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RESEARCH ARTICLE

10.1002/2014TC003529

Key Points:

- Three-dimensional rift architecture depends on the prerift structuration of the lithosphere
- The rift systems presented are strongly segmented both offshore and onshore
- The formation of the Pyrenean orogen is controlled by rift domain inheritance

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Formation and deformation of hyperextended rift systems: Insights from rift domain mapping in the Bay of Biscay-Pyrenees

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Abstract The Bay of Biscay and the Pyrenees correspond to a Lower Cretaceous rift system including both oceanic and hyperextended rift domains. The transition from preserved oceanic and rift domains in the West to their complete inversion in the East enables us to study the progressive reactivation of a hyperextended rift system. We use seismic interpretation, gravity inversion, and field mapping to identify and map former rift domains and their subsequent reactivation. We propose a new map and sections across the system illustrating the progressive integration of the rift domains into the orogen. This study aims to provide insights on the formation of hyperextended rift systems and discuss their role during reactivation. Two spatially and temporally distinct rift systems can be distinguished: the Bay of Biscay-Parentis and the Pyrenean-Basque-Cantabrian rifts. While the offshore Bay of Biscay represent a former mature oceanic domain, the fossil remnants of hyperextended domains preserved onshore in the Pyrenean-Cantabrian orogen record distributed extensional deformation partitioned between strongly segmented rift basins. Reactivation initiated in the exhumed mantle domain before it affected the hyperthinned domain. Both domains accommodated most of the shortening. The final architecture of the orogen is acquired once the conjugate necking domains became involved in collisional processes. The complex 3-D architecture of the initial rift system may partly explain the heterogeneous reactivation of the overall system. These results have important implications for the formation and reactivation of hyperextended rift systems and for the restoration of the Bay of Biscay and Pyrenean domains.

1. Introduction

The description of repeated opening and closing of oceanic basins also referred to as the “Wilson Cycle” [Wilson, 1966] represents one of the main achievements of the plate tectonic theory. Plate tectonic cycle evolution suggests that mountain belts build on the former site of conjugate rifted margins and intervening oceanic domains. Therefore, the understanding of the formation and deformation of rift systems is critical to further understand plate tectonics. Over the past decades, the development of high-resolution long-offset seismic reflection data improved the imaging of the crustal architecture of rifted continental margins. These geophysical data combined with drill hole observations show that many rifted continental margins are formed by hyperextended domains consisting in extremely thinned continental crust and/or exhumed subcontinental mantle (e.g., Iberian margin: *Boillot et al.* [1987] and *Péron-Pinvidic and Manatschal* [2009]; Exmouth plateau: *Driscoll and Karner* [1998]; West African margin: *Contrucci et al.* [2004], *Aslanian et al.* [2009], and *Unternehm et al.* [2010]; mid-Norwegian margin: *Osmundsen and Ebbing* [2008]; and Australian and Antarctica margins: *Espurt et al.* [2012]).

In the meantime, on land studies in mountain belts showed that remnants of hyperextended domains could also be identified in internal parts of collisional orogens (e.g., Alps: *Lemoine et al.* [1987], *Manatschal* [2004], *Mohn et al.* [2010], *Masini et al.* [2012], and *Beltrando et al.* [2014]; Pyrenees: *Lagabrielle and Bodinier* [2008], *Jammes et al.* [2009], *Lagabrielle et al.* [2010], *Clerc et al.* [2012, 2013], and *Masini et al.* [2014]; and Caledonides: *Andersen et al.* [2012]). In spite of these discoveries, most studies on the formation of collisional orogens have not yet integrated the complexity of the precollisional rift architecture. The implications of the former rift-related thinning and the role of rift inheritance are progressively being further investigated [e.g., *Roca et al.*, 2011; *Jammes et al.*, 2014; *Mohn et al.*, 2014].

In this study, we focus on the Bay of Biscay and the Pyrenees, one of the rare examples where both the formation and progressive reactivation of rifted margins can be investigated in one and the same system.

This area corresponds to a polyphased Triassic to Early Cretaceous rift system leading to the formation of hyperextended basins and ultimately oceanic crust in the western Bay of Biscay [e.g., Vergés and García-Senz, 2001, and references therein]. The Late Cretaceous to Cenozoic convergence between the European and Iberian plates led to the heterogeneous deformation of the rift system, illustrated by changes in compressional architecture along strike [e.g., Muñoz, 2002]. Reactivation was relatively moderate along the southern Cantabrian margin [e.g., Pulgar et al., 1996; Gallastegui et al., 2002; Roca et al., 2011]. In contrast, the former hyperextended rift basins from the Pyrenean-Cantabrian domain (e.g., the Mauléon and Basque-Cantabrian basins [Pedreira et al., 2007; Jammes et al., 2009; Lagabrielle et al., 2010; Roca et al., 2011]) are completely inverted and integrated into the orogenic system. At present, the compressional units characterizing the Pyrenean orogen are well known [e.g., Mattauer, 1968; Choukroune and Séguret, 1973; Mattauer and Henry, 1974; Choukroune, 1992]. In contrast, the rift-related paleogeographic domains remain poorly or only locally defined and their architecture is mainly described on 2-D sections [e.g., Jammes et al., 2009; Lagabrielle et al., 2010; Masini et al., 2014]. A well-defined and uniform definition of precompressional rift domains across the overall system is still missing. This results in controversial interpretations of the continuity of some precompressional structures and of their role during the rifting episode (e.g., the North Pyrenean fault [Mattauer and Séguret, 1971; Canérot et al., 2001; Canérot, 2008]).

The aim of this work is twofold (1) to illustrate the complex 3-D evolution of strain partitioning and architecture within hyperextended rift systems and (2) to investigate the progressive role of rift inheritance from the initiation of reactivation to continental collision. We apply for the first time a new multidisciplinary approach designed by Tugend et al. [2014] to characterize and identify diagnostic elements defining similar rift domains in offshore and onshore settings. We combine gravity inversion results and seismic interpretations with field observations to propose a new map of rift domains from the offshore Bay of Biscay to their onshore fossil equivalents preserved in the Pyrenean orogen.

The mapping approach used in our study may be used in other orogenic systems and may bring new insights on the interpretation of the architecture of collisional orogens as well as on the restoration of the spatial and temporal evolution of fossil rift systems.

2. Geological Framework

The Bay of Biscay corresponds to a V-shaped oceanic basin opened westward toward the Atlantic Ocean. Located between the European and Iberian plates, it is bordered to the North by the Western Approach and Armorican margins and to the South by the North Iberian margin (Figure 1). The eastern termination is characterized by several Mesozoic rift basins recording geophysical and/or geological evidence for extreme crustal thinning both offshore (e.g., the Parentis basin: Pinet et al. [1987], Bois and Gariel [1994], Tomassino and Marillier [1997], and Jammes et al. [2010a, 2010c]) and onshore (e.g., the Aulus basin: Lagabrielle and Bodinier [2008], Lagabrielle et al. [2010], and Clerc et al. [2012]; the Arzacq-Mauléon basin: Daignières et al. [1994], Jammes et al. [2009], Lagabrielle et al. [2010], Debros et al. [2010], and Masini et al. [2014]; and the Basque-Cantabrian basin: Pedreira et al. [2007] and Roca et al. [2011]).

2.1. Tectonic and Sedimentary Evolution of the Bay of Biscay and Pyrenean Domains

The Bay of Biscay and Pyrenean domains represent a strongly structured region that is the result of consecutive extensive and compressive tectonic cycles that initiated in the early Palaeozoic. The formation of the Variscan orogen during the Carboniferous resulted from the collision of the Laurussia and Gondwana continental margins with intervening oceanic domains and microcontinents such as Armorica (for a review, see Matte [1991, 2001]). The post-Variscan evolution is related to the emplacement of strike-slip or transform faults throughout the Late Carboniferous to the Early Permian (e.g., Toulouse fault, Cévennes fault, Ventaniella fault, and North Pyrenean fault) that strongly structured the lithosphere. Two main scenarios have been proposed for this post-Variscan evolution: one that includes a compressional episode independent of Variscan tectonics [Arthaud and Matte, 1975, 1977] and a second that proposes an extensional to transtensional phase related to the postorogenic collapse of the chain [Burg et al., 1994a, 1994b].

The following Triassic to Jurassic rift events resulted in the formation of intracontinental basins bounded by NE-SW trending normal faults that may partly reactivate Palaeozoic structures (e.g., Aquitaine basin: Curnelle et al. [1982]). They are filled by thick sequences of Triassic siliciclastics, carbonates, and evaporites

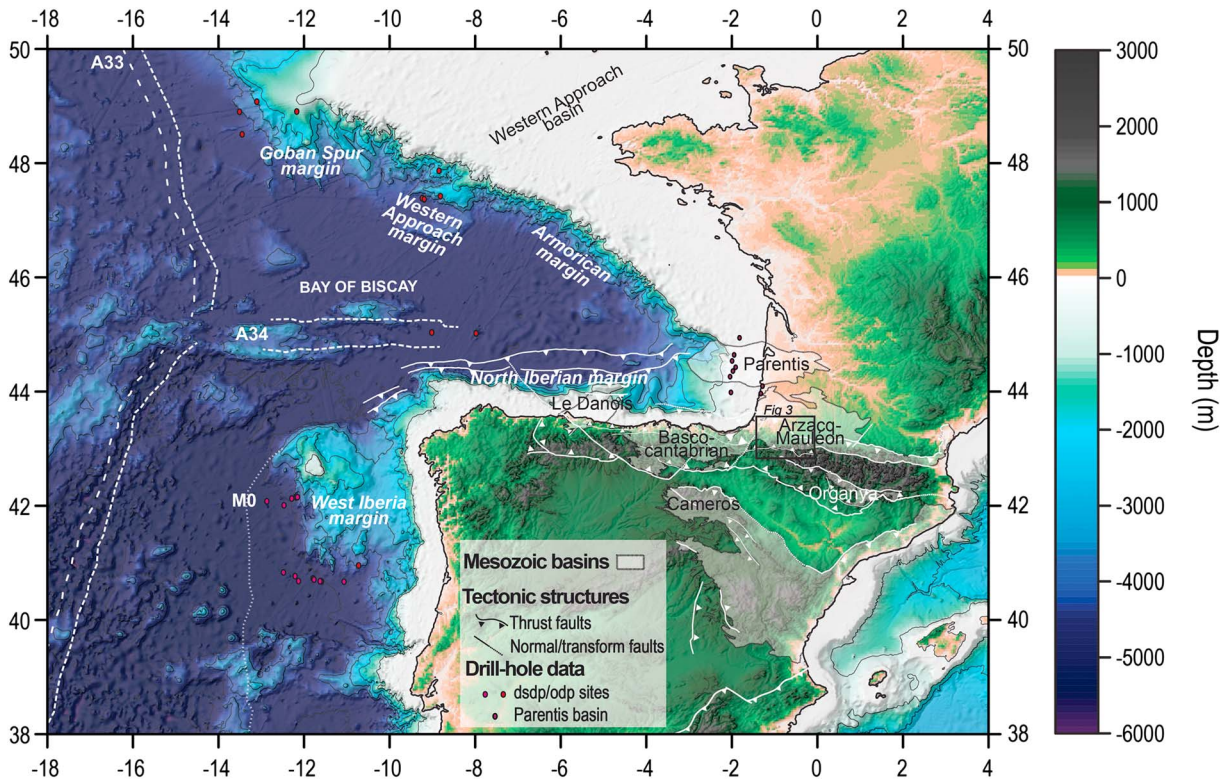


Figure 1. Bathymetric map of the Bay of Biscay and Pyrenees showing the major tectonic structures and the main Mesozoic basins. Magnetic anomalies are based on Sibuet et al. [2004].

(Germanic Facies: *Curnelle* [1983] and *Fréchengues* [1993]). Deposits belonging to the Keuper formation are associated with tholeiitic magmatism [e.g., *Montadert and Winnock*, 1971; *Winnock*, 1971; *Rossi et al.*, 2003]. The latest Triassic and Jurassic marine transgression led to the formation of a carbonate platform whose lateral extent is poorly constrained.

A major change occurred in the Late Jurassic to Early Cretaceous, related to the northward propagation of the Atlantic rift. The deposition of marine sediments in the Western Bay of Biscay is contemporaneous with the E-W reorganization of the depocenters in the present-day Arzacq, Tarbes, and Parentis basins [*Bureau de Recherches Géologiques et Minières (BRGM) et al.*, 1974; *Biteau et al.*, 2006]. Extreme crustal thinning in the Bay of Biscay resulted in continental breakup and seafloor spreading initiation during latest Aptian to early Albian time [e.g., *Montadert et al.*, 1979; *Boillot*, 1984]. At this stage, crustal and mantle exhumation in onshore rift basins (e.g., Basque-Cantabrian and Arzacq-Mauléon basins: *Jammes et al.* [2009], *Lagabrielle et al.* [2010], and *Roca et al.* [2011]) is related to an acceleration of subsidence. This event is recorded by the deposition of deep marine sediments [*Ducasse and Velasque*, 1988]. It is accompanied by alkaline magmatism (including intrusions and volcanic products) from late Aptian to early Santonian time (~113 to 85 Ma [*Lamolda et al.*, 1983; *Montigny et al.*, 1986]).

Onset of compressional deformation is recorded in Santonian sediments by a regional unconformity [*Garrido-Megías and Ríos*, 1972; *McClay et al.*, 2004] and a weak reactivation in the Northern Bay of Biscay [*Thinon et al.*, 2001]. The major collision phase was reached during the Eocene and continued until the end of the Oligocene [*Muñoz*, 2002; *Vergés et al.*, 2002] with the generalized uplift of the chain and formation of foreland basins.

Because this paper is mainly focused on the formation and reactivation of hyperextended basins, we will subdivide the sedimentary deposits into prehyperextension, synhyperextension, and posthyperextension and syncompressional to postcompressional sequences.

2.2. A Controversial Late Jurassic to Early Cretaceous Plate Kinematic Context

At present, there is no consensus on the Late Jurassic to Early Cretaceous kinematic evolution leading to the formation of the Bay of Biscay. Opening in a back-arc setting is proposed by *Sibuet et al.* [2004] and *Vissers*

and Meijer [2012]. Other hypotheses suggest that left-lateral strike-slip to transtensional deformation was accommodated along the North Pyrenean fault or within pull-apart basins [e.g., Le Pichon *et al.*, 1971; Mattauer and Séguret, 1971; Choukroune and Mattauer, 1978].

Most of the plate kinematic models proposed previously rely on the identification and restoration of magnetic anomalies of the M-series in the North Atlantic between Iberia and Newfoundland [e.g., Olivet, 1996; Srivastava *et al.*, 2000; Sibuet *et al.*, 2004]. These restorations assume minor prebreakup movements. This hypothesis is questioned by the discovery of hyperextended domains that can be mapped over hundreds of kilometers continentward of the first unambiguous magnetic anomaly related to breakup (Tucholke *et al.* [2007] or Péron-Pinvidic and Manatschal [2009]). Controversies also arise from the interpretation of the age and nature of magnetic anomalies in the Bay of Biscay and the southern North Atlantic in general. The M-series (M3–M0, 126 to 118.5 Ma) identified in the Iberia-Newfoundland and Bay of Biscay margins [e.g., Sibuet *et al.*, 2004] have been reinterpreted as either related to mantle exhumation [Sibuet *et al.*, 2007] or magmatic underplating [Bronner *et al.*, 2011, and references therein]. Therefore, these anomalies do not necessarily represent isochrons. This justifies a revision of existing plate kinematic models depending on the restoration of the M-series magnetic anomalies (see Bronner *et al.* [2011, 2012] and Tucholke and Sibuet [2012]).

Based on these new discoveries combined with field observations, new plate kinematic scenarios were proposed. Some authors suggested that the left-lateral displacement of the Iberian plate was already initiated in the Late Jurassic, resulting in a transtensional setting along the European and Iberian plates [e.g., Wortmann *et al.*, 2001; Schettino and Scotese, 2002; Canérot, 2008; Jammes *et al.*, 2009, 2010a]. Indirect evidence for this pre-Aptian movement comes from the thick Late Jurassic to Early Cretaceous sedimentary sequences in the Parentis and Cameros basins [e.g., Salas and Casas, 1993; Mas *et al.*, 1993; Jammes *et al.*, 2010a]. A major break occurred in Aptian time [Olivet, 1996] as a result of the counterclockwise rotation of Iberia [Gong *et al.*, 2008; Jammes *et al.*, 2009, 2010a]. As a consequence of this rotation, a NNE-SSW to NE-SW extension is initiated in rift basins preserved onshore [Jammes *et al.*, 2009; Lagabrielle *et al.*, 2010; Roca *et al.*, 2011; Tavani, 2012] as emphasized by the NE-SW segmentation observed (e.g., Pamplona, Toulouse, and Cevennes faults). These NE-SW transfer faults cross the Iberian-European plate boundary and are locally sealed by Albian sediments (Pamplona fault, between the Basque-Cantabrian and Arzacq-Mauléon basins [Razin, 1989; Claude, 1990]). In this paper, we will show that the complex polyphased history strongly influenced the 3-D architecture of the Bay of Biscay-Parentis and Pyrenean-Basque-Cantabrian rift systems.

2.3. Pyrenean Reactivation and Shortening Estimations

The palaeogeographic evolution of the Bay of Biscay and Iberia-Newfoundland rifted margins is relatively well constrained after the quiet magnetic period of the Cretaceous and the identification of the magnetic anomaly 34 (83 Ma, Santonian) [e.g., Roest and Srivastava, 1991; Rosenbaum *et al.*, 2002]. The northward movement of the African plate during the Late Cretaceous resulted in the initiation of compression in the Bay of Biscay and the Pyrenees. Although the shortening direction is reasonably coherent between different kinematic models (N-S to NE-SW, respectively, [Roest and Srivastava, 1991; Rosenbaum *et al.*, 2002]), the total amount of Late Cretaceous relative to Cenozoic shortening is still a matter of debate. At the scale of the Bay of Biscay and Pyrenean-Cantabrian orogen, the transition from embryonic subduction in the North Iberian margin to continental collision in the Pyrenees is interpreted to have resulted from an increase in convergence from west to east. Based on the restoration of magnetic anomalies, Rosenbaum *et al.* [2002] estimated about 144 km of shortening in the Western Pyrenees as compared to 206 km in the Eastern Pyrenees. Classical palinspastic restorations of sections across the Pyrenees have usually been based on restorations of the thick-skin deformation observed in the Axial zone [e.g., Teixell, 1998; Muñoz, 2002]. This approach underestimates the shortening related to the reactivation of hyperextended domains. It is therefore unable to decipher the overall amount of convergence accommodated in the Pyrenean domain.

