://doi.org/10.1051/bsgf/2021048

Lemirre B. 2018. Origine et développement de la thermicité dans les Pyrénées varisques. PhD thesis, Univ. Paul Sabatier, Toulouse, France, 299p.

Lemirre B, Cochelin B, Duchene S, de Saint Blanquat M, Poujol M. 2019. Origin and duration of late orogenic magmatism in the foreland of the Variscan belt (Lesponne — Chiroulet — Neouvielle area, french Pyrenees). *Lithos* 336-337:183-201, doi: 10.1016/j.lithos.2019.03.037

Lenoble JL. 1992. Les plates-formes carbonatées ouest-pyrénéennes du dogger à l'Albien, stratigraphie séquentielle et évolution géodynamique. Université Paul Sabatier de Toulouse (Sciences), 395 pp.

Lepvrier C, Martínez-García E. 1990. Fault development and stress evolution of the post-Hercynian Asturian Basin (Asturias and Cantabria, northwestern Spain). *Tectonophysics* 184:345–356.

Lescoutre R. 2019. Formation et réactivation du système de rift pyrénéo-cantabrique: héritage, segmentation et évolution thermique. Retrieved from http://www.theses.fr/2019STRAH003/document.

Lescoutre R, Tugend J, Brune S, Masini E, Manatschal G. 2019. Thermal Evolution of Asymmetric Hyperextended Magma-Poor Rift Systems: Results From Numerical Modeling and Pyrenean Field Observations. *Geochemistry, Geophysics, Geosystems*. 20(10):4567-4587.

Lescoutre R, Manatschal G. 2020. Role of rift-inheritance and segmentation for orogenic evolution: example from the Pyrenean-Cantabrian system. *Bulletin de la Société Géologique de France*. 191. https://doi.org/10.1051/bsgf/2020021

Liesa CL. 2011. Fracturación extensional cretácica en la Sierra del Pobo (Cordillera Ibérica, España). *Revista de la Sociedad Geológica de España* 24:23–40.

López-Gómez J, Martín-González F, Heredia N, de La Horra R, Barrenechea JF, Cadenas P, ... & García-Sansegundo J. 2019a. New lithostratigraphy for the Cantabrian Mountains: A common tectono-stratigraphic evolution for the onset of the Alpine cycle in the W Pyrenean realm, N Spain. *Earth-Science Reviews* 188, 249-271.

López-Gómez J, Alonso-Azcárate J, Arche A, *et al*. 2019b. Permian-Triassic Rifting Stage. In: Quesada, C. & Oliveira, J.T. (eds), Vergés, J. & Kullberg, J.C. (coord.), The Geology of Iberia: A Geodynamic Approach, Volume 3: The Alpine Cycle. Springer, 214-228. https://dx.doi.org/10.1007/978-3-030-11295-0_3

Lucas C. 1985. Le grès rouge du versant nord des Pyrénées: essai sur la géodynamique de dépôts continentaux du permien et du trias. PhD Thesis ('thèse d'état'), University of Paul Sabatier, Toulouse, France, 267 pp.

Malod JA, Mauffret M. 1990. Iberian plate motions during the Mesozoic. *Tectonophysics* 184, 261–278.

Malod J, Boillot G, Capdevila R, Dupeuble PA, Lepvrier C, Mascle G, *et al*. 1982. Subduction and tectonics on the continental margin off northern Spain; observations with the submersible Cyana. In

J. K. Legett (Ed.), Trench-fore arc geology. *Geological Society, London, Special Publications* 10:309–315.

Manatschal G, Müntener O. 2009. A type sequence across an ancient magma-poor ocean-continent transition: the example of the western Alpine Tethys ophiolites. *Tectonophysics* 473 (1–2):4–19.

Manatschal G, Chenin, P, Lescoutre R, Miro J, Cadenas P, Saspiturry N, Masini E, Chevrot S, Ford M, Jolivet L, Mouthereau F, Thinon I, Issautier B, Calassou S. 2021. The role of inheritance in forming rifts and rifted margins and building collisional orogens: a Biscay-Pyrenean perspective. *Bulletin de la Societe Geologique de France* 192(1–4). https://dx.doi.org/10.1051/bsgf/2021042

Mann P, Hempton MR, Bradley DC, Burke K. 1983. Development of pull-apart basins. *The Journal of Geology* 91:529–554.

Martín-Chivelet J, López-Gómez J, *et al*. 2019. The Late Jurassic–Early Cretaceous Rifting. In: Quesada, C. & Oliveira, J.T. (eds), Vergés, J. & Kullberg, J.C. (coord.), The Geology of Iberia: A Geodynamic Approach, Volume 3: The Alpine Cycle. Springer, 81 pp. https://dx.doi.org/10.1007/978-3-030-11295-0_5

Mas JR, Alonso A, Guimerà J. 1993. Evolución tectonosedimentaria de una cuenca extensional intraplaca: la cuenca finijurásica–eocretácica de Los Cameros (La Rioja–Soria). *Rev. Soc. Geológica Esp.* 6:129–144.

Mas R, Benito MI, Arribas J, Alonso A, Arribas ME, Lohmann KC, González-Acebrón L, Hernán J, Quijada E, Suárez P. 2011. Evolution of an intra-plate rift basin: the latest Jurassic-early Cretaceous Cameros basin (Northwest Iberian ranges, North Spain). *Geo-Guías* 8:117–154.

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

Mata MP, Casas AM, Canals A, Gil A, Pocovi A. 2001. Thermal history during Mesozoic extension and Tertiary uplift in the Cameros Basin, northern Spain. *Basin Res.* 13:91–111.

Mathieu C. 1986. Histoire ge´ologique du sous-bassin de Parentis. *Bulletin des Centres de Recherches Exploration–Production Elf-Aquitaine* 10:33–47.

Matte P. 1986. Tectonics and plate tectonics model for the Variscan belt of Europe. *Tectonophysics* 126:329–374.

Matte P. 2001. The Variscan collage and orogeny (480–290 Ma) and the tectonic definition of the Armorica microplate: a review. *Terra Nova* 13:122–128.

McKenzie D, Parker RL. 1967. The North Pacific: an example of tectonics on a sphere. *Nature* 216:1276–80

Mencos J, Carrera N, Muñoz JA. 2015. Influence of rift basin geometry on the subsequent postrift sedimentation and basin inversion: The Organyà Basin and the Bóixols thrust sheet (south central Pyrenees). *Tectonics* 34. https://doi.org/10.1002/2014tc003692.

