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► **To cite this version:**

Rodolphe Lescoutre, Gianreto Manatschal. Role of rift-inheritance and segmentation for orogenic evolution: example from the Pyrenean-Cantabrian system. Bulletin de la Société Géologique de France, 2020, 191, pp.18. 10.1051/bsgf/2020021 . hal-03102415

HAL Id: hal-03102415

<https://hal.science/hal-03102415>

Submitted on 8 Jan 2021

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Role of rift-inheritance and segmentation for orogenic evolution: example from the Pyrenean-Cantabrian system

Rodolphe Lescoutre^{*,a} and Gianreto Manatschal

IPGS, EOST-CNRS, Université de Strasbourg, 1, rue Blessig, 67084 Strasbourg, France

Received: 13 December 2019 / Accepted: 24 February 2020

Abstract – The Basque-Cantabrian junction corresponds to an inverted rift accommodation zone at the limit between the former hyperextended Pyrenean and Cantabrian rift segments. The recognition of an inherited rift segment boundary allows to investigate the reactivation associated with large-scale rift segmentation in an orogenic system. We use criteria from published field observations and seismic data to propose a new map of rift domains for the Basque-Cantabrian junction. We also provide balanced cross-sections that allow to define the along-strike architecture associated with segmentation during rifting and subsequent Alpine reactivation. Based on these results, this study aims to characterize and identify reactivated and newly formed structures during inversion of two rift segments and its intermitted segment boundary. It also aims to describe the timing of thin-skinned and thick-skinned deformation associated with the inversion of segmented rift systems. During convergence, two phases have been recognized within the rift segment (eastern Mauléon basin). The Late Cretaceous to Paleocene underthrusting/subduction phase was mostly governed by thin-skinned deformation that reactivated the former hyperextended domains and the supra-salt sedimentary cover. The Eocene to Miocene collisional phase, controlled by thick-skinned deformation that took place once necking domains collided and formed an orogenic wedge. At the rift segment boundary, the underthrusting/subduction phase was already controlled by thick-skinned deformation due to the formation of shortcutting thrust faults at the termination of overlapping V-shaped rift segments. This led to the formation of a proto-wedge composed of the Basque massifs. We suggest that this proto-wedge is responsible for the preservation of pre-Alpine structures in the Basque massifs and for the emplacement of subcontinental mantle rocks at a crustal level beneath the western Mauléon basin. These results argue for a first order cylindrical orogenic architecture from the Central Pyrenean segment to the Cantabrian segment (up to the Santander transfer zone) despite rift segmentation. They also highlight the control of 3D rift-inheritance for the initial phase of orogenic evolution and for the local architecture of mountain belts.

Keywords: rift-inheritance / segmentation / reactivation / orogenic evolution / Pyrenees / Basque massifs

Résumé – Rôle de l'héritage associé au rift et à sa segmentation pour l'évolution orogénique: exemple du système pyrénéo-cantabrique. La jonction pyrénéo-cantabrique correspond à une zone d'accommodation entre les segments de rifts hyper-étirés cantabrique et pyrénéen, qui ont été par la suite inversés lors de l'orogénèse alpine. La reconnaissance d'une telle zone de segmentation permet d'étudier les conséquences d'un héritage de rift en 3 dimensions sur l'évolution orogénique. A partir de nos précédents résultats ainsi que de la compilation de données de terrain et de sismique, nous proposons une nouvelle carte des domaines de rift dans la zone étudiée. L'élaboration de coupes restaurées permet de définir et comparer l'architecture actuelle et syn-rift entre la zone d'accommodation et les segments de rift (c.à.d. à distance de la zone de segmentation). A partir de ces résultats, cette étude vise à identifier et caractériser les structures réactivées et néo-formées à travers la zone d'étude. Elle entreprend également de décrire l'évolution de la déformation « thin-skinned » et « thick-skinned » au cours de la convergence dans ce type de système très

*Corresponding author: rodolphe.lescoutre@geo.uu.se

^aPresent address: Department of Earth Sciences, Geophysics, Uppsala University, Villavägen 16, 75236 Uppsala, Sweden.

segmenté. Lors de la convergence, deux phases de déformation peuvent être distinguées dans les segments de rift (bassin Est Mauléon). Une phase de sous-charriage tardi-Crétacé à Paléocène, principalement contrôlée par la déformation « thin-skinned » et qui réactive les domaines de rift hyper-étirés ainsi que la couverture Mésozoïque décollée sur les évaporites du Trias Supérieur. Une phase de collision Éocène à Miocène, qui s'initie lorsque les domaines d'étranglement des marges conjuguées se rencontrent et qui mène à la formation d'un prisme orogénique (« thick-skin »). Dans la zone d'accommodation, la phase de sous-charriage semble déjà contrôlée par la déformation « thick-skinned » par la formation de structures crustales néo-formées à vergences opposées à la terminaison des bassins. Ces dernières transfèrent la déformation entre les deux segments de rifts et forment un proto-prisme orogénique composé des massifs basques. Nous suggérons que ce proto-prisme orogénique est responsable de la préservation des structures pré-alpines dans les massifs basques ainsi que de l'emplacement à faible profondeur du manteau sous-continental sous le bassin Ouest Mauléon. Cette étude montre que l'architecture orogénique apparaît au premier ordre cylindrique des Pyrénées Centrales au segment cantabrique (jusqu'à la zone de Santander), malgré la segmentation du système de rift sur lequel la déformation s'initie. Elle souligne enfin le rôle de l'architecture héritée en 3 dimensions lors des phases précoces de l'évolution orogénique ainsi que pour l'architecture locale de l'orogène.

Mots clés : héritage / segmentation / réactivation / évolution orogénique / Pyrénées / massifs basques

1 Introduction

In most collisional orogens worldwide, the restoration of the pre-collisional stage and the role of rift-inheritance have been investigated in the external, fold-and-thrust belt domains by the help of 2D balanced cross-sections. Few studies attempted to restore the internal parts, where the pre-collisional architecture has been intensively reactivated or subducted. A further difficulty is that internal parts of collisional orogens generally correspond to former distal parts of rifted margins, domains that are yet poorly understood and from which fate and behaviour during reactivation remain little investigated. Of particular importance to understand the structural evolution of internal parts of orogenic systems are the boundaries between rift domains (Sutra *et al.*, 2013), where changes in mechanical and rheological properties occur (Mohn *et al.*, 2014; Tugend *et al.*, 2015; Chenin *et al.*, 2017). These studies stressed in particular the role of the “coupling point” defined as the boundary between the necking and hyperextended domains, corresponding to the limit between crust thicker than 10 km showing ductile levels in the crust; and crust thinner than 10 km where the residual continental crust is brittle and the top of the mantle is serpentinized and can act as an efficient decoupling horizon during reactivation (Péron-Pinvidic *et al.*, 2008). Due to the major change in bulk rheology, crustal thickness and mechanical coupling between mantle and crust, the coupling point may play a critical role in separating domains with different deformation style during tectonic inversion. In 2D sections, the coupling point may separate domains that can be subducted (hyperextended domain) from domains that can act as buttress and form the abutments of the future orogen (*e.g.* Lacombe and Bellahsen, 2016). While the role of the coupling point has been investigated in 2D sections (*e.g.* role of necking zone in Tugend *et al.*, 2014), the role of the along-strike evolution of the coupling point/line has not yet been considered in the orogenic evolution. Yet, the present-day architecture of rift systems reveals a significant along-strike variability associated with transfer zones or relay zones (*e.g.* Belgarde *et al.*, 2015; Péron-Pinvidic *et al.*, 2017). As a consequence, integrating 3D inheritance in the reactivation of

rift domains can complexify the reactivation pattern or lead to the formation of new structures that might explain the regional non cylindricity of collisional orogens (Jammes *et al.*, 2014; Chevrot *et al.*, 2018). Such 3D implications might account for some of the complexities encountered when dealing with 2D restorations and explain geological anomalies observed in orogenic systems.

In this study, we investigate the onshore Pyrenean–Cantabrian junction (Western Pyrenees), which corresponds to an overlapping rift relay system subsequently reactivated during Pyrenean convergence (Lescoutre, 2019). This area preserves the first order rift architecture and therefore allows to study the 3D reactivation of a segmented hyperextended system.