3. Mapping Hyperextended Domains: Combining Onshore and Offshore Observations

3.1. Hyperextended Rift Domains: Terminology and Identification

In spite of variable magmatic, structural, and sedimentary evolution that in turn depend on the amount and rates of extension, thermal history, and inheritance, most magma-poor rifted margins share comparable

large-scale architectures [Reston, 2009; Péron-Pinvidic *et al.*, 2013]. Using first-order geological and/or geophysical observations, distinctive structural rift domains can be identified. From continent to ocean, the following domains can be distinguished: the proximal, necking, hyperthinned, exhumed mantle, and oceanic domains (Figure 2, see also Figure 1 in Tugend *et al.* [2014] for comparison with alternative classifications). Extensional deformation related to the formation of these domains is polyphased, progressively localizing toward the location of final breakup [e.g., Péron-Pinvidic and Manatschal, 2009; Sutra *et al.*, 2013]. Therefore, these domains reflect successive steps in the formation of magma-poor rifted margins, suggesting that they may also correspond to genetic domains.

We use the approach developed by Tugend *et al.* [2014] to enable the characterization and identification of comparable rift domains in present-day magma-poor rifted margins and their fossil analogues preserved in collisional orogens (Figure 2). This approach and its related results are summarized hereafter. Offshore, quantitative techniques provide estimations of accommodation space, crustal thickness, and lithosphere thinning while seismic interpretation enables the recognition of extensional settings (low- and high- β settings [Wilson *et al.*, 2001]). Onshore, the identification relies on the description of key outcrops preserving the nature of sediments, basement rocks, and of their interface. This geological/geophysical approach can be further used as an interface between onshore and offshore observations and to suggest analogies. Offshore seismic interpretations can take advantage of onshore observations regarding the nature of sediment, basement, and of their interface. The large-scale geometry and stratigraphic architecture imaged offshore can be used to restore onshore fossil remnants back into a rifted margin context (Figure 2).

This combined approach is applied for the first time to map the overall rift system from the offshore Bay of Biscay to its onshore fossil analogues preserved in the Pyrenees (including the Basque-Cantabrian basin). Interpretations of structural domains along offshore seismic reflection profiles are combined with mapping of crustal thickness, lithosphere thinning, and Moho depth using gravity inversion. Onshore mapping relies on the identification of remnants of the rift system preserved within well-defined compressive tectonic units.

3.2. Onshore: Mapping Remnants of the Rift System

The mapping of rift domains in onshore deformed analogues depends on the ability to decipher the deformation and sedimentary history. The definition of compressive units is based on the identification of first-order compressive structures corresponding to the first generation of thrusts. These coherent tectonic units are usually bounded by major thrust contacts but are often only weakly deformed internally. The methodology used to map rift domains onshore is here exemplified by the example of the Arzacq-Mauléon basin. A summary of main observations is given below and summarized in Figure 3 (detailed descriptions of field observations in Jammes *et al.* [2009] and Tugend *et al.* [2014]).

3.2.1. Defining Coherent Tectonic Units: History of Compressional Deformation

In the Arzacq-Mauléon basin, different phases of deformation can be identified resulting in two opposite directions of thrusting. The shortening related to the initiation of Pyrenean compression is accommodated by Late Cretaceous, south-directed thrust systems (e.g., Sarrance, Mail Arrouy, or Lakoura thrust systems [Casteras *et al.*, 1970a, 1970b, 1970c; Teixell, 1998]; Figures 2 and 3). This initial sampling of the distal parts of the former rift system is locally overprinted by a second phase of deformation resulting in north-directed thrusts (e.g., the Saint Palais, Sainte Suzanne, and Ossau thrusts [Canérot *et al.*, 2001]) and south-directed backthrusting in the Axial zone (e.g., Gavarnie and Guarga thrust systems [Teixell, 1998]). As a result of this structural analysis, several tectonic units can be defined within the Arzacq-Mauléon basin (Figure 2). Within each unit, key outcrops preserving primary contacts between basement and the prehyperextensional, synhyperextensional, and posthyperextensional sediments can be found [e.g., Canérot, 2008; Jammes *et al.*, 2009; Lagabrielle *et al.*, 2010; Debroas *et al.*, 2010; Masini *et al.*, 2014].

3.2.2. Outcrops Preserving Remnants of the Former Rift System

Remnants of rift domains can be defined in the Arzacq-Mauléon basin from South to North (Figures 2 and 3, see also Tugend *et al.* [2014]).

In the axial zone (southernmost external Pyrenean unit)—former proximal rift domain, upper crustal rocks from the basement are eroded and directly overlapped by shallow marine posthyperextensional sediments (Figure 3) suggesting no or only a weak rift-related thinning.

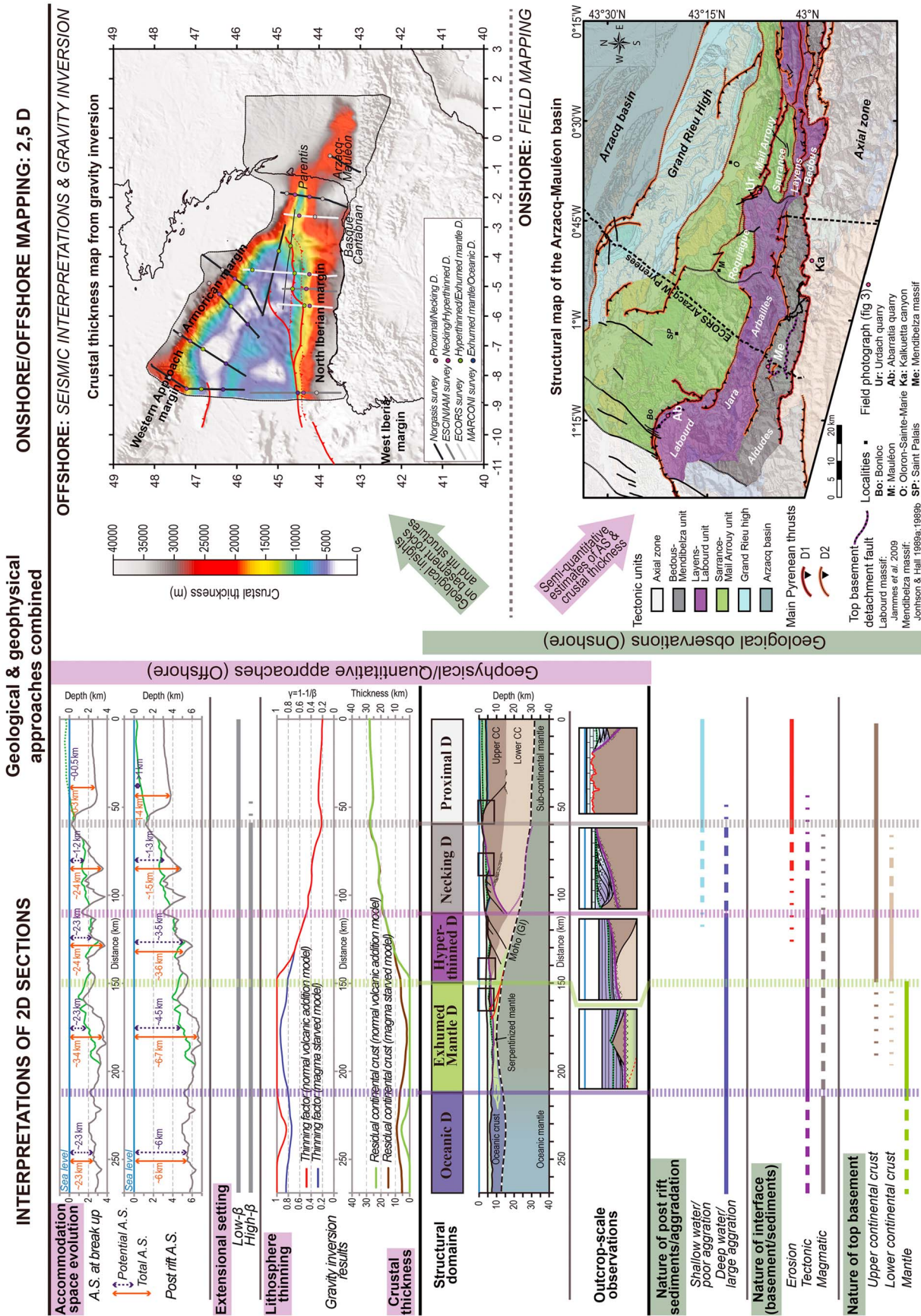


Figure 2. Philosophy of the onshore/offshore approach applied in this study. Left side: synthetic diagram combining geophysical (upper part) and geological (lower part) diagnostic elements of structural/genetic rift domains at continental rifted margins (after Tugend et al. [2014]). The terminology used in this study is indicated in the central part. Right side: this approach is used to map rifted domains offshore (gravity inversion results and seismic interpretations) and onshore (structural map of the Mauléon basin and of the southern part of the Arzacq basin and field observations).

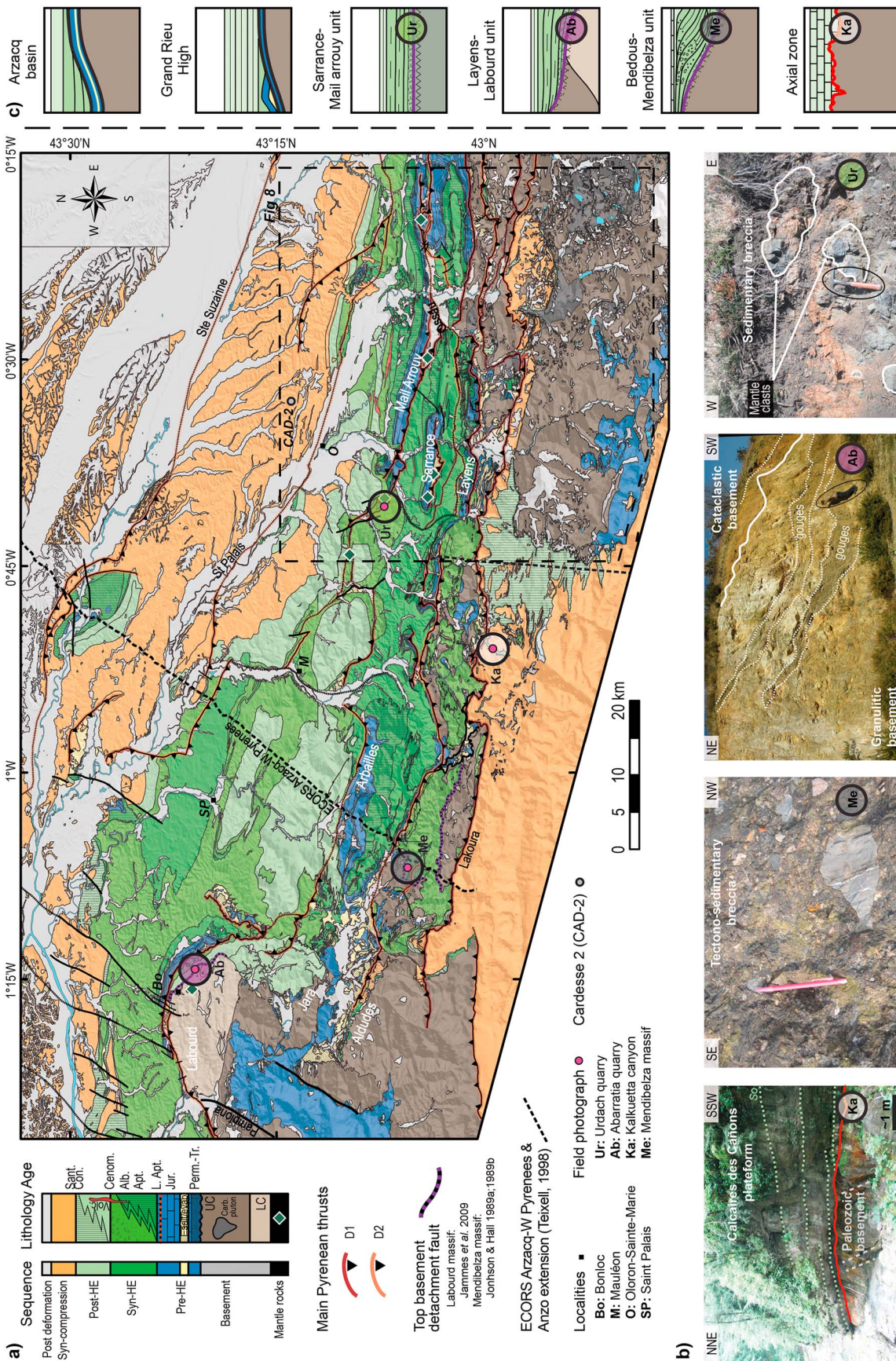


Figure 3. (a) Geological map of the Mauleon basin and the Southern part of the Arzacq basin. Lithologies and age of sequences are synthesized in a log. (b) Field photographs of the main observations. Ka: Kalkuetta canyon, contact between the "Calcaires des Cañons" platform and underlying eroded Palaeozoic basement (0°50'59,72"W/42°59'17,31"N). Me: Mendibelza massif, tectono-sedimentary breccia at the contact with the top basement detachment fault (1°6'55,78"W/43°5'40,16"N). Ar: Abarraia quarry, deformation of the granulitic basement and cataclastic overprint characterizing the top basement detachment fault described by *Jammes et al.* [2009] (1°14'17,69"W/43°20'55,64"N). Ur: Urdach quarry, synrift breccia reworking mantle and basement rocks (0°40'39,62"W/43°7'10,91"N). (c) Simplified cartoons of the key observations from remnants of the former rift system preserved in the Pyrenean nappe stack. Axial zone unit: remnant of the proximal domain. Bedous-Mendibelza unit: remnant of the Necking domain. Layens-Labourd unit: remnant of the hyperthinned domain. Sarrance-Mail arrouy unit: remnant of the exhumed mantle domain. Grand Rieu High: remnant of the hyperthinned domain. Arzacq basin: transition from proximal to necking domain. [Burger et al., 1972], Iholdy [Boissonnas et al., 1974], Laruns-Sompport [Ternet et al., 1970a], Orthez [Henry et al., 1970a], Lourdes [Casteras et al., 1970b], Oloron-Sainte-Marie [Casteras et al., 1970a], Orthez [Henry et al., 1970a], Mauléon-Licharre [Boltenhagen et al., 1976], Moitaàs [Delfaud et al., 1982], Pau [Bureau de Recherches Géologiques et Minières, 1963], Saint-Jean-Pied-de-Port [Le Pochat et al., 1978], and Tardets [Casteras et al., 1971].

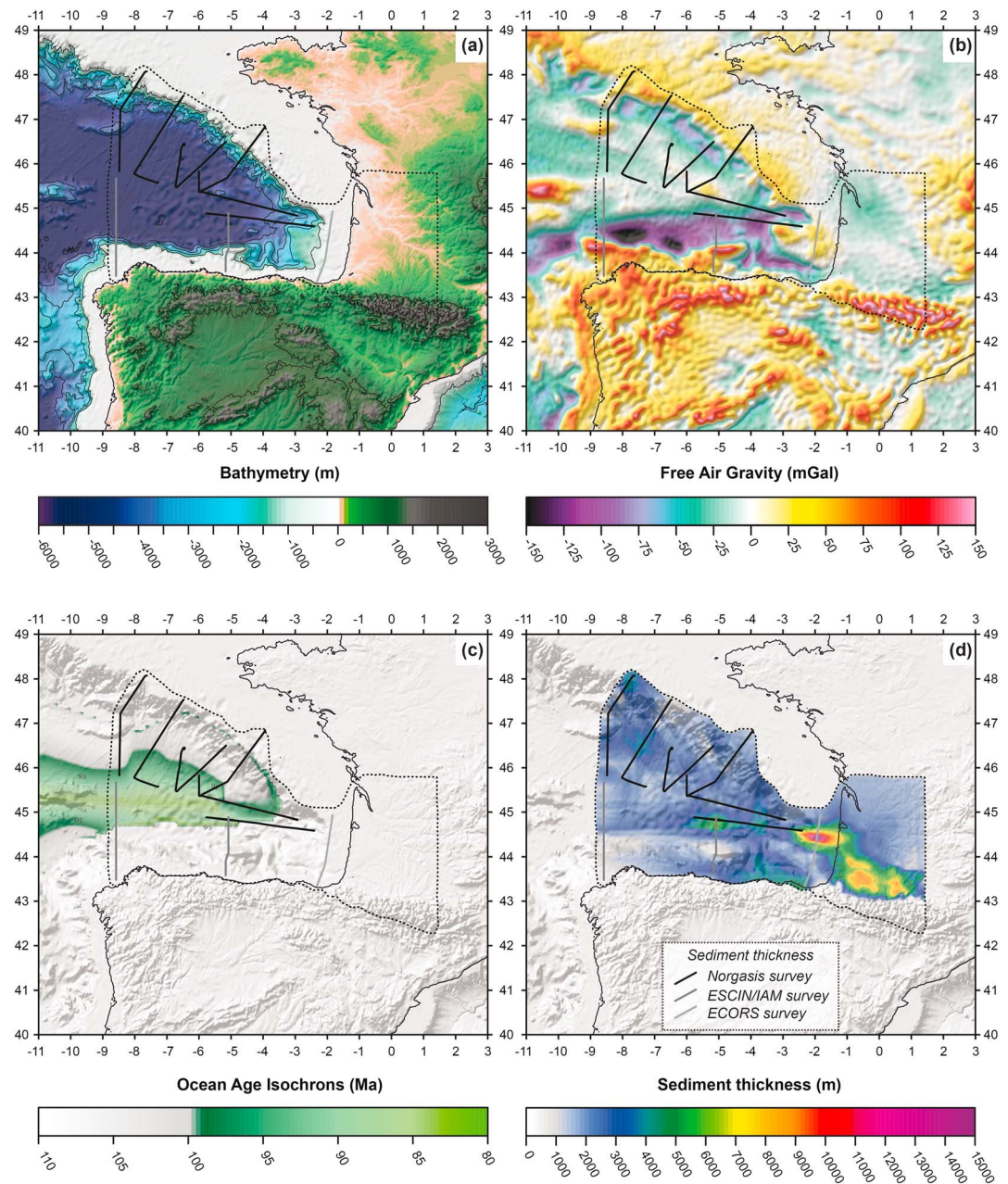


Figure 4. Raw data used for the gravity inversion. (a) Bathymetry and topography [Smith and Sandwell, 1997], (b) free-air gravity [Sandwell and Smith, 2009], and (c) oceanic age isochrones [Müller et al., 1997]. (d) Sediment thickness is derived from offshore seismic interpretations (raw seismic lines from the Norgasis survey: Thion [1999] and Avedik et al. [1993, 1996]; ECORS Bay of Biscay: Pinet et al. [1987] and Bois and Gariel [1994]; IAM 12 and ESCIN 4 seismic lines: Gallart et al. [2004], Gallastegui et al. [2002], and Banda et al. [1995]) and the depth to basement map of the Aquitaine basin from Serrano et al. [2006].