Mendia M, Gil Ibarguchi JI. 1991. High-grade metamorphic rocks and peridotites along the Leiza Fault (Western Pyrenees, Spain). *Geologische Rundschau* 80/1.

Mezger JE, Passchier CW. 2003. Polymetamorphism and ductile deformation of staurolite–cordierite schist of the Bossòst dome: indication for Variscan extension in the Axial Zone of the central Pyrenees. *Geol. Mag.* 140(5):595–612, doi:10.1017/S0016756803008112.

Mohn G, Karner GD, Manatschal G, Johnson CA. 2015. Structural and stratigraphic evolution of the Iberia-Newfoundland hyperextended rifted margin: A quantitative modeling approach. *Geological Society of London, Special Publication* 15:13810. https://doi.org/10.1144/SP413.9

Monchoux P. 1970. Les lherzolites pyrénéennes: contribution à l’étude de leur minéralogie, de leur genèse et de leurs transformations. Ph.D. thesis, 180 pp., Univ. of Toulouse, Toulouse, France.

Montadert L, Winnock E, Delteil JR, Grau M. 1974. Continental margins of Galicia–Portugal and Bay of Biscay. In: Burk, C.A. & Drake, C.L. (eds) Publisher, Town, 323–341.

Montadert L, Roberts DG, De Charpal O, Guennoc P. 1979. Rifting and subsidence of the northern continental margin of the Bay of Biscay. In: Montadert, L. & Roberts, D.G. (eds) Initial Reports of the Deep Sea Drilling Project, 48. US Government Printing Offic, Washington, DC, 1025–1060.

Montigny R, Azambre B, Rossy M, Thuizat R. 1986. K-Ar Study of cretaceous magmatism and metamorphism in the Pyrenees: Age and length of rotation of the Iberian Peninsula. *Tectonophysics* 129(1-4):257-273. doi:10.1016/0040-1951(86)90255-6

Moreau P. 1995. La transgression du Crétacé moyen sur la bordure nord-aquitaine (Charente) - Séance spécialisée de la Soc. géol. France “ Le Bassin d’Aquitaine, évolution sédimentaire et structurale”, Toulouse, 18 Septembre 1995. *Strata*, Toulouse, sér. 1, 7:52-54.

Mouthereau F, Filleaudeau PY, Vacherat A, Pik R, Lacombe O, Fellin MG, *et al*. 2014. Placing limits to shortening evolution in the Pyrenees: Role of margin architecture and implications for the Iberia/Europe convergence: Plate convergence in the Pyrenees. *Tectonics* 33:2283–2314. https://doi.org/10.1002/2014TC003663

Muñoz JA. 1992. Evolution of a continental collision belt: ECORS-Pyrenees crustal balanced cross-section. In: McClay KR (ed), Thrust Tectonics, Chapman and Hall, London:235–246.

Néraudeau D, Allain R, Ballèvre M, Batten DJ, Buffetaut E, Colin JP, Dabard MP, Daviero-Gomez V, El Albani A, Gomez B, Grosheny D, Le Lœuff J, Leprince A, Martín-Closas C, Masure E, Mazin JM, Philippe M, Pouech J, Tong H, Tournepiche JF, Vullo R. 2012. The Hauterivian-Barremian lignitic bonebed of Angeac (Charente, south-west France): stratigraphical, palaeobiological and palaeogeographical implications. *Cretac. Res.* 37:1–14. https://doi.org/10.1016/j.cretres.2012.01.006

Neres M, Miranda JM, Font E. 2013. Testing Iberian kinematics at Jurassiccretaceous times. *Tectonics* 32 (5):0278–7407.

Newman J, Lamb WM, Drury MR, Vissers RLM. 1999. Deformation processes in a peridotite shear zone: Reaction softening by an H2O-deficient, continuous net transfer reaction. *Tectonophysics* 303(1–4):193–222. https://doi.org/10.1016/S0040-1951(98)00259-5

Nirrengarten M, Manatschal G, Tugend J, Kusznir NJ, Sauter D. 2017. Nature and origin of the J-magnetic anomaly offshore Iberia-Newfoundland: Implications for plate reconstructions. *Terra Nova* 29:20–28. https://doi.org/10.1111/ter.12240

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

Nüchter JA, Ellis S. 2011. Mid-crustal controls on episodic stress-field rotation around major reverse, normal and strike-slip faults. *Geological Society, London, Special Publications* 359:187-201. doi: 10.1144/SP359.11

Odlum ML, Stockli DF. 2019. Thermotectonic evolution of the North Pyrenean Agly Massif during Early Cretaceous hyperextension using multi-mineral U-Pb thermochronometry. *Tectonics* 38(5):1509–1531.

Odlum ML, Stockli DF. 2020. Geochronologic constraints on deformation and metasomatism along an exhumed mylonitic shear zone using apatite U-Pb, geochemistry, and microtextural analysis. *Earth and Planetary Science Letters* 538. https://doi.org/10.1016/j.epsl.2020.116177

Oliva-Urcia B, Román-Berdiel T, Casas AM, Pueyo EL, Osácar C. 2010. Tertiary compressional overprint on Aptian–Albian extensional magnetic fabrics, North-Pyrenean Zone. *Journal of Structural Geology* 32:362–376.

Oliva-Urcia B, Casas AM, Soto R, Villalaín JJ, Kodama K. 2011. A transtensional basin model for the Organyà basin (central southern Pyrenees) based on magnetic fabric and brittle structures. *Geophysical Journal International* 184 (1):111–130.

Oliva-Urcia B, Román-Berdiel T, Casas AM, Bógalo MF, Osácar MC, García-Lasanta C. 2013. Transition from extensional to compressional magnetic fabrics in the cretaceous Cabuérniga basin (North Spain). *J. Struct. Geol.* 46:220–234.

Olivet JL. 1996. La cinématique de la plaque ibérique. *Bulletin du Centre de Recherches Exploration–Production Elf-Aquitaine* 20:131–195.