2 Generalities about the Pyrenees, rift architecture, segmentation and reactivation

2.1 The Pyrenean-Cantabrian case study

The Pyrenean and Cantabrian orogenic system is striking WNW-ESE between France and Spain and can be described as two segments of the same orogenic event separated by the Basque massifs, which represent as such, the Cantabrian-Pyrenean junction (Fig. 1). The present-day architecture of the Pyrenean-Cantabrian orogenic system corresponds to an asymmetric double-verging crustal wedge with a north-dipping underthrust/subducted “slab” (Choukroune, 1989; Roure *et al.*, 1989; Muñoz, 1992; Alonso *et al.*, 1996; Teixell, 1998; Beaumont *et al.*, 2000; Pedreira *et al.*, 2003; Chevrot *et al.*, 2018; Teixell *et al.*, 2018). Note that our study does not include the western part of the Cantabrian system, *i.e.* west of the Santander Transfer Zone (*e.g.* Roca *et al.*, 2011; Cadenas *et al.*, 2018), where the southern border of the Bay of Biscay has been thrust/subducted southwards underneath the North Iberian margin (Pulgar *et al.*, 1996; Fernández-Viejo *et al.*, 1998; Ruiz *et al.*, 2017). Origin and architecture of this domain remain discussed (*e.g.* Gallastegui *et al.*, 2002; Fernández-Viejo *et al.*, 2012; Teixell *et al.*, 2018). The north-dipping slab formed during the Late Cretaceous to Miocene

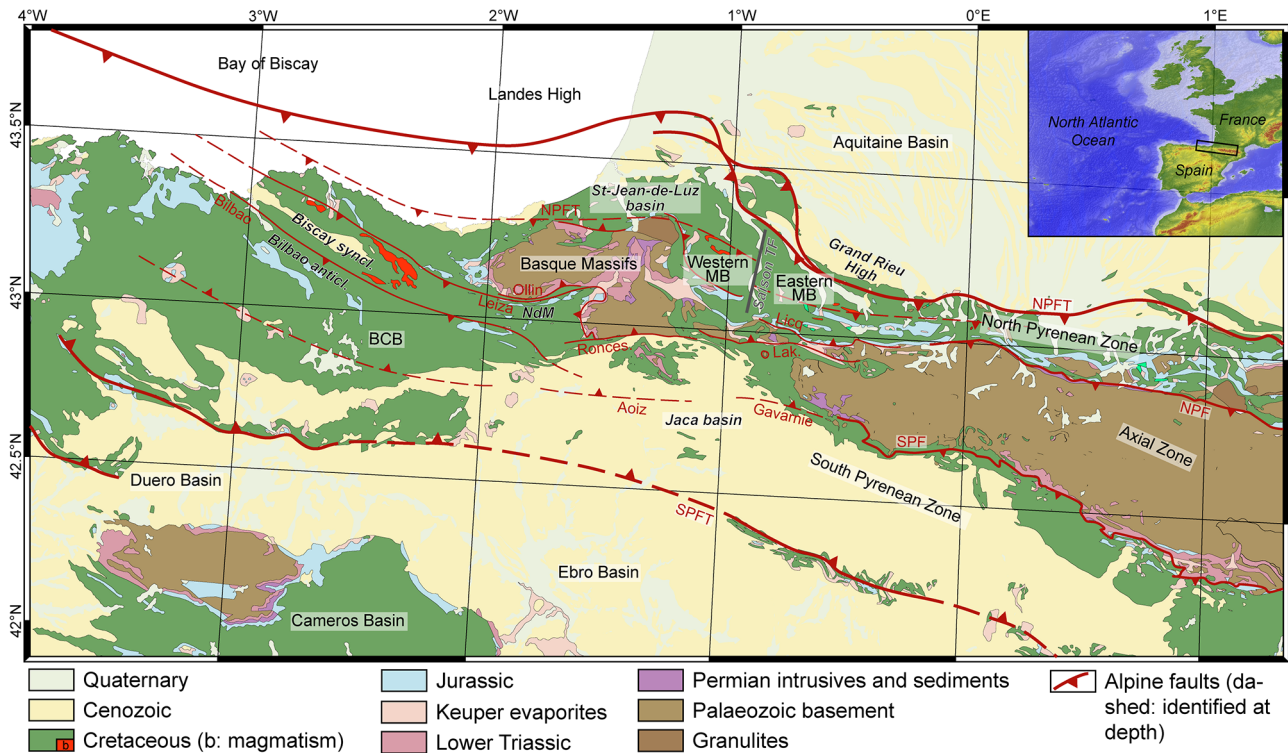


Fig. 1. Geological map of the Pyrenean-Cantabrian system with the main domains and structural units. Modified after [Chantraine et al. \(2003\)](#). BCB: Basque-Cantabrian basin; NdM: Nappe des Marbres; Ronces: Roncesvalles fault; Lak: Lakora fault; SPFT: South Pyrenean Frontal Thrust; NPFT: North Pyrenean Frontal Thrust; NPF: North Pyrenean Fault; SPF: South Pyrenean Fault; MB: Mauléon basin. Insert shows the location of the map.

N-S convergence (e.g. [Mouthereau et al., 2014](#); [Macchiavelli et al., 2017](#)) reactivating and inverting the former Cantabrian and Pyrenean mid-Cretaceous rift basins and forming the present-day mountain chain and fossil Eurasian and Iberian plate boundary. This rift system, which opened in a N-S to NNE-SSW extension direction (e.g. [Jammes et al., 2009](#); [Tavani et al., 2018](#)), reached mantle exhumation (e.g. [Lagabrielle et al., 2010](#); [DeFelipe et al., 2017](#)) and was associated with syn-rift High-Temperature/Low-Pressure (HT-LP) metamorphism of the pre- to syn-rift sedimentary succession ([Ravier, 1959](#); [Albarède and Michard-Vitrac, 1978](#); [Montigny et al., 1986](#); [Clerc et al., 2015](#); [Ducoux et al., 2019](#); [Lescoutre et al., 2019](#)). The latter was detached above the Upper Triassic evaporites, representing a prominent decoupling horizon during both the rifting and compressional events ([Vergés and García-Senz, 2001](#); [Lagabrielle et al., 2010](#)). No oceanic crust (ophiolite) or subduction-related features (e.g. arc volcanism, back-arc basin) have been evidenced in or around the inverted Cantabrian or Pyrenean basins, suggesting that the slab is only composed of continental and serpentinized mantle rocks.

On a map view, the Pyrenean segment of the orogen can be divided in 5 structural domains bounded by major WNW-ESE striking structures: the Axial Zone, the North Pyrenean Zone, the South Pyrenean Zone, the Aquitaine foreland basin (and Landes High), and the Ebro foreland basin (see details in [Mattauer and Henry, 1974](#)). The Axial Zone corresponds to the hinterland of the orogen and is composed of Palaeozoic rocks that represent the tectonic basement that was marginally

affected by several rift events and final Late Cretaceous to Miocene orogeny. It is bounded to the north by the North Pyrenean Zone, the latter corresponding to the former mid-Cretaceous hyperextended basins that have been subsequently inverted (e.g. [Lagabrielle et al., 2010](#)). They are bounded to the north by the North Pyrenean Frontal Thrust (NPFT) and the Aquitaine basin, which lies over European crust. Note that, towards the west of the Pyrenees, the Palaeozoic Basque massifs have been either attributed to the Axial Zone or to the North Pyrenean Zone, *i.e.* to belong either to the European or the Iberian plates (e.g. [Rat et al., 1983](#); [Schott and Peres, 1988](#)). To the south of the Axial Zone, the South Pyrenean Zone corresponds to piggyback basins ([Puigdefàbregas et al., 1992](#)) bounded to the south by the South Pyrenean Frontal Thrust (SPFT) and the Ebro foreland basin, which lies over Iberian crust.

In the Cantabrian segment, the Palaeozoic massifs of the Axial Zone are not observed anymore and therefore the South Pyrenean and North Pyrenean Zones cannot be defined. Instead, this terminology is replaced by WNW-ESE striking structural domains such as the Bilbao anticlinorium or the Biscay synclinorium, which are part of the Basque-Cantabrian basin (BCB) ([Fig. 1](#)). However, similarly to the Pyrenean segment, the lateral continuation of the NPFT juxtaposes the inverted BCB and the Landes High, the latter corresponding to the westward prolongation of the Aquitaine foreland. Toward the south, the SPFT juxtaposes the BCB and the Ebro/Duero foreland basin such as observed in the Pyrenean segment.

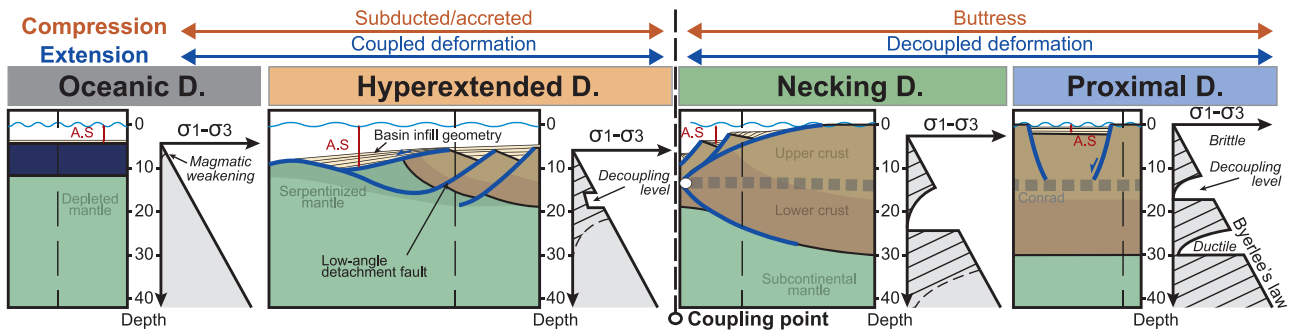


Fig. 2. Diagnostic structural and sedimentary relationships and rheological profiles characterizing the different rift domains. Note that the total accommodation space (A.S.; water plus sediments) can either be characterized by thickness (if subsidence rates equal sedimentation rates, in which case depositional environment remains shallow), or by a deepening of the depositional environment, in which case subsidence rates are higher than sedimentation rates. Thus, the proximal domain is formed by either continental or shallow marine sediments that remain thin; while the hyperextended domain is formed by either deep water facies and/or very thick shallow marine to continental sequences. The rheological profiles show the strength profile both at the end of rifting (hatched area) and after thermal relaxation (grey). The location of the rheological profiles is indicated by the vertical dashed lines in the sections. The main observation is that each rift domain is characterized by a different pre- and post-thermal relaxation rheological section with different locations for the potential crustal/mantle decoupling levels.

2.2 Formation and reactivation of rift domains

The crustal architecture of rifted margins, together with the thermal state at onset of convergence, are likely to control the evolution of orogenic systems (Mohn *et al.*, 2011; Jammes and Huismans, 2012; Erdős *et al.*, 2014; Vacherat *et al.*, 2016; Chenin *et al.*, 2017; Gómez-Romeu *et al.*, 2019; Jourdon *et al.*, 2019). Sutra *et al.* (2013) and Péron-Pinvidic *et al.* (2013) proposed that magma-poor rifted margins can be characterized by 4 domains, each one characterized by a different crustal architecture and rheology (Fig. 2).

The proximal domain corresponds to a 30 ± 5 km thick crust composed of brittle upper and ductile lower crusts and exhibiting local fault bounded basins and minor accommodation space outside these basins. At outcrop scale, this domain is characterized by thin, shallow marine and/or continental sediments deposited over partly eroded pre-rift upper crust.

The necking domain corresponds to an increase of the accommodation space related to oceanward crustal thinning (e.g. Osmundsen and Redfield, 2011). This domain preserves ductile levels in the crust and exhibits top-basement detachment faults that can exhume mid-crustal rocks. At outcrop scale, this domain is represented by slope to bathyal depositional environments onlapping onto either detachment surfaces characterized by gouges, cataclasites, tectono-sedimentary breccias or allochthonous crustal blocks.

The hyperextended domain shows a very large accommodation space and can be divided in two sub-domains, the hyper-thinned sub-domain corresponding to a < 10 km thick, often hydrated crust and the exhumed mantle domain, which corresponds to a basement floored by serpentinized mantle. At outcrop scale, this domain is characterized by deep marine sediments downlapping onto detachment surfaces floored by either crustal or serpentinized mantle rocks. This rifting stage ultimately leads to the accretionary stage with the formation of a ~ 6 km thick magmatic oceanic crust consisting of tholeiitic igneous material (Anonymous, 1972).

During rifting, once the crust and the mantle are coupled (e.g. coupling point separating necking and hyperextended domains; Fig. 2), rift evolution can develop asymmetrically

and an upper plate and a lower plate can be distinguished, the former presenting the hangingwall and the latter the footwall of the main exhumation fault system (e.g. Lister *et al.*, 1986; Sutra *et al.*, 2013; Brune *et al.*, 2014; Péron-Pinvidic *et al.*, 2017). Note that oceanic crust was not developed in the Pyrenean-Cantabrian rift system, as shown by the absence of tholeiitic basalts and therefore will not be discussed in this paper.

Initiation of convergence should be expected to occur in the weakest part of the margin (e.g. Erdős *et al.*, 2014). Péron-Pinvidic *et al.* (2008) and Lundin and Doré (2011) showed for the N-Atlantic margins that convergence initiated in the exhumed and hyper-thinned domains, *i.e.* oceanward of the coupling point. It appears that the compressional structures tend to use existing structures (e.g. top basement eventually composed of serpentinized mantle) and low-angle detachment faults (e.g. Stern, 2004; Jammes *et al.*, 2014; Tugend *et al.*, 2014; Epin *et al.*, 2017). The underthrust of the hyperthinned and exhumed domains is favoured and sustained by low frictional slip surfaces composed of hydrated material (serpentine, talk, clays etc.) (Hilaret *et al.*, 2007; Beltrando *et al.*, 2014). Since the hyperextended domain can exceed 100 km in width (Chenin *et al.*, 2017), it is wide enough to be pulled down into the eclogite facies, as indicated by the occurrence of ultra-high pressure rocks in orogenic domains. During this underthrusting/subduction stage, part of these domains can eventually be scraped and accreted within the accretionary wedge or transported within nappes (e.g. Andersen *et al.*, 2012; Beltrando *et al.*, 2014; Epin *et al.*, 2017). Collisional processes initiate when the necking zone is entering subduction, *i.e.* when the coupling points of the conjugate margins meet. At this stage, the > 10 km thick crust of the necking domain can form a buttress (Mohn *et al.*, 2014; Tugend *et al.*, 2014) and a crustal wedge related to continental collision starts to develop (Mouthereau *et al.*, 2014). The singular point (S point), which corresponds to the location where one plate slides below the other (e.g. basal tip of the wedge; Willett *et al.*, 1993; Beaumont *et al.*, 2000), may coincide with the coupling point inherited from the former margin structure. Note that the occurrence of an effective

decoupling layer in the crust or within the sedimentary cover can lead to the formation of a secondary S point (e.g. Roure *et al.*, 1990). In the final collisional episode, rift-related high-angle normal faults of the proximal margin are reactivated locally (e.g. Buiter and Pfiffner, 2003; Butler *et al.*, 2006; Carrera *et al.*, 2006; Granado *et al.*, 2016; Lacombe and Bellahsen, 2016) adding to local complexity to the formation of the fold-and-thrust belt forming the external part of the orogen.

The previously described 2D inversion of a hyperextended rift system might be hampered in case of non-cylindrical along-strike variation of the rift architecture. In particular, the V-shaped basin architecture or transfer/accommodation zones might precursory lead to the collisional stage along-strike and impede subduction to nucleate and can complexify the orogenic framework at former rift segment terminations. In this study, we aim to study the role of segmentation and along-strike rift-inheritance on the 3D orogenic architecture using the example of the Western Pyrenees.

2.3 Along-strike segmentation

The along-strike architecture of rift systems has been shown to be highly variable in most present-day margins (Nonn *et al.*, 2017; Péron-Pinvidic *et al.*, 2017), very often controlled by pre-rift inheritance (e.g. Belgarde *et al.*, 2015; Mercier de Lépinay *et al.*, 2016). Junction between rift segments can occur *via* a transfer/transform fault (see review of Basile, 2015), a transfer zone (Faulds and Varga, 1998) or an accommodation zone associated with relay ramps (Faulds and Varga, 1998; Acocella *et al.*, 2005; Bubeck *et al.*, 2017). However, the 3D architecture of such junctions remains poorly-understood, with respect to the 2D dip architecture of rifted margins.

In an accommodation zone, rift systems overlap parallel or slightly oblique to the direction of extension (Wilson, 1990; Corti, 2012; Zwaan *et al.*, 2016). This overlapping geometry is favoured by orthogonal rifting and by a large offset between rift segments (Le Calvez and Vendeville, 2002; Zwaan *et al.*, 2016; Zwaan and Schreurs, 2017), providing that the total length of the rift segments is much greater than the distance between the overlapping rift axis (Acocella, 2008). In detail, segment rotation or second order transfer zones and relay zones can accommodate the termination of rift segments (e.g. Tapponnier *et al.*, 1990; Faulds and Varga, 1998; Le Calvez and Vendeville, 2002). The reactivation of transfer zones during tectonic inversion has been only little investigated (e.g. Calassou *et al.*, 1993; Ustaszewski *et al.*, 2005; Konstantinovskaya *et al.*, 2007; Granado *et al.*, 2016, 2017), whilst the reactivation of overlapped rift systems and their implication for the orogenic architecture have yet to be explored.

3 The Pyrenean-Cantabrian study case

3.1 Identification of former rift domains

Tugend *et al.* (2014; see also Roca *et al.*, 2011 and Cadenas *et al.*, 2018) identified and mapped former rift domains of the study area based on gravity inversion, seismic interpretation and field observations. However, the transition between the

Pyrenean and Cantabrian rift systems was attributed by the authors to a crustal-scale transform/transfer fault (Pamplona fault) and, as a consequence, the termination of rift domains along-strike was assumed to end abruptly. In a recent study, Lescoutre (2019) showed that the paleogeography of the area actually corresponds to overlapping rift basins, the Mauléon basin propagating westward in the St-Jean-de-Luz basin whilst the BCB propagated eastward in the Jaca-Pamplona basin. These results require a re-mapping of the rift domains in this area (Fig. 3) based on the criteria presented in the previous chapter and ask for an evaluation of the consequences for the subsequent convergence.

Proximal domain: The Aquitaine, Landes High and Ebro/Duero units correspond to domains with a > 20 km thick crust (Bois *et al.*, 1997; Fernández-Viejo *et al.*, 2000; Pedreira *et al.*, 2003; Tugend *et al.*, 2014), which is compatible with the occurrence of upper Cretaceous erosional surfaces or thin, shallow water sedimentary sequences (García-Mondéjar, 1986; García-Mondéjar *et al.*, 1996; Vergés and García-Senz, 2001). The Axial Zone, the South Pyrenean Zone and the Basque massifs correspond during the upper Cretaceous to shallow marine and/or emerged areas suggesting that these domains were also formed over crust > 20 km (Casteras, 1949; Feuillée and Sigal, 1965; Razin, 1989; Bodego and Agirrezabala, 2017; Vacherat *et al.*, 2017).

Necking domain: In the Pyrenean segment, transitional slope facies associated with detachment faulting have been observed over the Mendibelza massif (Boirie and Souquet, 1982) and more generally on the northern margin of the Basque massifs (Johnson and Hall, 1989a, 1989b; Razin, 1989; Masini *et al.*, 2014; Vacherat *et al.*, 2017). In the Cantabrian segment, these transitional facies have been retrieved north of the Biscay synclinorium, south of the Basque massifs and north of the SPFT (Meschede, 1987; García-Mondejar, 1989; Fernandez-Mendiola and García-Mondejar, 1990; Gräfe, 1999; Mathey *et al.*, 1999; Bodego *et al.*, 2015). Reactivation of major basin bounding faults has been proposed to occur along the NPFT based on structural reconstruction in both the Pyrenean and Cantabrian segments (Baby *et al.*, 1988; Razin, 1989; Gómez *et al.*, 2002; Lagabrielle *et al.*, 2010). In the Pyrenees, the thinned crust of the Grand Rieu represented a topographic high between the Arzacq basin to the north and the Mauléon basin to the south (Masini *et al.*, 2014). As such, we assume that the necking domain extended from the north of the Arzacq basin up to the southern margin of the Grand Rieu High.

Hyperextended domain: This domain corresponds to thick turbidite sequences deposited during Albian to Cenomanian in the BCB, western Jaca-Pamplona basin, St-Jean-de-Luz basin and Mauléon basin (e.g. Souquet *et al.*, 1985; Rat, 1988) associated with serpentinized mantle rocks (Mendia and Iburguchi, 1991; Lagabrielle *et al.*, 2010), syn-rift HT/LP metamorphic rocks (Clerc *et al.*, 2015 and references therein) and sometimes alkaline magmatic rocks (Azambre and Rossy, 1976; Montigny *et al.*, 1986).

3.2 Present-day architecture

3.2.1 Rift segments

In the Pyrenean segment, the Grand Rieu High is located in the footwall of the NPFT, which transports the Mauléon basin

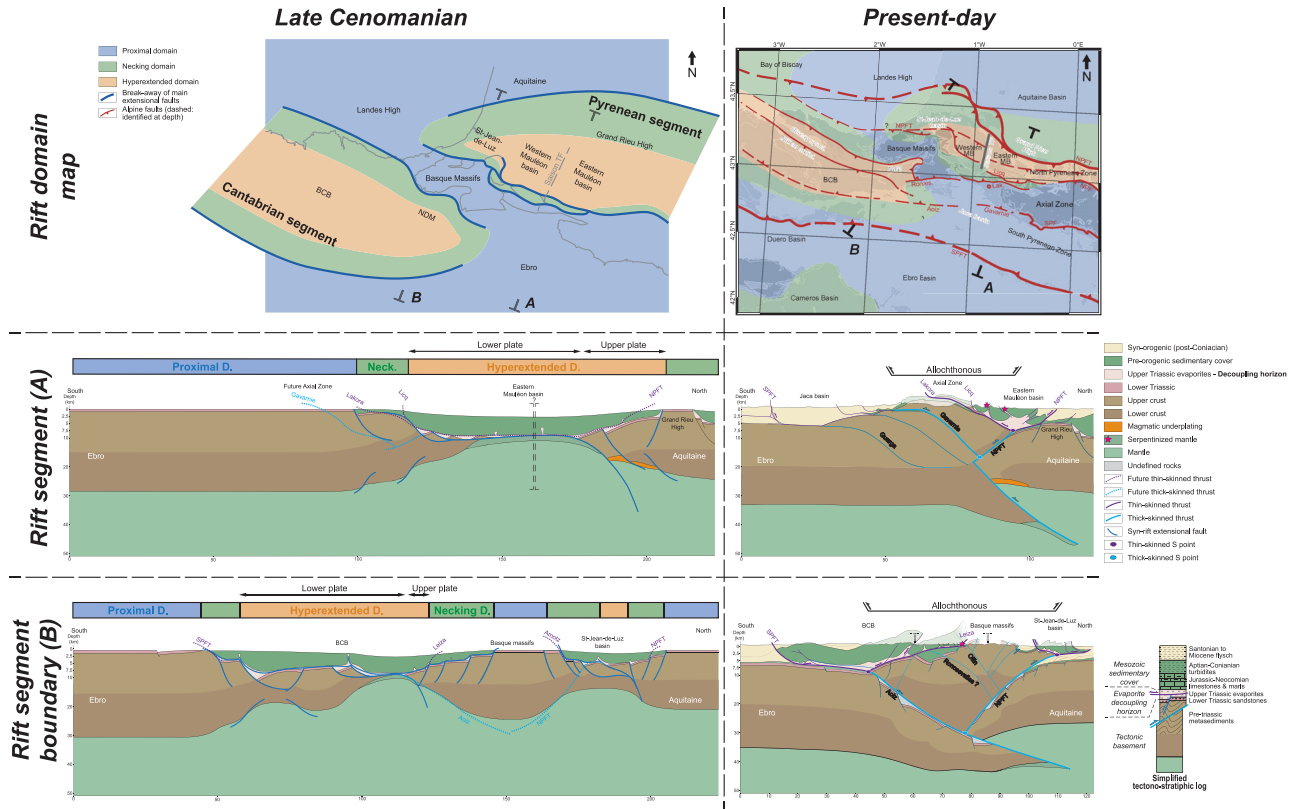


Fig. 3. Rift domain maps and cross-sections across the eastern Mauléon basin (rift segment) and the eastern BCB and St-Jean-de-Luz basin (rift segment boundary) at late rifting stage (Late Cenomanian) and after Alpine collision (present-day). Bottom-right figure shows a simplified tectono-stratigraphic log. For description and discussion of the figure see text.

and part of the upper crust of the Axial Zone (Ebro basement) towards the north (Daignieres *et al.*, 1982; Teixell, 1998; Biteau *et al.*, 2006). Towards the south, the reactivated thin-skinned Licq fault and the basement-involved thin-skinned Lakora thrust emplace the basin over the Axial Zone (Teixell, 1990; Masini *et al.*, 2014; Teixell *et al.*, 2016). Between the NPFT and the Licq fault, the Mauléon basin is affected by WNW-ESE striking folds and thrusts, the latter detached in the Upper Triassic evaporites. The Axial Zone corresponds to the north-dipping Gavarnie and Guarga imbricate thrust system (Teixell, 1990), at the front of which flysch sediments have been deposited in the South Pyrenean Zone (Labaume *et al.*, 1985).

As such, the thin-skinned S point corresponds to the base of the wedge formed by the supra-salt basin (*i.e.* intersection between the thin-skinned Licq and NPFT). At depth, the indentation of the Aquitaine crust at mid-crustal level within the Ebro crust led to a crocodile-shape architecture (Teixell, 1998). As such, the former hyperextended domain and lower crust of the Ebro lower plate represent the underthrust material, while the upper crust of the necking domain (Mendibelza/Igountze) has been thrust onto the indenter. In this segment, the Gavarnie and NPFT form the pro-wedge and retro-wedge respectively, of the orogenic wedge (Beaumont *et al.*, 2000).

In the Cantabrian segment, *i.e.* the central BCB, the thin-skinned SPFT juxtaposes the supra-salt BCB above the Ebro/Duero foreland basin (Camara, 1997; Martínez-Torres, 1993; Carola *et al.*, 2013). North of the basin, the reactivated NPFT

(Gómez *et al.*, 2002) brings the BCB and its para-autochthonous sedimentary cover over the Landes High (Pedreira *et al.*, 2007; Roca *et al.*, 2011; Quintana *et al.*, 2015). Between these two major faults, the BCB shows internal deformation mainly governed by WNW-ESE striking folds and thrusts (*e.g.* Abalos *et al.*, 2008), the latter detached along the Upper Triassic decoupling horizon. At depth, a high density, magnetic body attributed to lower crustal or mantle rocks has been described in the hangingwall of the NPFT (*e.g.* Aller and Zeyen, 1996; Pedreira *et al.*, 2007).

In the section, the thin-skinned S point can be defined, which corresponds to the base of the wedge formed by the supra-salt basin. The crustal wedge (and related thick-skinned S point) formed between the NPFT and the SPFT (*e.g.* Roca *et al.*, 2011), whilst the underthrust slab is composed, in the section, by crust derived from the former southern margin of the BCB.

As such, the SPFT/Licq and NPFT represent prominent structures for the Pyrenean-Cantabrian orogenic system as they delimit the allochthonous units of the orogenic wedge (Beaumont *et al.*, 2000) from the Ebro/Duero and Grand Rieu/Landes Highs autochthonous units, respectively (Fig. 1). Moreover, the NPFT and the SPFT have been shown to reactivate rift structures of the former necking domains in the Pyrenean and Cantabrian rift segments. This suggests that the limits of the orogenic structural units correspond, at a first order, to the limits of the former rift domains at rift segments.

3.2.2 Rift segment boundary

At the segment boundary, the inverted eastern BCB and St-Jean-de-Luz basin represent the southern and northern branch respectively, of two overlapping rift basins with the Basque massifs as the intermediate block (Fig. 3; Lescoutre, 2019). Here, the BCB and St-Jean-de-Luz basin are passively transported above the Basque massifs and the Ebro and Aquitaine foreland basins *via* the thin-skinned NPFT, SPFT, Leiza and Amotz reactivated structures detached in the evaporite horizon (see Fig. 3 for location; Razin, 1989; Martínez-Torres, 1993; Serrano *et al.*, 2006; DeFelipe, 2017; DeFelipe *et al.*, 2017; Lescoutre, 2019). The basement shows north-dipping thrusts south of the Basque massifs and south-dipping thrusts north of the Basque massifs. Southward, the Aoiz thrust (Cámara and Klimowitz, 1985; Lescoutre, 2019) juxtaposes the Basque massifs over the Ebro basement (4247 m deep in the Aoiz borehole; Instituto Geológico y Minero de España (IGME), 1990) whilst toward the north, the NPFT brings the Basque massifs over the Aquitaine crust (Razin, 1989; Serrano *et al.*, 2006). The NPFT is continuous toward the east in the western Mauléon basin up to the NNE-SSW Saison transfer fault, along which the NPFT is shifted toward the south (Masini *et al.*, 2014). Masini *et al.* (2014) noted that, in contrast to the eastern Mauléon basin (rift segment), the hyperextended basement of the western Mauléon basin, together with a piece of serpentized subcontinental mantle responsible for the gravity anomaly were thrust above the Aquitaine crust along the NPFT (Casas *et al.*, 1997; Jammes *et al.*, 2010; Wang *et al.*, 2016). Interestingly, at the south-western termination of the Mauléon basin, the South and North Mauléon Detachments (lateral equivalent to the Licq detachment fault) show no major Alpine overprint (Masini *et al.*, 2014), which is also true for the Permian basin located on the Basque massifs (Lucas, 1987; Lescoutre, 2019; Saspiturry *et al.*, 2019).

In the eastern continuation of the BCB, the E-W striking and north-dipping Roncesvalles thrust fault (or “faïlle de Bigorre” in Souquet *et al.*, 1977) seems to link the southern branch with the Pyrenean rift segment and strikes parallel to the Lakora thrust. In the western continuation of the northern branch, the strike of the NPFT changes from WNW-ESE to NE-SW and finally seems to link with the Cantabrian segment (e.g. Rat, 1988; Gómez *et al.*, 2002; Roca *et al.*, 2011).

At depth, the seismic profiles obtained from receiver function analysis (Díaz *et al.*, 2012) and velocity models (Antonio-Vigil *et al.*, 2019) suggest that the underthrust/subducted slab at the rift segment junction formed from the underthrusting of the southern margin of the BCB basin and is continuous toward the east, *i.e.* in the Jaca-Pamplona basin up to the Mauléon basin. In contrast, no slab is observed associated with the northward underthrusting of the Aquitaine crust in the northern Pyrenean branch (St-Jean-de-Luz) and the crustal thickness is about 20 to 30 km at present-day (Daignieres *et al.*, 1982; Pedreira *et al.*, 2003; Tugend *et al.*, 2014; Antonio-Vigil *et al.*, 2019), suggesting that it has been re-thickened back to initial crustal thickness during Pyrenean convergence.

At this segment boundary, the location of the thick-skinned S point is located at the intersection between the north-dipping slab (Aoiz fault) and the south-dipping NPFT identified below the St-Jean-de-Luz basin. As a consequence, and in contrast to the rift segments, the thick-skinned S point is not located below

the inverted rift basin and the orogenic wedge is formed by the entire Basque massifs. Moreover, two thin-skinned S points are identified corresponding to the allochthonous BCB and St-Jean-de-Luz overlapping rift basins.

3.3 Rift architecture

3.3.1 Rift segments

The restoration of the Pyrenean and Cantabrian rift segments at the end of rifting depicts the same first order architecture (e.g. Roca *et al.*, 2011; Masini *et al.*, 2014; Tugend *et al.*, 2014; Cadenas *et al.*, 2018).

In the Pyrenean segment (eastern Mauléon), the northern part of the Igountze-Mendibelza unit corresponds to the WNW-ESE striking north-dipping Licq detachment fault (or South Mauléon Detachment fault in Masini *et al.*, 2014) (Johnson and Hall, 1989a, 1989b; Masini *et al.*, 2014) over which Albian conglomerates have been deposited (Boirie and Souquet, 1982). This fault belongs to a set of extensional detachment faults that exhumed basinward serpentized mantle rocks underneath the detached supra-salt sedimentary cover (Lagabrielle *et al.*, 2010; Corre *et al.*, 2016) associated with deposition of deep water turbidites within the basin (Souquet *et al.*, 1985; Debros, 1990). The mantle exhumation led to a syn-rift HT/LP metamorphism of the pre- to syn-rift sequence toward the northern margin of the basin (Hart *et al.*, 2017; Lescoutre *et al.*, 2019) associated with magmatism (Genna, 2007). Northward, the south-dipping NPFT extensional fault controlled the northern margin of the basin (south of the Grand Rieu High) and was detached in the decoupling horizon made of evaporites.

In the BCB, the basement-sediment interface is hidden by a thick Mesozoic to Cenozoic sedimentary cover. However, and similarly to the Pyrenean segment, the tectono-stratigraphic reconstructions suggest north-dipping detachment faults (SPFT) that exhumed lower crustal levels and serpentized mantle rocks (Roca *et al.*, 2011; Carola *et al.*, 2013). Hydrothermal mineralisations (Cuevas and Tubía, 1999) and high vitrinite reflectance values (6–7%VR; Robert, 1971) have been described in the Lower Cretaceous sediments of the northern Bilbao anticline, suggesting that syn-rift HT/LP metamorphism also occurred in the BCB. Moreover, syn- to post-rift volcanism has been described in the Biscay synclorium (Azambre and Rossy, 1976; Castañares *et al.*, 2001). The dense and magnetic body defined in the central BCB could represent such underplated magmatic rocks (Aller and Zeyen, 1996; Casas *et al.*, 1997; Pedreira *et al.*, 2007).

All these observations suggest an asymmetry of the rift system, with a lower plate setting on the southern margin and an upper plate on the northern margin limited by north-dipping detachment faults in both the BCB and Mauléon basin. In both basins, the pre- to syn-rift sedimentary cover has been detached from the underlying basement along the Upper Triassic evaporite horizon.

3.3.2 Rift segment boundary

The eastern BCB (southern branch) architecture is similar to the BCB rift segment described above with the north-dipping SPFT detachment fault and mantle exhumation.

However, the hyperthinned domain appears to be wider, eventually taking over the large exhumed mantle domain suggested in the central segment. This exhumed mantle domain is overlain by the Nappe des Marbres unit (Lamare, 1936; Martínez-Torres, 1992), forming the hangingwall of the Leiza fault that is detached in the Upper Triassic evaporites (Mendia and Iburguchi, 1991; Mathey *et al.*, 1999). The northern margin of the basin corresponds to the present-day location of the Ollin thrust (Figs. 1 and 3; Bodego *et al.*, 2015), which is an E-W striking structure located on the southern border of the Basque massifs. The BCB propagated and narrowed eastward (*i.e.* the western Jaca-Pamplona basin; Lescoutre, 2019) as suggested by the thinning of the syn-rift sequence (Astrain-1 borehole; Instituto Geológico y Minero de España (IGME), 1990) and the apparent absence of syn-rift metamorphism (Robert, 1971). The Cantabrian segment probably wedged out south of the Roncesvalles fault as suggested by the deposition of shallow water sandstones, conglomerates and marls attributed to the Cenomanian over the Oroz-Betelu massif (Ciry *et al.*, 1963).

The Late Albian to Cenomanian St-Jean-de-Luz basin probably underwent less extension as suggested by the 2000 m thick syn-rift succession (Razin, 1989) that is significantly thinner than that in the main depocenter of the Mauléon basin that can be up to 4 km (Masini *et al.*, 2014; Vacherat *et al.*, 2014) and the very low-grade syn-rift metamorphism. The geometry of the basin can be defined by the E-W striking Amotz fault on the southern border of the basin, whilst the geometry of the northern border could roughly correspond to the present-day orientation of the reactivated WSW-ENE striking Ste-Barbe back-thrust, as suggested by Razin (1989). This basin was fed by siliciclastic sediments derived from the south and the west (Razin, 1989), suggesting that the basin terminated north-west of the Basque massifs. This suggests a V-shape, westward termination of the Mauléon basin.

3.4 Time constraints on the contractional deformation

The timing of the contractional deformation is difficult to assess in the north-western Pyrenees due to ill-recorded syn-orogenic sediments. Field evidence for inversion is provided by the Lower Eocene flysch sediments (Hecho Group) associated with the Gavarnie and Guarga thrusts (Labaume *et al.*, 1985; Teixell, 1996). Cooling ages measured on this imbricate thrust system yield a Late Eocene to Miocene age of exhumation (Fitzgerald *et al.*, 1999; Bosch *et al.*, 2016), coeval with the main subsidence episode recorded in the southern Aquitaine basin (Desegaulx and Brunet, 1990). The timing of fault activity along the Lakora thrust is ill-constrained (Teixell, 1990, 1996) but could have initiated already in the Late Cretaceous, as suggested by the flexure of the Upper Cretaceous Carbonate platform in the footwall of the thrust (Teixell, 1996; Teixell *et al.*, 2016). Note that in the Central-Eastern Pyrenees, Mouthereau *et al.* (2014 and references therein) identified the initiation of reactivation at 70–75 Ma in the North Pyrenean basins based on inverse modelling of AFT data, with a rapid exhumation of the Palaeozoic massifs from 50 Ma onward. More recently, Grool *et al.* (2018) suggested a Late Santonian-Early Campanian age for the first phase of deformation along the NPFT in the same area, while the onset of contractional deformation in the Southern Central Pyrenees

has been clearly defined as Late Santonian (Nagtegaal, 1972; Boillot and Capdevila, 1977; Bond and McClay, 1995; Mencos *et al.*, 2015; Tavani *et al.*, 2017).

Similar to the Western Pyrenees, the timing of deformation is ill-constrained in the BCB (*e.g.* Camara, 1997; Gómez *et al.*, 2002). Syn-tectonic conglomerates along the SPBT suggest that this thrust was active at least from Oligocene onwards (Portero *et al.*, 1979; Carola *et al.*, 2013). Analysis of the tectonic subsidence on the Landes High suggests that the major subsidence on the northern margin of the basin occurred during the Early to Late Eocene (Gómez *et al.*, 2002), probably related with the NPFT.

In the northern branch (Pyrenean segment), the NPFT initiated at mid-Eocene according to Razin (1989) based on the age of the first syn-folding sediments in the Aquitaine basin. Late Eocene to Early Miocene ages have been defined based on seismic interpretation for a thrust fault attributed to the NPFT in the offshore Bay of Biscay (Ferrer *et al.*, 2008). Fission track analyses on apatite and zircons on the Ursuya massif (north Basque massifs) yield ages at 48.3 Ma and 81.8 Ma respectively (Vacherat *et al.*, 2014), suggesting exhumation between Late Cretaceous to Eocene. Note that the Eocene cooling ages are common throughout the Pyrenean and Cantabrian systems (*e.g.* Fitzgerald *et al.*, 1999; Jolivet *et al.*, 2007; Vacherat *et al.*, 2014; Bosch *et al.*, 2016; DeFelipe *et al.*, 2019). Additional thermochronological data from the Cinco Villas and Aldudes massifs suggest that the exhumation of these massifs may have occurred already from the Early Paleocene (60 Ma) to present with a more rapid exhumation from Eocene onward (DeFelipe *et al.*, 2019).

In the southern branch (Cantabrian segment), the age of the SPBT could be similar to the Cantabrian rift segment (*i.e.* Oligocene or older; Carola *et al.*, 2013) while thermochronological data on a sample located along the Leiza fault suggests rapid cooling prior to 40 Ma (DeFelipe *et al.*, 2019). To the east, the Roncesvalles thrust fault brings the Santonian limestones over the late Upper Cretaceous mudstones in which it seems to vanish, probably sealed by the Paleocene sediments (Del Valle *et al.*, 1972). This suggests that the Roncesvalles fault could be Late Cretaceous in age and thus potentially coeval to the E-W striking Lakora thrust located in its eastern prolongation.

It results that the Eocene to Miocene collisional episode is very well dated throughout the Palaeozoic massifs, both from syn-orogenic sediments and thermochronological data. However, convergence already initiated at Late Santonian to Early Campanian in the Pyrenees as attested by plate kinematic considerations (Macchiavelli *et al.*, 2017) and geological/thermochronological records from the Central Eastern Pyrenees and South Central Pyrenees, but it is hardly recognized in the Western Pyrenees and beyond. This suggests that the initial stage of underthrusting of the hyperextended crust may correspond to a phase that is difficult to recognize within orogens. Reasons may be that the lithosphere may not be thermally equilibrated at the onset of convergence (*e.g.* Vacherat *et al.*, 2014) and as a consequence, the use of isostasy and/or thermochronology to date onset of convergence is difficult. Moreover, this initial stage is likely to be overprinted by later stage structures. From the Central Western Pyrenees to the BCB, the underthrusting/subduction stage seems to be best recorded in the Basque massifs by thermochronological data

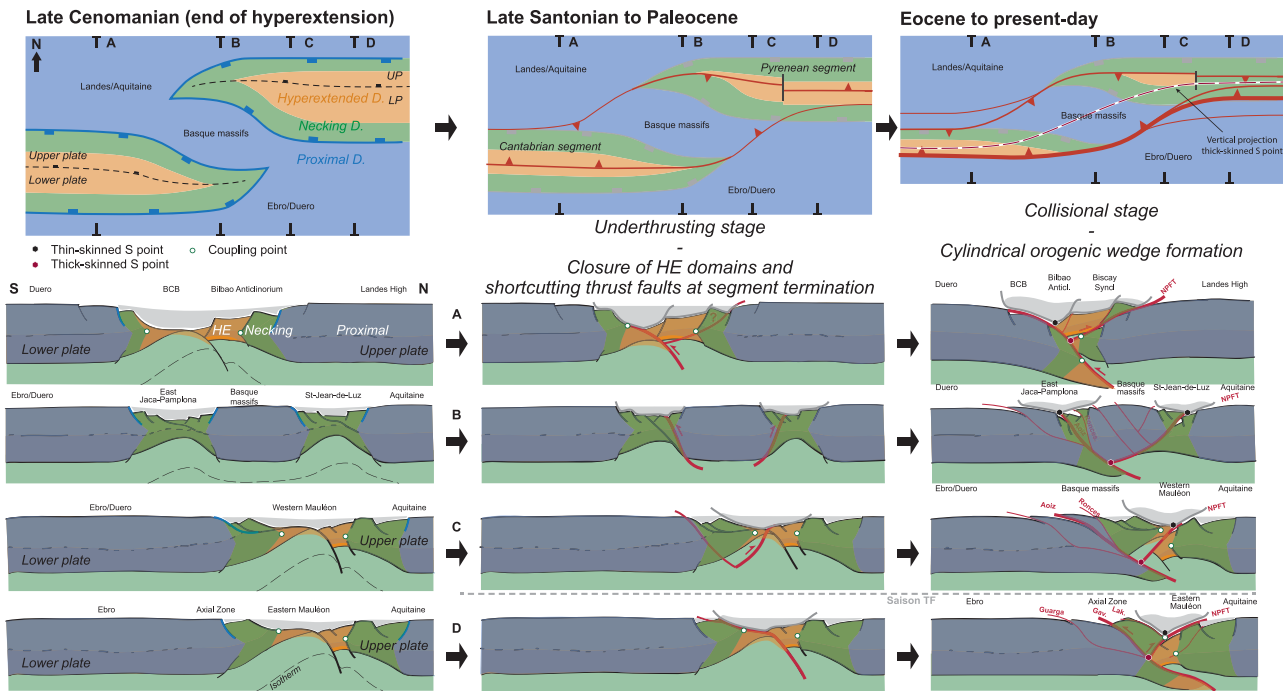


Fig. 4. Schematic evolution of the Pyrenean-Cantabrian system from Late Cenomanian to present-day. Note that maps do not represent the sedimentary infill but show the crustal rift domain distribution. Note in particular the variation in the style of deformation on both sides of the Saison TF between sections C and D, in relation with the early proto-wedge at rift segment boundary. Description of the figure is provided in the text.

(DeFelipe *et al.*, 2019) and along the Roncesvalles fault, *i.e.* at the termination of rift segments, which may, as discussed below, be related to the reactivation history of the segment boundary.

4 Discussion

4.1 Role of rift-inheritance at the Pyrenean-Cantabrian junction

4.1.1 Structural evolution and implications for the present-day architecture

In the following, we will refer to the **Figures 4** and **5** to depict the structural evolution at the Pyrenean-Cantabrian junction from the initiation of reactivation to the present-day situation. For convenience, the Landes High, Grand Rieu High and Aquitaine will be referred to the Eurasian plate in the following, whilst the Ebro and Duero will be referred to the Iberian plate.

4.1.1.1 Underthrusting stage

In the Pyrenean and Cantabrian segments, the hyperextended domains from the Iberian plate were underthrust below the Eurasian plate from the Late Santonian to the Early Eocene. Meanwhile, the thin-skinned Licq, Leiza, SPFT and NPFT as well as intra-basin folding likely accommodated the shortening of the supra-salt sedimentary cover (**Figs. 4** and **5**; Mouthereau *et al.*, 2014; Grool *et al.*, 2018).

At the segment boundaries corresponding to the V-shaped terminations, besides the evaporite decoupling horizon, there

was no inherited weak structure (*e.g.* serpentinized level) available to be reactivated. As such, new structures had to develop in order to accommodate the shortening in these domains. In the northern branch of the overlapping rift system, the north-vergent WNW-ESE striking NPFT transferred the deformation from the western termination of the Pyrenean segment to the Cantabrian segment, whilst in the southern branch, the south-vergent E-W striking Roncesvalles thrust transferred the deformation between the eastern termination of the Cantabrian segment to the Pyrenean segment (**Figs. 4** and **5**). Based on the geographic link and the similarities between the basement-involved Roncesvalles and Lakora thrusts, *i.e.* the E-W orientation and syn-underthrusting stage activity, we propose that the Lakora thrust might represent the eastward prolongation of the shortcutting Roncesvalles thrust. Note that the formation of new thrust faults that shortcut external domains to connect offset rift structures has been described in analogue sandbox models of transfer zones by Konstantinovskaya *et al.* (2007) and Granado *et al.* (2017).

At this segment boundary, and in contrast to the rift segments, the Eurasian plate underthrust the Basque massifs and the dip of the underthrust is in opposite direction between the eastern Mauléon basin (rift segment) and the western Mauléon basin (segment boundary) (**Fig. 4**). As a consequence, in the eastern Mauléon segment, the former lower plate (Iberia) underthrust the upper plate (Eurasia), whereas in the western Mauléon the lower plate (Basque massifs/Iberia) and its subcontinental mantle overrode the upper plate (Eurasia). This structural evolution allowed to emplace the subcontinental mantle at a crustal level (**Fig. 4**, cross-section C) such as

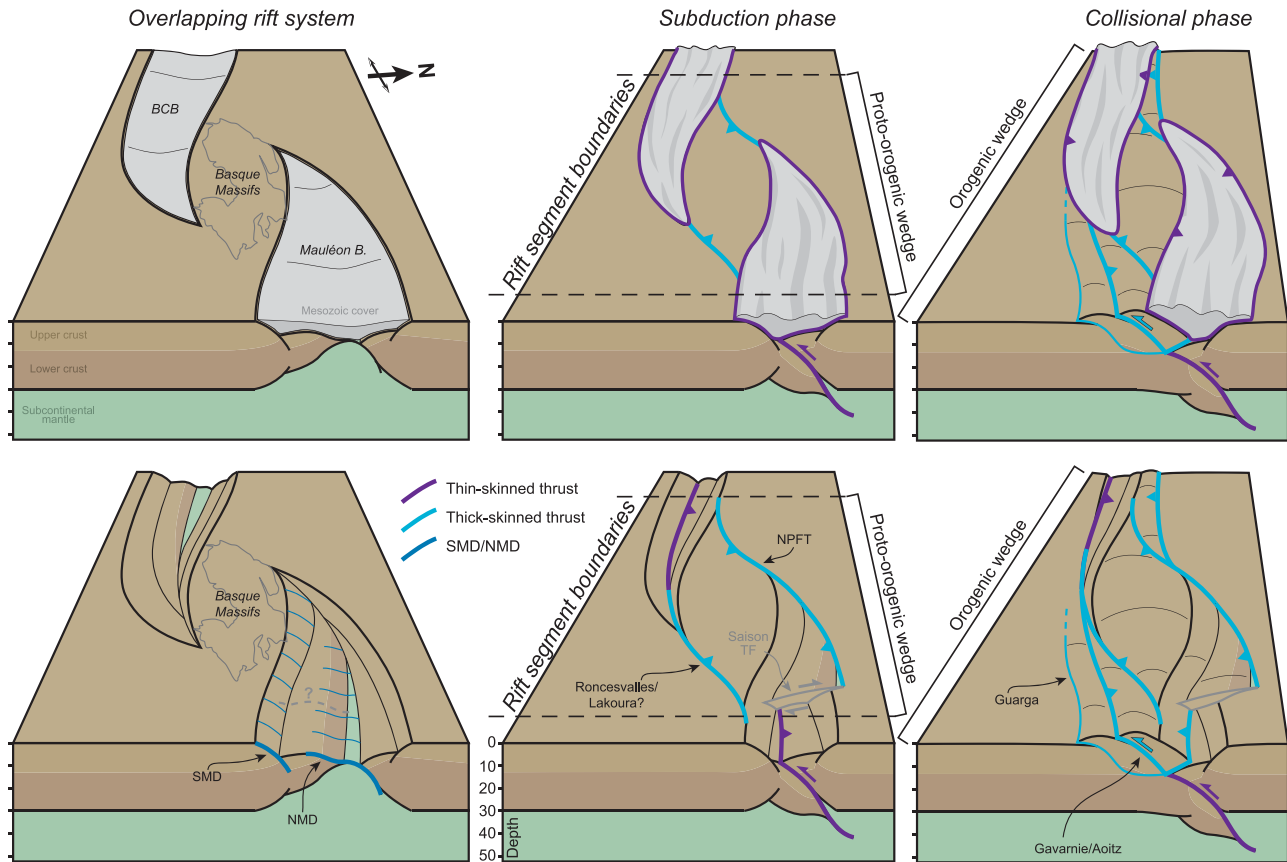


Fig. 5. Schematic 3D evolution of the Pyrenean-Cantabrian junction highlighting the structural evolution during the subduction (Late Santonian – Paleocene) and collisional (Eocene – Miocene) phases. The uppermost 3D block diagrams show the evolution with the decoupled sedimentary basins while the lowermost show the crustal architecture only. Saison TF: Saison Transfer Fault; SMD; South Mauléon Detachment; NMD: North Mauléon Detachment.

observed in seismic refraction profiles and on gravity anomaly maps from the western Mauléon basin (Casas *et al.*, 1997; Wang *et al.*, 2016). Moreover, it allowed to keep the hyperextended basement of the western Mauléon basin (Masini *et al.*, 2014) and related pre-Alpine features (e.g. South and North Mauléon detachments, Bidarray Permian basin) in a pop-up structure similar to an orogenic wedge throughout the convergence. This change in tectonic style probably occurred across the NNE-SSW striking Saison transfer fault (Fig. 5; Le Pochat *et al.*, 1976; Masini *et al.*, 2014).

These observations suggest that this initial stage of reactivation was mainly controlled by rift-inheritance within rift segments (Jammes *et al.*, 2009; Lagabrielle *et al.*, 2010; Roca *et al.*, 2011; Tugend *et al.*, 2014; Quintana *et al.*, 2015; Teixell *et al.*, 2016) whereas new structures formed at segment boundaries by shortcutting the area, initiating a proto-crustal wedge at the location of the Basque massifs (Fig. 5) where the onset of exhumation may have initiated as early as Late Cretaceous. These new structures involved thick-skinned deformation of the necking and proximal domains at the termination of rift segment. Since such zones can preserve embryonic stages of convergence, they represent critical domains to date the initiation of reactivation.

4.1.1.2 Collisional stage

The collisional stage corresponds to the thickening of the crust at Eocene time related to the development of thick-skinned thrusts such as the imbricated north-dipping Gavarnie and Guarga thrusts (Figs. 4 and 5) and associated with an episode of subsidence of the southern Eurasian plate. This stage corresponds to the collision of the conjugate necking domains that initiated when the coupling points intersected. It was also synchronous with the onset of the formation of the orogenic wedge (Sinclair *et al.*, 2005; Mouthereau *et al.*, 2014), whose pro- and retro-wedge structures correspond to the Gavarnie fault and NPFT respectively. The wedge is formed by the former upper crust of the necking domain. Note that the related S point will migrate through time due to the progressive indentation of the Eurasian crust at a mid-crustal level (*i.e.* ductile-brittle transition) within the Iberian crust (Fig. 4). At depth, the former hyperextended domain and the lower crust of the necking domain of the Iberian plate formed the underthrusting slab. In the Cantabrian segment, the thick-skinned deformation is controlled by the NPFT and SPFT and the orogenic wedge is formed by the former hyperextended and necking domains of the Eurasian plate. The underthrusting slab is formed by the hyperextended and necking domains of the Iberian plate.

Towards the segment boundaries, the entire Basque massifs form an orogenic wedge bounded by the Aoiz fault (pro-wedge) and the NPFT (retro-wedge) and the underthrusting slab is composed of the necking to proximal domains of the Iberian plate. The Aoiz thrust could correspond to the westward continuation of the Gavarnie thrust. As such, the width of the crustal wedge is increasing at the segment boundary, defined by the distance between the overlapping rift systems (Figs. 3 and 5).

Our study shows that, despite a complex inherited structural pattern during the initiation of reactivation, a unique orogenic wedge formed ultimately on top of a north-dipping underthrusting/subducting slab from the central Pyrenean segment to the eastern Cantabrian segment (Chevrot *et al.*, 2018; Teixell *et al.*, 2018). These observations reveal a cylindrical of the first order architecture from the Western Pyrenean to Cantabrian segments once the collisional stage began (Fig. 5).

4.1.2 Role of structural and thermal inheritance at segment boundaries

The mid-Cretaceous rift structural inheritance has shown to control both the location and the evolution of the contractional deformation in the Pyrenean and Cantabrian rift segments. Toward rift segment boundaries, structural anomalies such as shallow mantle emplacement and preservation of pre-Alpine structures have been described (Jammes *et al.*, 2009; Masini *et al.*, 2014; Wang *et al.*, 2016). Moreover, we identify an along-strike change of the main underthrust dip direction during the initiation of reactivation related to segmentation. This structural change cannot be easily explained by reactivation of former rift structures as it did not reactivate the north-dipping detachments associated with mantle exhumation (*e.g.* North Mauléon Detachment). One can partly argue with the deformation associated with soft transfer zones. In the latter, Konstantinovskaya *et al.* (2007) showed that during tectonic inversion, new thrusts can emerge between shifted reactivated extensional faults in the transfer zone. However, to our knowledge, the tectonic inversion has not been tested for overlapping rift systems in which extensional faults of opposite dip direction could complexify the reactivation pattern. Besides the structural control, one can suggest that the thermal state related to hyperextension and not yet equilibrated at the onset of convergence (Vacherat *et al.*, 2014) could have had a role on the reactivation of this system (*e.g.* Jourdon *et al.*, 2019 for 2D implications). Indeed, the thermal inheritance involved by the two overlapping, thinned lithospheres might influence the reactivation at the junction between rift segments. However, in order to make prediction on the control of the thermal structure at onset of convergence, 3D thermo-mechanical models are needed.

4.2 Implications for the reactivation of hyperextended rift systems

4.2.1 Role of 3D rift-inheritance for the 2D architecture of orogenic systems

The Pyrenean-Cantabrian case study shows that the dip evolution and architecture of reactivated hyperextended rift

systems are strongly controlled by 3D rift-inheritance. Rift structures might be preserved whilst new structures might form in order to accommodate along-strike complexities. Dealing with 2D balanced cross-sections in these areas without considering the lateral evolution may lead to unpredicted reactivation patterns. In particular, sampling of mantle or lower crustal rocks in orogenic systems might be favoured by along-strike structural reorganisation related to segment boundaries as suggested in this study (Fig. 4).

Present-day analogues showing substantial along-strike rift segmentation have been recognized worldwide (Orphan: Skogseid, 2010; East African rift system: Corti, 2012; Australia: Belgarde *et al.*, 2015; Central Atlantic: Péron-Pinvidic *et al.*, 2017). Yet, only few studies working on orogenic systems have considered the role of rift segmentation to account for the orogenic architecture (*e.g.* Beauchamp, 2004; Thomas, 2006; Roca *et al.*, 2011; Likerman *et al.*, 2013; Granado *et al.*, 2016, 2017).

We believe that further studies are needed to better investigate the role and importance of rift-inheritance (structural, compositional and thermal) associated to rift segment boundaries (transfer fault, overlapping rift systems) in controlling the 3D architecture of orogenic systems.

4.2.2 Relative control of inheritance on the contractional deformation through time

Our study shows that during the first stage of rift inversion (*i.e.* closure of hyperextended domains) rift segment evolution is controlled by the reactivation of the hyperextended domain, *i.e.* oceanward of the coupling point, where the crust and upper mantle deformation is governed by brittle rheology. The decoupling levels at this stage correspond to zones with strong lithological contrast, *e.g.* serpentized mantle (Fig. 2; Péron-Pinvidic *et al.*, 2008). However, once conjugate necking domains collide, *i.e.* when coupling points overlap, ductile rheology is implemented to the system and the upper crust and mantle are decoupled in the ductile lower crust. At this stage, it has been shown that the orogenic evolution of accretionary wedges can be predicted by the classical Coulomb wedge theory (Davis *et al.*, 1983). As such, new contractional structures may form in the brittle crust and detach in the ductile middle and/or lower crust as proposed by authors in the Pyrenees (*e.g.* Muñoz, 1992; Teixell *et al.*, 2016). While we do not pretend that inheritance does, at this stage, not anymore influence the architecture and the structural evolution (*e.g.* in the Pyrenees: Martinez *et al.*, 1989; Saura and Teixell, 2006), we suggest that once thick, partly ductile crust is implemented in the orogen, the overall first order architecture becomes mainly controlled by the mechanics controlling the formation of accretionary wedges. This suggests that, on a first order, two main processes can be distinguished during contractional deformation: a first “subduction” stage, which is mostly controlled by rift-inheritance, and a second “collisional” stage mainly governed by the Coulomb wedge theory.

Interestingly, this correlation between inheritance and coupled/decoupled structural evolution is opposite to that described during extension. Indeed, during rifting the formation of the proximal and necking domains have been shown to be mainly controlled by pre-rift inheritance, whereas the formation of the hyperextended and oceanic domains

represent new real estate domains that are mostly controlled by large-scale rift-induced processes such as hydration/serpentinization and magmatic processes (Manatschal *et al.*, 2015).

5 Conclusion

The aim of our study was to investigate the reactivation of segmented hyperextended rift systems based on the Pyrenean-Cantabrian example. Based on restored cross-sections and an updated map of the rift domains, we identified reactivated or newly formed orogenic structures and their relative timing in order to characterize the reactivation of the overlapped Pyrenean and Cantabrian rift basins.

We showed that reactivation can be divided in two phases controlled by rift inheritance in rift segments, the underthrusting/subduction phase and the collisional phase. On the one hand, the hyperextended domain is underthrust during the Santonian to Late Paleocene, reactivating extensional detachment faults, locally flooring exhumed serpentinized mantle. Supra-salt rift basins are inverted *via* the reactivation of the evaporite decoupling horizon. On the other hand, when conjugate necking domains meet, the contraction is mostly governed by thick-skinned deformation as testified by the formation of the Eocene to Miocene Gavarnie and Guarga thrusts. This phase is responsible for the formation of an orogenic wedge in between the Eurasian (Landes) and Iberian (Ebro) plates.

This evolution is complexified at rift segment boundaries, *i.e.* where the Pyrenean and Cantabrian rift segments overlapped (Basque massifs area). At the tip of V-shaped basins, the lack of hyperextended domains and therefore weak decoupling levels (*e.g.* serpentinized levels) impeded reactivation to proceed. As such, new, shortcutting structures such as the NPFT and Roncesvalles faults were created in order to transfer the deformation to rift segments. These thick-skinned NPFT and Roncesvalles thrust faults led to the formation of a precursor orogenic wedge at the rift junction that corresponds to the Basque massifs. At this stage, we suggest that the E-W striking basement-involved thin-skinned Lakora thrust might represent the eastern continuation of the shortcutting Roncesvalles thrust. Moreover, we propose that this precursor pop-up structure (orogenic wedge) is responsible for the preservation of pre-Alpine structures and the emplacement of subcontinental mantle rocks at a crustal level at the southern margin of the western Mauléon basin (north-western Basque massifs).

The final architecture results in a continuous E-W striking orogenic wedge overlaying a north-dipping underthrust/subducted slab from the Pyrenean segment to the Santander transfer zone in the Cantabrian segment. This study highlights a first contractional phase dominated by rift-inheritance, followed by a second collisional phase which seems mainly controlled by the Coulomb wedge theory and where inheritance may result in local complexities in relation with rift basin inversion.

Acknowledgments. This study was funded by the Orogen project, a tripartite joint academic-industry research program between the CNRS, BRGM, and Total R&D Frontier Exploration program. We thank the reviewers Gabriela Fernández-Viejo and Pablo Granado for their constructive

comments that helped to improve the manuscript as well as the Associate Guest Editor Stefano Tavani and the Guest Editor Olivier Lacombe for handling the manuscript.

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Cite this article as: Lescoutre R, Manatschal G. 2020. Role of rift-inheritance and segmentation for orogenic evolution: example from the Pyrenean-Cantabrian system, *BSGF - Earth Sciences Bulletin* 191: 18.