In the Bedous-Mendibelza unit—former necking domain, the exhumed basement of the Mendibelza and Igounze massifs [Johnson and Hall, 1989a, 1989b; Miranda-Aviles et al., 2005; Masini et al., 2014] is overlapped by synhyperextension sequences progressively thickening and deepening northward. This domain marks a progressive transition from shallow to deep water sediments (conglomerates from the Mendibelza formation, passing laterally to turbidites and marls) as a consequence of the initiation of crustal thinning.

In the Layens-Labourd unit—former hyperthinned domain, granulites derived from the prehyperextension middle crust [Vielzeuf, 1984] are exhumed in the Labourd massif [Jammes et al., 2009]. They are overlapped by

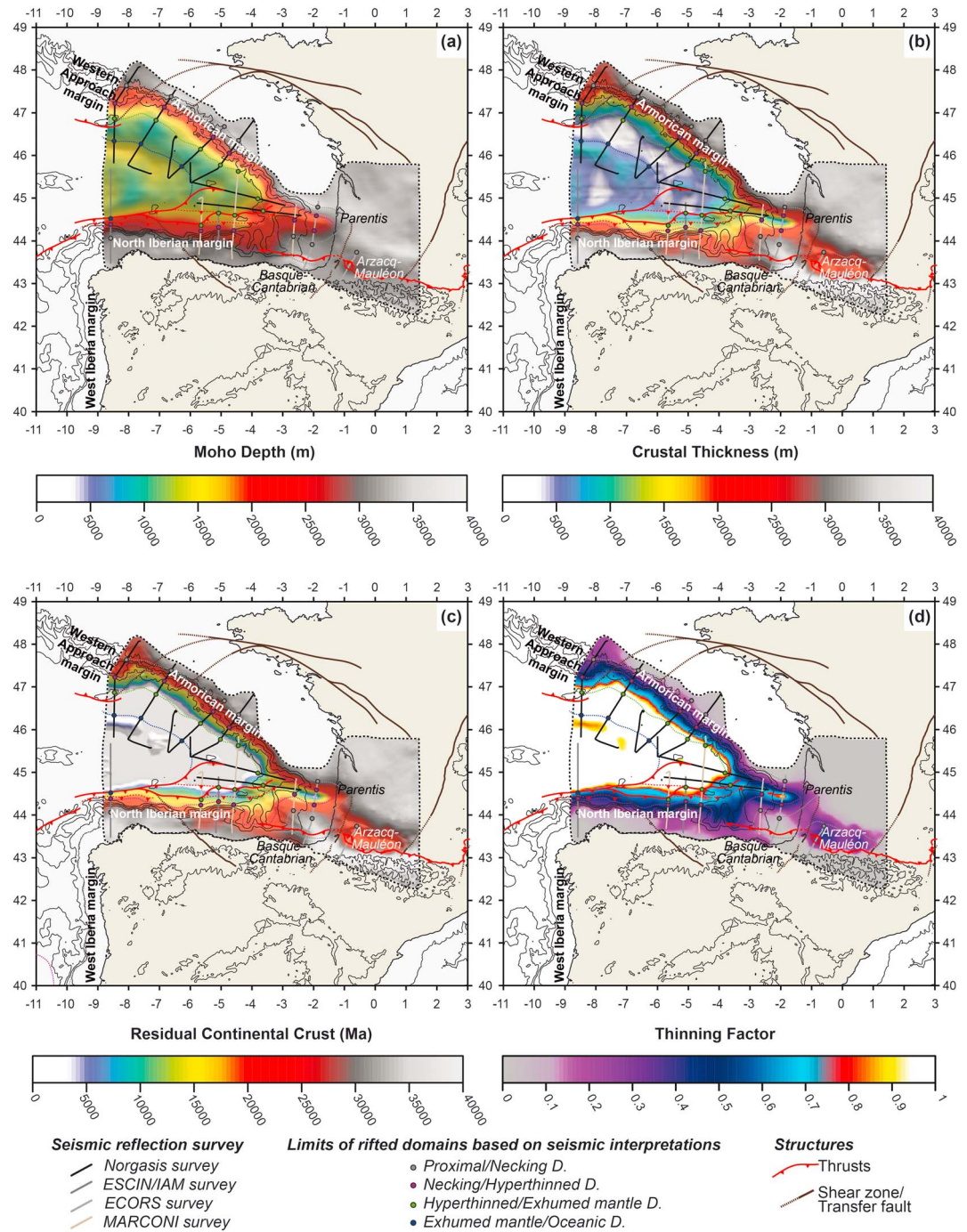


Figure 5. (a) Moho depth, (b) crustal thickness, (c) residual continental crust, and (d) continental lithosphere thinning factor maps resulting from gravity inversion. The limits of rifted domains determined from seismic interpretations are also indicated.

late synhyperextension to posthyperextension sediments containing reworked pieces of exhumed granulite (Bonloc breccias [Claude, 1990]). Observations from this domain indicate that at least locally, the whole upper crust had been removed and consequently the crust had to be thinned.

In the Sarrance-Mail Arrouy unit (internal orogenic unit)—former exhumed mantle domain, synhyperextension sediments are more than 4 km thick near the city of Mauléon [Roux, 1983; Fixari, 1984; Souquet et al., 1985]. Numerous outcrops of mantle rocks are observed that are associated to thin slices of continental crust [Duée et al., 1984; Fortané et al., 1986; Lagabrielle et al., 2010; Debroas et al., 2010]. Mantle rocks are also

Table 1. Parameters Used for Gravity Inversion

Parameters	Value and Reference Data Set
Critical thinning factor (γ)	0.7
Reference crustal thickness	40 km
Breakup age	110 Ma
Volcanic additions	7 km

reworked in Cenomanian breccias indicating that at least locally, mantle rocks had to be exhumed at the seafloor (Figure 3; e.g., Urdach breccias: *Jammes et al.* [2009], *Lagabrielle et al.* [2010], *Debroas et al.* [2010], and *Masini et al.* [2014]).

In the Grand Rieu high unit—former hyperthinned domain, a thick posthyperextension sequence may directly onlap onto basement as indicated by the Cardesse 2 drill hole (location Figure 3 [BRGM et al., 1974; Serrano et al., 2006]). This local observation may reflect a large sedimentary aggradation consecutive to posthyperextension thermal subsidence in a former hyperthinned domain (Figure 2).

In the Arzacq basin—former proximal to necking domain, the progressive thinning of the continental crust (from about 25 km to the north to about 20 km below the Grand Rieu high [Daignières et al., 1982, 1994]) is concomitant with a southward thickening of synhyperextension sequences [Biteau et al., 2006]. This progressive creation of accommodation space may indicate the progressive transition from a proximal to a necking domain (from north to south).

The mapping of former rift domains onshore relies on the exposed surface observations (here locally supported by drill hole data) and reflects the integration of the former rift into the orogenic system.

3.3. Offshore: Seismic Interpretations and Gravity Inversion Mapping

Gravity inversion results have already been used to characterize and identify structural domains on 2-D sections at rifted continental margins (Figure 2 [Tugend et al., 2014]). In this paper, the aim is to associate this technique with local seismic interpretations to map and unravel the spatial evolution of structural/genetic rift domains from the offshore Bay of Biscay to the onshore Mesozoic Arzacq basin buried under posthyperextension sediments and the thick syncompressional sequences of the Tertiary Aquitaine basin.

3.3.1. Gravity Inversion: Scheme and Data Sets

Gravity inversion was based on public domain data (Figure 4): free-air gravity [Sandwell and Smith, 2009], bathymetry [Smith and Sandwell, 1997], and oceanic isochrons [Müller et al., 1997]. Information on sedimentary thickness comes from a compilation of offshore seismic interpretations combined with the depth to basement map of the Aquitaine basin from Serrano et al. [2006] (Figure 4). Seismic reflection data were derived from different surveys: the Norgasis survey [Avedik et al., 1993, 1996; Thionon, 1999], the ECORS Bay of Biscay section [Pinet et al., 1987; Bois and Gariel, 1994], the IAM 12, and the ESCIN 4 seismic lines [e.g., Banda et al., 1995; Gallastegui et al., 2002; Gallart et al., 2004].

Moho depth, crustal thickness, continental lithosphere thinning factor, and residual continental crust maps (Figure 5) were produced by gravity inversion. This technique includes a thermal gravity anomaly correction and a parameterization of decompression melting to predict volcanic additions (detailed scheme described by Greenhalgh and Kuszniir [2007], Chappell and Kuszniir [2008a], Alvey et al. [2008], and Cowie and Kuszniir [2013]; parameters for this study are presented in Table 1). A compaction-controlled density-depth relationship is applied to sedimentary sequences [Chappell and Kuszniir, 2008b].

3.3.2. Three-Dimensional Mapping Derived From Gravity Inversion and Seismic Interpretations

The maps resulting from gravity inversion presented in Figure 5 were computed assuming a “normal” volcanic addition (corresponding to a standard oceanic crust thickness of about 7 km [White et al., 1992]). This solution assumes the occurrence of decompression melting during rifting once the lithosphere is thinned below a critical value ($\gamma = 0.7$; Table 1), producing magmatic additions to the extended continental crust. In the case of a magma-poor rifted margin as proposed for the Bay of Biscay [e.g., De Charpal et al., 1978; Montadert et al., 1979; Avedik et al., 1982; Le Pichon and Barbier, 1987; Thionon et al., 2003], the transition zone between unequivocal oceanic and continental crusts may be interpreted as exhumed mantle (Figure 2). The characterization of structural domains on 2-D sections (Figure 2) partly relies on diagnostic elements

determined from gravity inversion results [Tugend *et al.*, 2014]. The combined analysis of Moho depth, crustal thickness, and lithosphere thinning maps (Figure 4) can be further used to delimit offshore structural domains and identify their evolution in 3-D.

The proximal domain presents relatively constant and limited values of crustal and lithosphere thinning (Figure 5d) and a smooth Moho topography (Figure 5a). The rapid increase in lithospheric thinning values coincides with a Moho rise delimiting the proximal from the necking domain (Figure 5a/5d). The transition from the necking to hyperthinned domain can be identified on seismic sections (Figure 2; e.g., Sutra *et al.* [2013]) and corresponds in this example to thinning values between 0.5 and 0.6 and crustal thicknesses of about 10 to 15 km (Figure 5b/5c). The beginning of the exhumed mantle domain can be interpreted at a first order at the termination of the continental crust (Figure 5c). Moho topography derived from gravity inversion [Greenhalgh and Kusznir, 2007; Chappell and Kusznir, 2008a; Alvey *et al.*, 2008] is slightly curved through this domain enabling the shallowest Moho depth to be reached (Figure 5a). Gravity inversion provides indirect observations compatible with the existence of an exhumed mantle domain in the Bay of Biscay. This hypothesis is further supported by reflection and refraction seismic interpretations [e.g., Fernández-Viejo *et al.*, 1998; Thion *et al.*, 2003; Ruiz, 2007] and by analogy with the existence of such a domain onshore (Arzacq-Mauléon; Figure 3). The oceanic domain is marked by a deepening of the Moho (Figure 5a) and a thickening of the crust at the oceanward edge of the exhumed mantle domain (Figure 5b). Residual patches of thicker crust are observed within the oceanic domain (Figure 5c/5d) and can be interpreted as a locally overthickened oceanic crust (in comparison with the 7 km thick volcanic addition used for gravity inversion; Table 1).

The resulting maps show the present-day distribution of oceanic and continental crust as well as a possible extent of exhumed mantle in the Bay of Biscay. In areas that underwent reactivation and crustal thickening during compression (e.g., the North Iberian margin), these maps need to be interpreted carefully and are further constrained by seismic interpretations. Onshore, in the Western Pyrenees, the former rift-related thinning of the northern Arzacq basin can still be deduced from lithosphere thinning and crustal thickness maps (Figure 5).

4. Map of the Bay of Biscay-Pyrenean Rift System

Offshore and onshore observations are combined to recognize, describe, and map structural/genetic rift domains and their compressional overprint from the Bay of Biscay to the Pyrenean-Cantabrian orogen (Figure 6). We apply the terminology and geological/geophysical approach described in the previous section and synthesized in Figure 2 (see also Tugend *et al.* [2014]).

4.1. Definition of Rift Domains

4.1.1. Proximal Domain

Proximal domains are characterized by only weak to no rift-related lithosphere and crustal thinning (Figure 5). Creation of accommodation space is restricted to graben and half-graben basins characterizing low- β extensional systems (Figure 2). The sedimentary record of this domain may include subaerial exposure, continental to shallow water sedimentary systems, and no or minor aggradation of postrift sequences (Figures 2 and 3).

Offshore, this domain corresponds to the continental shelves (e.g., the Armorican platform, the western part of the North Iberian shelf, near Ortegale Spur, and Landes high; Figure 6). Onshore, it can be mapped in external parts of the orogen and may be partly buried below Tertiary foreland basins such as the Duero basin (south of the Basque-Cantabrian orogen), the Jaca and Ebro basins south of the Pyrenees, or in the northern part of the Aquitaine basin (Figure 6).

4.1.2. Necking Domain

Lithosphere and crustal thinning are initiated in the necking domain (Figure 5). The oceanward increasing accommodation space and deepening of the top basement coincides with the ascending Moho topography defining a taper geometry [Osmundsen and Redfield, 2011]. The necking domain is limited by the oceanward embrittlement of the continental crust in the hyperthinned domain [Pérez-Gussinyé and Reston, 2001] that controls mode of deformation of the continental crust [Sutra *et al.*, 2013]. Deformation is decoupled at midcrustal ductile levels in the necking domain [Sutra *et al.*, 2013]. In the hyperthinned domain, deformation is coupled at the scale of the crust, i.e., faults may cut through the remaining

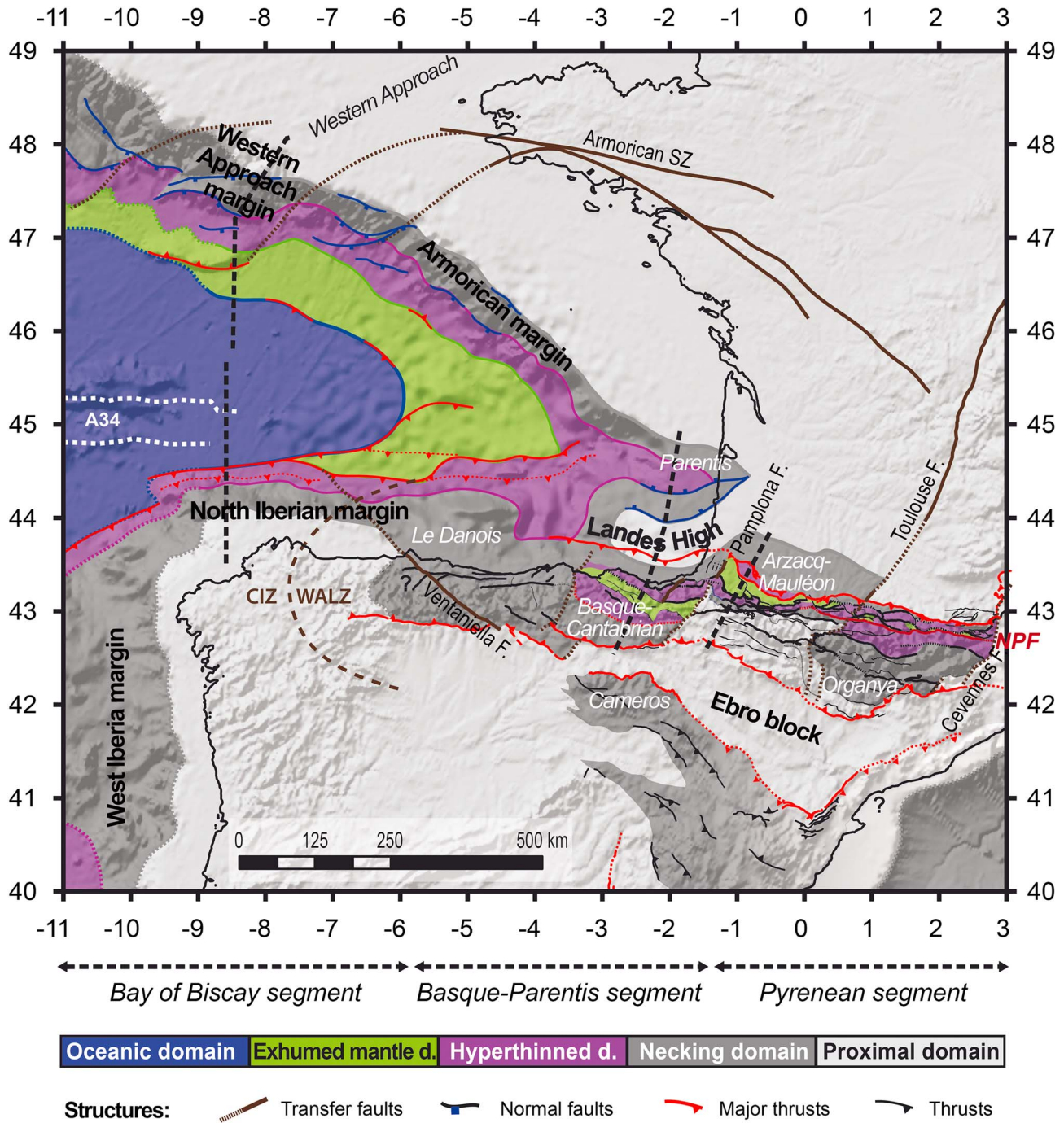


Figure 6. Map of the rift domains preserved in the Bay of Biscay and their fossil analogues from the Pyrenean domain. Extensional rift structures and thrust faults from the Armorican and Western Approach margins are based on the work of *Thinon* [1999] and own observations. CIZ: Central Iberian zone. WALZ: West Asturian-Leonese zone. NPF: North Pyrenean fault. The location of the geological sections from Figure 7 is indicated in dashed line.

continental crust and penetrate into mantle [*Pérez-Gussinyé and Reston, 2001*]. The transition from decoupled to coupled deformation at a crustal scale is interpreted to occur at the coupling point [*Sutra et al., 2013*]. It is accompanied by a tectonic migration of the deformation indicated by a change in the age of the syntectonic sediments that are getting younger oceanward (as observed for the Iberian margin [*Péron-Pinvidic et al., 2007*] or in the Alps [*Mohn et al., 2010; Masini et al., 2013*]). Tilted block geometries and/or exhumation surfaces related to top basement detachment faulting can be observed (Figure 2).

The sedimentary architecture can often be defined by offlapping packages and by onlaps backward onto the basement of the necking domain (outcrop scale observations; Figure 2). The progressive creation of accommodation space can be recorded by deltaic sedimentary systems or slope facies including gravitational systems. A transition from shallow to deeper marine environments can also be observed in underfilled basins (Figure 2).

In the Bay of Biscay, the necking domain corresponds to the continental slope of the Western Approach (over the Meriadsek Terrace), Armorican, and North Iberian margins (including the “Le Danois basin” in the eastern part; Figure 6). The southern part of the Basque-Cantabrian basin, the Organya and Pedraforca basins (as suggested by the restorations of Muñoz [1992], Vergés and García-Senz [2001], and Lagabrielle *et al.* [2010]), and most of the Arzacq basin may represent fossil analogues of this domain (Figure 6). Narrow remnants of this domain can also be mapped in basins from the eastern and western Pyrenees, respectively, south of the North Pyrenean Frontal thrust and north of the Lakoura thrust (Figure 6; e.g., in the Mendibelza massif [Masini *et al.*, 2014]).

4.1.3. Hyperthinned Domain

Continental crust is typically less than 15 to 10 km thick and associated with a large accommodation space (Figures 2 and 5). Both low- and high- β extensional settings may be observed (Figure 2) and are characterized by half-graben and hyperextended sag basin architectures [Tugend *et al.*, 2014, Figure 2]. Top basement detachment faults commonly lead to local exhumation of middle to lower crustal levels as observed in onshore fossil remnants (e.g., Manatschal [2004] and Figure 2). The infilling history of this domain mainly depends on sedimentary supply and sedimentary sources but is usually associated to thick aggradational sequences and/or deep marine sedimentary sequences (Figure 2).

The occurrence of extremely thinned continental crust was already recognized in the Parentis basin [e.g., Pinet *et al.*, 1987; Bois and Gariel, 1994; Tomassino and Marillier, 1997] and at the toe of the continental slope of the Armorican and Western Approach margins (“neck area” in Thinon *et al.* [2003]). In the southern Bay of Biscay, this domain is integrated into the accretionary prism of the North Iberian margin, as indicated by refraction velocities [e.g., Ruiz, 2007; Gallart *et al.*, 2004; Roca *et al.*, 2011; Fernández-Viejo *et al.*, 2012]. Onshore in the Pyrenees (Figure 6), this domain is characterized by numerous granulitic rocks (e.g., in the Labourd, Trois Seigneurs, and Agly massifs) interpreted as middle to lower crustal rocks [e.g., Vielzeuf, 1984] exhumed during Cretaceous rifting [e.g., Jammes *et al.*, 2009; Vauchez *et al.*, 2013].

4.1.4. Exhumed Mantle Domain

The onset of the exhumed mantle domain can be observed where complete thinning of the continental crust is achieved (Figure 5c/5d). Local remnants of continental crust may be preserved as extensional allochthons on top of the exhumed mantle basement of this domain (outcrop scale observation; Figure 2). The seismic reflection pattern and velocity structure described from suspected and drilled exhumed mantle domains contrasts with the adjacent hyperthinned and oceanic domains. Seismic reflection observations show a complex set of deep intrabasement reflections (e.g., Armorican margin: Thinon *et al.* [2003] and Iberian margin: Pickup *et al.* [1996], Dean *et al.* [2001], Reston and McDermott [2011], and Sutra *et al.* [2013]). Refraction studies indicate a downward gradient of velocities commonly interpreted as the progressive decrease in serpentinization with depth [e.g., Minshull, 2009; Reston, 2009, 2010]. Magmatic additions can also be observed within this domain, as indicated by the local occurrence of synhyperextension to posthyperextension alkaline magmatism in onshore remnants of exhumed mantle in the Pyrenees. Offshore, volcanic bodies and volcanoclastic sediments are interpreted on the Armorican margin [Thinon *et al.*, 2003]. This magmatic overprint may progressively become more important toward the oceanic domain. Hyperextended sag basins are often observed in the exhumed mantle domain, sometimes extending to the hyperthinned and necking domains in the case of overfilled basins (e.g., the Angola margin [Unternehm *et al.*, 2010]).

Exhumed mantle has already been proposed to floor the Armorican basin [Thinon *et al.*, 2003] and suggested in the South Iberian margin [Roca *et al.*, 2011]. Gravity inversion results combined with seismic interpretations enable us to map the eastern termination of the exhumed mantle domain toward the hyperthinned Parentis basin (Figure 6). Onshore, this domain is characterized by the occurrence of mantle bodies and Mesozoic metamorphic rocks included in tectonic units near the North Pyrenean fault in the Pyrenees (Figure 6; e.g., Monchoux [1970], Fabriès *et al.* [1991, 1998], Lagabrielle and Bodinier [2008], Lagabrielle *et al.* [2010], and Clerc *et al.* [2012, 2013]) or within the so-called Nappe des Marbres in the Basque-Cantabrian basin (Figure 6 [Lamare, 1936; Mendia and Gil-Ibarguchi, 1991]).

4.1.5. Oceanic Domain

The transition to the oceanic domain is characterized by a deepening of the Moho and the ramp morphology of the basement referred to as an outer high [Péron-Pinvidic and Manatschal, 2010; Péron-Pinvidic et al., 2013]. Refraction data across this basement high in the Bay of Biscay indicate the presence of an underplated high-velocity body originating in the exhumed mantle domain [Thinon et al., 2003]. This velocity structure may suggest a possible overlap between the exhumed mantle and oceanic domains [see also Roca et al., 2011]. It may be interpreted as an underplated gabbroic body similarly to the interpretation of Bronner et al. [2011] for the Iberian-Newfoundland rifted margins. It may also represent the oceanward termination of serpentinized mantle [Thinon et al., 2003] that is overprinted by the first oceanic crust. Both interpretations suggest a possible overlap or transition zone between the exhumed mantle and oceanic domains. A specific seismic pattern is also observed, characterized by diffractive and irregular reflections in the upper basement [Thinon et al., 2003] and locally strong reflections parallel to the top basement at deeper levels [Sutra et al., 2013]. The first onlapping and overlying sediments are of postrift age. In the central part of the Bay of Biscay, one drill hole (DSDP site 118 and leg 12 [Laughton et al., 1972]) reached the oceanic basement. This domain is characterized by E-W to ESE-WNW trending magnetic anomalies [Matthews and Williams, 1968] attributed to the magnetic anomaly 34 [e.g., Srivastava et al., 1990]. The absence of the magnetic anomaly 33 [Cande and Kristoffersen, 1977] suggests that seafloor spreading stopped after anomaly 34 and before anomaly 33, corresponding to Santonian-Early Campanian time [e.g., Montadert and Roberts, 1979; Montadert et al., 1979]. No remnants of oceanic domain (ophiolites) can be observed onshore in the Pyrenean or Basque Cantabrian basins [Lagabrielle and Bodinier, 2008].

4.2. Key Structures and Lateral Extent of Domains

The definition of rift domains also relies on the identification of key structures (i.e., compressional, extensional, and transfer fault systems) as they represent markers of the deformation during the different extensional and compressional events.

4.2.1. Compressional Systems

The overall WNW to ESE trend of compressional structures (foreland basins, boundary between internal and external domains) results from the Iberian/European convergence. Compressional deformation is important in the Southern Bay of Biscay and controls the evolution of the North Iberian frontal thrust system [e.g., Derégnaucourt and Boillot, 1982; Roca et al., 2011; Fernández-Viejo et al., 2011, 2012]. In its eastern termination, it represents the boundary between continental and oceanic domains without evidence for oceanic subduction ([Ayarza et al., 2004]; refraction data along the IAM 12 line; [Fernández-Viejo et al., 1998]). To the West, it delimits the accretionary prism and reactivation in the exhumed mantle domain [Roca et al., 2011; Fernández-Viejo et al., 2012]. Locally NW-SE trending thrusts are observed in the Northern Bay of Biscay, mainly located at domain transitions [Thinon et al., 2001].

Most of the compressive structures can be observed onshore. The North and South Pyrenean frontal thrusts delimit the almost E-W trending Pyrenean-Cantabrian orogen from the adjacent foreland basins. Onshore remnants of rift domains are delimited by thrusts systems. Among them, the North Pyrenean fault [e.g., Mattauer, 1968; Choukroune and Mattauer, 1978] and Basque-Cantabrian equivalent, the Leiza fault [Boillot et al., 1973; Choukroune, 1976; Rat, 1988; Combes et al., 1998; Mathey et al., 1999] can be mapped discontinuously.

4.2.2. Extensional Faults

NW-SE to E-W trending extensional structures can be mapped in the Northern Bay of Biscay [Derégnaucourt and Boillot, 1982; Thinon, 1999; Thinon et al., 2003] related to the rifting phase in the Bay of Biscay. Top basement detachment faults may develop to become the boundary between the proximal and necking domains (e.g., Southern boundary of the Parentis basin [Jammes et al., 2010b, 2010c]). Only few half-graben basins (i.e., low- β extensional settings; Figure 2) are described from the hyperthinned domain of the Armorican margin [Thinon, 1999; Thinon et al., 2003]. Remnants of extensional rift structures and top basement extensional detachment faults are described locally onshore in the Mauléon basin [e.g., Canérot et al., 1978; Canérot, 1989; Johnson and Hall, 1989a, 1989b; Jammes et al., 2009; Masini et al., 2014], in the Aulus basin [e.g., Lagabrielle et al., 2010], or in the Basque-Cantabrian basin [e.g., Tavani and Muñoz, 2012; Bodego and Agirrezabala, 2013, and references therein].

4.2.3. Transfer/Transform Faults

A striking observation resulting from this mapping is the importance of transfer faults. These structures strongly segment offshore and onshore rift systems. The segmentation of the Northern Biscay margin is

characterized by NE-SW transfer faults [Derégnaucourt and Boillot, 1982; Thinon et al., 2003] that may be partly related to the Variscan structuration observed onshore [Thinon, 1999]. The offshore prolongation over the continental shelf is underlined by magnetic and gravity trends and is suggested to be partly controlled by the Armorican shear zone [e.g., Sibuet, 1973; Thinon, 1999]. The influence of the inferred structures can be observed on the segmentation of the limit between necking and exhumed mantle domains between the Goban Spur, Western Approach, and Armorican margins (Figure 6). Other inherited structures locally break the NW-SE straight orientation of the southern part of the Armorican margin [Thinon, 1999], but the control of these structures on the subsequent rift structures is complex and not directly observable. In contrast, the South Iberian margin is segmented by NW-SE structures [Derégnaucourt and Boillot, 1982], such as the Ventaniella fault that records a Permo-Carboniferous post-Variscan evolution [Burg et al., 1994a, 1994b].

Fossil remnants of the rift system preserved in the Pyrenean-Cantabrian orogen are segmented by NNE-SSW to NE-SW trending structures. These structures may result from the partial reactivation of Permo-Carboniferous strike-slip or transfer faults [Arthaud and Matte, 1975, 1977; Burg et al., 1994a, 1994b]. Locally they may have been reactivated as normal faults during the formation of Permo-Triassic intracontinental basins [Curnelle et al., 1982]. The observed segmentation may reactivate existing faults, but these preexisting faults (Permian or older) cannot be traced with confidence across the Pyrenees.

To the east, the Cevennes fault system delimits the Pyrenean from the Provençal domain (Figure 6); to the south, it also may partly control the shape of the South Pyrenean compressional thrust system [Vergés et al., 2002; Muñoz, 1992].

The Toulouse fault, also referred to as the Villefrance or Sillon Houiller fault, can be mapped from the Massif Central region to the northern Aquitaine basin (Figure 6). The southern continuation toward the Pyrenees delimits the eastern termination of the Arzacq-Aquitaine basin from the Occitan high [Curnelle et al., 1982]. This structure can be identified on gravity inversion maps as a major crustal discontinuity (Figure 5). In the Axial zone, a transfer zone may be mapped discontinuously at the eastern boundary of a large Carboniferous basin and farther to the south to the west of the Organya basin (Figure 6) in the South Pyrenean zone (segmentation also described by Muñoz [1992] and Vergés and García-Senz [2001]).

The Pamplona fault delimits the Mauléon and the Basque-Cantabrian basins [Turner, 1996]. Although this structure is not exposed continuously, it controlled the Mesozoic sedimentation [Larrasoña et al., 2003] and represents a major crustal offset observed from gravity modeling (Bouguer anomaly map [Jammes et al., 2010c]).

The segmentation of the Basque-Cantabrian basin is well defined from its subdivision into an eastern “Alava” and western “Peri-Asturian” domain [e.g., Rat, 1988; García-Mondéjar et al., 1996]. This NE-SW structuration terminates toward the Landes High to the north. The western termination of Basque-Cantabrian basin is poorly defined due the Cenozoic tectonic uplift and erosion of Mesozoic sediments south of the Le Danois basin and north of the Duero basin [Gallastegui et al., 2002; Pedreira et al., 2003, 2007; Alonso et al., 2007]. In this area, Roca et al. [2011] proposed the existence of the Santander soft transfer zone that would relay the compressional front of the Pyrenees to the north into the Bay of Biscay. This transfer zone may also be suggested from gravity inversion maps (Figure 5) facilitating the relay of the necking domain of the South Iberian margin to the South at the eastern termination of the Le Danois basin (Figure 6).

4.3. Two Distinct Rift Systems

The previous definition of rift domains, associated structures, and segmentation enables us to distinguish two extensional systems: (1) the Bay of Biscay-Parentis rift in the NW and (2) the Pyrenean-Basque-Cantabrian rift to the SE. Both preserve a specific spatial and temporal evolution.

4.3.1. The Bay of Biscay-Parentis Rift

The V-shaped Bay of Biscay-Parentis rift system preserves different stages of the lithospheric-scale thinning process ranging from hyperthinned basins in the East to oceanic domains in the West. The Parentis basin is interpreted to show a progressive lateral decrease in extension going eastward [Jammes et al., 2010c]. Onshore, a crustal discontinuity is observed (Figure 5) that may represent the northern continuation of the Pamplona fault (e.g., the Bordeaux fault [Lefort et al., 1997]). This structure corresponds to the eastern termination of the Parentis basin. We have mapped the continuation of the relatively sharp necking and

hyperthinned domains of the northern Parentis basin westward into the Armorican margin. To the south, the Landes High forms a weakly thinned crustal block connecting south-westward to the necking domain of the North Iberian margin (Figure 6).

The initiation of extensional to transtensional deformation in the Bay of Biscay rift system is difficult to date with precision and relies on local observations. A phase of pre-Cretaceous extensional deformation may be recorded by a Late Jurassic subsidence in the Parentis basin [Brunet, 1994] and by a thickening of the pre-Cretaceous sequence toward the basin center (e.g., Ibis fault of *Bois and Gariel* [1994] and *Jammes et al.* [2010a, 2010b, 2010c]). Hyperextensional processes may have been initiated during the Early Cretaceous (Berriasian to Barremian) resulting in the formation of the necking and hyperthinned domains. During the late Aptian, mantle may have been exhumed in the Bay of Biscay as suggested by *Thinon et al.* [2002]. The onset of seafloor spreading is dated around Aptian-Albian time [Montadert et al., 1979; Boillot, 1984; Vergés and García-Senz, 2001] but may not be synchronous throughout the entire Bay of Biscay.

The major change in rift domain architecture between the Western Approach and Armorican margins occurs across the Armorican shear zone corresponding to a partially inherited transfer/transform fault (Figure 6). A similar change in the overall domain architecture can be observed between the eastern and western North Iberian margin west of the Le Danois basin (Figure 6).

4.3.2. The Pyrenean-Basque-Cantabrian Rift

The Landes High and the Ebro block (Figure 6) form weakly thinned crustal blocks delimiting to the North and to the South the Pyrenean-Basque-Cantabrian rift system from the Bay of Biscay-Parentis (Figures 5 and 6; see also *Roca et al.* [2011]) and Central Iberian rift systems [e.g., *Salas and Casas*, 1993; *Salas et al.*, 2001]. Onshore, the overall crustal architecture of the different domains is not preserved. Only remnants included in the compressional nappe stack can be observed. Complete ophiolite sequences that could be considered as remnants of typical oceanic lithosphere are never observed within the Pyrenean-Basque-Cantabrian rift system [Lagabrielle and Bodinier, 2008]. The only Cretaceous magmatic additions observed are late Aptian to early Santonian (~113 to 85 Ma [Lamolda et al., 1983; Montigny et al., 1986]) alkaline sills and flows preserved into remnants of an exhumed mantle domain or the overlying sediments. This observation suggests that this extensional system did not evolve into a mature oceanic domain. Furthermore, mantle outcrops are usually associated with small fragments of continental crust (in the Pyrenees: *Duée et al.* [1984], *Fortané et al.* [1986], *Lagabrielle et al.* [2010], and *Debroas et al.* [2010]; and Basque-Cantabrian basin: *Mendia and Gil-Ibarguchi* [1991]) indicating that probably only local windows of exhumed mantle existed.

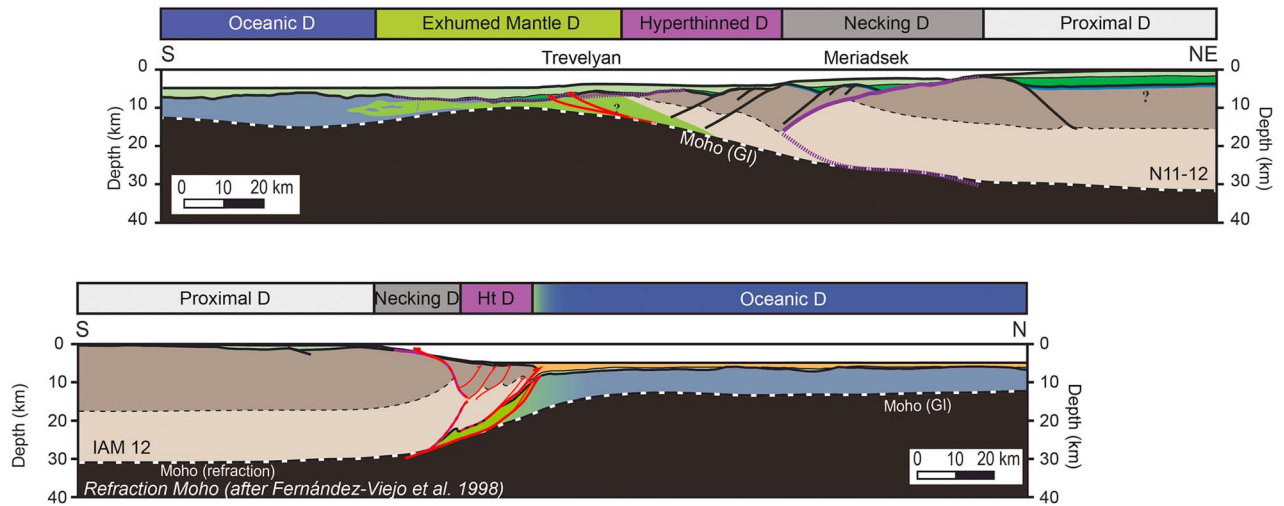
The increasing subsidence recorded in the onshore Arzacq and Tarbes basins [Déségaulx and Brunet, 1990] during the Late Jurassic to Early Cretaceous may indirectly date the onset of transtensional deformation [Canérot, 2008; Jammes et al., 2009]. Hyperextension only initiated in the late Aptian to Albian time in the Pyrenean-Basque-Cantabrian rift [Jammes et al., 2009; Lagabrielle et al., 2010] coinciding with the onset of seafloor spreading in the Bay of Biscay [Montadert et al., 1979]. The sedimentary record preserved in the Pyrenean-Cantabrian orogen indicates a progressive deepening of the basin from late Aptian to mid-Albian (Pyrenees: *Debroas* [1987, 1990] and Basque-Cantabrian basin: *García-Mondéjar et al.* [1996, 2005]). Mantle exhumation processes may have lasted until early Cenomanian as suggested by the reworking of mantle rocks in mid-Albian to lower Cenomanian breccias (Figure 3; Urdach breccia: *Jammes et al.* [2009], *Debroas et al.* [2010], and *Lagabrielle et al.* [2010]; and Aulus breccia: *Clerc et al.* [2012]).

In spite of the well-defined NE-SW segmentation, an overall lateral continuity of hyperextended domains can be observed throughout the Pyrenean orogen (Figure 6). The Pamplona fault represents a major crustal discontinuity [Turner, 1996; Larrasoña et al., 2003; Jammes et al., 2010c] delimiting the Basque-Cantabrian from the Arzacq-Mauléon basin.

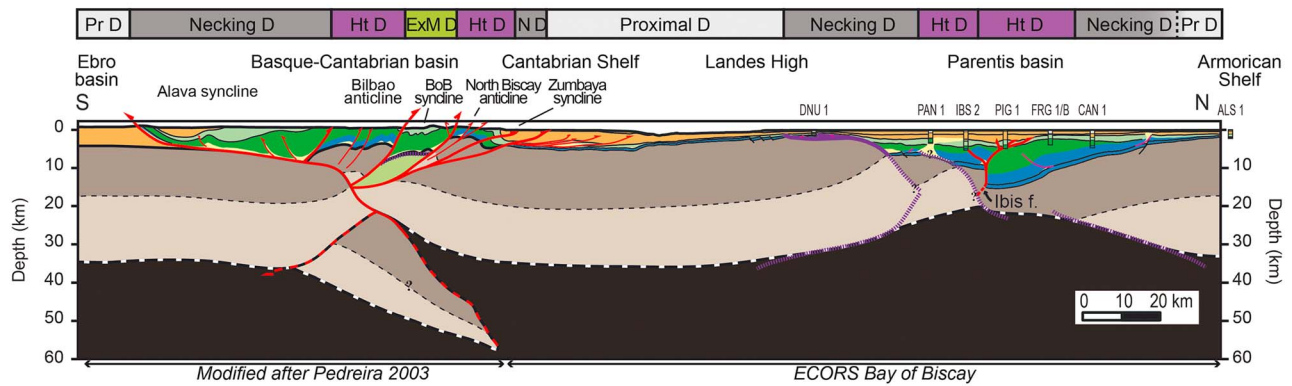
5. Structural Evolution: Insights From Geological Sections

The mapping of the rift domains across the Bay of Biscay-Pyrenees enables us to characterize the progressive compressional overprint of the former rift systems. To the west, the initiation of reactivation can be investigated to the east, a complete reactivation of rift structures is observed. In order to decipher the possible interaction between the two extensional rift systems during the Late Cretaceous

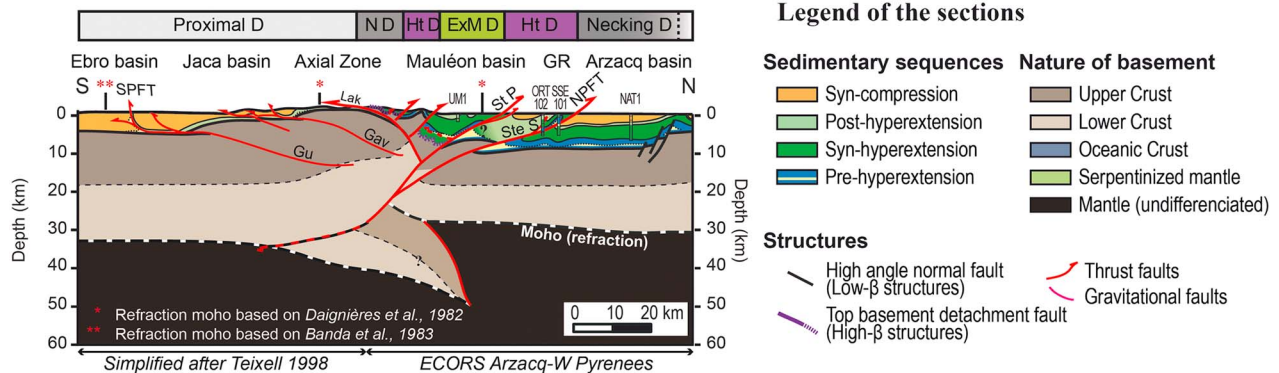
(a) Bay of Biscay segment



(b) Basque-Parentis segment



(c) Pyrenean segment



Legend of the sections

- | Sedimentary sequences | Nature of basement |
|-----------------------|---------------------------|
| Syn-compression | Upper Crust |
| Post-hyperextension | Lower Crust |
| Syn-hyperextension | Oceanic Crust |
| Pre-hyperextension | Serpentinized mantle |
| | Mantle (undifferentiated) |
-
- Structures**
- High angle normal fault (Low-β structures)
 - Thrust faults
 - Top basement detachment fault (High-β structures)
 - Gravitational faults

Figure 7. Geological sections, location Figure 6 (a) Bay of Biscay segment: the architecture is based on the Norgas 11–12 [after Tugend et al., 2014] and IAM 12 seismic profiles (see also Figure 8). (b) Basque-Parentis segment: the section is a composite between the depth interpretation of the ECORS Bay of Biscay seismic profile and the gravity modeling proposed by Pedreira et al. [2003] for the Basque-Cantabrian basin. (c) Pyrenean segment: the section is based on the interpretation of the ECORS Arzacq-W Pyrenees and the southern extension is modified after Teixell [1998].

to Oligocene compression, three segments are distinguished (Figures 6 and 7): (1) a western “Bay of Biscay segment”; (2) a central “Basque-Parentis segment” preserving heterogeneously reactivated hyperextended domains; and (3) an eastern “Pyrenean segment” that is completely inverted, exemplified by the Mauléon-Arzacq basin.

5.1. Western Bay of Biscay Segment

5.1.1. Constraints From Seismic Interpretations and Gravity Inversion

The western Bay of Biscay segment initiates at the western termination of the onshore Pyrenean-Basque-Cantabrian rift system. Located at the junction with the Atlantic Ocean, it preserves the ultimate stage of lithosphere thinning in the Bay of Biscay.

In order to characterize the architecture of this domain, two conjugate geological sections are proposed, extending from the proximal to oceanic domains in the Western Approach margin to the North (Figures 7a and 8) and across the North Iberian margin to the South (Figures 7a and 9). The sediment and basement architectures of these sections are derived from the interpretation of the Norgasis 11–12 seismic sections (Figure 8 [Avedik *et al.*, 1993, 1996; Thinon, 1999]) and IAM 12 line (Figure 8 [Banda *et al.*, 1995; Alvarez-Marron *et al.*, 1997]), extending into the Western Approach and North Iberian margins, respectively. Moho depth is determined from gravity inversion results (Figure 5; parameters are given in Table 1) combined with refraction data under the proximal domain of the North Iberian margin [Fernández-Viejo *et al.*, 1998].

5.1.2. Architecture of the Western Approach Margin

The rift-related crustal architecture of the Western Approach margin is well preserved. Detailed descriptions of seismic observations supporting the interpretation of this section are proposed by Tugend *et al.* [2014] and summarized below. The proximal domain is characterized by half-graben type basins (Figures 7a and 8) and by deformation interpreted to decouple at midcrustal levels. No drill hole has reached the basement of the necking domain, but based on the overlying sedimentary architecture (Figure 8) and onshore analogy (Figure 2 [Tugend *et al.*, 2014]), it is suggested to be structured by a conjugate set of top basement detachment faults delimiting a crustal necking zone [Mohn *et al.*, 2012; Sutra *et al.*, 2013]. The hyperthinned domain is characterized by a tilted block architecture limited by short-offset normal faults dipping oceanward (Figures 7a and 8). These structures are rooting onto the “S”-reflector (Figure 8 [De Charpal *et al.*, 1978; Montadert *et al.*, 1979; Thinon, 1999]) that is interpreted as the crust-mantle boundary. The southern edge of this domain is proposed to be structured by a top basement detachment fault that exhumed rocks from the lower crust and mantle to the seafloor during the final stage of rifting. The occurrence of an extensional allochthon overlaying the exhumed mantle is proposed. It is delimited at its base by the “S”-reflector on seismic sections (Figure 8; [Thinon, 1999]). The transition to the oceanic domain may not be a sharp boundary and may result from a progressive magmatic overprint of the exhumed mantle domain as suggested by refraction data [Thinon *et al.*, 2003]. The only important compressional reactivation is observed close to the transition between the exhumed mantle and hyperthinned domains, forming the Trevelyan structure [Debyser *et al.*, 1971; Derégnaucourt and Boillot, 1982; Thinon *et al.*, 2001]. The associated thrust fault system is interpreted to root in the serpentinized upper mantle (Figures 7a and 8).

5.1.3. Reactivation of the North Iberian Margin

The distal part of the North Iberian margin was interpreted in the past as an accretionary prism related to the formation of an oceanic subduction [e.g., Boillot, 1984; Alvarez-Marron *et al.*, 1997]. Based on the refraction results [Fernández-Viejo *et al.*, 1998; Ruiz, 2007], any important underthrusting of oceanic crust below the South Iberian margin is precluded. Therefore, many authors suggested a complete or partial overprint of the former rift architecture [Gallastegui *et al.*, 2002; Fernández-Viejo and Gallastegui, 2005; Alonso *et al.*, 2007; Roca *et al.*, 2011; Fernández-Viejo *et al.*, 2012]. The identification of the rift domains (Figure 6) enables us to propose a new interpretation that characterizes the deformation in each rift domain clearly unraveling the role of the rift-inherited architecture. No major evidence of reactivation can be observed from the proximal and necking domains preserving their rift-related architecture delimited oceanward by a crustal necking zone similar to the structures proposed for the Western Approach margin. The accretionary wedge characterizing the distal part of the North Iberian margin (Figure 9) is interpreted as the former hyperthinned domain that has been reactivated (Figure 7a). Refraction velocities are compatible with the hypothesis of a deformed wedge made of continental crust and sediments rather than of sediments only [Ruiz, 2007; Fernández-Viejo

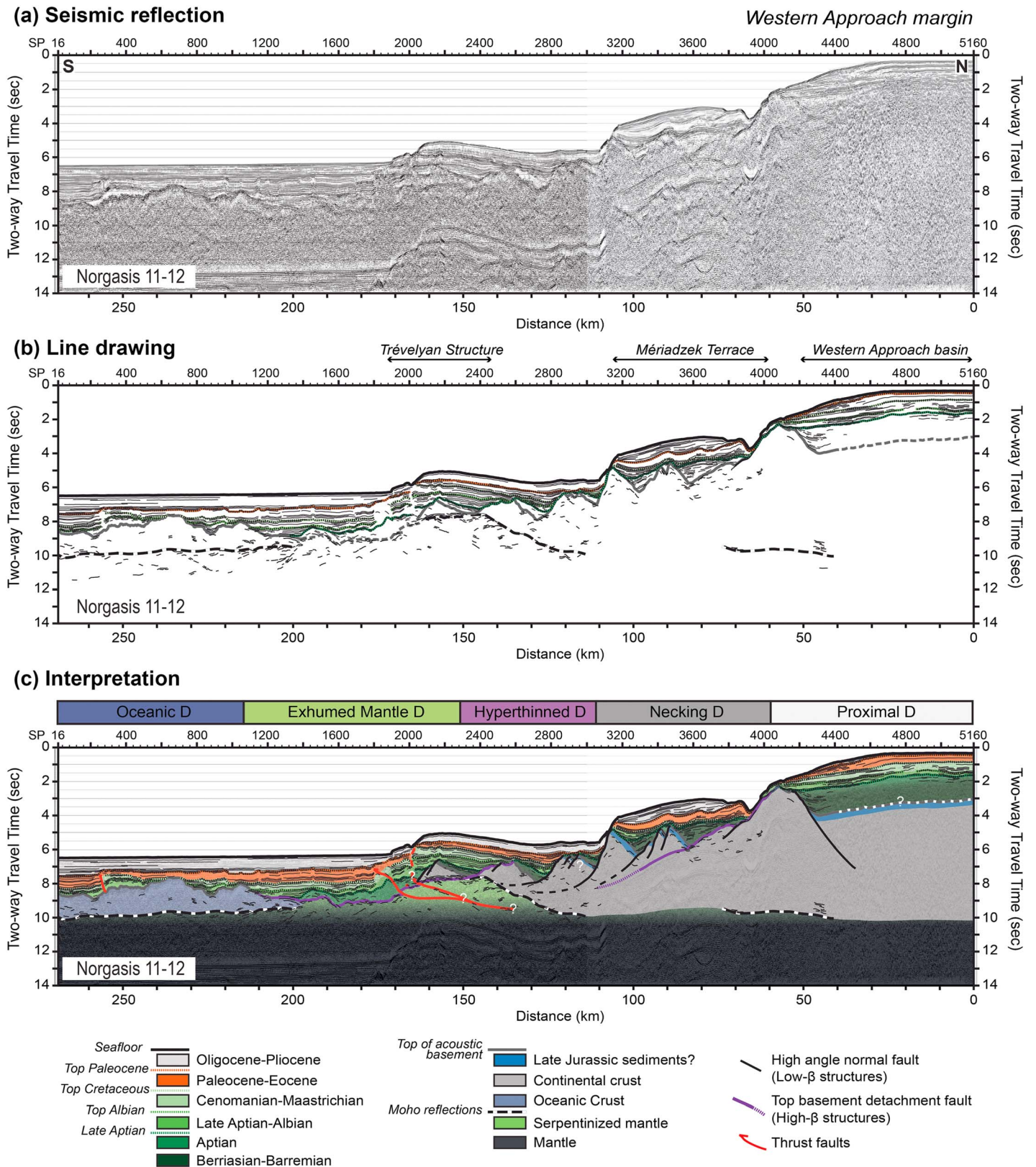


Figure 8. Norgasis 11 and 12 seismic section along the Western Approach margin. (a) Seismic reflection, (b) line drawing, and (c) interpretation proposed in this study. The location of the seismic lines is the same as Figure 7a.

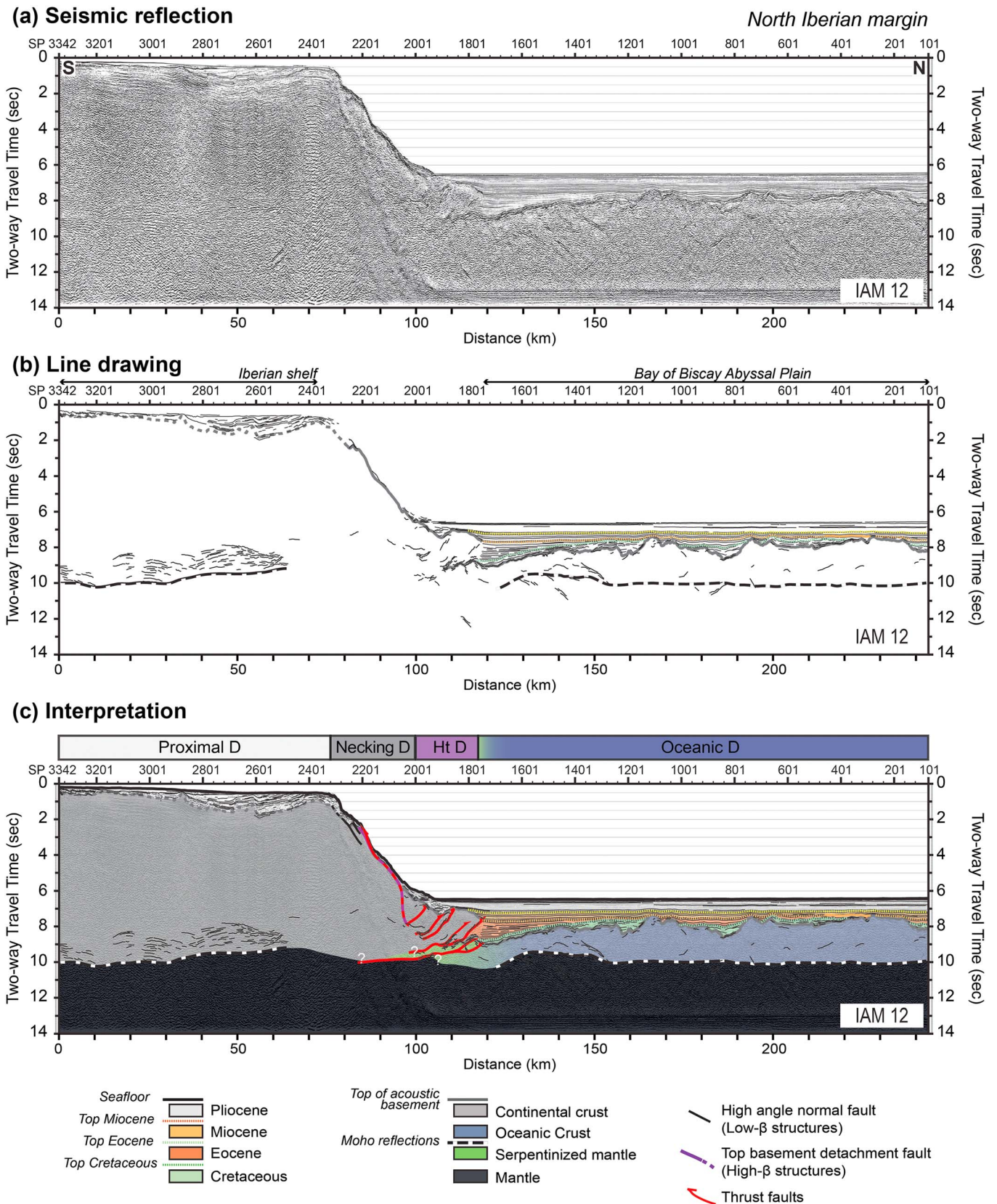


Figure 9. IAM 12 seismic section along the North Iberian margin. (a) Seismic reflection, (b) line drawing, and (c) interpretation proposed in this study. The location of the seismic lines is the same as Figure 7a.

et al., 2012]. The existence of an exhumed mantle domain is proposed northward and eastward and may have also occurred in this part of the Bay of Biscay. We suggest that it may be partly underthrust below the hyperthinned domain during the compressional overprint and formation of a Tertiary flexural basin on top of the oceanic domain (Figures 7a and 9 [Alvarez-Marron *et al.*, 1997]). In our interpretation, the exhumed serpentinized mantle represents a low-friction surface between the hyperthinned domain and the oceanic domain (Figure 7a).

5.2. Eastern Bay of Biscay: Parentis and Basque-Cantabrian Segment

5.2.1. Constraints From Geological and Geophysical Data Sets

In the Parentis and Basque-Cantabrian segment, both preserved and reactivated rift structures can be investigated. The eastern Bay of Biscay is characterized by its progressive termination into the hyperthinned Parentis basin. Eastward this segment terminates toward the Pamplona fault delimiting the Basque-Cantabrian basin from the Western Pyrenees.

The geological section shown in Figure 7b is based on the interpretation of the sedimentary and top basement architecture of the ECORS Bay of Biscay section [Pinet *et al.*, 1987; Bois and Gariel, 1994] located in the Parentis basin. The southward extension into the Basque-Cantabrian basin is based on published field studies supported by local subsurface data [Instituto Geológico Y Minero De España (IGME), 1987]. Moho depth is based on refraction studies in the Parentis basin [Tomassino and Marillier, 1997]. In the Basque-Cantabrian basin, the crustal architecture is based on one of the possible solutions derived from gravity and magnetic modeling proposed by Pedreira *et al.* [2007].

5.2.2. The Rift Architecture Preserved in the Parentis Basin

The Parentis basin is only weakly reactivated in its central part and the overall rift-related sedimentary and crustal architectures are relatively well preserved (Figure 7b). The architecture of the basin is strongly asymmetric unraveling a major crustal discontinuity toward the emplacement of the so-called subvertical Ibis fault (Figure 7b [Jammes *et al.*, 2010a, 2010b, 2010c]). The northern geometry is characterized by the progressive transition from a proximal to a hyperthinned domain without any major rift structure and the complete record of the prehyperextension, synhyperextension, and posthyperextension sedimentary sequences. The southern part of the basin is more complex. The necking domain is structured by a conjugate system of detachment faults. Evidence for such structures is based on drill hole observations (the Saint Girons en Marensin and Contis boreholes [Jammes *et al.*, 2010b]). The structural limit between the northern and southern part of the hyperthinned domain of the Parentis basin is also interpreted as a top basement detachment fault rooting toward the Ibis fault and associated with salt tectonics and diapir formation [e.g., Mathieu, 1986; Biteau and Canérot, 2007; Jammes *et al.*, 2010b]. The Landes High and the Cantabrian shelf belonging to the proximal domain represent a weakly thinned crustal block and form a major boundary between the Parentis and Basque-Cantabrian basin [see also Roca *et al.*, 2011].

5.2.3. Rift Remnants and Reactivation in the Basque-Cantabrian Basin

In contrast the Basque-Cantabrian basin to the South is completely inverted (Figure 7b). Sedimentary sequences are decoupled on upper Triassic evaporites [Cámara, 1997] and the basement is buried under thick sedimentary sequences. Field and subsurface observations provide good constraints on the stratigraphic evolution of the Mesozoic sediments [e.g., Soler *et al.*, 1981; García-Mondéjar *et al.*, 1985; Rat, 1988; IGME, 1987] and on locally preserved rift-related structures [e.g., García-Mondéjar *et al.*, 1996; Tavani and Muñoz, 2012; Bodego and Agirrezabala, 2013]. Similarly as for the northern Landes high, the Rioja shelf to the South (buried under the Ebro basin and forming the western continuation of the Ebro block, Figure 6) is representative of a proximal domain, characterized by the deposition of thin Late Cretaceous posthyperextension shallow marine sediments [e.g., Cámara, 1997]. The sedimentary sequences of the conjugate necking domains are preserved in the Zumbaya and Alava synclines (respectively, in the northern and southern part of the basin). These units are characterized by thickening of synhyperextensional (late Aptian to Cenomanian) to posthyperextensional sequences toward the basin axis and locally absent prehyperextensional sequences (Castillo 5 [IGME, 1987]). The North Biscay and Bilbao anticline are mapped as remnants of hyperthinned domains and characterized by thick prehyperextension sediments. The Bay of Biscay syncline is mapped as the western continuation of the “Nappe des Marbres” locally sampling mantle rocks and associated high-temperature low-pressure (HT-LP) metamorphic marbles of Mesozoic age [Mendia and Gil-Ibarguchi, 1991] representative of a former exhumed mantle domain. An important gravity anomaly is centered on the basin and interpreted to result from the stacking of lower crustal rocks

[Pedreira *et al.*, 2003, 2007] or mantle rocks emplaced at shallow levels during compression. In analogy with the interpretation proposed for the Labourd anomaly [Jammes *et al.*, 2010c], we favor the mantle body solution that would be coherent with this unit being a remnant of a former exhumed, partly serpentinized, mantle domain. Nevertheless, the lower crustal interpretation proposed by Pedreira *et al.* [2003, 2007] cannot be excluded. Another important observation resulting from the gravity modeling proposed by Pedreira *et al.* [2007] is the occurrence of a large northward dipping crustal root reaching a 55 to 60 km depth and interpreted as the former thinner basement of the Basque-Cantabrian basin [Pedreira, 2004; Pedreira *et al.*, 2007].

5.3. Arzacq-Mauléon Basin: Pyrenean Segment

5.3.1. Constraints From Field and Subsurface Geology

The Pyrenean segment initiates at the eastern termination of the Parentis and Basque-Cantabrian basins and is delimited from the two basins by the Pamplona fault. Therefore, this segment only preserves rift remnants derived from the former hyperextended Pyrenean-Basque-Cantabrian rift system.

Insights on the sedimentary and basement architecture come from the reinterpretation of the ECORS Arzacq-W Pyrenees seismic profile [Daignières *et al.*, 1994] extended to the South based on the Anso transect proposed by Teixell [1998]. Field geology, subsurface observations [BRGM *et al.*, 1974], and local refraction data [Daignières *et al.*, 1982; Banda *et al.*, 1983] are combined to further constrain the interpretation proposed in Figure 7c.

5.3.2. Compressional Architecture of a Reactivated Hyperextended Basin

Arguments for the determination of rift-related remnants in the Arzacq-Mauléon basin have been previously presented and described relying on the identification of key field observations (Figure 3; see also Tugend *et al.* [2014]). Field observations from the “Béarnais range” area, in the eastern part of the basins (Figure 3) are used to further constrain the compressional overprint of former rift domains (Figures 7c, 10, and 11). The present-day geometry of the Mauléon basin results from its inversion within a large pop-up structure along north and south vergent thrusts (Figures 7c and 10).

To the south, distal parts of the basin (corresponding to the former hyperextended domain) are thrust over the proximal domain preserved in the axial zone along the south-directed Lakoura thrust system and lateral equivalents (Figures 7c, 10, and 11 [Muñoz, 1992; Teixell, 1998]). The proximal domain is weakly deformed as a large-scale anticline (geological sections Figure 10; see also Teixell [1990]) and by local thick-skin structures related to the final stage of deformation (D2 phase; e.g., Guarga and Gavarnie thrusts Figure 7c and Eaux-Chaudes thrust Figure 10). The sedimentary cover of the axial zone is characterized by thin-skin thrusts decoupling in Upper Triassic evaporites (Teixell [1998]; geological section BB' Figure 10).

The transition from the proximal to necking domains (see structural maps; Figures 3, 10, and 11) corresponds to a thrust fault characterized by an intense deformation of the sediments close to the contact (e.g., Upper Triassic formation within the Bedous unit; Figure 11 [Canérot *et al.*, 2001; Ternet *et al.*, 2004a, 2004b]). Locally, this thrust fault is folded by the anticlinal deformation of the axial zone as indicated by the steep northward dipping Cretaceous cover of the axial zone (Figures 10 and 11). Remnants of the necking domain are only locally sampled within the Bedous-Mendibelza unit as syncline structures. In contrast, the rift-related sedimentary and basement architecture of the conjugate remnants of the necking domain preserved in the Arzacq basin is interpreted to be well preserved (Figure 7c).

The initial contact between units preserving the necking and hyperthinned domains is only locally preserved [Masini *et al.*, 2014]. In most cases it is overprinted by north-directed thrusts resulting from the second phase of deformation (Figures 7c, 10, and 11). The hyperthinned and exhumed mantle domains are characterized by the widespread occurrence of this second phase of deformation that locally invert and overprint the tectonic units where remnants of these domains are preserved (e.g., the Ossau thrust [Canérot *et al.*, 2001]; Figures 7c, 10, and 11). As a result, a large part of the hyperthinned and exhumed mantle domains may be underthrust as suggested in the geological sections in Figures 7c and 10.

Field observations from the Mauléon basin unravel the contrast in compressional deformation between the different rift domains. The proximal domain is only weakly deformed, whereas the hyperthinned and exhumed mantle domains are affected by a stronger compressional overprint.

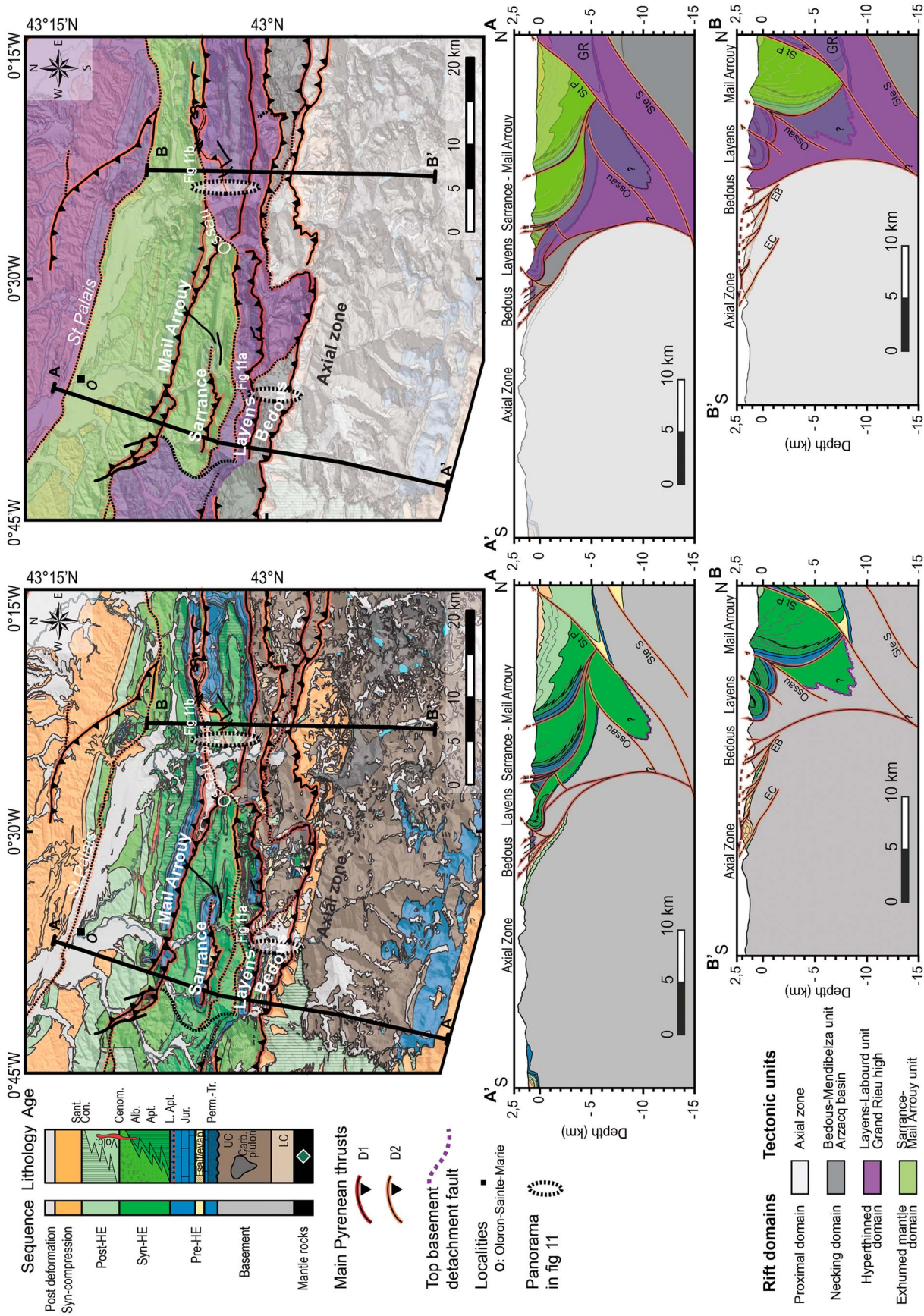


Figure 10. Zoom over the Béarnais Range area (location Figure 3). To the left: geological map and two geological sections (AA' and BB'). To the right: the same map indicating the remnants of rift domains. The associated cross sections illustrate the reactivation of the former rifted domains. EB: Eaux-Bonnes thrust; EC: Eaux-Chaudes thrust; GR: Grand Rieu High; St P: Saint Palais thrust system; Ste S: Sainte Suzanne thrust system.

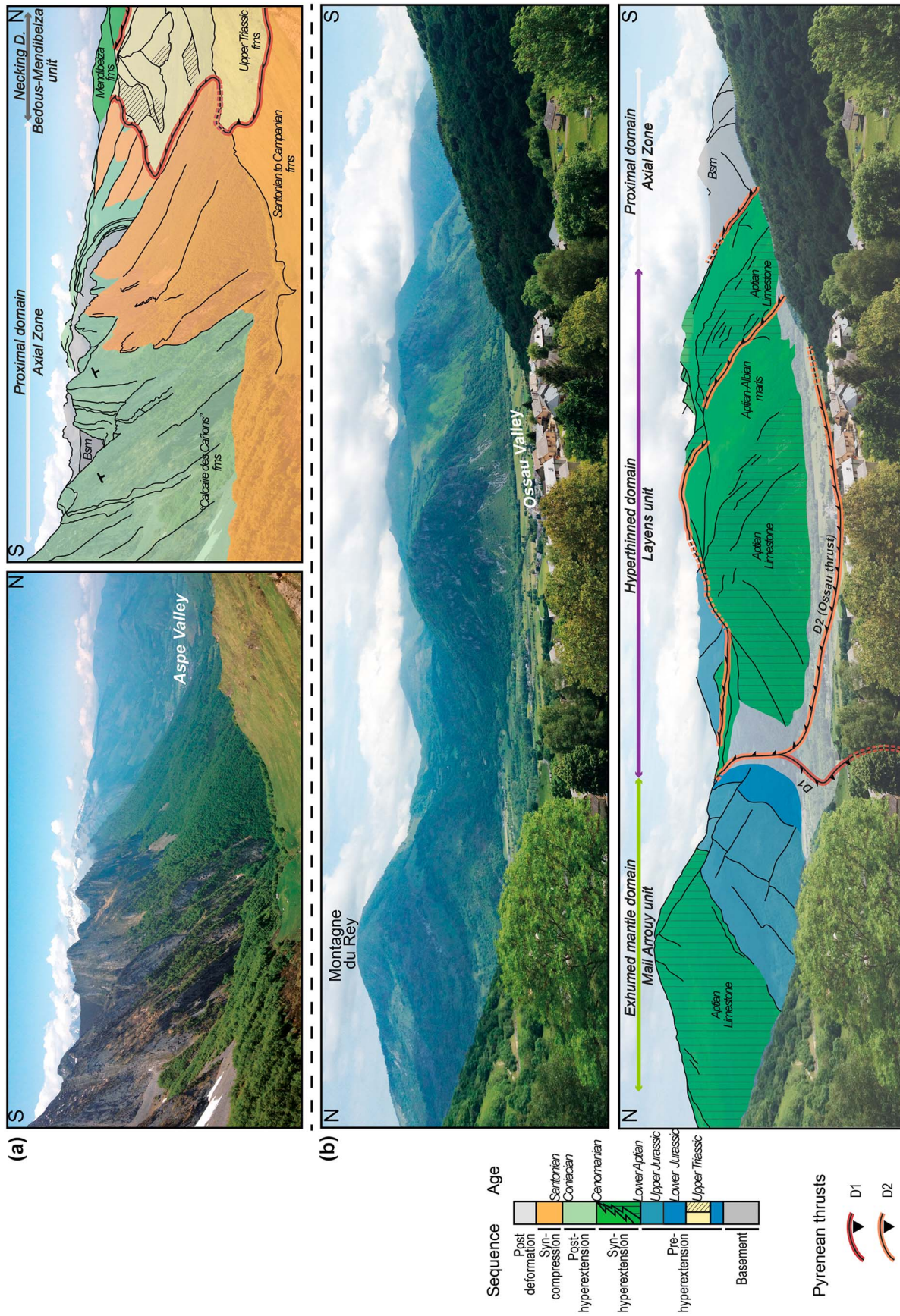


Figure 11. (a) Panoramic view showing the contact between the proximal (axial zone) and necking domains (Bedous-Mendibelza unit). Note that the contact is steepening eastward ($0^{\circ} 31'45.07''W/42^{\circ}57'08.21''N$). (b) Panoramic view showing the relationships between the different phases of deformation observed in the hyperthinned (Laysens unit) and exhumed mantle domains (Mail Arrouy unit). The initial south-directed stacking of units (D1) is overprinted by north-directed deformation (D2), exemplified here by the Ossau thrust ($0^{\circ}27'16.21''W/43^{\circ}03'30.98''$). The location of the photographs is indicated in Figure 9. The coordinates indicate the location from which the photographs were taken.