Olivier P, Gleizes G, Paquette JL, Muñóz Sáez C. 2008. Structure and U-Pb dating of the Saint-Arnac pluton and the Ansignan charnockite (Agly Massif): a cross-section from the upper to the middle crust of the Variscan Eastern Pyrenees. *J. Geol. Soc.* 165:141–152.

Omodeo-Salé S, Guimerà J, Mas R, Arribas J. 2014. Tectono-stratigraphic evolution of an inverted extensional basin: the Cameros Basin (north of Spain). *Int. J. Earth Sci.* 103:1597–1620. https://doi.org/10.1007/s00531-014-1026-5

Omodeo-Salé S, Salas R, Guimerà J, Ondrak R, Mas R, Arribas J, Suárez-Ruiz I, *et al*. 2017. Subsidence and thermal history of an inverted Late Jurassic-Early Cretaceous extensional basin (Cameros, north-central Spain) affected by very low- to low-grade metamorphism. *Basin Research* 29:156–174. https://doi.org/10.1111/bre.12142

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

Ortiz A, Guillocheau F, Lasseur E, Brias J, Robin C, Serrano O, Fillon C. 2020. Sediment routing system and sink preservation during the post-orogenic evolution of a retro-foreland basin: The case example of the North Pyrenean (Aquitaine, Bay of Biscay) Basins. *Marine and Petroleum Geology* 112:104085.

Passchier CW. 1982. Mylonitic deformation in the St Barthélémy Massif, French Pyrenees, with emphasis on the generation relationship between ultramylonite and pseudotachylite. *GUA Pap. Geol.* 1 (16):1-173.

Passchier CW. 1984. Mylonite-dominated footwall geometry in a shear zone, central Pyrenees. *Geol. Mag.* 121:429–436. doi:10.1017/S0016756800029964

Peace A, Welford JK, Ball P, Nirrengarten M. 2019. Deformable plate tectonic models of the southern North Atlantic. *J. Geodyn.* 128:11-37. https://doi.org/10.1016/j.jog.2019.05.005.

Pedrera A, García-Senz J, Ayala C, Ruiz-Constán A, Rodríguez-Fernández LR, Robador A, González Menéndez L. 2017. Reconstruction of the exhumed mantle across the North Iberian Margin by crustal-scale 3-D gravity inversion and geological cross section. *Tectonics* 36. https://doi.org/10.1002/ 2017TC004716

Péllissié T, Astruc JC. 1995. Tectonique et dissolution dans la sédimentation du Jurassique moyen-supérieur quercynois - Séance spécialisée de la Soc. géol. France " Le Bassin d'Aquitaine, évolution sédimentaire et structurale", Toulouse, 18 Septembre 1995 - *Strata*, Toulouse, sér. 1, 7:56-57.

Peybernes B. 1978. Dans les Pyrenees la paleogeographie antecenomanienne infirme la theorie d'un coulissement senestre de plusieurs centaines de kilometres le long de la "faille nord-pyreneenne" des auteurs. *Bulletin de la Société Géologique de France* S7-XX (5):701–709. doi: https://doi.org/10.2113/gssgfbull.S7-XX.5.701

Peybernès B, Souquet P. 1984. Basement blocks and tecto-sedimentary evolution in the Pyrenees during Mesozoic times. *Geol. Mag.* 121:397–405. doi:10.1017/S0016756800029927

Pieren AP, Areces JL, Toraño J, Martínez-García E. 1995. Estratigrafía y estructura de los materiales permotriásicos del sector Gijón-La Collada (Asturias). *Cuadernos de Geología Ibérica* 19:309–335.

Pinet B, Montadert L, Curnelle R, Cazes M, Marillier F, Rolet J, Tomassino A, Galdeano A, Patriat P, Brunet MF, Olivet JL, Shaning M, Lefort JP, Arrieta A, Riaza C. 1987. Crustal thinning on the Aquitaine shelf Bay of Biscay, from deep seismic data: letters to nature. *Nature* 325:513–516.

Platel J.P. 1987. Données récentes sur la connaissance géologique de la région du sud des Charentes. *Norois*, Poitiers 100:601-608.

Platel JP. 1996. Stratigraphie, sédimentologie et évolution géodynamique de la plateforme carbonatée du Crétacé supérieur du nord du bassin d'Aquitaine. *Géologie de la France* 33–58.

Platt NH.,1990. Basin evolution and fault reactivation in the western Cameros Basin, Northern Spain. *J. Geol. Soc.* 147:165–175. https://doi.org/10.1144/gsjgs.147.1.0165

Puigdefàbregas C, Souquet P. 1986. Tecto-sedimentary cycles and depositional sequences of the Mesozoic and Tertiary from the Pyrenees. *Tectonophysics* 129(1–4):173–203.

Puigdefàbregas C, Muñoz JA, Marzo M. 1986. Thrust belt development in the eastern Pyrenees and related depositional sequences in the southern foreland basin. In: Foreland Basins, eds Allen, P.A. & Homewood, P., Spec. Publ. Int. Ass. Sediment., 8, 229–246.

Puigdefàbregas C, Muñoz JA, Vergés J. 1992. Thrusting and foreland basin evolution in the southern Pyrenees. In: Thrust Tectonics. Springer, pp. 247–254.

Pulgar J, Gallart J, Fernández-Viejo G, Pérez-Estaún A, Álvarez-Marrón J, ESCIN Group. 1996. Seismic image of the Cantabrian Mountains in the western extension of the Pyrenees from integrated ESCIN reflection and refraction data. *Tectonophysics* 264:1–19.

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

Rat P. 1988. The Basque–Cantabrian basin between the Iberian and European plates: some facts but still many problems. *Rev Soc Geol Esp* 1(3–4):327–348

Ravier J. 1959. Le métamorphisme des terrains secondaires des Pyrénées. *Soc. Géol. Fr. Mém.* 86:1–250.

Razin P. 1989. Evolution tecto-sédimentaire alpine des Pyrénées basques à l'ouest de la transformante de Pamplona, Province du Labourd. PhD thesis, University of Bordeaux 3, France, 464 p.

Roca E, Guimerà J, Salas R. 1994. Mesozoic extensional tectonics in the southeast Iberian Chain. *Geological Magazine* 131(2):155.

