Received: 18 July 2020 | Revised: 18 July 2021 | Accepted: 22 July 2021

DOI: 10.1111/bre.12595

RESEARCH ARTICLE

Basin Research EAGE WILEY

Reactivation of a hyperextended rift system: The Basque–Cantabrian Pyrenees case

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Funding information
OROGEN Project

Abstract

This contribution investigates the role of a hyperextended rift system in the formation of the Basque–Cantabrian Pyrenees by discussing their present-day architecture as well as the inherited rift template. Moreover, this work attempts to decipher the onset of reactivation of a hyperextended system and to discuss the related processes during collision. To carry out this study, two regional, crustal-scale cross-sections are presented that provide geological and geophysical information and interpretations across the Central and Western Basque–Cantabrian Pyrenees. Moreover, the two sections are restored back to the Cenomanian and Barremian, corresponding to the end of two independent rift stages respectively. The two sections document different structural styles observed along the orogenic belt. The Central section, involving the Iberian and European plates, shows a thin-skinned structural style, where the Upper Triassic salt acted as a decoupling level between the sedimentary cover and the underlying basement during both extension and reactivation. The Western section, by contrast, crosses only the Iberian plate (i.e., intra-plate section) and displays a hybrid situation showing both thin- and thick-skinned structural styles that were conditioned by the irregular distribution of Triassic salt. Extensional deformation was localised in the north (i.e., Bay of Biscay) and less important in the south. Despite compressional reactivation, the northern part of the Western section preserves its rift template, which provides key insights to restore the internal part of the Central section. In contrast to the Western section, the Central section shows stacked depocenters, resulting from overprinted Mesozoic rift events that had a first order control on the subsequent reactivation. This study corroborates the importance of rift inheritance during the onset of convergence by reactivating the most distal and weak part of the rift system (i.e., serpentinised mantle) before starting the collision phase. A key learning is that the understanding of the nature and distribution of decoupling levels at a crustal scale is fundamental to reconstruct the structural evolution during the formation and reactivation of a hyperextended rift system.

KEYWORDS

Basque–Cantabrian Pyrenees, hyperextended rift system, multistage, polyphase, reactivation, rift-inheritance, thin- versus thick-skin

1 | INTRODUCTION

The Pyrenean orogenic system has been used by the Earth Science community for decades as a natural laboratory to study fold and thrust belts and more recently also to investigate the reactivation of rift systems. This is mainly thanks to the dense available data sets including geological, geophysical and geochemical data (Carola et al., 2015; Chevrot et al., 2015; Choukroune & ECORS Team, 1989; Díaz et al., 2012; Fernández-Viejo et al., 2000; Fillon et al., 2016; Pedreira et al., 2003, 2007; Pous et al., 1995; Roca et al., 2011; Ruiz et al., 2017; Teixell et al., 2018; Wehr et al., 2018; among many others), as well as the good outcrop conditions and easy accessibility. Ground-breaking studies focussed on orogenic processes at the Pyrenees sensu *stricto* (Pyrenees s.s.), where the archetypal orogenic architecture of the fold and thrust belt has been defined (e.g., Beaumont et al., 2000; Campanyà et al., 2012, 2018; Chevrot et al., 2018; Choukroune & ECORS Team, 1989; Mouthereau et al., 2014; Muñoz, 1992; Muñoz et al., 2018; Teixell et al., 2016). Other studies addressed the orogenic architecture of the westward continuation of the Pyrenean belt to the Basque–Cantabrian Pyrenees (e.g., García-Senz et al., 2019; Pedreira et al., 2003, 2007; Pedrera et al., 2017; Quintana et al., 2015) and to the Asturian Massif, also referred to as the Cantabrian Mountains in the literature (e.g., Alonso et al., 1996, 2007; Pulgar et al., 1996, 1999) (Figure 1). More recent research, however, has focussed on the rift evolution preceding the Alpine orogeny and the inversion mechanisms (e.g. DeFelipe et al., 2017, 2018; Ducoux et al., 2019; Gómez-Romeu et al., 2019; Jammes et al., 2009; Lescoutre, 2019; Pedreira et al., 2015; Pedrera et al., 2017; Tugend et al., 2014).

The Basque–Cantabrian Pyrenees have been historically referred to as the Basque–Cantabrian Basin or Basque–Cantabrian Zone (see Miró et al., 2020 for a revision of terminology). Here we use the term Basque–Cantabrian Basin to refer to the Mesozoic extensional basin that was subsequently inverted and incorporated into the Basque–Cantabrian Pyrenees, which also involve other basins such as the Miranda-Villarcayo Paleogene-Neogene piggy-back basin. The area has been intensively explored for hydrocarbon purposes from the 60s to the 90s, leading to the acquisition of a vast amount of commercial seismic reflection profiles and drill hole data. This provides a valuable field example to study the evolution of a hyperextended rift system and the role of rift inheritance during the contractional reactivation and incorporation of a passive margin/rift system into an orogenic belt (Masini et al., 2014; Mohn et al., 2012; Teixell et al., 2018; Tugend et al., 2014, 2015; Vergés & García-Senz, 2001). However, many questions remain concerning the role of the Mesozoic rift template during the Alpine reactivation leading to the formation of the Basque–Cantabrian Pyrenees. Key questions relate to the nature and distribution of decoupling levels and buttresses inherited from rifting processes and their exerted control on the temporal and spatial evolution of deformation during reactivation.

Highlights

- The Basque–Cantabrian Pyrenees as a natural laboratory to investigate hyperextended rift systems.
- The importance of inheritance for the rift evolution and subsequent contractional reactivation.
- Mechanisms of initial reactivation of rift systems.

Previous studies show geological cross-sections across the central part of the studied area to explain the evolution and architecture of the Basque–Cantabrian Pyrenees (e.g., Pedrera et al., 2017, 2021; Quintana et al., 2015). In this work, we present a reinterpreted Central section integrating new and existing geological and geophysical data. Moreover, we introduce a new section across the western termination of the Basque–Cantabrian Pyrenees in order to analyse the along strike structural variability. Such variability will enable to characterise and discuss the multistage Mesozoic rift evolution of the area (see below for the definition of a multistage rift system) and its reactivation and incorporation into the Pyrenean orogen. The aim of the study is therefore twofold: (a) at a regional scale, to propose a new interpretation for the development of the Basque–Cantabrian Pyrenees, deciphering their present-day architecture but also the Mesozoic rift template, and (b) in a more generic sense, to decipher the role of the rift template and the extensional decoupling levels during the contractional reactivation.

1.1 | From rift basins to rift systems: Concepts and terminology

The Basque–Cantabrian Basin has been explained by using three different models of rift basins (Figure 2a): (a) a strike

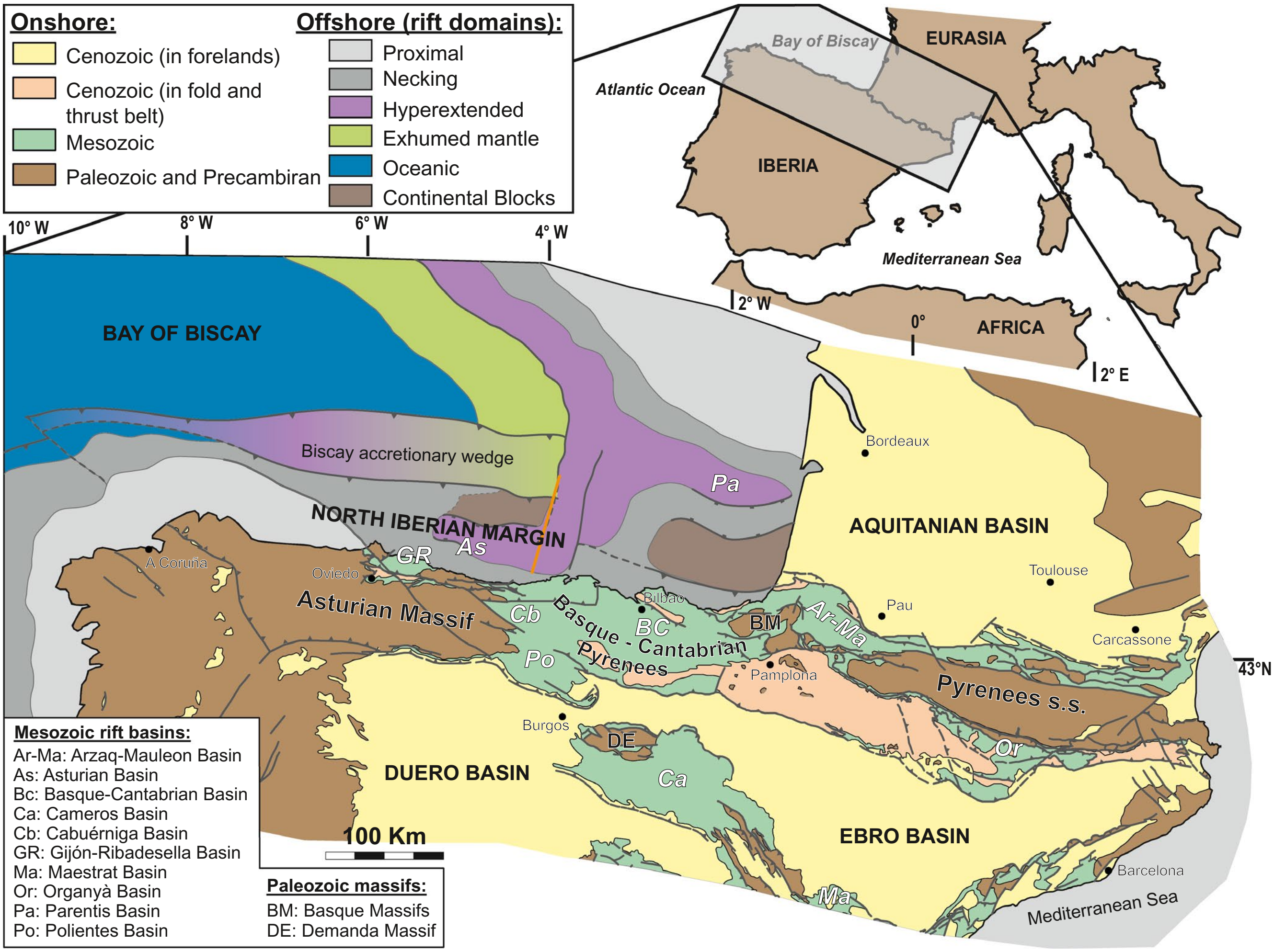

FIGURE 1 Structural map of the Pyrenean orogen and surrounding areas with the main terminology used in this work (modified from Carola et al., 2013). The offshore geology shows the rift domain mapping (from Cadenas et al., 2018; Tugend et al., 2014). Mesozoic rift basins are labelled in white and the orange line shows the position of the CS-146 section modified in this work

slip transtensional basin model (Garcia-Mondejar et al., 1989; García-Mondéjar et al., 1996), (b) a classical low-ß extensional basin model (Cámara, 2017; Quintana, 2012; Quintana et al., 2015), or (c) a hyperextension, high-ß extensional basin model overprinting initial low-ß extensional basins (García-Senz et al., 2019; Pedrera et al., 2017, 2021). In this work, we study rift basins preserved within the Basque–Cantabrian Pyrenees by integrating recent concepts on rifted margins that explain the formation and architecture of multi-stage and polyphase rift systems (Cadenas et al., 2020; Sutra et al., 2013; Tugend et al., 2014).

A recent study of rifting processes and related rift templates has been developed by Cadenas et al. (2020) along the North Iberian margin/southern Bay of Biscay defined three rift systems, showing a characteristic crustal structure and basin architecture, which resulted from three successive rift events:

- A first event is linked to low-ß, classical extensional rift basins, such as the Triassic Gijón–Ribadesella rift system (Figure 1) (Cadenas et al., 2020) that are bounded by listric extensional faults controlling the creation of accommodation space (Figure 2a). The syn-tectonic sequence usually thickens towards the bounding fault with the main depocenter remaining near the major fault. The hanging wall typically forms rollover anticlines, while the footwall experiences a flexural response generating some relief. The pre-rift sequence is preserved at both hanging wall and footwall. Crustal thinning related to such classical extensional structures is minor at a margin scale and ß factors are typically <1.5.
- A second transtensional event is interpreted to form basins related to strike slip faults. An example is the narrow, deep, Late Jurassic-Barremian Asturian Basin (Figure 1) (Cadenas et al., 2020), which is limited by high-angle normal faults.
- A third Aptian to Cenomanian event includes hyperextended (high-ß) basins floored by crust thinner than 10 km and/or exhumed mantle (see Tugend et al., 2014 for detailed explanation). In such basins, the footwall is made of exhumed

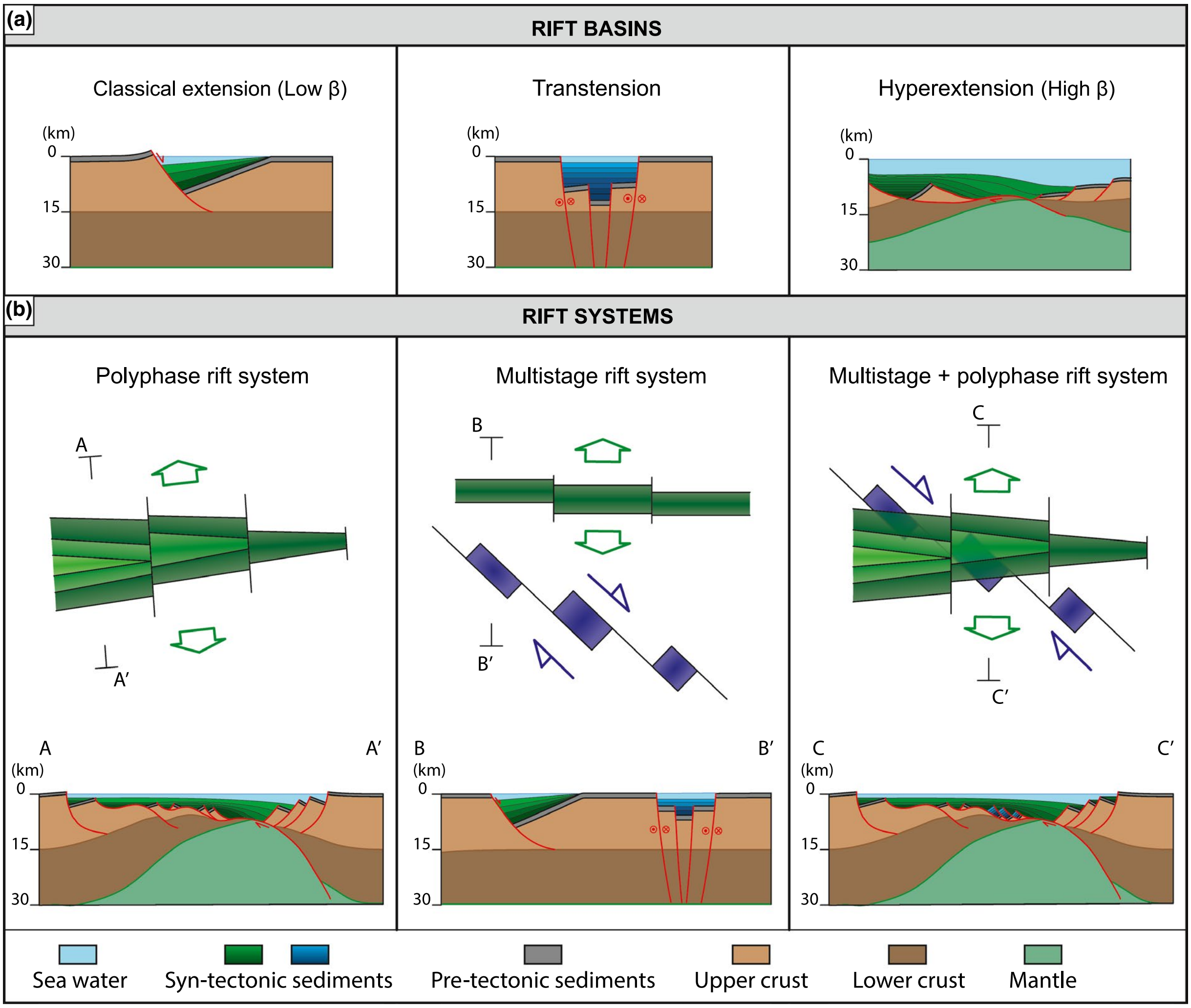

FIGURE 2 (a) Classification of extensional rift basins. (b) Theoretical sketch showing the rift system variability (see the text for further details)

crust or mantle and the hanging wall consists of extensional allochthons and/or syn-tectonic sediments, and the main depocenter is migrating opposite to the sense of exhumation (e.g., Gillard et al., 2015).

In contrast to simple mono-phase rifting models, recent studies have revealed that rift systems evolve through either different phases and/or different stages (Figure 2b). A polyphase rift system as used in this study was defined by Lavier and Manatschal (2006), which has been extensively used by the rifting community. Such system follows an evolution described by different phases, referred to as stretching, thinning, hyperextension, exhumation and seafloor spreading (Péron-Pinvidic & Manatschal, 2009). These phases led to a continuous strain localisation following the same kinematic framework. By contrast, multistage rift systems result from the superposition of distinct rift systems, which develop within different kinematic frameworks (Cadenas et al., 2020). In a multistage rift system, the different rift events can be either mono or polyphase, but most importantly, they can be aborted and overprinted by new rift events. The complexity of multistage rift systems, therefore, is minimal if the overprinting systems are monophase but can become significant if the overprinting systems are polyphase. In such cases, thick, earlier syn-rift sequences may be pre-rift to a later rift stage, creating complexities that are difficult to reconstruct when looking locally without considering the large scale. Thus, recognising and mapping different rift systems as well as defining their maturity may be key to unravel complex rift architectures, such as those observed at present-day in the Basque–Cantabrian Pyrenees.

In this study, we do not consider the Basque–Cantabrian Pyrenees as a single rift basin, but we define and map rift stages, define the kinematics and maturity of each stage and investigate the overprinting of later rift stages relative to previous ones. With the aim to perform a complete analysis of rift systems, we used the approach and terminology introduced and developed by Sutra et al. (2013); Tugend et al. (2014); and Cadenas et al. (2020). We present seismic interpretations of commercial reflection profiles, combined with borehole data, field observations and published geophysical constraints. A complete analysis of rift systems is proposed that can be used in other orogenic belts incorporating passive margin sequences. This approach enabled not only to define the rift template, but also allowed to investigate its role during reactivation.

2 | GEOLOGICAL SETTING

The northern Iberian Peninsula experienced a protracted tectonic evolution that started in the Paleozoic with the Variscan orogeny (Martínez Catalán et al., 2007; Matte, 1991). From Permian to Cretaceous, the tectonic setting changed to a multistage extensional regime related to the opening of the Central and North Atlantic Oceans and the opening of the Bay of Biscay (Roest & Srivastava, 1991; Ziegler, 1988). After the Permian extensional collapse of the Variscan orogen, a Triassic rift event resulted in the development of rift basins surrounding the Paleozoic massifs (López-Gómez et al., 2019). The shallow marine to subaerial facies and thickness distribution of the Triassic succession suggests relatively minor development of accommodation space, compatible with a normal crustal thickness of ca. 30 km. As discussed below, the deposition of salt during the late stages of this Triassic event (i.e., Keuper) and its distribution, had a major control on the subsequent tectonic evolution of the study area (Cámara, 2017, 2020; Carola et al., 2013; Gómez et al., 2007; Gómez-Romeu et al., 2019; Muñoz, 2019). A second Late Jurassic to Early Cretaceous rift event resulted into the formation of NW–SE and W–E trending basins (Cadenas et al., 2020; Tavani et al., 2018) and the development of NW–SE basins aligned along the southern limit of the Ebro Block (e.g., Cameros, Maestrat and Columbrets basins) (Salas et al., 2001). It is important to note that the Late Jurassic–Barremian rift basins used partly the Triassic rift template (López-Gómez et al., 2019). A third Aptian to Middle Cenomanian rift event led to the development of wide, E–W trending basins in the Pyrenean rift system (Jammes et al., 2009; Lescoutre & Manatschal, 2020; Masini et al., 2014; Roca et al., 2011; Tugend et al., 2015).

The Basque-Cantabrian Pyrenees include three Mesozoic depocenters (Figures 1 and 3) referred to as: (a) the Basque–Cantabrian basin to the east, striking in a NW–SE direction for more than 100 km and filled by a more than 12 km thick Upper Jurassic to Middle Cenomanian succession (Brinkmann & Lögters, 1968); (b) the Polientes basin to the south-west, presenting more than 4 km of Upper Jurassic to Middle Cenomanian sediments (García de Cortázar & Pujalte, 1982; Pujalte, 1982) and (c) the Cabuérniga basin to the north-west, including an up to 3 km thick Upper Jurassic to Barremian succession and a thinner Aptian to Albian succession (Pujalte, 1979, 1981). The Cabuérniga basin is bounded to the north by the so-called Santander

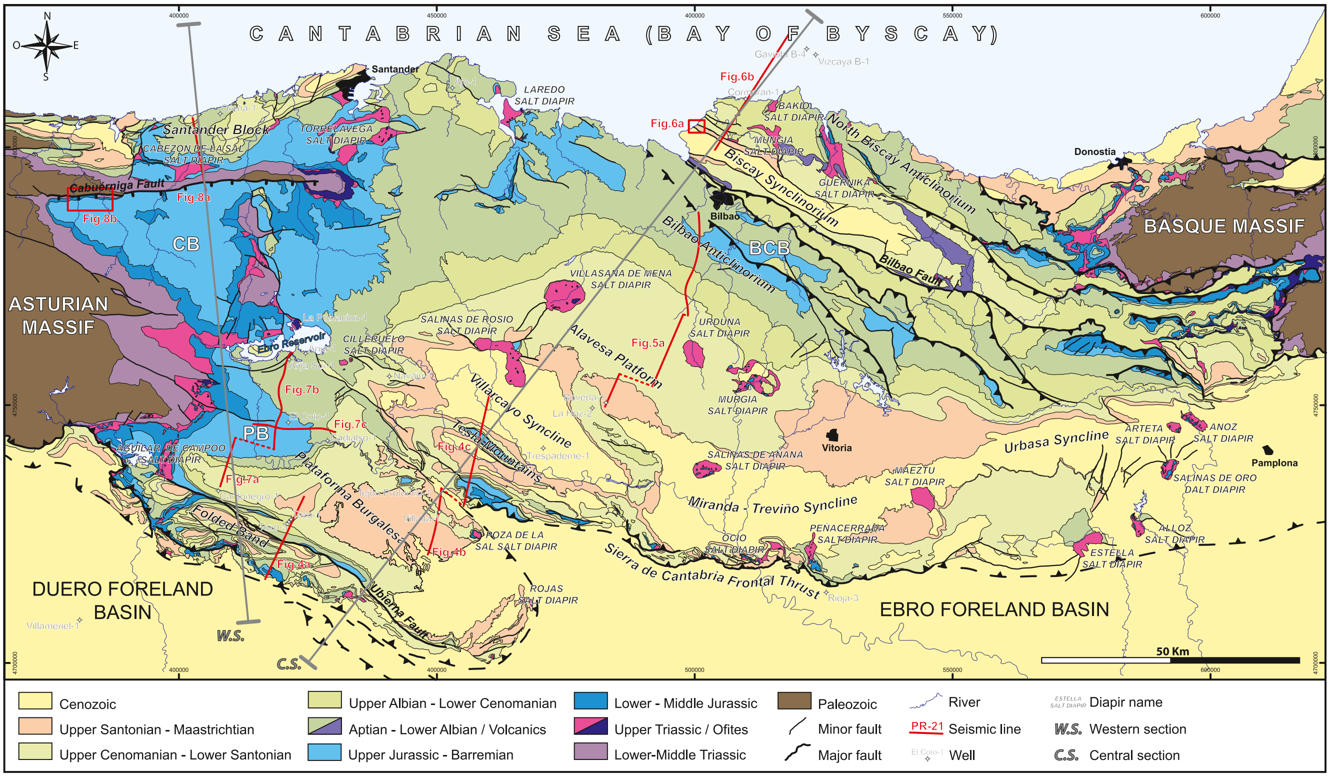

FIGURE 3 Tectono-stratigraphic map of the Basque–Cantabrian Pyrenees and surroundings with the location of the different seismic lines and wells shown in this work as well as the position of the Central and Western sections presented in this study (Figures 11 and 12). BCB, Basque–Cantabrian basin; CB, Cabuérniga basin; PB, Polientes basin

Block (Robles et al., 2014). This block has been interpreted as a basement high during the Mesozoic. The presence of a thin succession of Lower Jurassic to Cenomanian sediments in the eastern part and the lack of Mesozoic sediments in the western sector support this interpretation (García Senz et al., 2019; Pujalte, 1979, 1981). Nevertheless, the southern Cabuérniga basin was limited by the Reinosa/Ebro Reservoir area, which has been also interpreted to represent a structural high between the Cabuérniga and the Polientes basins during Early Cretaceous (Espina, 1996; Pujalte, 1982) but also as a diapiric high (García Mondéjar, 1982; García-Senz et al., 2019).

The lowermost Cretaceous successions in the previous basins are described by Pujalte (1989), Pujalte et al. (1996) and Robles et al. (1996). They consist of fluvio-lacustrine sediments with minor alluvial sediments interbedded. The Aptian–Albian succession is characterised by shallow carbonate platforms in the Cabuérniga basin and surrounding the Basque–Cantabrian basin, with facies changing basinwards to slope and deep marine sediments (García-Mondéjar & Fernández-Mendiola, 1993; García-Mondéjar & Robador, 1987). On the contrary, the Aptian–Albian facies observed in Polientes basin to the south are mainly fluvial. In the Polientes and Cabuérniga basins, the Upper Jurassic to Lower Cretaceous infill progressively thins towards the S, W and NW and unconformably overlies the Lower to Middle Jurassic rocks and the Triassic sediments (García de Cortázar & Pujalte, 1982; Pujalte, 1982). The Paleozoic basement located to the west includes meta-sediments but also limestones and igneous rocks (Robles, 2004; Robles & Pujalte, 2004; Tavani et al., 2013) (Figure 3).

From a structural point of view, Espina (1994), Espina et al. (1996) interpreted a thick-skinned structural style with a N–S extension reactivating previous Variscan faults. Subsequent compression reactivated these structures in the Polientes–Cabuérniga sector. In the Basque–Cantabrian basin, Garcia–Mondéjar (1989), Garcia–Mondéjar et al. (1996) described the tectonic pattern during Middle Cretaceous times arguing for a strike slip evolution, which resulted into a transtensional basin. The most recent and complete studies addressing the entire Basque–Cantabrian Pyrenees have been from Cámara (2017), Garcia-Senz et al. (2019), Pedrera et al. (2017, 2021) and Quintana et al. (2015). These studies developed a complete tectono-stratigraphic description of the evolution for the area with interpretations that are, in particular in the case of Pedrera et al. (2021), opposed to those proposed in this study. Main differences include: (a) the polarity of the principal detachment fault system, (b) the amount of extension, (c) the interpretation of the Bilbao anticlinorium, and (d) the role of salt during convergence. The previous interpretations (e.g. Pedrera et al., 2021) are internally consistent, but result in an extreme endmember interpretation. The interpretation of a south dipping detachment system is not only contradictory to the classical hyperextended models where the long, wedging margin corresponds to the lower plate and the shorter to the upper plate (e.g., Haupert et al., 2016 and references in there), but more problematic, the amount of calculated extension using a south dipping detachment is in the order of 28 km. This value is surprisingly low to explain mantle exhumation of a crust that is generally assumed to be 30 ± 5 km thick and equilibrated before onset of extension. The very low values of shortening (30–40 km) proposed by Pedrera et al. (2021) are the logical consequence of low extension values that can only be explained by the absence of decoupling between the sedimentary section and the basement. Moreover, due to the low values of shortening, these authors also interpret the Bilbao anticlinorium as a rollover anticline formed during extension. Apart from the fact that rollover anticlines have not been described from hyperextended basins, it is important to note that such an interpretation is based on stratigraphic correlations that exclude a possible decoupling between the sedimentary section and the underlying basement. While in our study we cannot demonstrate that the Bilbao anticlinorium did not form as an inherited structure (the key sections are eroded), we can show evidence for thin skin reactivation and can reproduce extensional values that are similar to those of hyperextended systems going to mantle exhumation, i.e., values that are more than twice the initial thickness of the crust. Moreover, our restored values for shortening are compatible with those observed in the reminder of the Pyrenean system.

3 | OBSERVATIONS IN THE BASQUE–CANTABRIAN PYRENEES: GEOLOGICAL CROSS SECTIONS

Field observations and the interpretation of commercial seismic reflection lines together with borehole data enable us to define the main stratigraphic and structural features of the region. We integrated all the available data into the 3D Move software. Seismic data as well as borehole data, all of which are in the public domain, were provided by the Instituto Geológico y Minero de España (IGME). The seismic data presented here consist of old scanned images of time migrated seismic lines. We tied highly reflective seismic horizons to well-defined stratigraphic units and/or limits, such as the Lower-Middle Jurassic carbonates, or the top basement, that we interpret to be responsible for the observed reflectivity (e.g., El Coto-1, Navajo-1, Rioja-3, Figure 3). Based on drillhole to seismic ties, we calculate a mean velocity value of 4,400 m/s to convert to depth the sedimentary infill. To obtain the mean velocity, we selected prominent horizons such as the base of the Jurassic unit and compared the calculated depth and real depth drilled by wells in different positions such as El Coto well and Boveda-1bis well. The uncertainty is estimated to be around 400–500 m which correspond to 9%–15% of error calculated in the previous wells. Therefore, we consider to be below the resolution required, and so acceptable, for the purpose of this study, which is the construction and restoration of crustal-scale cross sections. Previous studies performed detailed depth conversion of commercial seismic profiles from the seismic campaigns also used in this study. The results, however, are not significantly different from those obtained by our simpler first order approach (for discussion see Fernández, 2004). We describe two regional cross sections from south to north: (a) a SW–NE section crossing the central Basque–Cantabrian Pyrenees perpendicular to the main extensional and contractional structures and where the Mesozoic syn-rift sediments are the thickest; and (b) a S–N section across the western termination of the area, where the Basque–Cantabrian Pyrenees links the Asturian Massif (Figure 3).

3.1 | The Central Basque–Cantabrian Pyrenees

The SW–NE-oriented Central section runs from the Duero foreland basin in the south to the offshore Landes High in the north (Figure 3). The interpretation of this section generated long-lasting debates regarding the rift architecture, the nature of high magnetic and gravimetric anomalies flooring the Bilbao Anticlinorium, and the reactivation of the area (e.g., Pedreira et al., 2018, 2021; Pedrera et al., 2017, 2018; Quintana et al., 2015; for discussion see previous section). In this chapter, we present new observations, extracted from field, seismic reflection and borehole data in order to propose a new interpretation of this Central section.

A south-directed frontal thrust delineates the southern limit of the Basque–Cantabrian Pyrenees (Muñoz, 2019). This thrust is detached into the Triassic salt and thrust a thin Jurassic to Cretaceous succession on top of the flat Cenozoic sediments of the Duero foreland basin (Figure 4a, Figure S1). Underlying this succession, a thin Upper Albian to Cenomanian detrital package lays on top of the Palaeozoic basement, which was drilled at the San Pedro borehole site to the south (for details see Carola et al., 2015). Above, an Upper Cretaceous to Paleocene succession of carbonates precedes the Paleogene clastic formations of the Duero and Ebro basins. These carbonates have been well imaged by the seismic surveys and can be mapped easily along the northern Duero basin and the western Ebro basin (Carola et al., 2015; Gallastegui et al., 2016). In the 2D seismic profiles, high amplitude reflections correspond to the Meso-Cenozoic sedimentary cover while chaotic or transparent seismic facies define the Palaeozoic basement, which is slightly tilted towards the north (Figure 4a, Figure S1). The Villameriel-1 and the Rioja-3 wells sampled all this sedimentary succession as well as the top of the basement in similar structural positions along strike, supporting this interpretation (Figure 3). The so-called Folded Band (Carola et al., 2015), a highly deformed area between the most frontal thrust to the south and the Ubierna Fault (Tavani et al., 2011), presents a thin stratigraphic succession on top of a thick Upper Triassic salt unit. Small, imbricated structures characterise this area that resulted from the inversion of extensional faults (Figures 3 and 4a, Figure S1). To the north, the Burgalesa Platform (Carola et al., 2015) is interpreted as an allochthonous unit. This implies that the thick Mesozoic succession is transported towards the south-east over the Late Triassic salt, representing a salt-detached domain oblique to the main Pyrenean trend (Figure 3) (see Hernaiz et al., 1994 and Carola et al., 2015 for a detailed description of this domain). Alternatively, the Burgalesa Platform has been interpreted as a thick-skinned para-autochthonous unit (Pedrera et al., 2021; Quintana et al., 2015; Tavani et al., 2013). The restoration of this unit remains therefor debated but does not have a major impact on the main conclusions of this study. At its northern edge, a repetition of Lower Jurassic to Barremian shallow marine

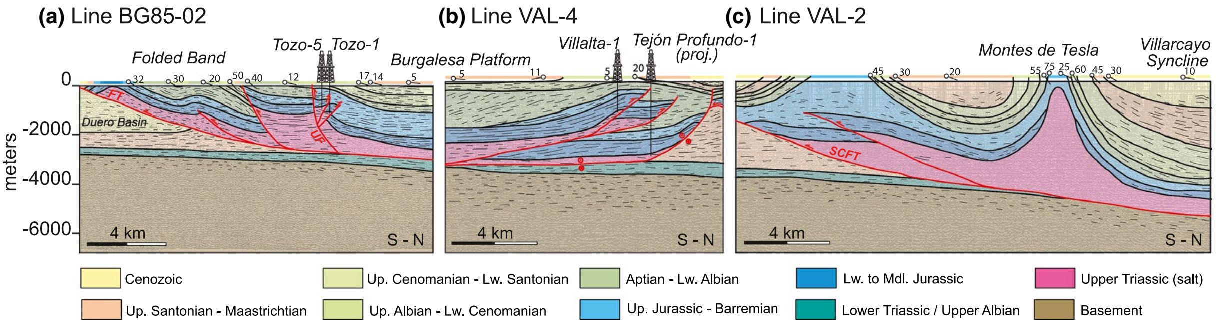

FIGURE 4 N–S seismic sections in the (a) Folded Band, (b) Burgalesa Platform and (c) Sierra de Cantabria Frontal Thrusts-Montes de Tesla areas with the projection of Tozo and Villalta wells as well as the field data and outcrops showing the structure of the southern Central section. FT: frontal thrust; UF: Ubierna Fault; SCFT: Sierra de Cantabria Frontal Thrust. See Figure 3 for location. Higher-resolution and enlarged images of the seismic sections and line drawings are provided Appendix S1

successions, which were sampled at the Tejón-Profundo-1 borehole (Carola et al., 2015) but not in the Villalta-1 borehole, suggests a decoupling on the Upper Triassic salt level. These successions are unconformably overlain by Upper Albian detrital sediments (Figure 4b, Figure S1). Between the Burgalesa Platform and the Sierra de Cantabria Frontal Thrust (SCFT), sparse Cenozoic sequences crop out, resulting in different interpretations (Hernaiz et al., 1994; Rodríguez-Cañas et al., 1994). However, the seismic section VAL-4 (Figure 4b, Figure S1) shows the northern limit of the Burgalesa Platform characterised by a panel of reflectors (Mesozoic in age) tilted to the south, whereas, immediately to the north, these reflectors, corresponding to the infill of Ebro basin, are flat. In between, a steeply dipping transpressional fault with a SE displacement of the hanging wall (i.e., Burgalesa Platform) is interpreted to truncate the south directed SCFT, as documented in the next VAL-2 seismic line (Figure 4b, Figure S1). The SCFT is a major and continuous feature along the southern border of the Basque–Cantabrian Pyrenees (Figure 3). It detaches into the Upper Triassic salt thrusting the Mesozoic succession of the Basque–Cantabrian basin on top of the Cenozoic sediments of the Ebro foreland basin. The underlying basement is slightly tilted to the north beneath the SCFT, an inherent feature of foreland basins in front of thin-skinned fold and thrust belts [e.g., Canadian Rockies (Bally et al., 1966); Bolivian Andes (McQuarrie et al., 2005)] (Figure 4c, Figure S1). Salt structures can be observed both to the south (i.e., Montes de Tesla area [Figure 4c, Figure S1]) and to the north where diapirs developed (e.g., Salinas de Rosio, Figure 3). More than 2,500 m of Late Triassic evaporites were sampled in the Navajo-1 well few kilometres to the west of Montes de Tesla salt structure before reaching top basement at 3,940 m. The Montes de Tesla salt wall has been squeezed so as the thin sedimentary succession of the roof has been folded and locally overturned. This structure constitutes the southern limb of the Villarcayo Syncline (Figure 4c, Figure S1). A thick synorogenic succession (more than 2,600 m thick), sampled at the Trespaderne-1 borehole, cores the syncline. The Villarcayo Syncline represents the western continuation of the Miranda–Treviño and Urbasa synclines, a continuous synform for more than hundred kilometres parallel to the SCFT (Figure 3) (Riba & Jurado, 1992). The northern limb of the Villarcayo Syncline is characterised by a salt inflated area that forms the Salinas de Rosio and the Salinas de Añana salt diapir lineament (Figure 3). The La Hoz-2 borehole sampled more than 1,600 m of Upper Triassic evaporites in this position. A flat area corresponding to the so-called Alavesa Platform is observed at the surface between the Salinas de Añana- Salinas de Rosio diapir alignment and the Villasana de Mena–Orduña–Murgia salt diapirs limiting the Bilbao Anticlinorium to the south (Figure 3).

The Bilbao Anticlinorium to the north includes the thickest sedimentary succession of the Basque–Cantabrian basin (Quintana, 2012). Figure 5 shows the final distribution of depocenters corresponding to Upper Jurassic to Barremian, Aptian to Middle Albian and Upper Albian to Middle Cenomanian extensional phases, which are shifted progressively to the south-west (Figure 5a, Figure S2). The Upper Jurassic to Barremian succession includes more than 4,000 m of shales and siliciclastic sandstones (Quintana, 2012). The total thickness cannot be estimated because the base of the unit is not cropping out. This succession shows a narrow distribution near the Bilbao Fault along tens of kilometres in a NW–SE direction (Figure 5b, Figure S2). The Aptian–Middle Albian is wider to the south, with thickness estimated at about 6,000 m (Quintana, 2012) but made of deep marine marls with isolated limestone successions in the centre of the basin while more continuous limestones in the surrounding domains. The Upper Albian to Lower Cenomanian extends farthest to the south and is thinner than the Aptian to Middle Albian succession. This unit is made of shallow to deltaic facies to the south, whereas it is dominated by deep marine facies to the north as observed and interpreted in the field. Finally, in the Alavesa Platform, the Upper Cenomanian to Lower Santonian sediments show a change in facies from a bioclastic carbonate platform (prominent and characteristic in the landscape) in the south to a slope facies and deep marine environment in the north near the Bilbao Anticlinorium.

The northern limb of the Bilbao Anticlinorium corresponds to a highly deformed area and involves three main north vergent thrust sheets (Figure 3). From south to north these are the Villaro, the Mondragon, and the Durango slices (see Ábalos et al., 2008 for further details on this area). The northern limit of the Bilbao Anticlinorium is characterised by the Bilbao Fault (Quintana et al., 2015), a NW–SE continuous structure all along the Basque–Cantabrian basin, but is poorly imaged in seismic data (Figure 3). Immediately to the north of the Bilbao Fault, the tight Biscay Syncline includes a thick Late Cretaceous to Cenozoic syn-orogenic succession. At its northern edge, it shows a fault system characterised by steep faults and squeezed salt structures, such as the one interpreted in the Sopela beach (Figure 6a). At the northern limit, the North Biscay Anticlinorium crops out (Muñoz, 2019) including two stacked structural units of Aptian to Cenomanian sediments overlying a thin autochthonous succession of middle Cenomanian clastic sediments that in turn overlies Palaeozoic basement at 3,300 m, which were sampled by the borehole Cormorán-1. Offshore, the Gaviota B-4 and Vizcaya B-1 boreholes reached the basement at around 3,000 m depth. The overlying sedimentary sequence includes a thin Upper Albian to Middle Cenomanian clastic succession and a thicker Upper Santonian to Oligocene syn-orogenic succession (Figure 6b) (Miró et al., 2020; Roca et al., 2020).

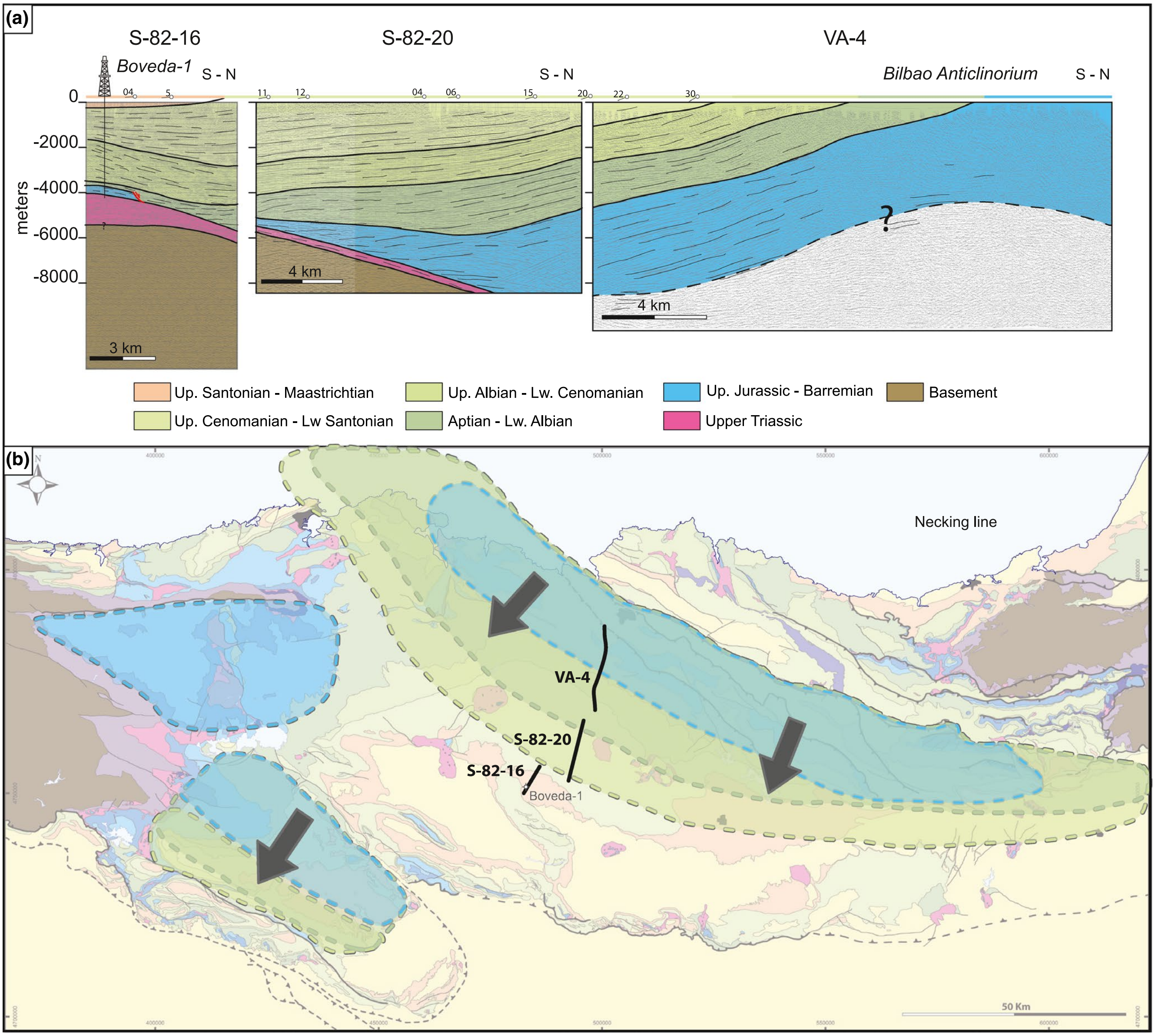

FIGURE 5 (a) N–S seismic section in the Alavesa Platform and Bilbao Anticlinorium areas showing the overlapping of Mesozoic syn-rift depocenters shifting to the south. See Figure 3 and (b) for location. (b) Map of the different Mesozoic syn-rift depocenters of more than 2 km thick in the Basque–Cantabrian Pyrenees build from seismic interpretation and field observations. See colour legend in Figure 5a. Higher-resolution and enlarged images of the seismic sections and line drawings are provided as Appendix S2

3.2 | The Western Basque–Cantabrian Pyrenees

The Western section runs from the Duero foreland basin in the south to the Bay of Biscay in the north (Figure 3). In this study, we present a new onshore cross section, significantly different from recently published ones in terms of structural style and crustal structure (e.g., García-Senz et al., 2019). For the offshore segment, we performed a depth conversion of the CS01-146 section of Cadenas et al. (2020) (see location in Figure 1).

The southern limit of the Basque–Cantabrian Pyrenees, as well as the Folded Band area, displays a similar structure as the one observed in the Central section. Northward of the Ubierna Fault, however, major structural variations occur. The western section crosses the inverted Polientes basin, where the Upper Jurassic to Lower Albian depocenters migrate towards the south. These sediments onlap onto Lower to Middle Jurassic units that detach on the Triassic salt and thicken slightly towards the north (Figure 7a,b, Figure S3). These are typical characteristics of salt detached basins (Roma et al., 2018). An anticline of Upper Jurassic to Middle Albian sediments represents the surface expression of the reactivation of the Polientes basin. The E-W trending PR-21 seismic line and the Cadialso-1 well show the contact between the sedimentary cover and the basement (Figure 7c, Figure S3).

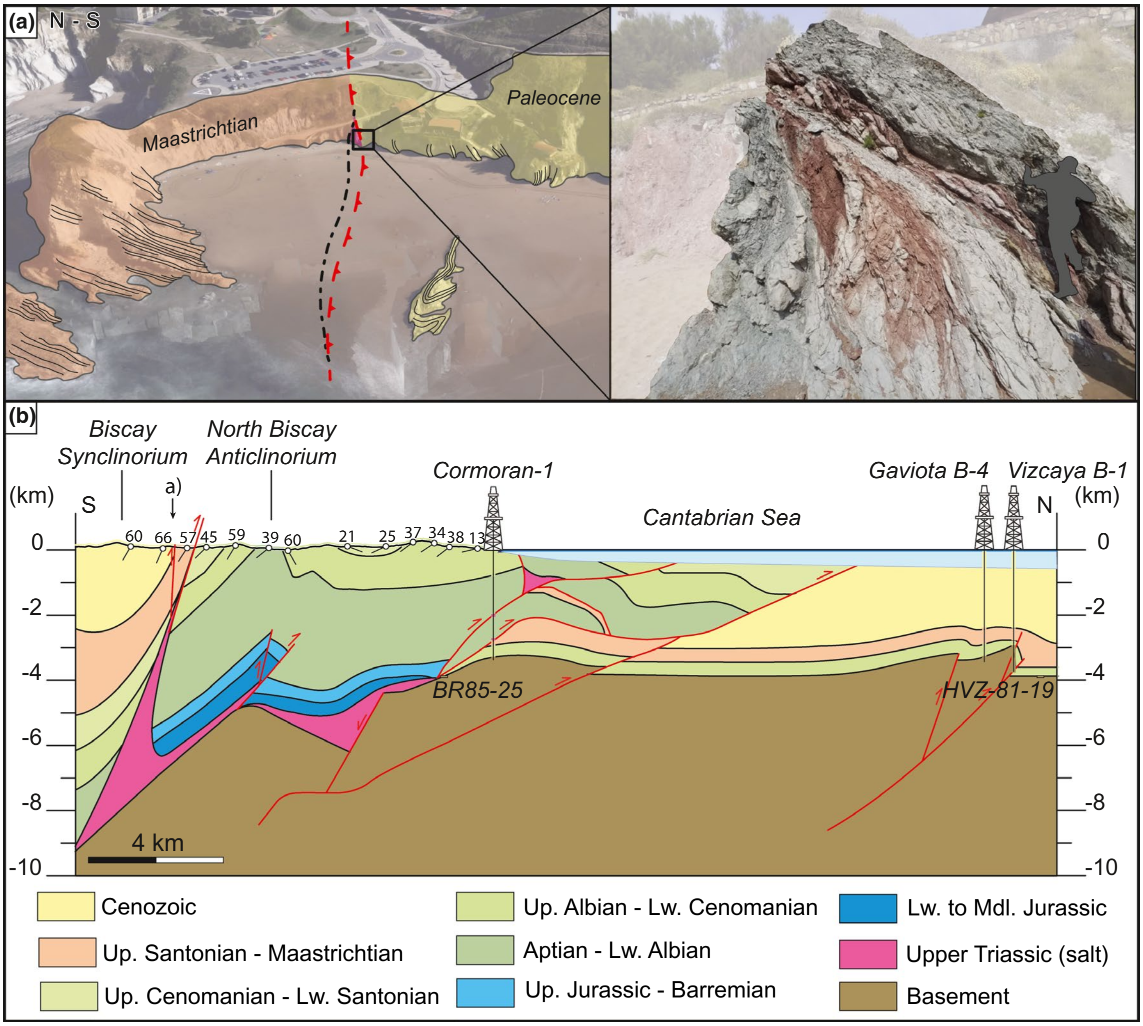

FIGURE 6 (a) Aerial oblique photograph from the Sopelana beach with the interpretation of the thrust weld and a field image of the detailed weld with the characteristic shear deformation. See location in Figures 3 and 6b. (b) Geological cross section in the northern Central section modified after Roca et al. (2020), with the integration of field data, observations from BR85-25 and HZV-81–19 interpreted seismic lines and the projections of Cormoran-1, Gaviota B-a and Vizcaya B-1 boreholes. Note that (a) and (b) are shown in opposite direction

In the southern Polientes basin, a thin package of reflections, consisting of Upper Albian to Middle Cenomanian clastic sediments, unconformably overlie Upper Jurassic to Middle Albian depocenters (Figures 3 and 7a, Figure S3). The northern limit of the Polientes basin is an area where both reactivation of basement faults and salt structures are observed (Figure 3). The Cilleruelo diapir crops out at surface (García Mondéjar, 1982) and diapir contacts were sampled at the Arija-1 and La Poblacion-1 boreholes (Figures 3 and 7b, Figure S3). North of the Ebro Reservoir, the Cabuérniga basin includes up to 900 m of Lower to Middle Jurassic carbonates and up to 3,000 m of Upper Jurassic to Barremian fluvial and lacustrine sediments. Few small outcrops of Aptian carbonate platforms are preserved to the east of the basin (Figure 3). Long wavelength large-scale folds affected the Cabuérniga basin. Despite that salt has not been observed in the western Cabuérniga basin, some outcrops of evaporites next to the poorly understood N–S Besaya structure (also called Pas Fault, Carola et al., 2013) are observed, in the eastern Cabuérniga basin (Figure 3). The Cabuérniga Fault bounds the basin to the north. This fault trends in an E-W direction along more than 50 km (Figures 3 and 8). The hanging wall includes the Lower Cretaceous succession described before, whereas in the footwall, Palaeozoic and Lower Triassic rocks crop out at the Sierra de Cabuérniga and the Santander Block (Figure 8). To the north, a thin Mesozoic stratigraphic succession lies on top of an evaporitic unit (Triassic in age). The Santander Block includes salt structures, such as Cabezón de la Sal and Torrelavega salt diapirs, as well as thrusts and salt-cored anticlines (Figures 3 and 8a).

The area north of the Santander Block corresponds to the offshore part of the section that has been modified from Cadenas et al. (2020). However, the seismic line interpreted by the previous authors is in time and therefore a depth

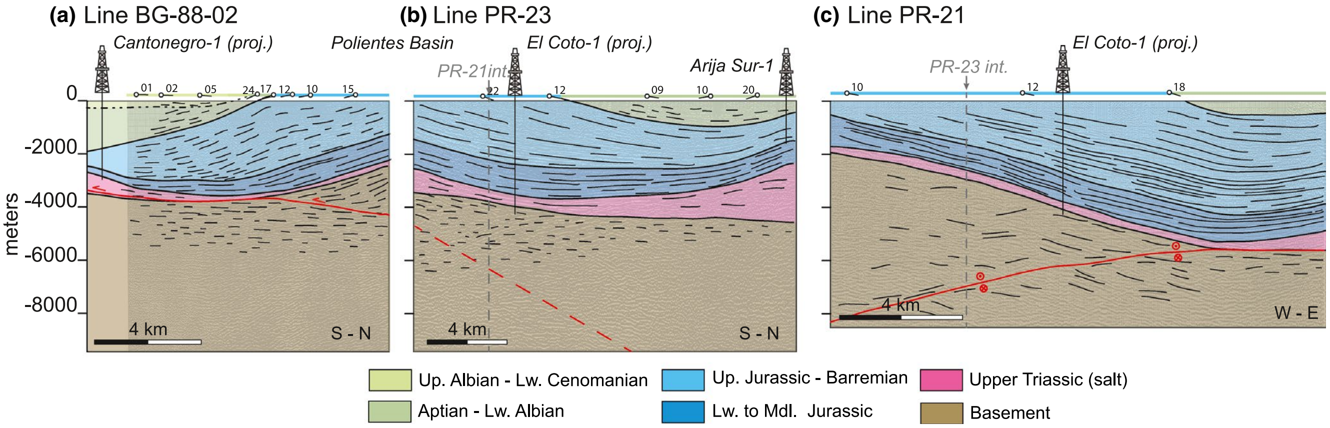

FIGURE 7 N–S seismic sections (a and b) and E-W seismic section (c) in the Polientes Mesozoic basin with the projection of the Cantonegro-1, El Coto-1 and Cadialso-1 boreholes and the surface data and geology. The E-W (c) section shows the thick- to thin-skin transition in the Western Basque–Cantabrian Pyrenees and the dip data observed in the sediments at surface controlled by the basement at depth. See Figure 3 for location. Higher-resolution and enlarged images of the seismic sections and line drawings are provided as Appendix S3

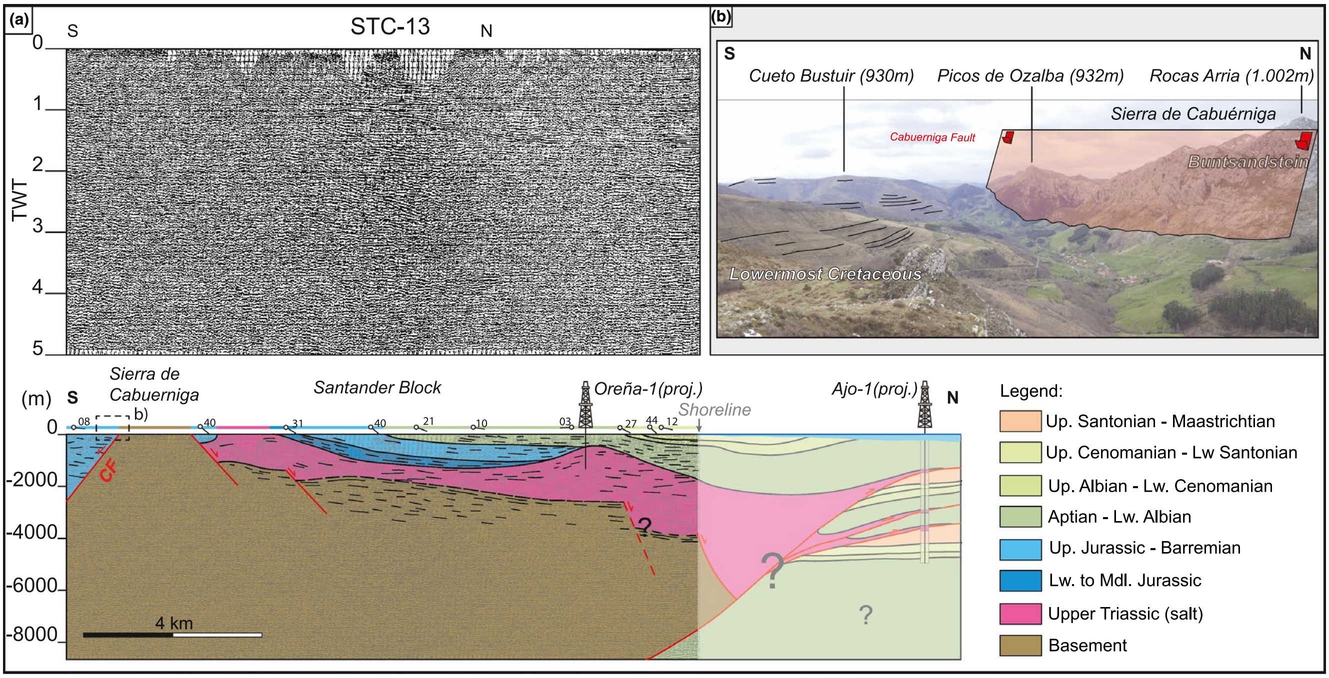

FIGURE 8 (a) N–S seismic section in the Santander Block area with the projection of the field data and surface geology as well as the Oreña-1 borehole and the Ajo-1 borehole to link the onshore with the offshore sections. CB: Cabuérniga Fault. (b) Field image of the northern limit of the Cabuérniga basin with the view to the Cabuérniga Fault. See location in Figure 3

conversion was applied to the interpreted section. The offshore part of the section presented here in depth resulted from the combination of two different methods. We defined a generic velocity model for the sedimentary section to determine top basement by using $V_z = V_0 + k{\cdot}z$ where: V_0 is 1.75 km/s (i.e. water velocity) and k is 0.4, according to reference values from Van Dalfsen et al. (2006). These authors used values from lithologies comparable with those described in the wells offshore Cantabria. The depth of Moho is from the velocity model of Ruiz (2007), the neighbouring MARCONI-6 refraction/wide-angle profile. We consider that the sum of the possible errors that each of the previous methods can contribute is below the resolution required for our interpretations and would not significantly change the proposed restoration.

Some onshore observations are fundamental to interpret the onshore-offshore link and they agree well with the offshore interpretation in terms of first order architecture. The Ajo-1 well, located towards the east, near the Ajo Cape (Figure 3), sampled three repetitions of Aptian–Albian successions with Upper Triassic salt in between, but no basement was described in the 4,970 m of the well log (Cámara Rupelo, 1989). Onshore, a thin but complete Lower Cretaceous succession overlies Jurassic sediments. Offshore, a thick succession of more than 1,300 m of Aptian to Cenomanian sediments is interpreted (Figure 8a). Thus, an important omission of stratigraphy from Lower Jurassic to Barremian is inferred in the onshore–offshore transition. Relying on the interpretation of reflectivity patterns and tectono-stratigraphic relationships, a set of north-dipping extensional detachment faults and related tilted and allochthon blocks were interpreted by Cadenas et al. (2020), a work based on the analysis of a 3D data set including drill hole data (Figure 9).

4 | CRUSTAL ARCHITECTURE: GEOPHYSICAL CONSTRAINTS AND INTERPRETATIONS

In this section, we summarise the main geophysical constraints defining the crustal architecture of the area. We used published velocity models (e.g., Fernández-Viejo et al., 2000; Pedreira et al., 2003; Ruiz et al., 2017) to constrain the Moho depth, and we define the position of the top basement.

In the Central section (Figure 10a), the Iberian crust to the south shows the top basement slightly tilted to the north. Crustal thickness is of about ca. 30 km from the Duero basin until the lineament described by the Villasana de Mena–Urduña–Murgia salt diapirs (Fernández-Viejo et al., 2000) (Figure 3). Further north, top basement dips towards the north suggesting a thinning of the crust, as the base of the crust follows a similar trend. To the north, two inter-wedged Moho surfaces have been interpreted, corresponding to the Iberian and European Moho surfaces (Ruiz et al., 2017). Although top basement has not been imaged, the thickening of the sedimentary succession described in the Bilbao Anticlinorium suggests that the remaining crust must be considerably thinned along the underthrust slab (i.e., necking domain). By contrast, the European crust shows its base at around 30 km depth northwards of the Bilbao anticlinorium (Ruiz et al., 2017). Offshore, the Cormoran-1, Gaviota B-4, and Vizcaya B-1 boreholes reached the top basement between 3,000 and 3,500 m depth. Thus, a normal crustal thickness (i.e., ca. 30 km) is inferred in the northernmost part of the section. Further to the south, there is no evidence of the top basement beneath the Biscay Sinclinorium. However, the significant stratigraphic thickness reported in the literature (Meschede, 1987) also suggests significant crustal thinning (i.e., necking domain sensu Tugend et al., 2014).

In the Western section (Figure 10b), a ca. 30 km thick Iberian crust is interpreted in the southernmost part, beneath the Duero basin. Both, the top basement and the Moho are slightly tilted to the north beneath the Polientes basin (Fernández-Viejo & Gallastegui, 2005). The top basement is at around 1–3 km depth in the Reinosa area, as well as beneath the Cabuérniga basin. The base of the crust has been interpreted at ca. 45 km depth underneath the Santander Block, while the top basement crops out to the south and is interpreted at 2 km depth to the north. Thus, a thickening of the crust from ca. 30 km to more than 40 km can be inferred from south to north. At the same position, the base of the crust is at ca. 25 km depth (Ruiz, 2007) further north where top basement lays between 6 and 8 km of depth (Figure 9). The base of the crust is at almost 20 km at this location (Ruiz et al., 2017). Thus, the present-day architecture of the northern Western section still preserves the inherited crustal structure of the rift period, despite the Alpine reactivation.

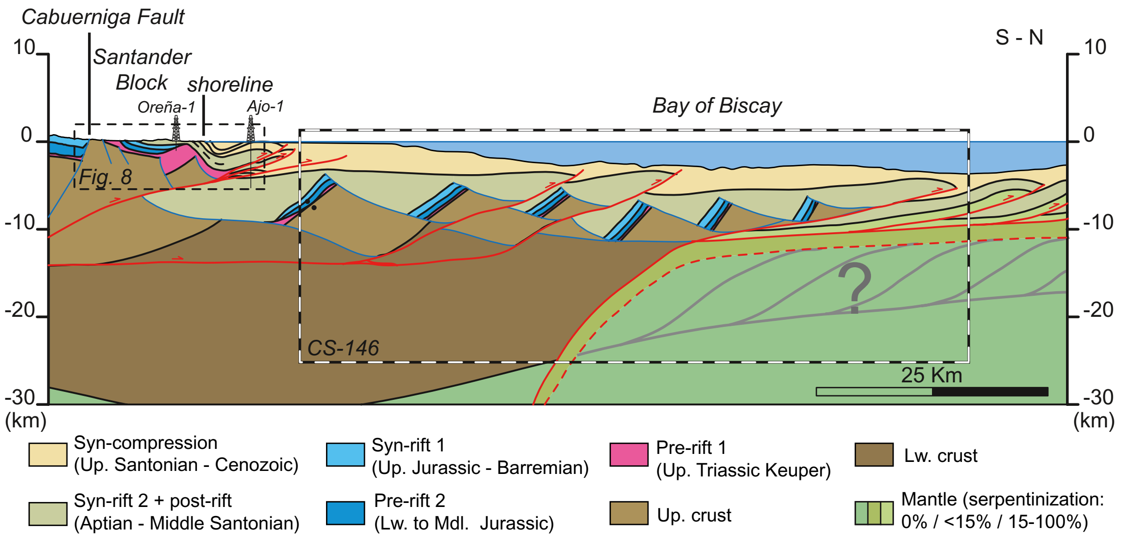

FIGURE 9 Northern part of the Western section combining the STC-13 seismic line (Figure 8) and a modified depth converted interpretation from the CS-146 seismic line of Cadenas et al. (2020). See Figures 1 and 3 for location

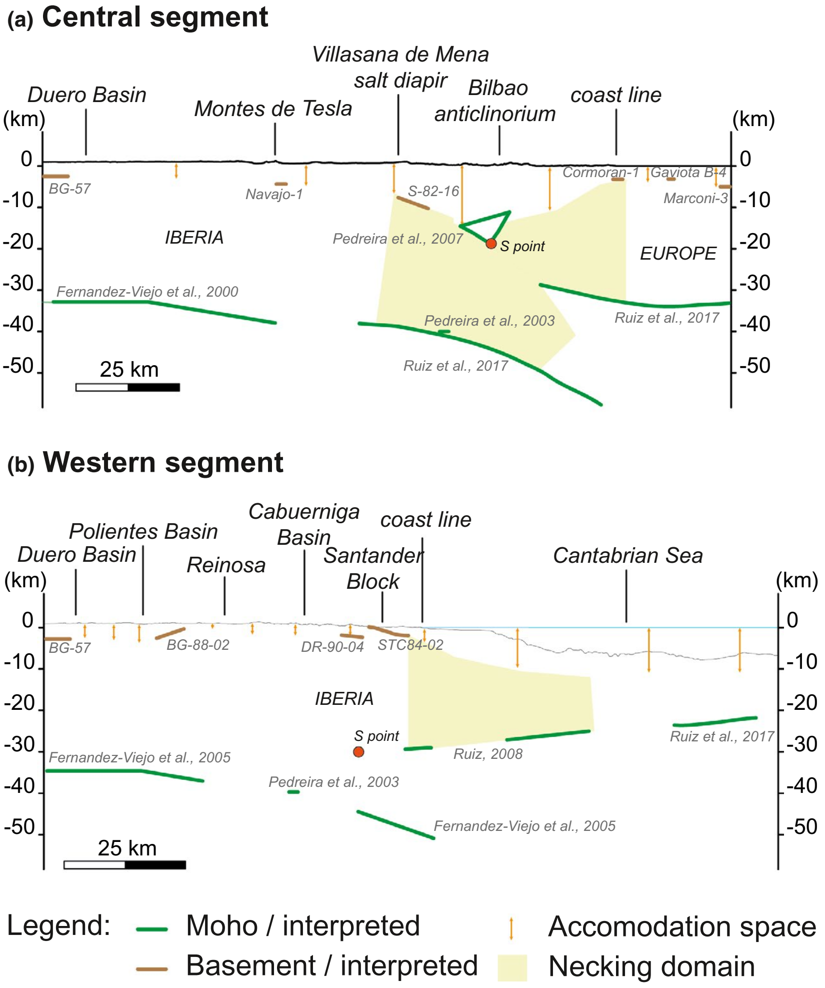

FIGURE 10 Compilation of geological and geophysical interpretations used to constrain the crustal structure in the Central section (a) and in the Western section (b) including seismic, borehole and published velocity models. S-point and necking domains are interpreted from the geophysical data and represented in the geophysical compilation sections

5 | DISCUSSION

5.1 | Present-day architecture of the Basque– Cantabrian Pyrenees

Geological observations and geophysical interpretations presented in previous sections enable us to construct two crustal-scale sections, which show the present-day crustal structure of the area. Substantial differences can be observed comparing both sections at a basin as well as at a crustal scale. While the Central section preserves a mature orogenic architecture, the Western section exhibits embryonic stages of the reactivation of a rifted margin. Comparing and understanding the link between the two sections is fundamental to restore the Basque–Cantabrian rift template and to understand its importance in subsequent compressional reactivation.

5.1.1 | Central section

In the Central section (Figure 11a), a traditional interpretation is the inter-wedging of the Iberian and the European Moho surfaces (Muñoz, 2019; Pedreira et al., 2007, 2015; Roca et al., 2011). We distinguish two plates: the Iberian/Ebro plate to the south and the European plate to the north. The singular point (i.e., S-point corresponding to a point which delimits the pro-wedge to the south from the retro-wedge to the north; Jamieson & Beaumont, 2013; Willet et al., 1993) is interpreted underneath the Bilbao Anticlinorium at about 17 km depth (Figures 10 and 11a). Its position is based on the refraction data determining the Moho surface, the thickness of the stratigraphic pile and the crustal thickness that is in isostatic equilibrium with the stratigraphic pile and that is also coherent with the refraction and reflection seismic data. Although none of the methods can be considered precise, their combination leads to a significant reduction in the degree of uncertainty associated to the S-point location. Southward of this point/line, south-vergent structures predominate in the pro-wedge, whereas the retro-wedge includes north-vergent structures. The European crust (i.e., retro-wedge) thins from a normal crustal thickness (i.e., ca. 30 km) beneath the Landes High to the north to about 20 km underneath the Biscay Synclinorium towards the south (Figure 11). By contrast, the Iberian crust (i.e., pro-wedge) thins from 30 km beneath the Duero foreland basin to less

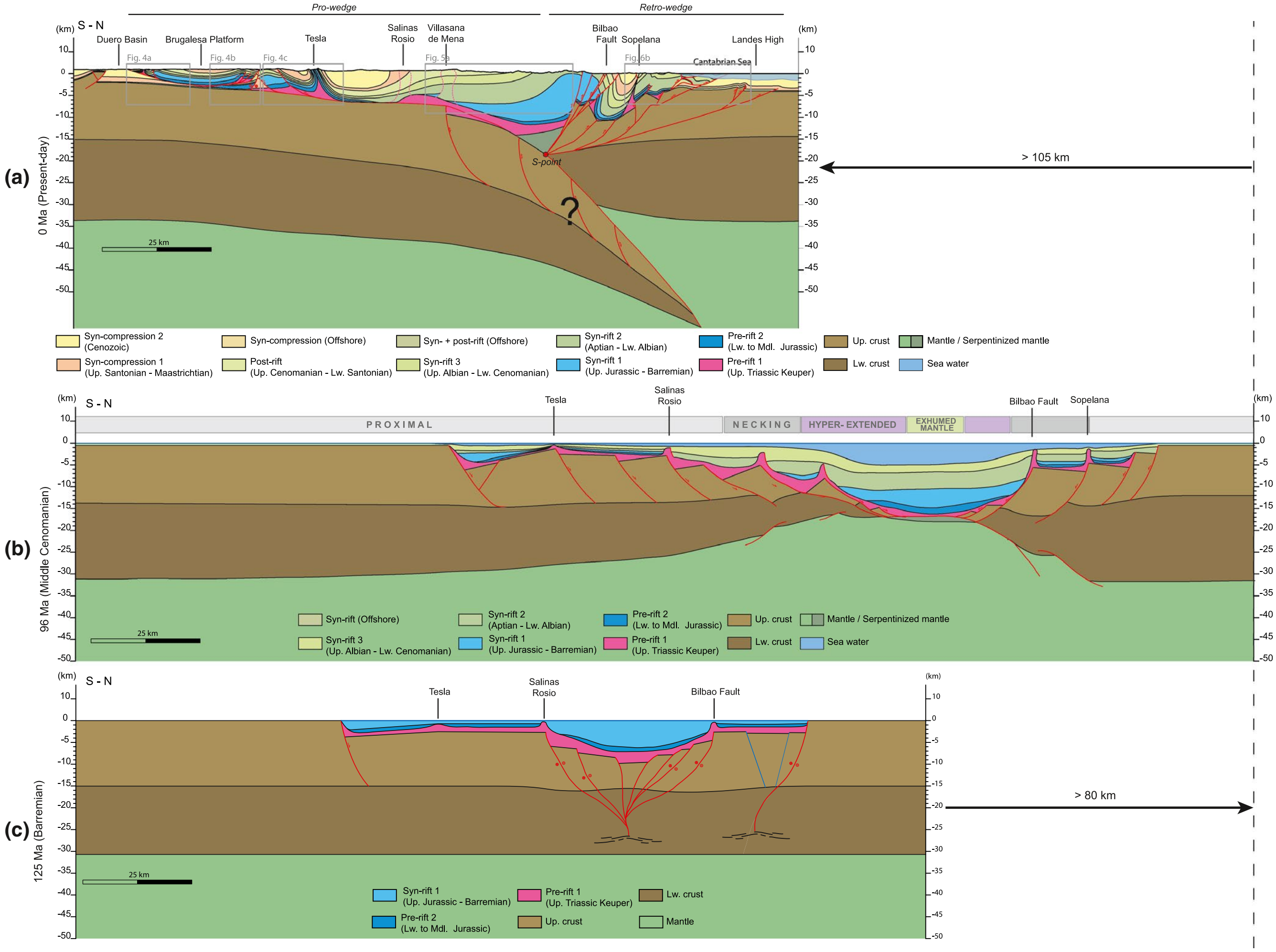

FIGURE 11 (a) Present-day crustal-scale cross section across the central Basque–Cantabrian Pyrenees (modified from Muñoz, 2019). Grey labels indicate the lateral equivalent position of seismic section shown in the results. See Figure 3 for location. (b) Restoration of the Central section at middle Cenomanian times (end of multistage and polyphase extension) with the rift domains depicted on top. (c) Restoration of the Central section at Barremian times (end of the first rift stage)

than 10 km in the underthrust slab (Figure 11a). No intra-crustal contractional features have been interpreted in the Iberian crust, whereas the European crust displays basement-involved contractional structures that have been interpreted to decouple in a mid-crustal detachment (Figure 11a). On top, the allochthonous sedimentary cover is detached into the Upper Triassic salt level. We deduce, therefore, a relative southward displacement of the Basque–Cantabrian basin of about ca. 35 km over the Duero foreland basin (Figure 11a) showing a well-developed thrust and fold system (i.e., Sierra de Cantabria Frontal Thrust).

Salt structures in the distal domain in the pro-wedge were transported passively with the sedimentary cover to the south. The preservation of the shape and morphology of diapirs at a map scale indicate minor or no reactivation. By contrast, the salt structures located near the thrust front and the ones located in the retro-wedge were reactivated and squeezed during contractional deformation (e.g., weld observed in Sopela beach, Figure 6a).

A high magnetic and gravimetric anomaly has been modelled beneath the Bilbao Anticlinorium, where we locate the S-point, which has been interpreted as a body of intrusive rocks (Aller & Zeyen, 1996) or lower crustal rocks (Pedreira et al., 2007; Quintana et al., 2015). Nevertheless, recent studies addressing the eastern Basque–Cantabrian basin (DeFelipe et al., 2018; Ducoux et al., 2019; García-Senz et al., 2019; Lagabrielle et al., 2020; Pedrera et al., 2017; Tugend et al., 2014) and surrounding basins, such as the Mauleón basin (Jammes et al., 2009; Masini et al., 2014), have documented evidence of mantle exhumation in their distal parts. Therefore, and consistent with previous interpretations, we suggest that this positive gravimetric anomaly might have resulted from a partly serpentinised mantle body, which was exhumed during extension and latterly captured during the first stages of reactivation and subsequent collision of the hyperextended rift system (for details see next section). Regarding its position, there is a consensus in the literature to locate the major magnetic anomaly (i.e.,

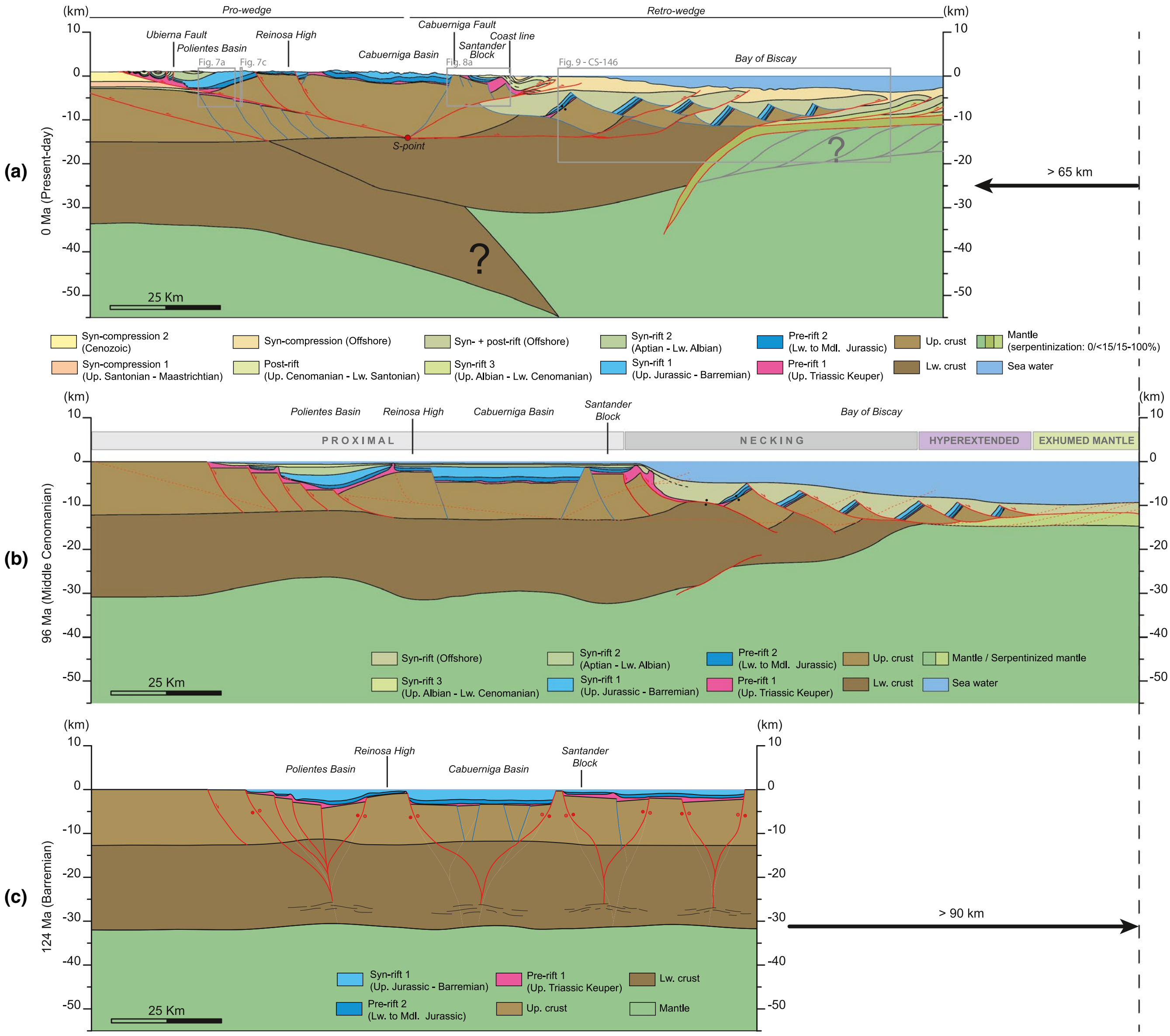

FIGURE 12 (a) Present-day crustal-scale cross section across the western termination of the Basque–Cantabrian Pyrenees to the Bay of Biscay. Grey labels indicate the lateral equivalent position of seismic section shown in the results. See Figure 3 for location. (b) Restoration of the Western section at middle Cenomanian times (end of polyphase extensional event) with the rift domains depicted on top. Dashed lines show the future compressional structures. (c) Restoration of the Western section at Barremian times (end of the first monophase rift stage)

strongest signal) beneath the Bilbao fault to the south-east of Bilbao (figure 2 of Aller & Zeyen, 1996; figure 8 of Pedreira et al., 2003; figure 4 of Pedrera et al., 2017). However, its full shape and termination to the north-west, coincident with the trend of the Central section, is not well defined due to a much weaker signal. A similar trend has been observed also for a high density/magnetic body underneath the Mauléon Basin (Western Pyrenees) and their lateral disappearance has been interpreted by Lescoutre and Manatschal (2020) as an interference between rift-inherited and subduction/collision related structures. Therefore, and based on the arguments presented above, we interpret the position of the high density/magnetic body to be located south of the Bilbao Fault and underlying the Bilbao anticlinorium.

Based on these interpretations, we interpret the Central section as a classical collisional-type section with a double-wedge geometry and with the following features:

1. The S-point defines the retro- versus pro-wedge and delimits the position of the northward underthrusting of the Iberian Moho.
2. Both top basement and base of the crust (i.e., Moho) are observed but its internal architecture is ill defined in seismic data and is therefore difficult to resolve and interpret.

3. The sedimentary cover is allochthonous due to the presence of Triassic salt, which acted as a decoupling level. Therefore, no direct correlation can be done between the sedimentary cover and the underlying basement, which makes the description of the rift architecture difficult along this section. Moreover, a 12 km thick Mesozoic sedimentary cover argues for extreme crustal thinning in the Basque–Cantabrian basin and favours the presence of a north-dipping extensional detachment system flooring its southern margin, which is contradictory with a major south-dipping fault at the northern border.
4. There is a strong gravimetric anomaly underneath the Bilbao Anticlinorium, which is, according to the interpretation proposed in this paper, linked to the presence of a serpentinised mantle body.

5.1.2 | Western section

The Western section crosses the Iberian plate. However, we favour the interpretation of two underthrust slabs, a southward underthrusting of exhumed mantle within the Biscay abyssal plain (Cadenas et al., 2020) and a northward underthrusting of the Iberian lower crust (Pedreira et al., 2003). We interpret the S-point at~15 km depth under the Cabuérniga basin (Figure 12a). Thus, a thickening of the crust is deduced from south to north in the pro-wedge, while crustal thinning is observed from south to north in the retro-wedge. Due to the irregular distribution of Upper Triassic salt in the western termination of the Basque–Cantabrian Pyrenees (López-Gómez et al., 2019), the section combines both decoupled and coupled domains. The frontal structure that locates the Folded Band and the Polientes basin over the Duero foreland basin and the displacement of the Santander Block are governed by a thin-skinned structural style (see Ajo-1 well sampling Triassic and major salt structures at surface), whereas the Cabuérniga basin and the offshore North Iberian Margin mostly show thick-skinned reactivation (Figures 3 and 8).

Moreover:

1. Exhumation of mantle is interpreted to the north (Cadenas et al., 2018; Tugend et al., 2014).
2. Salt is limited to some parts and primary contacts between sedimentary sequences and basement occurs where salt is absent.
3. Mid-crustal levels acted as decoupling levels and the rift-related crustal architecture is partially preserved offshore (Cadenas et al., 2020).

These observations contrast with those made in the Central section, where salt is present and acted as a decoupling level throughout the section. Thus, the early stages of reactivation, recognised in the Western section, may be crucial for the understanding of the internal part of the Central section.

5.2 | Basque–Cantabrian rift template

In this chapter we discuss a kinematic restoration of the Western and Central cross-sections back to the end of rifting (Cenomanian) and to the early stage of rifting (Barremian). The restoration follows three fundamental concepts:

1. Areal crustal conservation: In 2D restorations of dip sections the initial and final crustal area need to be balanced assuming no movement out of the section and no or little erosion (Figure 13a) (e.g., Sutra et al., 2013). Furthermore, the length of the initial top basement (top

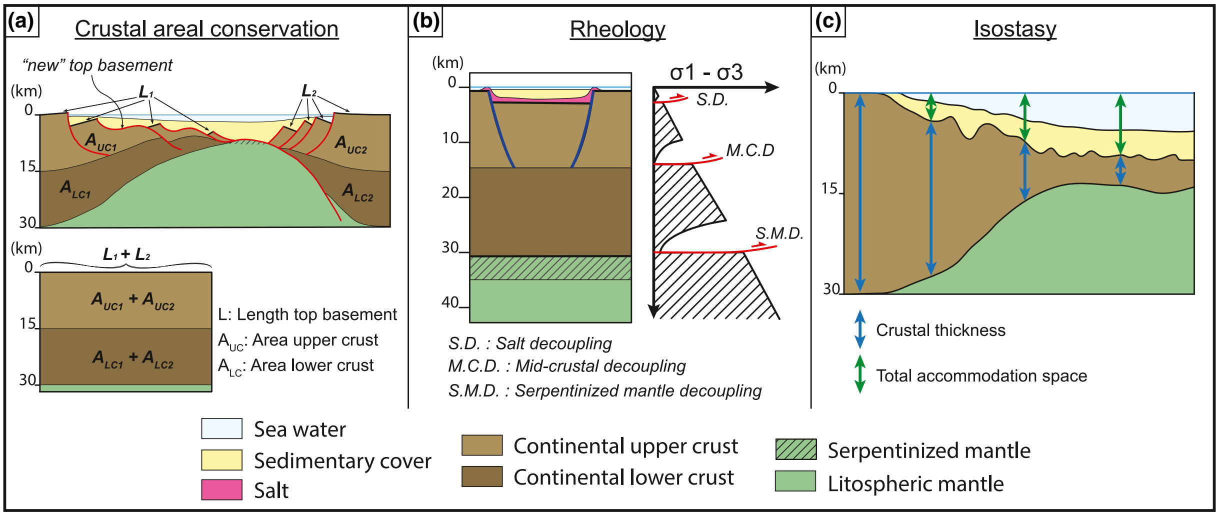

FIGURE 13 The three basic concepts for a restoration of a hyperextended rifted margin. (a) Crustal areal conservation and pre-rift length conservation. (b) Rheological component by considering the influence of the different decoupling levels present in the crust. (c) Isostasy, considering the crustal thickness versus total accommodation space relation

pre-rift) needs to be preserved, i.e., the initial length of the top crust must equal the final length. By contrast 'new' top basement-sediment interfaces created through extensional exhumation surfaces need to be restored.

2. Bulk rheological evolution and implications for decoupling levels: During reactivation of hyperextended systems three potential decoupling levels can be activated, which are serpentinised mantle (low friction), weak mid-crustal layers (thermal/compositional) and salt (low friction). Serpentinised mantle is known to represent an efficient decoupling level (Gillard et al., 2019; Lescoutre & Manatschal, 2020; Sutra & Manatschal, 2012; Figure 13b). By contrast fresh mantle, when not serpentinised, may remain coupled to the crust during deformation. A weak mid-crustal rheology not only controls extensional thinning (e.g., necking: Mohn et al., 2012) but can also localise deformation during thick-skin reactivation (Lescoutre & Manatschal, 2020). The presence of a salt layer promotes decoupling of the sedimentary cover from the basement during both extension and contractional reactivation, disconnecting the final position of a sedimentary package from its initial position in the margin. Thus, the lateral continuity of salt, which may be an issue in hyperextended domains, is a key point (see discussion below).
3. Isostasy: In thermally equilibrated extensional settings there is an inverse proportional relation between crustal thickness and total accommodation space (Figure 13c; Tugend et al., 2014). Thus, thick and/or deep syn- to post-rift sedimentary packages cannot overlie thick crust, or inversely, thin shallow marine syn- to post-rift sedimentary packages cannot overlie thin crust. Therefore, even in absence of direct observations of crustal thickness, the sedimentary sequence can provide vital information about the original thickness of the underlaying crust prior to reactivation. This is particularly important for settings where the sedimentary section is allochthonous and not sitting anymore on its initial pre-compressional basement, as is the case in the Basque–Cantabrian basin.

5.2.1 | Western section

The Aptian to Cenomanian rift stage accommodated most of the extension and rift-related accommodation space along this section (e.g., Cadenas et al., 2020; Roca et al., 2011; Tugend et al., 2014). However, fluvial to deltaic sediments of Aptian-Albian age are observed in the Polientes basin and a thin Aptian–Albian shallow marine carbonate platform is observed in Cabuérniga basin (Pujalte, 1979, 1981). These observations suggest that minor accommodation space was created outside the Bay of Biscay, where the presence of kilometre thick depocenters with deep marine sediments supports major thinning of the crust (Figure 12b). The final architecture of the late Aptian to Cenomanian event was linked to a polyphase rift evolution, from stretching, thinning, mantle exhumation, and finally oceanic accretion in the Bay of Biscay (Cadenas et al., 2018, 2020; Tugend et al., 2014).

At the end of the Late Jurassic to Barremian rift stage, we interpret three basins along the Western section (i.e., Polientes, Cabuerniga and future Bay of Biscay), each filled by fluvial to lacustrine sediments with interbedded alluvial sediments (Pujalte, 1989; Pujalte et al., 1996). These basins were separated by two basement highs (Figure 12c): the so-called Reinosa or Pantano del Ebro high (Escudo High according García Mondéjar, 1982), between the Polientes and Cabuérniga basins, and the Santander Block north of the Cabuérniga basin. We propose that the boundaries of some of the previous basins such as Cabuérniga basin were established by high-angle faults (i.e., Cabuérniga fault) that did not thin the crust significantly. Therefore, we interpret these basins to have formed as isolated and localised basins that have similar characteristics and ages as the offshore Asturian basin (Cadenas et al., 2020) as well as other Late Jurassic to Barremian basins, which have been interpreted to form within a transtensional setting (Angrand et al., 2020; Barnett-Moore et al., 2016; Nirrengarten et al., 2018).

Thus, the Western section is characterised by a multi-stage rift system (Figure 12). We distinguish a first distributed Triassic stage, which is relevant in terms of salt deposition for the subsequent evolution (López-Gómez et al., 2019). A second Late Jurassic to Barremian stage resulted into the development of localised basins, such as the Cabuérniga basin (i.e. monophase rift stage). A third and most important Aptian to Cenomanian polyphase rift event was linked to major extension focussing on the Bay of Biscay and resulting in mantle exhumation in the most distal parts (see also Cadenas et al., 2020; García-Senz et al., 2019). As a result, the different rift stages only slightly overlapped and therefore can be identified and evaluated. Despite remarkable differences with the Central section regarding the sedimentary infill and the fact that a transfer zone is described in between (i.e., Santander Transfer Zone; Roca et al., 2011), the crustal architecture observed in the northern part of the Western section may provide clues to restore back the rift template of the Central section.

For the Western section, a minimum value of 90 km of crustal extension can be deduced. This is, however, a minimum value since the method does not enable to quantify the extension linked to mantle exhumation in the northern part of the section. The obtained value is consistent with restorations of hyperextended systems that reached mantle exhumation, where estimated minimum values are above 60 km (Jammes et al., 2010). Shortening is estimated to be in the order of 65 km (Figure 12a). However, it is important to note that the shortening accommodated in the northern part of the section (i.e., offshore) is difficult to constrain due to the lack of data.

Therefore, it is reasonable to think that shortening could be significantly higher than 65 km. Some previous studies have proposed significantly lower shortening values for this area (e.g., 35 km proposed by García-Senz et al., 2019).

5.2.2 | Central section

The Central section shows three main differences with respect to the Central Section: (a) the Basque – Cantabrian basin resulted from the stacking of several depocenters during successive multistage rift stages, which are overlapped instead of distributed along the section; (b) the crust had to be extremely thin in order to allow the deposition of more than 12 km of sediments (see isostatic concept in Figure 13c), which is also compatible with the occurrence of either very thin crust and/or exhumed serpentinised mantle; and (c) thick salt was present across the whole section, as indicated by decoupling between the basement and post-salt sequences. As a consequence, extensional faults affecting the basement are not recognised, and the former distal parts of the rift system are buried beneath thick sediments and/or underthrust. Therefore, the extensional evolution in the Western section, where different rift stages have been recognised separately and the salt was not continuous throughout the whole section, is fundamental to restore the Central section.

The Upper Jurassic to Barremian sediments of the Central section show similar, i.e., shallow depositional environments as those deposited in the Polientes and Cabuérniga basins reported from the Western section (Pujalte, 1989). Therefore, we suggest that they formed in the same kinematic framework, i.e., in a transtensional setting controlled by steep faults rooting down into deep levels without significantly thinning the crust outside the basin (Figure 11c). However, the presence of thick Late Triassic salt masks the direct link between the surface and deep structures making it difficult to interpret the link between the Triassic and Late Jurassic structures. From Aptian to Cenomanian, extension localised over the locus of earlier extension, resulting into the deposition of more than 8 km of shallow to deep marine sediments on top of the Late Jurassic to Barremian succession. Thus, in the Central section, the second rift event was followed and overprinted by a polyphase rift event, which led to necking, crustal thinning, and, locally, mantle exhumation (Figure 11b). The Upper Jurassic to Barremian depocenter acted as a pre-rift unit during the subsequent Late Aptian to Cenomanian rift event, but due to the presence of salt acting as a decoupling level, a continuous depocenter recorded the complete extensional evolution. In fact, the presence of a thick pre-rift salt layer kept the sedimentary cover decoupled during the extensional process, enabling the preservation of salt into the new real state, including exhumed mantle (e.g., Jammes et al., 2010). At the same time, salt structures continued to develop, triggered by the first stages of extension, being more significant than the ones located in the necking domains. Prominent salt diapirs are located at the upward projection of the necking zone (i.e., Alavesa Platform, Figure 11). During subsequent stages of compression, these diapirs were slightly squeezed and transported passively to the south, preserving their former geometry (e.g., Villasana de Mena and Salinas de Rosio salt diapirs) (Figures 3 and 11). This is also consistent with field observations showing that the leading edge of the post-rift Coniacian platform and its change to slope and deep marine facies occurred in the Alavesa Platform, suggesting a basin deepening northwards within a necking domain (i.e., the location where the crust thinned from 30 ± 5 km to ≤10 km (Mohn et al., 2012; Tugend et al., 2014). Regarding the conjugate European margin, it is narrower and steeper, which is compatible with an upper plate geometry (Figure 11). Thus, we interpret the northern European margin as an upper plate and the southern Iberia margin as a lower plate, following the architecture characteristics of asymmetric hyperextended rift systems (Haupert et al., 2016). The interpretation proposed here contrasts with previous interpretations where Iberia has been interpreted as an upper plate and Europe as a lower plate (García-Senz et al., 2019; Pedrera et al., 2017; Quintana et al., 2015; see also discussion above).

For the Central section, minimum extension values are in the order of 80 km, which is a first-order estimate. This value is significantly higher than estimations proposed by previous authors such as Pedrera et al. (2021), who proposed values of about 30–40 km. Nevertheless, it is consistent with our interpretation of mantle exhumation, which suggests extension values higher than 60 km (Jammes et al., 2010(G3); Sutra & Manatschal, 2012) while the shortening obtained from the restoration (Figure 11) is 105 km. However, we assume that the real value must be higher due to the simplifications considered in this study regarding the scale of the work (e.g., the Bilbao Anticlinorium presents a higher complexity than represented here) and the fact that our restoration cannot quantify shortening due to mantle underthrusting. The value estimated in this study is similar to the ones proposed by Roca et al. (2011), Quintana et al. (2015) and Muñoz (2019).

5.3 | The role of decoupling levels during the reactivation of a hyperextended rift system

The role of decoupling levels is fundamental to understand the final architecture of the orogenic system. In the hyperextended Basque–Cantabrian rift system, up to three main decoupling levels have been identified and can be reactivated during convergence, which are: (a) the serpentinised mantle, (b) the ductile middle crust, and (c) weak horizons within the sedimentary succession (i.e., salt) (see rheological concept when restoring hyperextended rift systems explained above and Figure 14).

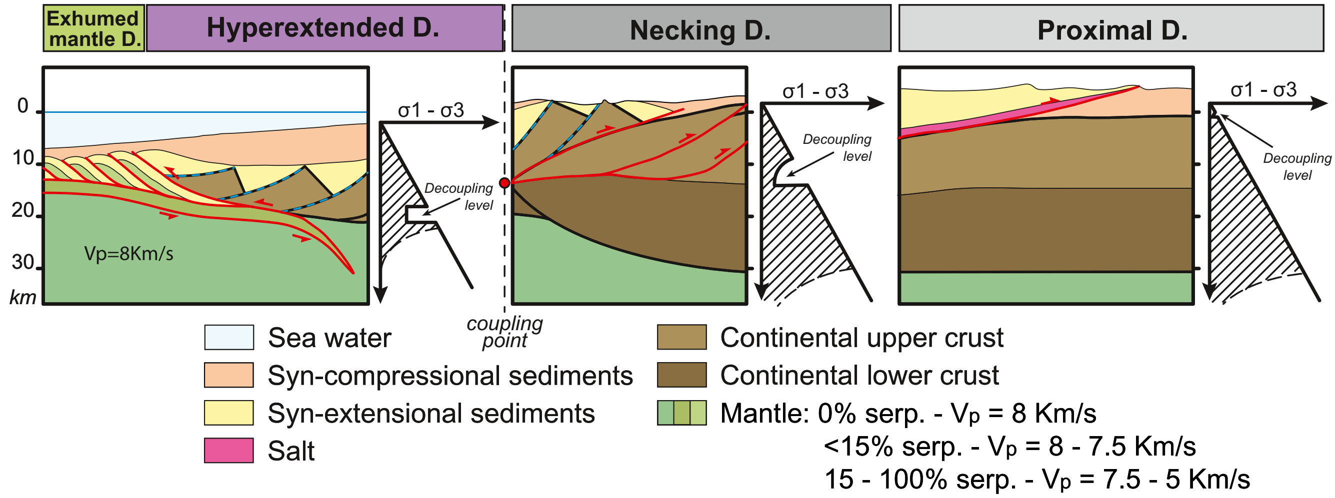

FIGURE 14 Theoretical distribution of decoupling levels at the end of extension that will control the reactivation of a hyperextended margin. At first the reactivation of the serpentinised mantle occurring in the more distal domains, initiating the underthrusting, to the later reactivation of a mid-crustal decoupling in the necking domain. Finally, the activation of the salt decoupling beneath the sedimentary cover where salt is available

In the Western and Central sections presented in this study, similarities and differences can be observed. The onset of compression is difficult to constrain due to the overprint observed in the Central section and the lack of drill hole data in the Western section. Moreover, in contrast to collisional systems that are tightly linked to the creation of topography and well documented in the Pyrenees s.s. (e.g., Boillot & Capdevila, 1977; McClay et al., 2004; Mencos et al., 2015), the age of initial subduction remains difficult to date. However, regional observations from the offshore Parentis area, located in the eastern North Iberian margin (e.g., Ferrer et al., 2014; Pérez-García et al., 2009), suggest that onset of compression started during the Late Cretaceous (Santonian/Campanian). Moreover, local observations near some diapirs (e.g., Campanian sediments onlapping Cenomanian sandstones are observed near Salinas de Rosío diapir) support the syn-contractional character of the Uppermost Cretaceous to Cenozoic succession. Despite the lack of abundant and strong field evidence, from a kinematic point of view, onset of compression is constrained based on magnetic anomalies in the North Atlantic (Macchiavelli et al., 2017).

Péron-Pinvidic et al. (2008) and Lundin and Doré (2011) suggested that the first decoupling level used during the reactivation of a rifted margin was the serpentinised mantle, which is underthrust beneath stronger and denser fresh mantle. The underthrusting and reworking of exhumed mantle with the serpentinised mantle acting as a decoupling level has been interpreted in the Western section (Cadenas et al., 2020). Although not well imaged, part of the distal domain is interpreted to be underthrust and reworked. We suggest that this event had few or no topographic response in the proximal domains exposed onshore. The exact structure of the reactivated zone is not understood in detail but based on analogies from field observations in the Alps (Epin et al., 2017), we speculate that the strongly serpentinised upper mantle acted as a decoupling/shear zone, while the less serpentinised underlying mantle, characterised by higher densities and velocities and lower frictional coefficients, formed duplexes over the subducting, stronger and unserpentinzed mantle.

The subsequent evolution is different in the two sections. In the Western section, the main decoupling level used during the subsequent stage was the mid-crustal level allowing the reactivation of previous extensional shear zones and, eventually, creating new thrusts ramping up through the crust and resulting in crustal thickening (Cadenas et al., 2020). However, in the proximal domain, i.e., in the Polientes basin and Folded Band, as well as in the necking domain, where salt was present, compressional structures detached on the Upper Triassic salt horizon. Thus, a complex interplay between thick and thin skin reactivation can be observed (Figure 12). By contrast, the Central section preserved a continuous salt layer at the end of extension, which allowed for the accommodation of most of the contractional deformation by transporting the sedimentary infill to the south on top of the foreland basins. No evidence of contractional structures are observed in the Iberian crust in the central part of the Basque–Cantabrian Pyrenees and just few reactivated normal faults are interpreted in the asymmetric European margin (Figure 11).

6 | CONCLUSION

Two main questions guided this work. The first addressed the present-day structure and architecture of the Basque–Cantabrian Pyrenees and the second studied the role of the rift template on subsequent compressional reactivation and, more precisely, how the former hyperextended system was reactivated. Based on geological observations and geophysical interpretations, we developed two cross-sections through the central and western Basque–Cantabrian Pyrenees. The Central section shows a classical double wedge orogenic architecture with two tectonic plates implicated and the sedimentary cover deformed in a thin-skinned structural style. By contrast, the Western section shows an intraplate compressional architecture where both thin-skinned and thick-skinned structural styles controlled the final architecture.

Moreover, while both sections may have undergone a similar initial reactivation during which the exhumed serpentinised mantle was used as the main decoupling level, the subsequent evolution might have been substantially different between the two sections. In the Central section, salt controlled the reactivation and resulted into decoupling of the sedimentary cover from the underlying basement. Thus, this section shows a classical thin-skinned architecture in which basement structures played a minor role during compression. By contrast, the Western section shows an intraplate orogenic architecture in which only the Iberian plate is involved and, unlike the Central section, collision with the conjugate margin did not occur. In the interpretation presented here, the final architecture of the Western section shows two distinct north and south dipping underthrusting architectures that are separated in space and likely also in time. To the north, the section is limited by the southward underthrusting of exhumed mantle (i.e., Bay of Biscay) whereas to the south, a northward underthrusting of the Iberian lower crust resulted into the indentation and thickening of the Iberian crust. On top, a combination of thick- and thin-skinned structural styles coexists due to the uneven distribution of salt.

This study integrates the three fundamental concepts: (a) restoration (Figure 13); (b) rheology (Figure 14); and (c) polyphase versus multistage rifting (Figure 2). All the three have fundamental implications in analysing and restoring collisional orogens and deciphering the underlying processes.

The Basque–Cantabrian Pyrenees offer the possibility to propose a complete kinematic reconstruction of an orogenic system back to its initial hyperextended state. However, it is not a unique place. Most collisional orogens may have gone through similar stages that may have been obliterated by the complexity of an orogenic overprint. Unravelling the rift inheritance is not a detail, but necessary to understand orogenic processes. This study is a first step, others are necessary to further improve our understanding of the growth of orogenic systems. Thus, the major conclusion of this paper is that the recognition and understanding of the nature and distribution of decoupling levels during extension and subsequent reactivation are essential to reconstruct the structural evolution associated with the formation and reactivation of hyperextended rift systems or rifted margins.

ACKNOWLEDGEMENTS

This work was supported by the OROGEN Project. The seismic and borehole data have been provided by the Instituto Geológico y Minero de España (IGME) and Midland Valley is also thanked for providing the Move software. We thank Nick Kusznir for helping with the depth conversion process and Rodolphe Lescoutre and the Orogen community for fruitful geological discussions. Kerry Gallagher as deputy editor, as well as the reviewers Antonio Pedrera, Antoni Teixell, Luis Quintana and Hugh Sinclair are acknowledged for their constructive comments, which significantly improved the initial manuscript.

PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1111/bre.12595.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

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How to cite this article: Miró, J., Manatschal, G., Cadenas, P., & Muñoz, J. A. (2021). Reactivation of a hyperextended rift system: The Basque–Cantabrian Pyrenees case. *Basin Research*, 33, 3077–3101. https://doi.org/10.1111/bre.12595