6. Discussion

6.1. Spatial and Temporal Evolution of Hyperextended Rift Systems

6.1.1. Insights on the Formation and Architecture of Hyperextended Rift Systems

The mapping of rift domains across the Bay of Biscay and Pyrenees unraveled the occurrence of two spatially disconnected hyperextended rift systems characterized by a strong segmentation (Figures 6 and 12). These rift systems are delimited by the “Landes High” and “Ebro block” representing crustal blocks probably characterized by a rheologically stronger basement inherited from the prerift history [Matte, 1991; Lefort *et al.*, 1997] resulting in their weak crustal thinning (Figures 6 and 12). Their crustal structure and their relationship to the surrounding hyperextended domains (Figure 12) compares well with continental ribbons described by Péron-Pinvidic and Manatschal [2010] from the North Atlantic (e.g., Flemish Cap, Rockall Bank, and Galicia Banks).

The relative timing of hyperextensional processes is diachronous between the Bay of Biscay-Parentis and Pyrenean-Basque-Cantabrian rift systems (respectively, Berriasian-Barremian to late Aptian and Aptian-Albian to at least early Cenomanian [see also Jammes *et al.*, 2009; Roca *et al.*, 2011]). This diachronous evolution may illustrate the eastward migration of extension in the Pyrenean-Basque-Cantabrian rift system contemporaneous with ongoing seafloor spreading in the western Bay of Biscay. The complexity of rift system architecture has also been exemplified by Gernigon *et al.* [2014] for the Southwestern Barents Sea, emphasizing the 3-D polyphased evolution of rift systems and eventually the role of inheritance.

6.1.2. The Role of Prerift Inheritance: Insights From the Bay of Biscay-Parentis System

The southern edge of the hyperthinned domain of the Western Approach margin is suggested to be structured by the breakaway of a detachment system related to final crustal thinning and mantle exhumation (Figure 7a). This architecture is interpreted to characterize distal lower plate margins [Sutra *et al.*, 2013], implying that the Western Approach margin may correspond to a lower plate margin (Figures 7a and 8). The situation is inverted at the eastern end of the Bay of Biscay where the northern part of the Parentis basin can be interpreted as an upper plate margin [see also Jammes *et al.*, 2010a, 2010b, 2010c]. This change between upper and lower plate margins seems well expressed from a mapping point of view (Figures 6 and 12). The Western Approach margin is characterized by wide necking and hyperthinned domains, contrasting with sharper domains observed from the Armorican margin to northern Parentis basin. This switch from an upper to a lower plate margin occurs where the Armorican Shear zone intersects with the margin. The shear zone structure is described as a major lithospheric structure delimiting Variscan domains [e.g., Sibuet, 1973; Matte, 2001; Ballèvre *et al.*, 2009, 2012, and references therein].

In the North Iberian margin, the hyperthinned and exhumed mantle domains are reactivated within north-directed thrust systems, precluding the identification of the rift vergence of the detachment system in seismic sections. However, along the North Iberian margin (exemplified by the IAM 12 section; Figures 7a and 9) and the Le Danois basin, a change in the size of the necking and hyperthinned domain can be observed in the map view (Figure 6). The transition is relatively abrupt and not progressive, probably not resulting from a difference of shortening along strike. This change could be inherited from the former rift architecture, as proposed for the northern Bay of Biscay margin. It may illustrate a former switch between an upper plate margin (to the west) and a lower plate margin (to the east). Furthermore, this variation of architecture seems to coincide with the intersection of the rift system with major inherited Variscan structures separating the Central Iberian Zone to the West from the West Asturian Leonese Zone to the East (Figures 6 and 12 [e.g., Matte, 2001; Martínez-Catalán, 2012, and references therein]).

Based on observations from the conjugate margins of the Bay of Biscay, it seems that switches between upper and lower plate architecture impact the architecture of the necking, hyperthinned, and exhumed mantle domains. It is therefore likely that the evolution of these domains was controlled by the prerift history and inherited rheology of the crust as they bound distinct Variscan domains (also discussed by Pérez-Gussinyé *et al.* [2003] or Sutra and Manatschal [2012] for the West Iberia margin). It is interesting to note that these inherited structures do not seem to offset the contact to the first oceanic crust. This observation may suggest that while rift systems may be controlled by crustal and lithospheric inheritance, oceanic systems are mainly controlled by deep-seated asthenospheric processes and are therefore insensitive to continental lithospheric inheritance.

6.1.3. Importance of Segmentation: Insights From the Pyrenean-Basque-Cantabrian Hyperextended Rift System

The Pyrenean-Basque-Cantabrian rift system is characterized by its strong segmentation corresponding to a set of NE-SW to NNE-SSW trending transfer/transform faults regularly spaced across the studied area (e.g., the Santander, Pamplona, Toulouse, and Cevennes faults, Figures 6 and 12 [see also Jammes *et al.*, 2009; Roca

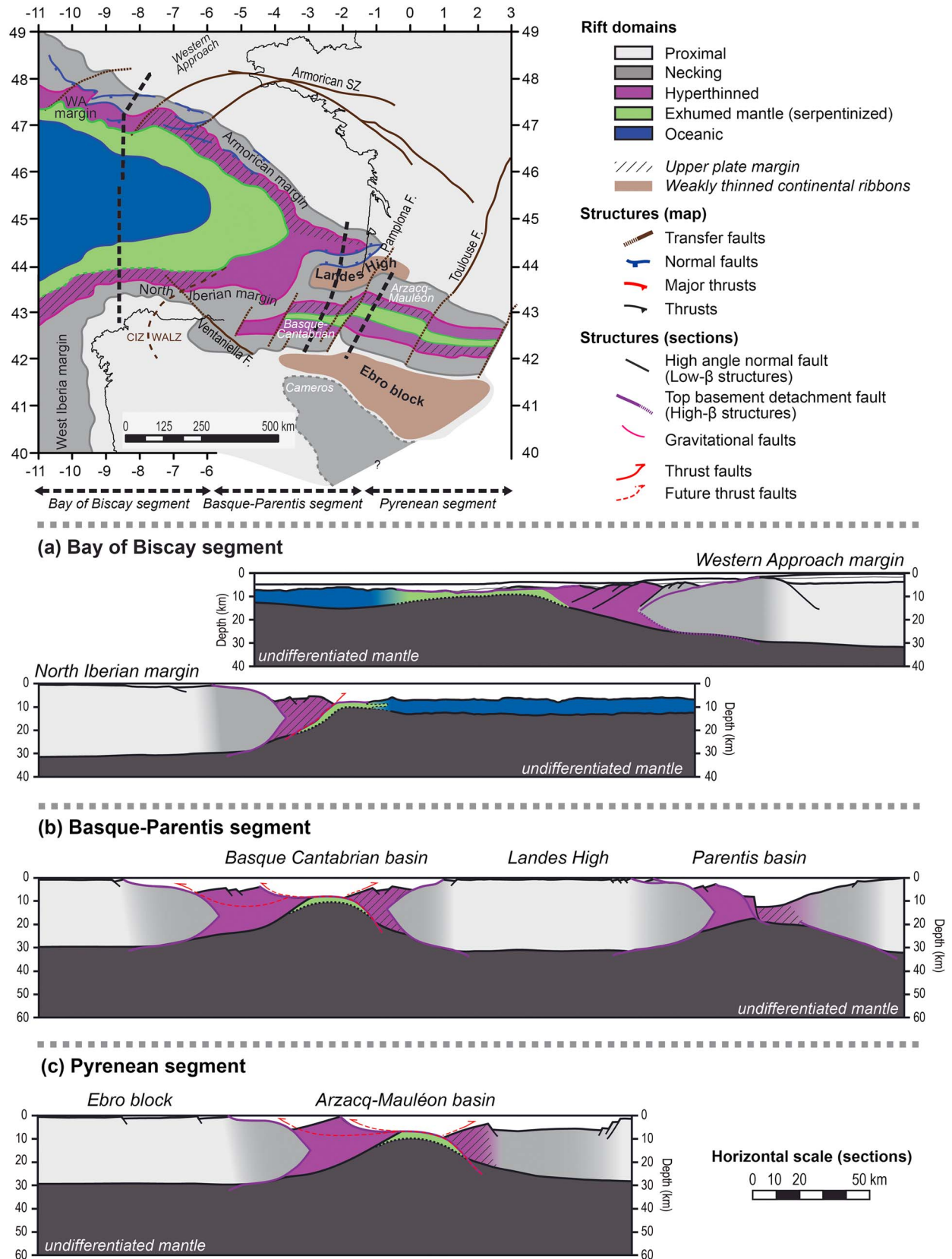


Figure 12. Restoration of the Bay of Biscay and Pyrenean rift systems prior to the onset of compression (before the Santonian). Restored sections are proposed in the (a) Bay of Biscay segment, (b) Basque-Parentis segment, and (c) Pyrenean segment. WA margin: Western Approach margin.

et al., 2011]). These transfer faults control the large-scale lateral evolution of the late Aptian-early Albian hyperextended rift system (see the restoration prior to the onset of compression; Figure 12). They can either juxtapose rift domains that experienced different amounts of extension (e.g., the Santander transfer zone in the Basque-Cantabrian basin) or transfer the overall extension to another basin as observed along the Pamplona fault (Figure 12). The segmentation pattern of the Pyrenean-Basque-Cantabrian rift system is presumably controlled by lithospheric-scale structures inherited from the late to post-Variscan evolution [e.g., *Arthaud and Matte*, 1975, 1977; *Burg et al.*, 1994a, 1994b].

The Toulouse fault may have played an additional role. A switch in exhumation vergence is proposed to have occurred along the Toulouse fault [*Jammes*, 2009]. This change may have controlled variations of the rift architecture between the western and eastern Pyrenees, as described in the Western Bay of Biscay between the Western Approach and Armorican margins. In the western Pyrenees, top basement detachment fault systems that exhumed midcrustal granulites and mantle rocks are described to be north-dipping (e.g., in the Arzacq-Mauléon basin [*Jammes et al.*, 2009; *Lagabrielle et al.*, 2010; *Masini et al.*, 2014]). In the eastern Pyrenees, the situation seems to be inverted. *Vauchez et al.* [2013] showed the occurrence of south-dipping detachment fault systems that exhumed the Agly massif. A similar exhumation of the North Pyrenean massif in the eastern Pyrenees is possible as most of them are also characterized by a tectonic contact between middle to lower crustal rocks and Cretaceous sediments (as suggested by *Vauchez et al.* [2013]).

The suggested change in the rift-related precompressional architecture may partly explain the change in the orogen architecture described between the western and eastern Pyrenees [e.g., *Muñoz*, 2002, and references therein]. Also, this interpretation emphasizes the necessity to evaluate the former rift-related architecture to understand the present-day structuration of orogenic systems [see also *Roca et al.*, 2011; *Jammes et al.*, 2014; *Mohn et al.*, 2014].

6.2. Role of Rift Inheritance for Reactivation Initiation and Mountain Building Processes

6.2.1. Role of Hyperextension for the Heterogeneous Reactivation

The Late Cretaceous to Late Oligocene convergence shows a heterogeneous distribution of compressional deformation. Based on the mapping of rift domains (Figure 5) and on the restoration of the stage prior to compression (Figure 12), we aim to discuss the role of the complex 3-D rift architecture in the subsequent reactivation. In the previously described Bay of Biscay and Pyrenean segments, deformation is only accommodated in one of the rift systems (respectively, the Bay of Biscay-Parentis and Pyrenean-Basque-Cantabrian rift systems). In the Western Bay of Biscay, deformation is localized in between the exhumed mantle and hyperthinned domains (Figures 7 and 12) while the oceanic domain is characterized by a diffuse deformation [*Thinon et al.*, 2002]. In the Pyrenean segment, former hyperextended rift basins are completely inverted and integrated in the orogen (Figure 6 [e.g., *Roca et al.*, 2011, and references therein]). One of the major differences between the two settings is related to the initial size, structure, and nature of basement in the different rift basins. In the Basque-Parentis segment, the occurrence of the two rift systems will lead to a “competition” during convergence. The Parentis basin is well preserved and only minor reactivation can be observed in the central part of the basin where the crust is extremely thinned [*Jammes et al.*, 2010a, 2010b, 2010c; *Tugend et al.*, 2014]. In contrast, the Basque-Cantabrian basin is completely inverted (Figure 7). It is difficult to understand why the Parentis basin was preserved while the Basque-Cantabrian basin was reactivated. One possible interpretation could be that the Basque-Cantabrian basin was locally floored by exhumed serpentinitized mantle (as proposed by *Roca et al.* [2011]) and was consequently easier to reactivate. Westward where mantle may be exhumed, compressional deformation is partitioned between the Bay of Biscay-Parentis and Pyrenean-Basque-Cantabrian rift systems, as indicated by the occurrence of the North Iberian Frontal thrust system [e.g., *Derégnaucourt and Boillot*, 1982; *Roca et al.*, 2011; *Fernández-Viejo et al.*, 2012] and by the tectonic uplift of the western termination of the Basque-Cantabrian basin [*Gallastegui et al.*, 2002; *Pedreira et al.*, 2003, 2007; *Alonso et al.*, 2007].

6.2.2. Conceptual Model to Explain the Evolution From Inversion Initiation to Orogen Formation

Thanks to the heterogeneous reactivation of the rift systems, we have access to the different stages of the compressional deformation. This enables us to propose a conceptual model that explains the progressive integration of the rift-related domains into the orogen architecture.

6.2.2.1. Initiation of Reactivation: The Role of Exhumed Serpentinized Mantle

Only a weak reactivation is described on the Western Approach and Armorican margins mainly at the boundary between the exhumed mantle and hyperthinned domains [Thinon *et al.*, 2001]. The serpentinisation of exhumed mantle rocks may be responsible for the creation of a weak horizon where compressional deformation may initiate (as previously described for the West Iberian margin by Péron-Pinvidic *et al.* [2008]; also discussed by Lundin and Doré [2011]). At this stage, the former top basement detachment fault may be used as a decoupling layer, potentially resulting in the sampling of mantle rocks. The former vergence of the detachment system may not play an important role for the onset of reactivation. In the Bay of Biscay, compressional deformation in the exhumed mantle domain can be observed on conjugate margins as exemplified by the Western Approach and North Iberian margin examples (Figures 7a, 8, 9, and 12 [Thinon *et al.*, 2001; Fernández-Viejo *et al.*, 2012, and references therein]).

6.2.2.2. Accretionary Prism and “Subduction” Stage: The Role of Hyperthinned Domains

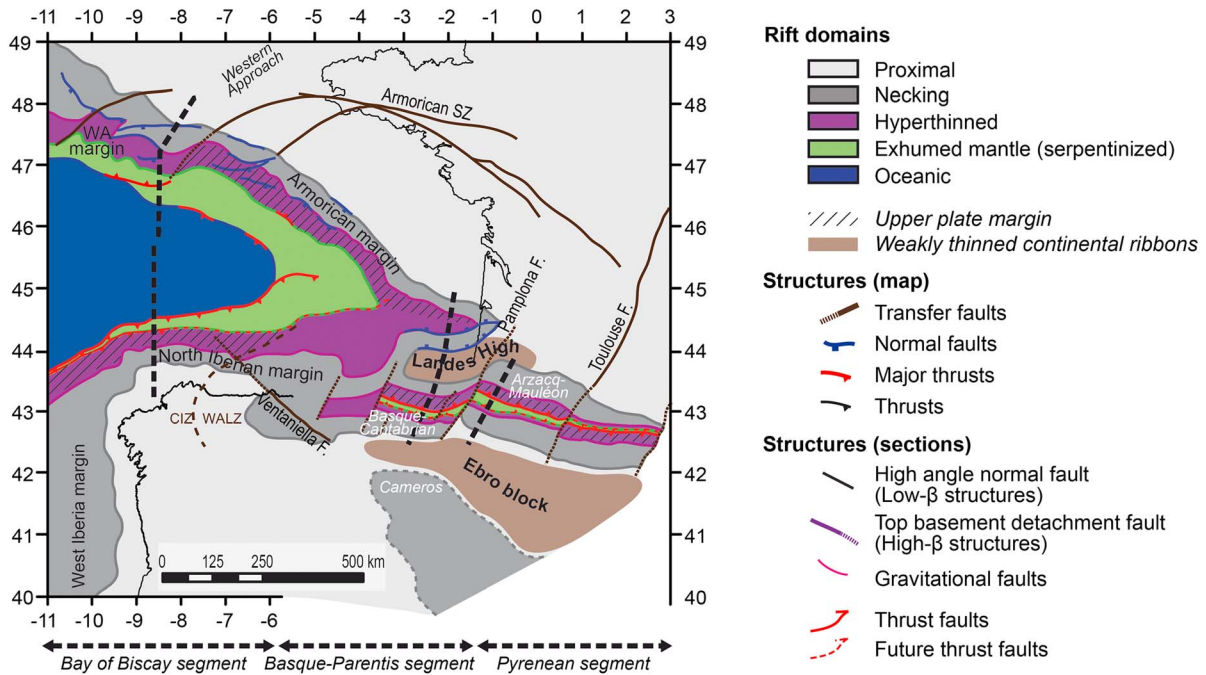
The progressive underthrusting of the former exhumed mantle domain will lead to the propagation of compressional deformation into the hyperthinned domain. This domain is characterized by a strongly hydrated, brittle crust containing low-friction minerals such as clays [Pérez-Gussinyé and Reston, 2001; Reston and Pérez-Gussinyé, 2007]. At this stage the former hyperthinned domain can be progressively deformed, resulting in structures similar to those observed in accretionary prisms, however, with a larger component of crustal material. Such structures have been observed along the North Iberian margin [e.g., Fernández-Viejo *et al.*, 2012]. In the former hyperextended basins, the initially smaller size of the system will lead to the progressive closure of exhumed mantle domain. Subsequently, the convergence of the two conjugate margins may trigger the initiation of a protosubduction of the former hyperthinned domain as exemplified by the Arzacq-Mauléon and Basque-Cantabrian examples (Figure 13). Shortcuts or incisions from new thrust faults may occur into the footwall of the former top basement detachment fault while it is progressively reactivated. They can result in the emplacement of hyperthinned and exhumed mantle rocks within the overlying compressional stack system formed predominantly by rocks originally located in the former detachment faults [e.g., Lagabrielle *et al.*, 2010]. An example of a former hyperthinned domain incorporated into an accretionary prism has been described from the SW termination of the Taiwan Island [McIntosh *et al.*, 2013].

6.2.2.3. Continental Collision and Orogen Formation: The Role of the Necking Domain

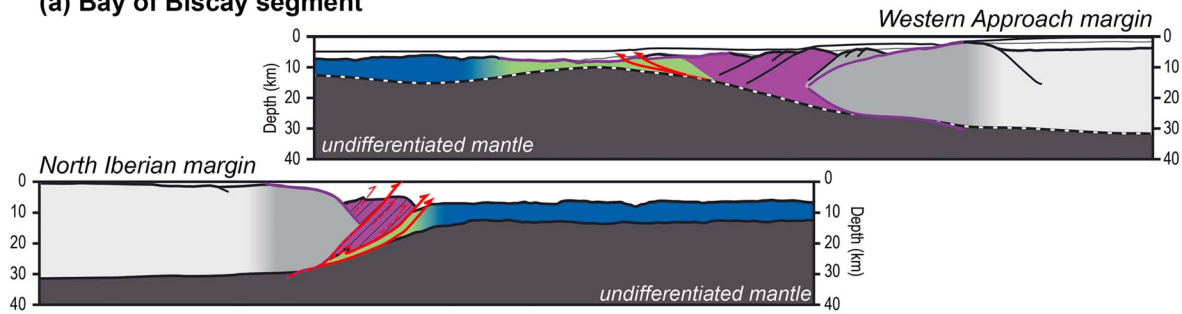
In a later stage of convergence, after the early deformation and progressive subduction/underthrusting of the hyperthinned and exhumed mantle domains, the arrival of the necking and proximal domains result in a major change in the compressional history. This stage is related to a new phase of deformation as observed and described for the Arzacq-Mauléon example. We interpret this second phase of deformation as related to the progressive collision between the former conjugate necking and proximal domains. The former set of conjugate top basement detachment faults interpreted to structure the necking domain [Mohn *et al.*, 2012; Sutra *et al.*, 2013] may be reactivated during the onset of collision. At this stage, the former necking domains can act as buttresses [Mohn *et al.*, 2014]. The collision between these two “buttresses” leads to a change in the mode of deformation. The subduction stage is mainly controlled by asymmetric deformation. In contrast, the collision stage may induce symmetric processes including prothrusting and retrothrusting (e.g., Pyrenean segment; Figures 7c and 10). In the Pyrenean segment, a new phase of deformation can initiate the pop-up inversion of the Arzacq-Mauléon basin along north vergent thrusts (e.g., the Saint Palais, Sainte Suzanne, and Ossau thrusts) and south-directed backthrusting in the Axial zone (e.g., Gavarnie and Guarga thrust systems [Teixell, 1998]).

In this new interpretation of the orogen architecture (Figure 14), the crustal roots imaged from geophysical methods [e.g., Daignières *et al.*, 1994; Roure and Choukroune, 1998; Pedreira *et al.*, 2003, 2007] represent the subducted hyperthinned and exhumed mantle domain. In the case of the North Iberian margin, the necking domain may play a similar role, representing the buttress for the accreted hyperthinned domain. Neves *et al.* [2009] proposed a similar model to explain the distribution of compressional deformation observed in the Tagus Abyssal plain (West Iberian margin) and interpreted the former necking zone as a crustal indenter.

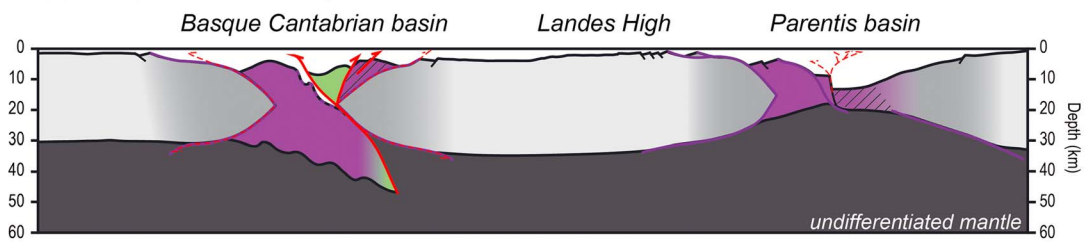
This evolutionary model underlines two major points: (1) most of the deformation is located at the limits of rift domains implying that the former extensional structures separating rift domains were preferentially reactivated during compressional processes [Jammes *et al.*, 2009; Roca *et al.*, 2011] and (2) the hyperthinned and exhumed mantle domains accommodate most of the deformation while the necking and proximal domains act as buttresses and consequently accommodate a relatively weak crustal shortening.



(a) Bay of Biscay segment



(b) Basque-Parentis segment



(c) Pyrenean segment

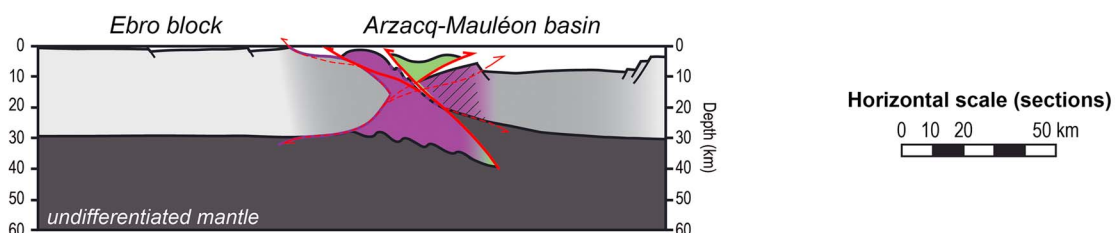
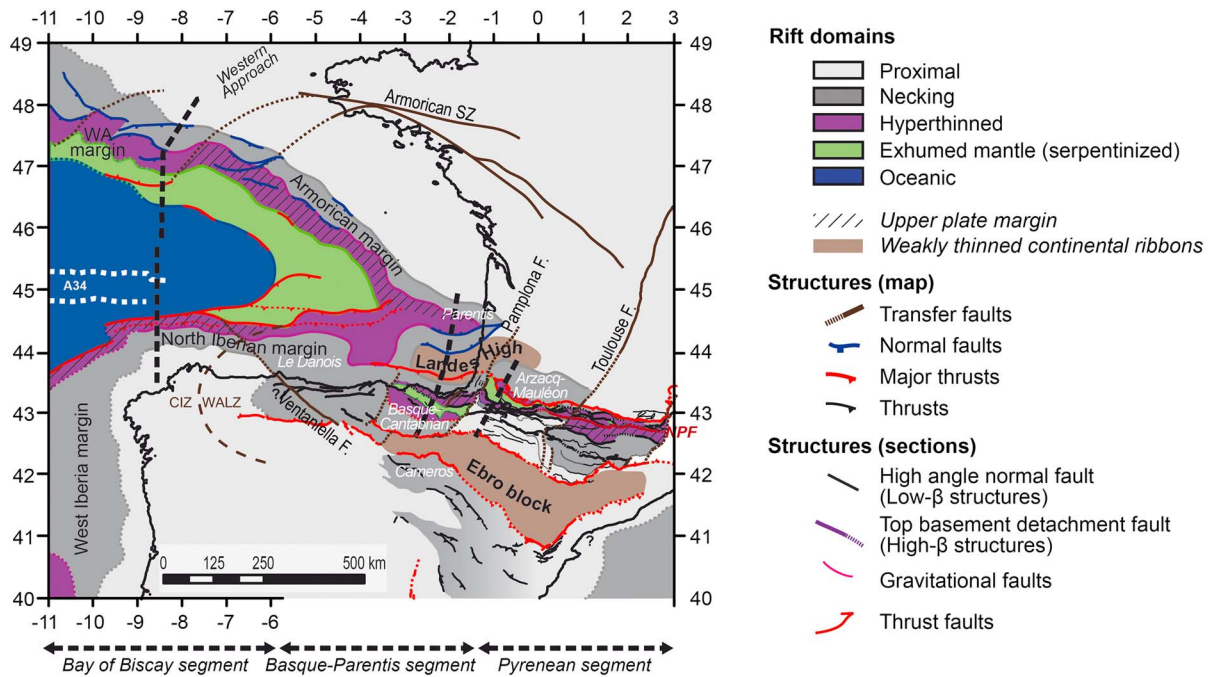
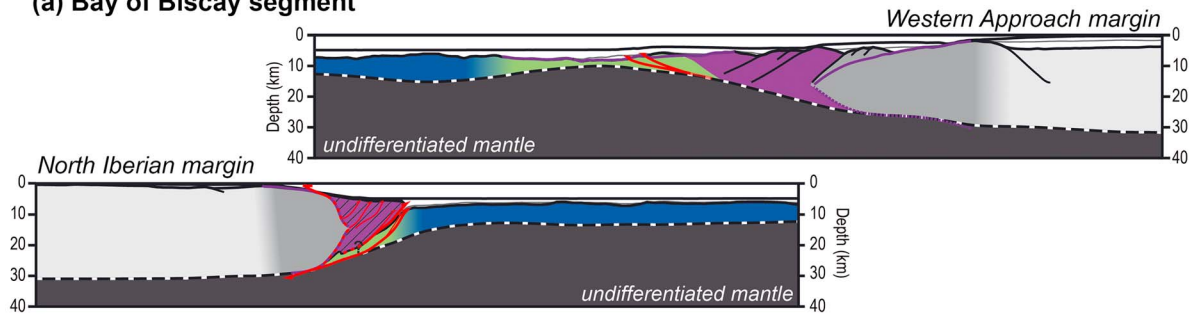


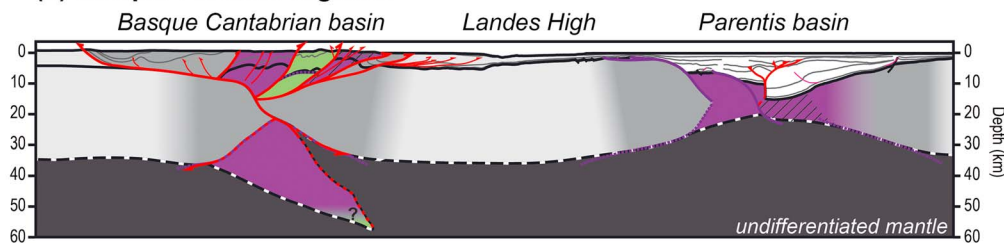
Figure 13. Accretionary prism and subduction stage (Santonian-Campanian to Eocene) of the Bay of Biscay and Pyrenean rift systems. Sections are proposed in the (a) Bay of Biscay segment, (b) Basque-Parentis segment, and (c) Pyrenean segment. WA margin: Western Approach margin.



(a) Bay of Biscay segment



(b) Basque-Parentis segment



(c) Pyrenean segment

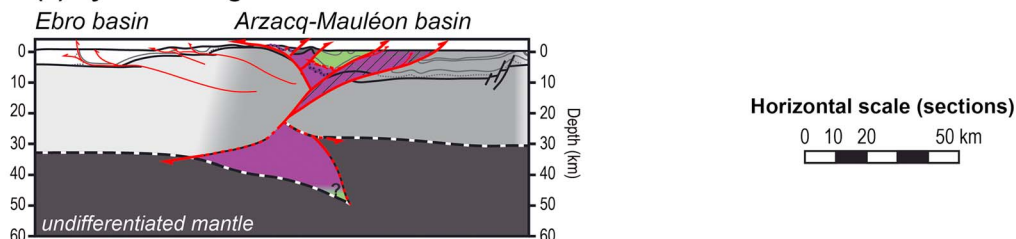


Figure 14. Collision stage of the Bay of Biscay and Pyrenean rift systems. Sections are proposed in the (a) Bay of Biscay segment, (b) Basque-Parentis segment, and (c) Pyrenean segment to illustrate the buttress role of necking domains. WA margin: Western Approach margin.

6.3. General Implications

6.3.1. Partitioning of the Deformation and Shortening Rate Estimations

The reinterpretation of the orogen architecture proposed in this study (Figure 14) emphasizes the role of the former rift domains (and not only of rift-inherited structures) for reactivation and collisional orogen formation (Figures 12–14). It has additional implications for the restoration of the area and hyperextended rift systems in general. In order to propose a complete restoration of the former rift architecture, it is necessary to quantify the horizontal movement accommodated during the reactivation of rift structures (in particular, top basement detachment faults) and to estimate the underthrust/subducted part of the hyperthinned and exhumed mantle domains (Figures 13 and 14).

Many restorations are focused on the thick-skin deformation observed in external parts of the orogens (e.g., in the Western Pyrenees [Teixell, 1996, 1998]). In the previous discussion, we showed that at least in the Western Pyrenees, this deformation may be minor and only corresponds to the final stage of compression (Figures 13 and 14). Therefore, only considering the restoration of structures in the external domains leads to underestimations of the initial shortening related to the underthrusting/subduction of the hyperthinned and mantle domains preserved in the internal parts of the orogen (Figure 14).

Restorations of the crustal roots inferred from geophysical methods (e.g., refraction and gravity modeling) are also proposed [e.g., Muñoz, 1992; Daignières *et al.*, 1994; Pedreira, 2004]. Although some of these restorations unraveled previously thinned domains, they cannot restore quantitatively the underthrust/subducted portions of the former exhumed mantle domain based on crustal scale geophysical imaging alone.

Finally, in order to estimate the shortening accommodated at the scale of the overall Bay of Biscay and Pyrenees, it is necessary to apprehend the partitioning of compressional deformation between two former rift systems and their complex 3-D rift architecture (Bay of Biscay-Parentis and Pyrenees-Basque-Cantabrian rift systems). Therefore, the increasing deformation observed eastward from the Bay of Biscay to the Pyrenees may not be related to an increasing shortening but related to the heterogeneous reactivation of a complex pattern of rift systems.

6.3.2. Nature of the North Pyrenean Fault and Plate Kinematic Implications

The NNE-SSW to NE-SW segmentation characterizing the Pyrenean-Basque-Cantabrian rift system [see also Jammes *et al.*, 2009; Roca *et al.*, 2011] controls the spatial evolution of the rift domains mapped in this study at least from late Aptian to early Albian. The relative continuity of these structures across the former rift system preclude any strike-slip or major left-lateral movements after late Aptian time (as previously discussed by Jammes *et al.* [2009, 2010a]).

The North Pyrenean fault was interpreted as a major crustal discontinuity defining the plate boundary between the European and the Iberian plates [Mattauer, 1968; Choukroune and Mattauer, 1978; Choukroune and ECORS Team, 1989]. This structure was supposed to accommodate a left-lateral displacement of the Iberian plate during mid-Cretaceous time [e.g., Le Pichon *et al.*, 1971; Mattauer and Séguret, 1971; Olivet, 1996]. However, the nature and lateral continuity of this fault was questioned by several authors [e.g., Mattauer and Séguret, 1971; Canérot *et al.*, 2001; Canérot, 2008, and references therein].

In the light of our mapping results, the North Pyrenean fault system coincides with the occurrence of the exhumed mantle domain. In the east, this domain corresponds to a narrow, subvertical zone that can be mapped as a highly deformed zone (see geological sections in Lagabrielle *et al.* [2010]) indirectly also characterized by HT-LP metamorphism attributed to the extreme rift-related thinning [e.g., Golberg and Leyreloup, 1990]. Controversies on the western continuation of this structure [Canérot *et al.*, 2001; Mattauer and Séguret, 1971] correspond with the progressive widening of the exhumed mantle domain characterized by a weaker compressional overprint. Therefore, we suggest that the North Pyrenean Fault represents a “suture” zone related to the inversion of the former hyperextended and exhumed mantle domains.

7. Conclusions

The aim of this study was to characterize the spatial and temporal evolution of hyperextended rift systems and their progressive reactivation. We used gravity inversion, seismic interpretation, and field mapping to

propose a map of the rift domains from the offshore Bay of Biscay to their onshore fossil remnants preserved in the Pyrenees. The key observations and learnings of this work on the formation and deformation of hyperextended systems can be summarized as follows:

1. Two spatially distinct rift systems can be described: the Bay of Biscay-Parentis and the Pyrenean-Basque-Cantabrian rift systems characterized by the diachronous initiation of hyperextensional processes.
2. These rift systems are characterized by a strong segmentation that may be partially inherited from the complex structuration of the Variscan orogen and/or from the Permo-Carboniferous post-Variscan history. This segmentation may control lateral variations in the architecture of the rift systems but does not control the formation of the oceanic domain. This last observation may indicate that rift systems are sensitive to inherited structures and rheology while oceanic domains are more likely to be controlled by asthenospheric processes.
3. The NE-SW to NNE-SSW segmentation observed across the Pyrenean-Basque-Cantabrian rift system preclude the accommodation of an important left-lateral movement after late Aptian to early Albian time in this rift system as proposed from previous studies.
4. Different steps in compressional deformation are related to the rift domain inheritance. At first, reactivation is initiated in the serpentinized layers of the exhumed mantle domain. The progressive closure of this domain may lead to the propagation of compressional deformation to the hyperthinned domain resulting in the formation of an accretionary prism. In the former rift system preserved onshore, the proximity of the conjugate system enables the underthrusting/subduction of the former hyperthinned domains. The final architecture of the orogen is acquired during the collision of the former necking domains representing conjugate buttresses.

Finally, we believe that the complex evolution and architecture of the Bay of Biscay and Pyrenees may be used as an analogue to understand the partitioning of extensional deformation in other rift systems. Additionally, the role of rift inheritance for reactivation and orogen formation may provide new insights for the formation of collisional orogens.

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