Roca E, Muñoz JA, Ferrer O, Ellouz N. 2011. The role of the Bay of Biscay Mesozoic extensional structure in the configuration of the Pyrenean orogen: Constraints from the MARCONI deep seismic reflection survey. *Tectonics* 30:TC2001. doi:10.1029/2010TC002735

Rougier G, Ford M, Christophoul F, Bader AG. 2016. Stratigraphic and tectonic studies in the central Aquitaine Basin, northern Pyrenees: Constraints on the subsidence and deformation history of a retro-foreland basin. *Compt. Rendus Geosci.* 348(3–4):224–235. https://doi.org/10.1016/j.crte.2015.12.005.

Roure F, Choukroune P, Berastegui X, Munoz JA, Vilien A, Matheron P, Bareyt M, Seguret M, Camara P, Deramond J. 1989. Ecors deep seismic data and balanced cross sections: geometric constraints on the evolution of the Pyrenees. *Tectonics* 8:41–50.

Salas R, Casas A. 1993. Mesozoic extensional tectonics, stratigraphy and crustal evolution during the Alpine cycle of the eastern Iberian basin. *Tectonophysics* 228:33–55.

Salas R, Guimerà J, Mas R, Martín-Closas C, Meléndez A, Alonso A. 2001. Evolution of the Mesozoic central Iberian Rift System and its Cainozoic inversion (Iberian chain). *Peri-Tethys Mem.* 6:145–185.

Salas R, García-Senz J, Guimerà J, Bover-Arnal T. 2010. Opening of the Atlantic and development of the Iberian intraplate rift basins during the late Jurassic-early Cretaceous. II Central & North Atlantic Conjugate Margins Conference – Lisbon 2010: Re-Discovering the Atlantic, New winds for an old sea - Extended Abstracts. Edited by: Pena dos Reis, R. and Pimentel, N.

Sanderson DJ, Marchini WRD. 1984. Transpression. *J. Struct. Geol.* 6:449 – 458.

Saspiturry N, Cochelin B, Razin P, Leleu S, Lemirre B, Bouscary C, Issautier B, Serrano O, Lasseur E, Baudin T, Allanic C. 2019a. Tectono-sedimentary evolution of a rift system controlled by Permian post-orogenic extension and metamorphic core complex formation (Bidarray Basin and Ursuya dome, Western Pyrenees). *Tectonophysics* 768:228180. https://doi.org/10.1016/j.tecto.2019.228180.

Saspiturry N, Razin P, Baudin T, Serrano O, Issautier B, Lasseur E, Allanic C, Thinon I, Leleu S. 2019b. Symmetry vs. asymmetry of a hyper-thinned rift: example of the Mauléon Basin (Western Pyrenees, France). *Mar. Pet. Geol.* 104:86–105. https://doi.org/10.1016/j.marpetgeo.2019.03.031.

Saspiturry N, Allanic C, Razin P, Issautier B, Baudin T, Lasseur E, Serrano O, Leleu S. 2020a. Closure of a hyperextended system in an orogenic lithospheric pop-up, Western Pyrenees: the role of mantle buttressing and rift structural inheritance. *Terra Nova*. https://doi.org/10.1111/ter.12457

Saspiturry N, Lahfid A, Baudin T, Guillou-Frottier L, Razin R, Issautier B, Le Bayon B, Serrano O, Lagabrielle Y, Corre B. 2020b. Paleogeothermal Gradients across an Inverted Hyperextended Rift System: Example of the Mauléon Fossil Rift (Western Pyrenees). *Tectonics*. https://doi.org/10.1029/2020TC006206

Saspiturry N, Issautier B, Razin P, Baudin T, Asti R, Lagabrielle Y, Allanic C, Serrano O, Duretz T. (2021). Review of Iberia-Eurasia plate-boundary basins: Role of sedimentary burial and salt tectonic during rifting and continental breakup. *Basin Research*. https://doi.org/10.1111/bre.12529

Serrano A, Martínez del Olmo W. 2004. Estructuras diapíricas de la zona meridional de la Cuenca Vasco-Cantábrica. In: Vera, J.A. (Ed.), Geología de España.Sociedad Geológica de Espan˜adInstituto Geológico y Minero de España, Madrid, pp. 334–338.

Serrano O, Delmas J, Hanot F, Vially R, Herbin JP, Houel P, Tourlière B. 2006. Le bassin d'Aquitaine: valorisation des données sismiques, cartographique structurale et potentiel pétrolier. BRGM (Ed), Orléans.

Sibuet JC. 1974. Histoire tectonique du Golfe de Gascogne. Contribution no 137 du département Scientifique, Centre Océanologique de Bretagne, 297–312.

Sibuet JC, Srivastava SP, Spakman W. 2004. Pyrenean orogeny and plate kinematics. *Journal of Geophysical Research* 109, B08104. https://doi.org/10.1029/2003JB002514

Simón JL, Arlegui LE, Liesa CL, Maestro A. 1999. Stress perturbations registered by jointing near strike-slip, normal and reverse faults. Examples from the Ebro Basin (Spain). *J. geophys. Res.* B104(7):15 141–15 153.

Soares DM, Alves TM, Terrinha P. 2012. The breakup sequence and associated lithospheric breakup surface: their significance in the context of rifted continental margins (West Iberia and Newfoundland margins, North Atlantic). *Earth Planet Sci.Lett.* 355–356:311–326. https://doi.org/10.1016/j.epsl.2012.08.036.

Sopeña A, Lopez J, Arche A, Perez-Arlucea M, Ramos A, Virgili C, Hernando S. 1988. Permian and Triassic rift basins of the Iberian Peninsula. In: W. Manspeizer (Editor), Triassic-Jurassic Rifting. Elsevier, Amsterdam, pp. 757-786.

Soto R, Casas-Sainz AM, Villalain JJ, Oliva-Urcia B. 2007. Mesozoic extension in the Basque-Cantabrian basin (N Spain): contributions from AMS and brittle mesostructures. *Tectonophysics* 44:373–394.

Soto R, Casas-Sainz AM, Villalain JJ, Gil-Imaz A, Fernández-González G, Del Río P, Calvo M, Mochales T. 2008. Characterizing the Mesozoic extension direction in the northern Iberian Plate margin by anisotropy of magnetic susceptibility (AMS). *J. Geol. Soc. Lond.* 165:1007–1018.

Soto R, Casas-Sainz AM, Villalaín JJ. 2011. Widespread Cretaceous inversion event in northern Spain; evidence from subsurface and paleomagnetic data. *Journal of the Geological Society of London* 168 (4):899-912.

Souquet P, Peybernès B, Bilotte M, Debroas EJ. 1977. La Chaîne Alpine des Pyrénées. *Géologie Alpine* 53:193-216.

Souquet P, Debroas EJ, Boirie JM, Pons P, Fixari G, Dol J, Thieuloy JP, Bonnemaison M, Manivit H, Peybernès B. 1985. Le Groupe du Flysch Noir (Albo-Cénomanien) dans les Pyrénées. *Bull Cent Rech Exlpo-Prod Elf-Aquitaine* Pau 9:183–252.

Souquet P, (coord.) *et al*. 1995. Crétacé. In Barnolas A., Chiron J.C. : "Synthèse géologique et géophysique des Pyrénées". Édition BRGM - ITGE, vol. 2, pp. 242-458.

Srivastava SP, Roest WR, Kovacs LC, Oakey G, Levesque S, Verhoef J, Macnab R. 1990. Motion of Iberia since the Late Jurassic; results from detailed aeromagnetic measurements in the Newfoundland Basin. *Tectonophysics* 184:229–260.

Stampfli GM, Borel GD. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth Planet. Sci. Lett.* 196 (1):17–33.

Suárez-Rodríguez A. 1988. Estructura del área de Villaviciosa-Libardón (Asturias, Cordillera Cantábrica). *Trabajos de Geologia* 17:87–98.

Szameita LSA, Manatschal G, Nirrengarten M, Ferreira FJF, Heilbron M. 2020. Magnetic characterization of the zigzag shaped J-anomaly: Implications for kinematics and breakup processes at the Iberia-Newfoundland margins. *Terra Nova*. https://doi.org/10.1111/ter.12466

Tavani S. 2012. Plate-kinematics in the Cantabrian Domain of the Pyrenean Orogen. *Solid Earth* 3:265–292, doi:10.5194/se-3-265-2012.

Tavani S, Mencos J, Bausa J, Muñoz JA. 2011a. The fracture pattern of the Sant Corneli-Bóixols oblique inversion anticline (Spanish Pyrenees). *J. Struct. Geol.* 33(11):1662–1680. doi:10.1016/j.jsg.2011.08.007.

Tavani S, Quintà A, Granado P. 2011b. Cenozoic right-lateral wrench tectonics in the western Pyrenees (Spain): The Ubierna fault system, *Tectonophysics* 509:238–253.

Tavani S, Carola E, Granado P, Quintà A, Muñoz JA. 2013. Transpressive inversion of a Mesozoic extensional forced fold system with an intermediate décollement level in the Basque-Cantabrian Basin (Spain). *Tectonics*. 32:146–158, doi:10.1002/tect.20019.

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

Tavani S, Muñoz JA. 2012. Mesozoic rifting in the Basque–Cantabrian Basin (Spain): inherited faults, transversal structures and stress perturbation. *Terra Nova* 24:70–76.

Teixell A. 1998. Crustal structure and orogenic material budget in the west central Pyrenees. *Tectonics* 17:395–406. http://dx.doi.org/10.1029/98TC00561.

Teixell A, Labaume P, Lagabrielle Y. 2016. The crustal evolution of the west-central Pyrenees revisited: Inferences from a new kinematic scenario. *Comptes Rendus Geoscience* 348(3–4):257–267. doi:10.1016/j.crte.2015.10.010.

Teixell A, Labaume P, Ayarza P, Espurt N, de Saint Blanquat M, Lagabrielle Y. 2018. Crustal structure and evolution of the Pyrenean-Cantabrian belt: A review and new interpretations from recent concepts and data. *Tectonophysics* 724–725:146–170, https://doi.org/10.1016/j.tecto.2018.01.009.

Ternois S, Odlum M, Ford M, Pik R, Stockli D, Tibari B, *et al*. 2019. Thermochronological evidence of early orogenesis, eastern Pyrenees, France. *Tectonics* 38:1308–1336. https://doi.org/10.1029/2018TC005254

Thinon I. 1999. Structure profonde de la marge Nord-Gascogne et du Bassin armoricain (golfe de Gascogne). Thèse de doctorat, Université de Bretagne Occidentale, 332p.

Thinon I, Fidalgo-González L, Réhault JP, Olivet JL. 2001. Pyrenean deformation in the northern Bay of Biscay. *Comptes Rendus de l'Académie des Sciences* 332(9):561–568.

Thinon I, Réhault JP, Fidalgo-González L. 2002. La couverture sédimentaire syn-rift de la marge Nord-Gascogne et du Bassin armoricain (Golfe de Gascogne) à partir de nouvelles données de sismique de réflexion. *Bull. Soc. Geol. Fr.* 173(6):515–522, doi:10.2113/173.6.515.

Thinon I, Matias L, Réhault JP, Hirn A, Fidalgo-González L, Avedik F. 2003. Deep structure of the Armorican Basin (Bay of Biscay): A review of Norgasis seismic reflection and refraction data. *J. Geol. Soc*. 160:99–116. doi:10.1144/0016-764901-103.

Thinon I, Menier D, Guennoc P, Proust JN. 2008. Carte géologique à 1/250 000 de la marge continentale, feuille Lorient (Bretagne Sud). Coordinateurs: JN Proust & P Guennoc, Co-édition BRGM Orléans – CNRS. http://www.brgm.fr/cartegeol.jsp

Thinon I, Proust J N, Nalpas T, Elongo V, Vérité J. 2018. Structure of the Mesozoic sedimentary cover of the North Aquitaine continental shelf–New results from offshore and onshore observations in the Charente region (France). In: 26ème Réunion des Sciences de la terre-RST, octobre 2018, p. 239.

Tucholke BE, Sawyer DS, Sibuet JC. 2007. Breakup of the Newfoundland Iberia rift. *Geological Society of London, Special Publication* 282(1):9–46. https://doi.org/10.1144/SP282.2

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

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

Tugend J, Manatschal G, Kusznir NJ, Masini E. 2015b. Characterizing and identifying structural domains at rifted continental margins: application to the Bay of Biscay margins and its Western Pyrenean fossil remnants. In: Gibson, G. M., Roure, F. &Manatschal, G. (eds) Sedimentary Basins and Crustal Processes at Continental Margins: From Modern Hyper-extended Margins to Deformed Ancient Analogues. Geological Society, London, Special Publications, 413, http://dx.doi.org/10.1144/SP413.3

Umhoefer PJ, Dorsey RJ. 1997. Translation of terranes: Lessons from central Baja California, Mexico. *Geology* 25:1007–1010. doi:10.1130/0091-7613(1997)025<1007:TOTLFC>2.3.CO;2.

Uzkeda H, Bulnes M, Poblet J, García-Ramos JC, Piñuela L. 2013. Buttressing and reverse reactivation of a normal fault in Jurassic rocks of the Asturian Basin, NW Iberian Peninsula. *Tectonophysics* 599:117-134.

Uzkeda H, Bulnes M, Poblet J, García-Ramos JC, Piñuela L. 2016. Jurassic extensión and Cenozoic inversion tectonics in the Asturian Basin, NW Iberian Peninsula: 3D structural model and kinematic evolution. *Journal of Structural Geology* 90:157-176.

Vacherat A, Mouthereau F, Pik R, Bernet M, Gautheron C, Masini E, Le Pourhiet L, Tibari B, Lahfid A. 2014. Thermal imprint of rift-related processes in orogens as recorded in the Pyrenees. *Earth Planet. Sci. Lett.* 408:296–306, doi:10.1016/j.epsl.2014.10.014.

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

Valenzuela M, Garcia-Ramos JC, Suarez De Centi C. 1986. The Jurassic sedimentation in Asturias (N Spain). *Trab. Geol*., Univ. Oviedo 16:121-132.

Van der Voo R. 1969. Paleomagnetic evidence for the rotation of the Iberian Peninsula. *Tectonophysics* 7:5–56.

Van Wees JD, Arche A, Beijdorf CG, López-Gómez J, Cloethingh S. 1998. Temporal and spatial variations in tectonic subsidence in the Iberian basin (eastern Spain): inferences from automated forward-modelling of high-resolution stratigraphy (Permian-Mesozoic). *Tectonophysics* 300:285–310.

Vargas H, Gaspar-Escribano JM, López-Gómez J, Van Wees JD, Cloetingh S, De la Horra R, Arche A. 2009. A comparison of the Iberian and Ebro Basins during the Permian and Triassic, eastern Spain: A quantitative subsidence modelling approach. *Tectonophysics* 474:160-183.

Vauchez A, Clerc C, Bestani L, Lagabrielle Y, Chauvet A, Lahfid A, Mainprice D. 2013. Preorogenic exhumation of the North Pyrenean Agly massif (Eastern Pyrenees-France). *Tectonics* 32:95–106. https://doi.org/10.1002/tect.20015

Vergés J, García-Senz J. 2001. Mesozoic evolution and Cainozoic inversion of the Pyrenean Rift. In: Ziegler PA, Cavazza W, Robertson AHF *et al*. (eds), Peri-Tethyan Rift/Wrench Basins and Passive Margins. Mém Mus natn Hist Nat 186:187–212.

Vergés J, Marzo M, Santaeularia J, Serra-Kiel J, Burbank DW, Muñoz JA, Giménez-Montsant J. 1998. Quantified vertical motions and tectonic evolution of the SE Pyrenean foreland basin, in Cenozoic Foreland Basins of Western Europe, eds Mascle, A., Puigdefàbregas, C., Luterbacher, H.P. & Fernàndez, M., Geol. Soc. Spec. Publ., 134:107–134.

Vergés J, Fernàndez M, Martínez A. 2002. The Pyrenean orogen: pre-, syn-, and postcollisional evolution. In: Rosenbaum, J.G., Lister, G.S. (Eds.), Reconstruction of the evolution of the Alpine-Himalayan Orogen. J. Virt. Explorer 8:55–84.

Vergés J, Poprawski Y, Almar Y, Drzewiecki PA, Moragas M, Bover-Arnal T, Macchiavelli C, Wright W, Messager G, Embry JC, Hunt D. 2020. Tectono-sedimentary evolution of Jurassic–Cretaceous diapiric structures: Miravete anticline, Maestrat Basin, Spain. *Basin Research.* https://doi.org/10.1111/bre.12447

Vielzeuf D, Kornprobst J. 1984. Crustal splitting and the emplacement of Pyrenean lherzolites and granulites. *Earth Planet. Sci. Lett.* 67:87–96. doi:10.1016/0012-821X(84)90041-4

Vissers RLM. 1992. Variscan extension in the Pyrenees. *Tectonics* 11:1369–1384. https://doi.org/10.1029/92TC00823.

Vissers RLM, Drury MR, Newman J, Fliervoet TF. 1997. Mylonitic deformation in upper mantle peridotites of the North Pyrenean Zone (S France): Implications for strength and strain localization in the lithosphere. *Tectonophysics* 279(1–4):303–325. https://doi.org/10.1016/S0040-1951(97)00128-5

Vissers RLM, van Hinsbergen DJJ, van der Meer DG, Spakman W. 2016. Cretaceous slab break-off in the Pyrenees: Iberian plate kinematics in paleomagnetic and mantle reference frames. *Gondwana Res.* 34:49–59. doi:10.1016/j.gr.2016.03.006

Vissers RLM, Meijer PT. 2012. Mesozoic rotation of Iberia: Subduction in the Pyrenees? *Earth-Sci. Rev.* 110:93–110. doi:10.1016/j.earscirev.2011.11.001

Wehr H, Chevrot S, Courrioux G, Guillen A. 2018. A three-dimensional model of the Pyrenees and their foreland basins from geological and gravimetric data. *Tectonophysics* 734–735:16–32. https://doi.org/10.1016/j.tecto.2018.03.017

Williams CA. 1975. Sea-floor spreading in the Bay of Biscay and its relationship to the North Atlantic. *Earth and Planetary Science Letters* 24:440–456.

Wilson JT. 1965. A new class of faults and their bearing on continental drift. *Nature* 207:343–47.

Wilson RW, McCaffrey KJW, Holdsworth RE, Imber J, Jones R, Welbon A, Roberts DJ. 2006. Complex fault pattern, transtension and structural segmentation of the Lofoten Ridge, Norwegian Margin: Using digital mapping to link onshore and offshore geology. *Tectonics* 25. doi:10.1029/2005TC001895.

Withjack MO, Jamison WR. 1986. Deformation produced by oblique rifting. *Tectonophysics* 126(2):99–124.

Zamora G, Fleming M, Gallastegui J. 2017. Salt tectonics within the offshore Asturian Basin: North Iberian margin. In J. I. Soto, J. F. Flinch, & G. Tari (Eds.), Permo-Triassic salt provinces of Europe, North Africa and the Atlantic margins (chap. 16, pp. 353–368). Elsevier.

Ziegler PA. 1988. Evolution of the Arctic-North Atlantic and the Western Tethys. *American Association of Petroleum Geologists Memoir* 43:1–198.

Ziegler PA. 1996. Geodynamic processes governing development of rifted basins. In: Roure F, Shein VS, Ellouz-Zimmermann N, and Skvortsow L (eds.) Geodynamic Evolution of Sedimentary Basins, pp. 19–67. Paris: Technip.

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

Ziegler PA, Schumacher ME, Dèzes P, van Wees JD, Cloetingh S. 2006. Post-Variscan evolution of the lithosphere in the area of the European Cenozoic Rift System. *Geological Society Memoir* 32:97–112. https://doi.org/10.1144/GSL.MEM.2006.032.01.06.

## FIGURE CAPTIONS

**Fig. 1:** Simplified structural map of the Iberia/Eurasia diffuse plate boundary zone, with locations of the basins presented in this work (modified after Lagabrielle *et al*., 2020). Acronyms: NPFT, North Pyrenean Frontal Thrust; SPFT, South Pyrenean Frontal Thrust.

**Fig. 2:** Main plate kinematic models proposing a different Late Jurassic-Cretaceous evolution of the Iberia/Eurasia plate boundary. a) Model by Olivet (1996) proposing an Albian-Cenomanian eastward displacement of the Iberian plate accommodated along the North Pyrenean Fault (as redrawn by Mouthereau et a., 2014). b) Model by Jammes *et al*. (2009) proposing left-lateral displacement between Iberia and Eurasia accommodated along the North Pyrenean Fault between the Late Jurassic and the Aptian, followed by Albian-Cenomanian orthogonal (N-S) extension. c) Model by Srivastava *et al*. (2000) and Sibuet *et al*. (2004) proposing a scissor opening of the Bay of Biscay, implying subduction of a large oceanic domain during the Albian in the Pyrenean realm (as redrawn by Mouthereau et a., 2014).

**Fig. 3:** Recent plate kinematic models by (a) Tugend *et al*. (2015a), (b) Nirrengarten *et al*. (2018), and (c) Angrand & Mouthereau (2021) proposing a partitioning of the Late Jurassic-Early Cretaceous deformation between Iberia and Eurasia in two or three transtensional corridors located in the Iberian Chain Rift System, in the Pyrenees, and in the Bay of Biscay/Parentis system, separated by one or two intervening micro continental blocks (i.e. the Landes High and the Ebro Block).

**Fig. 4:** Geological map and structural pattern of the Asturian Basin. a) Geological map of the Asturian Basin (including the offshore Le Danois sub-basin) and of the surrounding Cantabrian

region (redrawn and modified after Pulgar *et al*., 1999). b) Simplified structural map of the onshore Asturian Basin with age of (re)activation of the main structures (redrawn and modified after Lepvrier & Martínez-García, 1990).

**Fig. 5:** a) Simplified geological map of the Iberian Chain System with locations of the main Permian-Mesozoic rift basins (modified after Guimerà, 2018); isolines in the Ebro Basin refer to base of the Cenozoic series. b) Evolution of extension directions (gray arrows) between the Late Jurassic and the Albian in the Cameros and in the Basque-Cantabrian basins as retrieved by anisotropy of magnetic susceptibility (AMS) analysis (modified after Soto *et al*., 2008). c) Backstripped tectonic subsidence curves for the southeastern part of the Iberian Chain System (Maestrat and South Iberian basins); see (a) for location of the wells (redrawn and modified after Salas *et al*., 2001). Note that during the Late Jurassic-Early Cretaceous rifting, tectonic subsidence curves are steeper for the Early Cretaceous interval than for the Late Jurassic one.

**Fig. 6:** a) Age map of the sedimentary series underlain below the Cenozoic cover of the Ebro Basin as derived from interpolation of well log data (modified after Filleaudeau, 2011). b) Tectonic subsidence curve for the Bujaraloz-1 well (see location in (a); modified after Vargas *et al*., 2009).

**Fig. 7:** Geological map of the Basque-Cantabrian Basin with locations of the structural maps presented in Fig. 8 outlined in red boxes (modified after Pedrera *et al*., 2017).

**Fig. 8:** a) Simplified geological map of the Basque-Cantabrian Basin with structural patterns related to the Late Jurassic-Early Cretaceous rifting phase and with the strain ellipse (in the inset) related to the inferred tectonic regime (redrawn and modified after Cámara, 2017). In green: Northern rift

fault system; in magenta: southern rift fault system; in blue: listric faults and salt-related structures. b) Geological map of the western Basque-Cantabrian Basin showing the structural pattern of the main faults controlling the mid-Cretaceous transtensional phase (modified after Soto *et al*., 2011). c) Schematic reconstruction of the relative position of Iberia and Eurasia between the Late Jurassic and the Early Cretaceous with the location of the Basque-Cantabrian Basin in the frame of the plate kinematic context; this model proposes an initial Tithonian phase of orthogonal rifting followed by a subsequent phase of left-lateral transtensional extension during the Albian (redrawn and modified after Soto *et al*., 2007).

**Fig. 9:** Geological map of the Pyrenean Belt with locations of the structural maps and schematic reconstructions presented in Figs. 10, 11 and 12 as the boxes outlined in red and of the wells from the Southern Aquitaine basins presented in Fig. 14 (modified after Ducoux *et al*., 2019).

**Fig. 10:** a) Geological map of the Eastern Mauléon/Chaînons Béarnais Basin with orientations of the magnetic lineations after bedding correction retrieved by AMS studies. b) Schematic model proposing the development of the Albian rifting phase in the Mauléon Basin under a sinistral strike-slip regime and illustrating the possible orientation of the magnetic lineations before the Cenozoic compression. Both images are modified after Oliva-Urcia *et al*., 2010.

**Fig. 11:** a) Schematic representation of the progressive development of the North Pyrenean basins between the Middle Albian and the Early Cenomanian by gradual connection of isolated pull-apart basins to form a single sedimentary trough in a left-lateral transtensional regime (modified after Debroas, 1995, 2003). b) Schematic structural model illustrating the opening of the rift basins

exposed in the Bigorre region as sinistral pull-apart basins during the Albian-Cenomanian (modified after Debroas, 1990).

**Fig. 12:** a) Schematic representation of faulting relationships in the Pre-Alpine basement of the Pyrenean Axial Zone and in the Mesozoic series of the South Pyrenean basins, with illustration of the extension directions (grey arrows) during the Aptian-Albian transtensional interval retrieved by structural and AMS studies (redrawn and modified after Oliva-Urcia *et al*., 2011). b) Schematic map view representation of the structural patterns related to the Early Cretaceous extensional phase on the southern margin of the Organyà Basin, showing the general orientation of the main extension-related structures such as normal faults and joints/veins (modified after Tavani *et al*., 2011a).

**Fig. 13:** a) Locations of the ECORS-Bay of Biscay seismic reflection profile across the Parentis Basin and of the boreholes used for its calibration (redrawn and modified after Bois *et al*., 1997). b) Line drawing and c) interpretation of the central portion of the ECORS-Bay of Biscay seismic reflection profile (modified after Jammes, 2009). Note the overall flower structure of the Parentis Basin in cross section, with most of the (reactivated) extensional structures converging towards the Ibis Fault. d) Tectonic subsidence curves and tectonic subsidence velocities corrected for sea-level and water depth variations for three oil wells (Ibis, Fregate and Cormoran) and one synthetic well (Parentis West S. B.; see Brunet, 1991) (redrawn and modified after Brunet, 1997). Upper curves represent tectonic subsidence under water with local isostatic compensation, while lower curves represent basement deepening curves with decompacted sediments (see Brunet, 1997 for details on applied corrections). Note that during the Late Jurassic-Early Cretaceous rifting, tectonic subsidence is noticeably faster in the Early Cretaceous interval than in the Late Jurassic interval.

**Fig. 14:** a) Simplified geological map of the Aquitaine Basin with locations of the main Late Jurassic-Early Cretaceous sub-basins reviewed in this study and of the wells presented in (b) (redrawn and modified after Bourrouilh *et al.*, 1995). Abbreviations: G.R.H. = Grand-Rieu High; N.P.F. = North Pyrenean Fault; N.P.F.T. = North Pyrenean Frontal Thrust; N.P.Z. = North Pyrenean Zone. b) Subsidence curves for the Lacq 1 (Arzacq Basin) and Ger 1 (Tarbes Basin) wells from the Southern Aquitaine Basin (redrawn and modified after Brunet, 1984; see Fig. 9 for location). Upper curves are tectonic subsidence curves with local isostatic compensation; lower curves represent progressive deepening of the Paleozoic basement with decompacted sediments (see Brunet, 1984 for details on the applied corrections). Note that during the Late Jurassic-Early Cretaceous rifting, tectonic subsidence curves are steeper for the Early Cretaceous interval than for the Late Jurassic one.

**Fig. 15:** Schematic diagram showing the main tectonic phases affecting the basins reviewed in this work during the Late Jurassic-Early Cretaceous interval. During the Late Jurassic, extension seems to have initially affected the most external parts of the system and then progressively affected the inner portions. During this phase, the Northern Aquitaine basins and the Asturian Basin, located at the boundaries of the system, underwent oblique rifting, while the rest of the system underwent orthogonal rifting. All the basins were affected by an episode of emersion and/or reduced subsidence during the Neocomian (~145 to 130 Ma). After the Neocomian, most of the rift basins experienced a phase of renewed subsidence controlled by oblique transtensional rifting, with the notable exception of the North Pyrenean basins. This phase coincided with crustal breakup in the inner Bay of Biscay margins. When oceanic spreading affected the Bay of Biscay domain during the Albian, most of the rift basins became inactive and transtensional rifting accommodating the

displacement between Iberia and Eurasia localized along the Basque-Cantabrian and North Pyrenean systems. Rifting finally terminated during the Cenomanian.

**Fig. 16:** Kinematic reconstruction of the Iberia/Eurasia diffuse plate boundary between the Late Jurassic and the Early Cretaceous, with representation of the rift domains reviewed in this study and their kinematic evolution through time. During the Late Jurassic (a) left-lateral displacement between the two plates concentrates on the edges of the system, while the rest of the plate boundary undergoes mainly orthogonal rifting. During the Neocomian (b) the whole plate boundary experiences a phase of reduced subsidence with localized exhumation events, while lithospheric breakup propagates northward on the Western Iberian margin. During the Aptian (c) most of the rift basins within the plate boundary zone are affected by left-lateral transtension controlling a phase of increased subsidence, with the notable exception of the North Pyrenean Rift System. During the Albian-Cenomanian (d) the Bay of Biscay realm undergoes oceanic accretion and the transtensional deformation localizes along the Basque-Cantabrian/North Pyrenean Rift System, which remains the only active domain while the rest of the sedimentary basins attain the post-rift stage. Plate kinematic model modified after Angrand *et al*. (2020). Acronyms: ACF, Ateca-Castellon Fault; AsB, Asturian Basin; ArS, Armorican Shelf; BCB, Basque-Cantabrian Basin; CAF, Celtaquitaine Flexure; CCRB, Catalan Coastal Range Basin; CoB, Columbrets Basin; HF, Hesperian Fault; IF, Ibis Fault; LF, Leitza Fault; MaB, Mauléon Basin; NAB, North Aquitaine basins; NIF, North Iberian Fault; NPB, North Pyrenean basins; PaB, Parentis Basin; SAB, South Aquitaine basins; SPB, South Pyrenean basins; VF, Ventaniella Fault.

**Fig. 17:** Schematic representation of (a) a narrow transform plate boundary and of (b) a diffuse transform plate boundary. In (a) the total left-lateral displacement between the two plates is accommodated by a single wrench structure. In (b) the very same amount of total displacement is

partitioned between a series of sub-parallel strike-slip structures, each of which accommodates a portion of the total left-lateral displacement between the stable parts of the plates.

**Declaration of interests**

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: