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The role of extensional detachment systems in thinning the crust and exhuming granulites: analogies between the offshore Le Danois High and the onshore Labourd Massif in the Biscay/Pyrenean rifts

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Abstract – Large uncertainties remain about the architecture, timing and role of the structures responsible for high degrees of crustal thinning and the exhumation of mid-crustal granulites in the Pyrenean and Biscay rift systems. Both, the Le Danois High in the North Iberian margin and the Labourd Massif in the Western Pyrenees preserve evidence of extensional detachment faults and include exhumed granulites, which are locally reworked in syn-rift sediments. In this study, we compare the crustal structure and its link to the overlying sediments at the two sites based on the interpretation of high quality 2D seismic reflection profiles offshore and field observations and published geological cross-sections onshore. New reported seismic and field observations support that extensional detachment systems delineate the top basement in the Le Danois High and the Labourd Massif, advocating for a similar tectonic evolution. We propose that the Le Danois and North Mauléon extensional detachment systems were responsible for high degrees of crustal thinning and the exhumation of the pre-rift brittle-ductile transition and associated mid-crustal granulites during Aptian to Cenomanian extension, leading to the formation of the Le Danois and Labourd crustal tapers. Subsequently tilted and uplifted during the Alpine convergence, the two taper blocks lay at present in the hanging-wall of major Alpine thrusts. Their position at overlapping, en-echelon hyperextended rift segments at the end of rifting, and the occurrence of shortcutting structures at depth linking neighbouring rift segments can explain the preservation of the rift-related detachment systems. This study proposes for the first time analogies between the offshore Le Danois High and the onshore Labourd Massif and demonstrates the importance of extensional detachment systems in thinning the crust and exhuming mid-crustal granulites at the seafloor in the Biscay and Pyrenean rift systems during Aptian to Cenomanian extension.

Keywords: extensional detachment system / crustal thinning / exhumation / granulite / rift segmentation / Bay of Biscay/Pyrenees

Résumé – Le rôle des systèmes de détachement dans l'amincissement crustal et l'exhumation des granulites : des analogies entre l'Haut du Danois et le Massif du Labourd dans les systèmes du rift de Biscaye et Pyrénéenne. De nombreuses questions se posent concernant l'architecture, l'âge et le rôle des structures à l'origine de l'amincissement crustal extrême et de l'exhumation des roches de croûte intermédiaire dans les systèmes de rift des Pyrénées et du Golfe de Gascogne. Le Haut du Danois, sur la marge ibérique nord, et le massif du Labourd, dans l'ouest des Pyrénées, préservent tous les deux des évidences de failles de détachements ainsi que des granulites exhumées redéposées dans les sédiments syn-rifts. Dans cette étude, nous comparons la structure crustale et l'architecture des bassins des deux sites à partir de l'interprétation de profils sismiques de réflexion de haute qualité en mer (offshore), et des

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observations de terrain couplées à une coupe géologique publiée à terre (onshore). Les nouvelles observations sismiques et de terrain nous permettent de suggérer que les systèmes de détachements du Danois et du Nord Mauléon représentent des structures cassantes majeures et analogues dans le système de rift nord ibérique. Nous proposons que ces deux détachements sont responsables de l'amincissement crustal extrême lors de l'Aptien au Cénomanien ainsi que de l'exhumation et la mise à l'affleurement des roches de croûte moyenne sur le fond marin. Ainsi, la transition crustale cassant-ductile pré-rift est exposée à la surface dans ces deux zones. Les deux blocs crustaux du Danois et du Labourd représentent aujourd'hui des hauts structuraux, soulevés et inclinés, dans le toit de chevauchements alpins majeurs. Nous suggérons que leur position, à la terminaison de segments de rifts en échelons, a permis de préserver l'architecture de rift dans le mur de structures orogéniques dites de « shortcut ». En plus de discuter, pour la première fois, de l'analogie entre le Haut du Danois et le massif du Labourd, cette étude montre l'importance des failles de détachement pour l'amincissement crustal et l'exhumation des granulites de croûte moyenne pendant l'extension crétacée dans les systèmes de rifts Pyrénéen et du Golfe de Gascogne.

Mots clés : système de détachements / amincissement crustal / exhumation / granulite / segmentation de rift / Golfe de Gascogne/Pyrénées

1 Introduction

Geological and geophysical observations have suggested the occurrence of highly thinned crust and exhumed mantle in the Bay of Biscay and in the Pyrenean domain (*e.g.*, Pinet *et al.*, 1987; Fernández-Viejo *et al.*, 1998; Thinon *et al.*, 2003; Lagabrielle *et al.*, 2010; Tugend *et al.*, 2014; DeFelipe *et al.*, 2017; Ruiz *et al.*, 2017), leading to a general agreement about the relevance of crustal attenuation and mantle exhumation during Mesozoic rifting. Many studies have proposed different tectonic scenarios to account for hyperextension in these domains (*e.g.*, Clerc and Lagabrielle, 2014; Masini *et al.*, 2014; Tugend *et al.*, 2014; Pedrera *et al.*, 2017; DeFelipe *et al.*, 2018; Ducoux *et al.*, 2019; Saspiturry *et al.*, 2019b; Miró *et al.*, 2021). However, large uncertainties and controversies remain about the structures responsible for crustal thinning, as well as their timing. The scarcity of exposed rift structures and related syn-rift sediments onshore and the shortage of drillhole data in distal domains offshore, as well as the structural imprint imposed by the subsequent Alpine overprint, challenge the study of the hyperextended rift systems in the Biscay and Pyrenean domains.

The Biscay, Basque-Cantabrian and Pyrenean hyper-extended rift segments developed from Aptian to Cenomanian (*e.g.*, Lagabrielle *et al.*, 2010; Tugend *et al.*, 2014; Quintana *et al.*, 2015; DeFelipe *et al.*, 2018; Cadenas *et al.*, 2020; Lescoutre *et al.*, 2021) as part of the North Iberian rift system (Fig. 1). Ductile deformation and symmetrical crustal thinning (*e.g.*, Clerc and Lagabrielle, 2014; Corre *et al.*, 2016), crustal scale listric faulting (*e.g.*, Saspiturry *et al.*, 2019a; Ducoux *et al.*, 2019), and extensional detachment faulting (*e.g.*, Jammes *et al.*, 2009; Cadenas *et al.*, 2020) are the mechanisms proposed to explain crustal thinning and mantle exhumation. Although granulites are spatially associated with Cretaceous rift systems, no consensus exists between their occurrence and the hyperextension processes responsible for the basin development (Vauchez *et al.*, 2013; Olivier, 2013; Clerc *et al.*, 2015; Odlum and Stockli, 2019; Saspiturry *et al.*, 2019a; Asti *et al.*, 2019). Alpine contraction of Mesozoic rift systems led to the formation of the Pyrenees, the Basque-Cantabrian Zone, and the Cantabrian Mountains onshore and distinctive reactivation of the North Iberian margin offshore (Fig. 1). While the North Pyrenean Zone and the Basque-Cantabrian Zone onshore show field remnants of these hyperextended rift systems, the North Iberian margin offshore partially preserves their former rift architecture and margin template (Fig. 1).

In this study, we address the problem of crustal attenuation and exhumation of pre-rift midcrustal granulites based on the analysis and comparison of the offshore Le Danois High and the onshore Labourd Massif. Both settings show mild contractional reactivation of extensional structures, display evidence of extensional detachment systems, and preserve granulites, which are locally reworked in tectono-sedimentary breccias of Aptian to Cenomanian age. Based on new seismic interpretations and field observations, combined with published geological and geochronological datasets, we describe and compare the syn-rift architecture preserved in the Le Danois High and the Labourd Massif. We discuss key structural and stratigraphic observations and first-order analogies reported at the two sites, as well as their implications for hyperextension models in the Pyrenean and Biscay hyperextended rifts. Finally, we propose a tectonic scenario to account for the preservation of rift-inherited structural and stratigraphic features at the Labourd Massif and the Le Danois High, which were uplifted and tilted during the Alpine convergence.

2 Extensional detachment systems linked to crustal thinning: a review

Extensional detachment faults, also known as, long offset, high-β, or low-angle normal faults, were firstly discovered and described in the Basin and Range Province in the United States (*e.g.*, Longwell, 1945; Wernicke, 1985). Large-scale, extensional detachment faults display classical upward to downward concave, irregular geometries, with high-angles at the break-away (≈60°), which rapidly become sub-horizontal (*e.g.*, <10°), resulting into large offsets, up to tens of kilometres (*e.g.* Wernicke, 1985; Lister, 1986; Lister and Davies, 1989; Axen, 2005).

Extensional detachment faults also occur at rifted margins. These structures accommodate high degrees of crustal thinning and exhumation, shaping largely the final architecture of

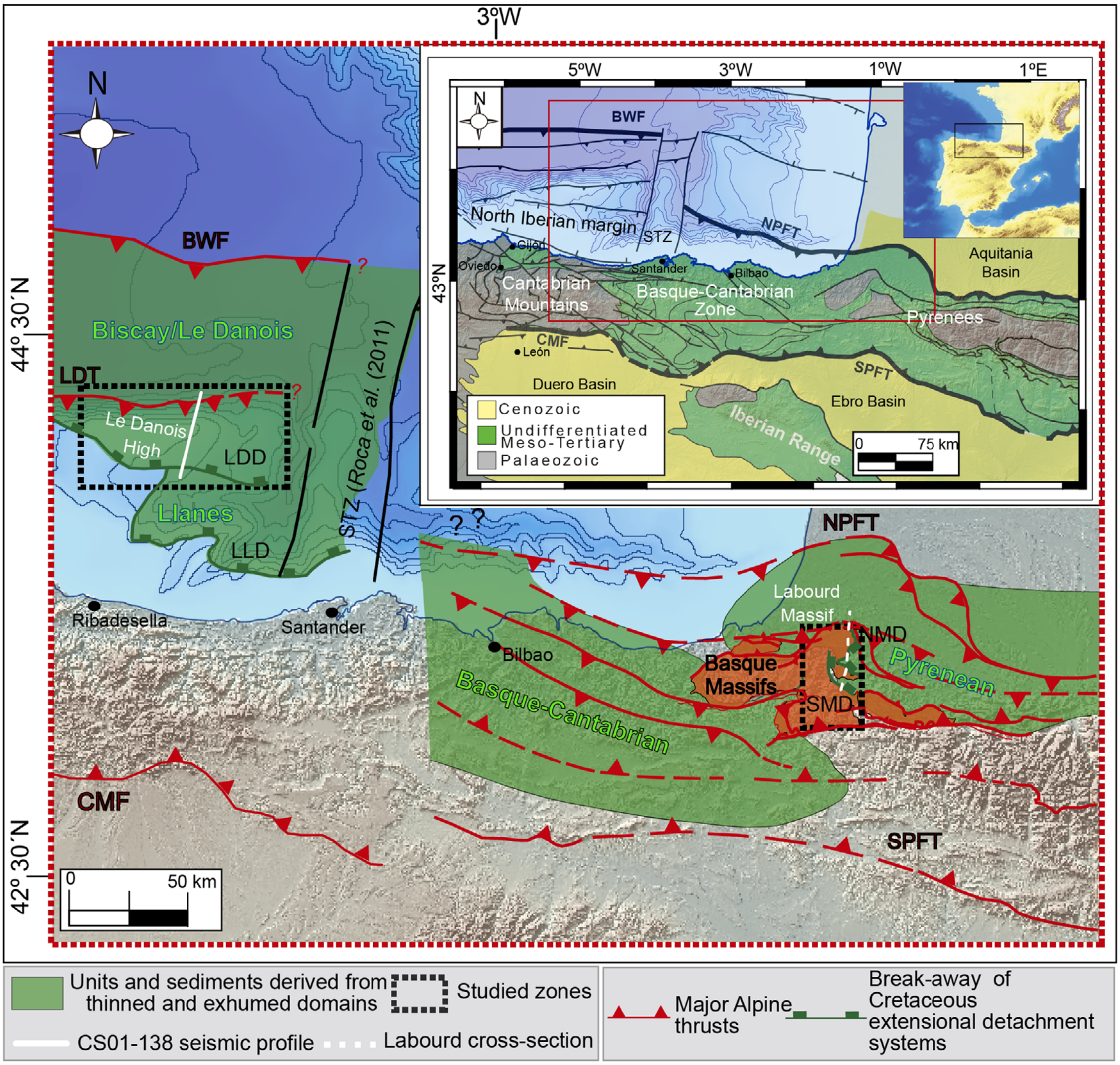

Fig. 1. Location and extent of the Biscay, Basque-Cantabrian and Pyrenean rifts in the context of the North Iberian hyperextended rift system. The map also displays major described Alpine thrusts. Basque-Cantabrian and Pyrenean rift segments and related structures are from Lescoutre and Manatschal (2020). Biscay and Llanes rift segments and their bounding breakaway structures and the Le Danois Thrust (LDT) are from Cadenas *et al.* (2020). The inset map displays the location of the studied zone in the context of the Pyrenean-Cantabrian orogen. BWF: Biscay Wedge Front (from Fernández-Viejo *et al.*, 2012); CMF: Cantabrian Mountains Front (from Alonso *et al.*, 1996); LDD: Le Danois Breakaway surface; LLD: Llanes Breakaway surface; NPFT: North Pyrenean Frontal Thrust; NMD: North Mauléon Detachment; SPFT: South Pyrenean Frontal Thrust; SMD: South Mauléon Detachment; STZ: Santander Transfer Zone (from Roca *et al.*, 2011).

magma-poor rifted margins (*e.g.*, Lister, 1986; Pérez-Gussinyé and Reston, 2001; Manatschal, 2004). Great efforts have been directed to study extensional detachments in hyperextended domains based on offshore seismic surveys (*e.g.*, Boillot *et al.*, 1988; Pérez-Gussinyé and Reston, 2001; Osmundsen and Ebbing, 2008; Lymer *et al.*, 2019) and onshore field analogues (*e.g.*, Froitzheim and Eberli, 1990; Mohn *et al.*, 2012; Epin and Manatschal, 2018; Ribes *et al.*, 2020). Numerical models have also successfully reproduced crustal thinning and exhumation along extensional detachment faults (*e.g.*, Brune *et al.*, 2014; Petri *et al.*, 2019; Chenin *et al.*, 2020). These experiments have revealed that the development of in-sequence extensional detachment faults occur when the strongest brittle layer in the lithosphere (typically the upper lithospheric mantle) yields and deformation in the crust starts to localize (*e.g.*, Chenin *et al.*, 2020). However, large uncertainties remain regarding the seismic expression of these structures and their role in crustal exhumation processes. Little understood are also early stages of development of such structures, documented in the breakaway zone, and their role in exhuming pre-rift mid-crustal rocks. In the field, Masini *et al.* (2014) and Epin and Manatschal (2018) described breakaway and allochthon blocks linked with extensional detachments. Offshore, breakaway complexes and in-sequence extensional detachment faults, which incise into ductile middle crust (inner break-away complexes) or penetrate into the mantle (outer break-away complexes), have been recently described in the Norwegian margin (Osmundsen and Péron-Pinvidic, 2018). However, it remains difficult to define the syn-tectonic sequences linked to such systems in seismic sections. Osmundsen and Redfield (2011) and Gillard et al. (2016) suggested that such sequences onlap or downlap onto exhumed, highly thinned crust and further outboard onto serpentinized mantle. Field observations reported by Masini et al. (2013) and Ribes et al. (2019) showed that deep marine syn-rift sediments onlap or downlap onto exhumed detachment surfaces. Crustal attenuation further inboard, in the so-called necking zone (*e.g.*, Mohn *et al.*, 2012), has also been related to the interplay of extensional detachment faults with major intra-crustal mylonitic shear zones, leading to seafloor exposure of middle crustal rocks and their reworking in the overlying sediments (*e.g.*, Weinberg and Rosenbaum, 2007; Jammes *et al.*, 2009).

In the Biscay and Pyrenean hyperextended rift segments, seismic reflection interpretations and field observations recognized and described extensional detachment faults (De Charpal *et al.*, 1978; Jammes *et al.*, 2009; Masini *et al.*, 2014; Cadenas *et al.*, 2020; Lescoutre *et al.*, 2021). However, none of the previous studies compared these onshore and offshore examples in an attempt to identify key structures and similar tectono-stratigraphic features, supporting a common kinematic framework during Mesozoic hyperextension. Combine off- and onshore observations from both the Le Danois High and the Labourd Massif enable to describe extensional detachment faults and their link to breakaway and allochthonous blocks, syn-rift tectono-sedimentary breccias and intra-crustal mylonitic shear zones from the outcrop to the large seismic scale.

3 Crustal thinning and exhumation processes along the Biscay and Pyrenean domains

The Le Danois High is a bathymetric high located between 5°30′W and 4°30′W in the central part of the North Iberian margin (Le Danois, 1948), 65 km offshore Asturias (Fig. 1). The Labourd Massif is one of the so-called Basque Massifs, situated onshore at the French-Spanish border, at the junction between the Pyrenees and the Basque-Cantabrian Zone (Fig. 1). Both sites are at present part of the Pyrenean-Cantabrian orogen, which developed from Santonian to Miocene driven by the convergence between the African and the European plates and the Iberia microplate (*e.g.*, Roest and Srivastava, 1991; Rosenbaum *et al.*, 2002; Vissers and Meijer, 2012; Macchiavelli *et al.*, 2017). The Alpine reactivation varies from incipient subduction and underthrusting of exhumed mantle and highly thinned crust in the Bay of Biscay (Ayarza *et al.*, 2004; Roca *et al.*, 2011; Fernández-Viejo *et al.*, 2012; Cadenas *et al.*, 2020), to a continent-continent collision in the Pyrenees (*e.g.*, Choukroune and ECORS Team, 1989; Daignières *et al.*, 1994; Muñoz, 1992; Pedreira *et al.*, 2003; Chevrot *et al.*, 2018; Teixell *et al.*, 2018 and references therein). However, the rift maturity decreases eastwards, from that of a passive rifted margin in the western Bay of Biscay (*e.g.*, Álvarez-Marrón *et al.*, 1996; Fernández-Viejo *et al.*, 1998) to a failed hyperextended rift in the Basque-Cantabrian and Pyrenean domains (*e.g.*, Masini *et al.*, 2014; Tugend *et al.*, 2014; Quintana *et al.*, 2015; DeFelipe *et al.*, 2017; Lagabrielle *et al.*, 2020). The complex and variable rift architecture resulted from successive and out of sequence rift events, which led to the formation and spatial overprint of distinctive rift systems (Boillot *et al.*, 1971; Cadenas *et al.*, 2020). The Le Danois High is part of the Biscay rift system and the Labourd Massif belongs to the Pyrenean rift system. Both rift systems have been interpreted to develop during an Aptian to Cenomanian polyphase rift event leading to extreme crustal thinning and mantle exhumation due to the emplacement of extensional detachment faults (*e.g.*, Masini *et al.*, 2014; Cadenas *et al.*, 2020) or crustal-scale listric faults (Saspiturry *et al.*, 2019a).

Geophysical methods and derived interpretations proposed the presence of highly thinned crust and exhumed mantle at distal parts of the North Iberian margin, although their extent and limits are currently debated (*e.g.*, Roca *et al.*, 2011; Fernández-Viejo *et al.*, 2012; Tugend *et al.*, 2014; Ruiz *et al.*, 2017; Cadenas *et al.*, 2018). Recovery and dating of dredged granulites reworked as clasts into Aptian to Albian breccias along the northern slope of the Le Danois High (Capdevila *et al.*, 1980; Malod *et al.*, 1982) supported crustal exhumation processes during Mesozoic rifting (Boillot *et al.*, 1979; Fügenschuh *et al.*, 2003), although the exhumation mechanisms are still uncertain. In the Pyrenean rift system, field outcrops include serpentinized mantle rocks (Choukroune, 1972; Walgenwitz, 1976; Fabriès *et al.*, 1998; Lagabrielle and Bodinier, 2008; DeFelipe *et al.*, 2017). It is widely accepted that extreme crustal thinning and mantle exhumation occurred from Aptian to Cenomanian (*e.g.*, Jammes *et al.*, 2010; Lagabrielle *et al.*, 2010; Clerc *et al.*, 2012; Masini *et al.*, 2014; DeFelipe *et al.*, 2017; Hart *et al.*, 2017), together with HT/LP metamorphism of the pre- to syn-rift sediments (*e.g.*, Albarède and Michard-Vitrac, 1978; Golberg and Leyreloup, 1990; Mendia and Ibarguchi, 1991; Martínez-Torres, 1992; Cuevas and Tubía, 1999; Lagabrielle *et al.*, 2010; Clerc *et al.*, 2015; Ducoux *et al.*, 2019; Lescoutre *et al.*, 2019). The Agly, Arize, Castillón, Trois-Seigneurs, and the Labourd basement include bodies of pre-rift mid-crustal granulites associated with Cretaceous rift basins (Boissonnas *et al.*, 1974; Walgenwitz, 1976; Vielzeuf, 1984; Vielzeuf and Kornprobst, 1984; de Saint Blanquat *et al.*, 1986; Lagabrielle *et al.*, 2010; Odlum and Stockli, 2019). However, the age and mode of exhumation of these granulites remain debated (*e.g.*, Vauchez *et al.*, 2013; Olivier, 2013; Clerc *et al.*, 2015; Asti *et al.*, 2019; Odlum and Stockli, 2019). Based on observations and derived interpretations, we perform a comparison of the Le Danois High and the Labourd Massif with the aim to discuss the conditions, the timing and the structures that were responsible for crustal thinning and exhumation during Mesozoic rifting. We also discuss the role of the architecture of the hyperextended rift systems on the preservation of extensional detachment faults at the Le Danois and the Labourd Massif.

4 The Le Danois High

4.1 Generalities

The Le Danois High corresponds to a basement high located between Upper Jurassic to Cretaceous depocentres in the south and the Biscay accretionary wedge to the north (*e.g.*, Boillot *et al.*, 1971; Álvarez-Marrón *et al.*, 1996; Gallastegui *et al.*, 2002; Cadenas *et al.*, 2020). Published velocity models (Fernández-Viejo *et al.*, 1998; Ruiz *et al.*, 2017) and a depth migrated seismic profile constrain at present a maximum crustal thickness of about 20 km (Cadenas *et al.*, 2018).

Sediments at the Le Danois High describe a southward tilted succession (Boillot *et al.*, 1979; Cadenas and Fernández-Viejo, 2017). Multi-channel seismic reflection profiles reveal a rather transparent character of the high and show that the basement outcrops locally at its top (Boillot *et al.*, 1979; Gallastegui *et al.*, 2002; Cadenas and Fernández-Viejo, 2017). A prominent discontinuity delineates the contact between the basement and the sedimentary cover along the southern slope and at the top of the high, corresponding to the major observed structural feature in seismic sections (Cadenas *et al.*, 2018). The Le Danois High has been traditionally interpreted as an Alpine promontory, resulting from the stacking of thrust sheets consisting of Mesozoic stretched/hyperextended crust emplaced along north-verging thrusts (Boillot *et al.*, 1979; Malod *et al.*, 1982; Gallastegui *et al.*, 2002; Roca *et al.*, 2011; Pedreira *et al.*, 2015). More recently, the basement high has been alternatively interpreted as an inherited rift-related structural feature (Cadenas and Fernández-Viejo, 2017), which was subsequently tilted and uplifted during the Alpine reactivation due to underthrusting of highly thinned crust (Cadenas *et al.*, 2020).

4.2 Dredging results: nature of basement and of the sediment cover

The *Cyana* submersible completed 9 dives and collected several dredges and cores across the Le Danois High, in between 5°05'W and 4°40'W, during the submarine *Cydanois* research campaign (Boillot *et al.*, 1979; Malod and Boillot, 1980; Malod *et al.*, 1982) (Fig. 2A and B). Dredged and cored samples provided a description of the nature of the basement and the stratigraphy of the sediment cover of the Le Danois High (Capdevila *et al.*, 1974; Boillot *et al.*, 1979; Capdevila *et al.*, 1980; Malod *et al.*, 1982) (Fig. 2B).

Basement samples were dredged from the talus and at the top of the High (Boillot *et al.*, 1979) ((Fig. 2A and B). It includes two types of assemblages (Capdevila *et al.*, 1974; Boillot *et al.*, 1979): (1) quartzites of probable Cambrian age, showing facies varying between greenschists and amphibolites, with undeformed granitoids and granophyres (*e.g.*, sample 6E1 in Fig. 2B) and (2) acidic granulites and acidic and basic Middle Precambrian charnokites. Samples 3E5 (dive 3) and 4E3 (dive 4) include clasts of granulites reworked into Aptian to Albian breccias and conglomerates (Malod *et al.*, 1982) (Fig. 2B). Fügenschuh et al. (2003) dated zircons and apatites from three granulite samples (Fig. 2A) using fission track methods. Sample W389 (Fig. 2A) yields a zircon age of 284 ± 58 Ma, revealing that this sample cooled through c. 240°C in the late Carboniferous to Early Permian. Apatite fission tracks of the three samples gave cooling ages through ∼100°C of 138 ± 7 (X367, Fig. 2A), 120 ± 8 (X343, Fig. 2A), and 52 ± 2 Ma (W389, Fig. 2A), and enabled these authors to propose that exhumation took place during Mesozoic extension, with subsequent local re-heating, as explained by younger ages of ≈ 52 Ma, during the Alpine convergence.

Sediment samples include Upper Jurassic to Lower Cretaceous rocks (Fig. 2A and B). A remarkable observation is that Triassic to Middle Jurassic and Upper Cretaceous samples are lacking (*e.g.*, Boillot *et al.*, 1979). Core B71-2, dredges H76-12, X-302, X-304, and X-307, samples 1E4, 2E3, 5E2, 7E7, 7E8, 8E4, 8E5, and samples 6E2 to 6E5 of dive 6 recovered Upper Jurassic sediments (Fig. 2A and B). Kimmeridgian to Portlandian limestones lies directly onto basement (Boillot *et al.*, 1979), showing that older pre-rift sediments are missing. Dredges H76-9 and H76-7 sampled Upper Jurassic to Neocomian sediments (Fig. 2A). The Upper Jurassic to lowermost Cretaceous sediments, ascribed to Kimmeridgian, Barremian, and Valanginian, include shallow platform carbonates with abundant fauna and pelagic sediments with planktonic micro-organisms (*e.g.*, Boillot *et al.*, 1979) (Fig. 2B). A Tithonian sample shows open sea sedimentation of medium depth (Boillot *et al.*, 1971). Cores B71-4, B71-5, and B71-7, and dredges X-325, 347, 378 and 348 sampled Aptian to Albian sediments (Fig. 2A). Samples 2E6, 2E7, 3E3, 4E2, 4E3, 7E1, 7E2, 7E5, 7E6, samples 9E2 and 9E4, and samples 9E6 to 9E8 recovered Lower Cretaceous sediments (Fig. 2B). Lower Cretaceous samples, spanning from Barremian to Upper Albian, correspond to siliciclastic, flysch-type sediments grading into marls, with limited pelagic micro-fauna, of open sea depositional environments, similar to black shales (Fig. 2B) (Boillot *et al.*, 1979; Malod *et al.*, 1982). Aptian to Albian conglomerates, including fragments of granulites, are interleaved with flysch-type deposits (Capdevila *et al.*, 1980; Malod *et al.*, 1982) (Fig. 2B). Reworked clasts of granulites ask therefore for a nearby exposure of granulites and also support the discontinuity of the pre-rift cover.

Based on samples recovered along the dives, Malod *et al.* (1980) developed detailed synthetic stratigraphic logs regrouping samples of neighbouring dives (Fig. 2B). Relying on these synthetic stratigraphic logs, Malod *et al.* (1982) proposed three archetype sedimentary sections/units, representative of the litho-stratigraphy of the Le Danois High (Fig. 2C). The so-called lower section/unit is described between 2000 m and 3000 m depth and consists of Kimmeridgian to Portlandian limestones with interbedded marls, massive Portlandian to earliest Cretaceous limestones, and Hauterivian sandstones capped by Barremian pelites. The so-called intermediate section/unit is described between 2000 and 1500 m depth and includes dolomites, tentatively ascribed from Late Jurassic to earliest Cretaceous, and Aptian sandstones, with levels of conglomerates, including clasts of reworked granulites, of Aptian to Albian age. The so-called upper section/unit is described from 1500 m upwards and shows basement at the bottom, which is overlain by Bajocian to Oxfordian limestones, Portlandian dolomites, and early Cretaceous marls at the top. It is important to note that the so-called "lower", "intermediate" and "upper" archetype sections/units summarise sample description and attempt to provide a general litho-stratigraphic description of the sedimentary succession. However, distinctive along-strike dives of variable trend recovered these samples (Fig. 2A and B). A continuous section downslope is solely provided by dive 6. This E-W/NE-SW trending dive recovered a basement sample at the top of the high along the E-W trending segment and five Upper Jurassic samples along the upper slope (Fig. 2B). Yet, in-place continuous sections showing the structure of the entire sediment cover onto the basement on the Le Danois High are missing.

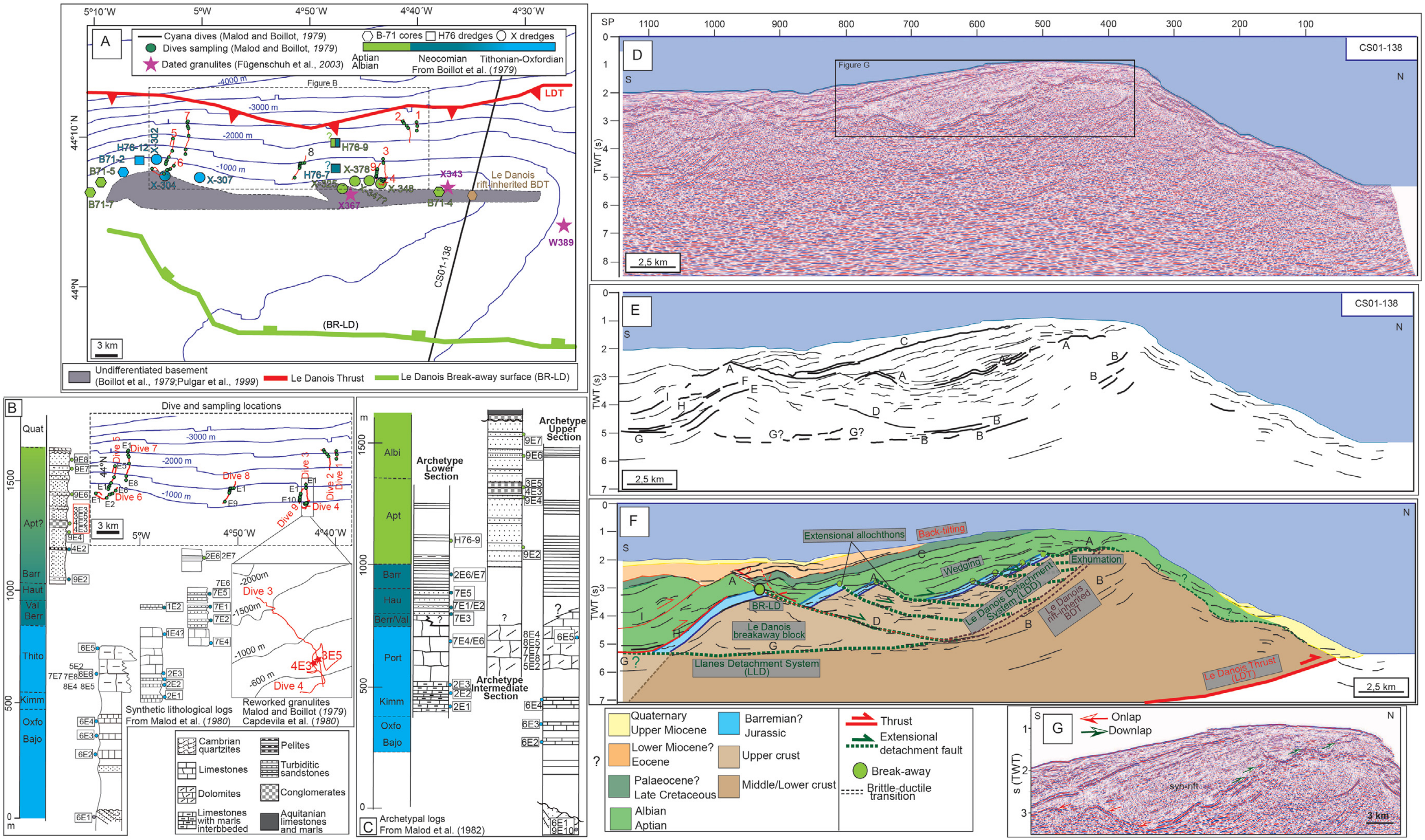

Fig. 2. **A.** Map showing the trend of the dives and the location of samples, dredges and cores along the top and northern slope of the Le Danois High. The map also illustrates the location of the CS01-138 seismic profile, the granulite samples dated by Fügenschuh *et al.* (2003) and basement outcrops interpreted by Boillot *et al.* (1979) and Pulgar *et al.* (1999). Displayed is also the trend of the Le Danois breakaway surface (BR-LD) and the Le Danois Thrust (LDT), taken from Cadenas *et al.* (2020). **B.** Synthetic lithological logs constructed by Malod *et al.* (1980) based on the integration of samples from neighbouring dives. The map show the trend and location of the dives and the distribution of samples, which are also located along the logs. The small inset map shows the location of recovered samples including reworked clasts of granulites. **C.** Three archetype stratigraphic columns describing the stratigraphy of the sediment cover within the Le Danois High defined by Malod *et al.* (1982). **D.** CS01-138 time migrated seismic profile running from south to north across the Le Danois High. **E.** Ray tracing interpretation displaying the analysis of reflectivity patterns. **F.** Geological interpretation showing major structures and tectono-stratigraphic units within the Le Danois High and the geometry and associated basement features of the Le Danois Detachment System (LDD). BR-LD: Le Danois breakaway surface. Age constrains are from Cadenas *et al.* (2020). **G.** Segment of profile CS01-138 showing in detail the reflectivity patterns at the breakaway zone of the LDD.

4.3 New seismic-derived observations

Figures 2D and 2E display the N-S striking, time migrated CS01-138 seismic profile across the Le Danois High and the ray tracing interpretation, respectively. A prominent and rough reflection of high amplitude images the top of seismic basement on the southern slope and at the top of the High (reflection A in Fig. 2E). It shallows progressively from 3 s to less than 1.5 s TWT northwards and is southward tilted. Locally, it is exposed at the seafloor at the northern slope of the Le Danois High (Fig. 2D). The top basement reflection (A) describes asymmetric structural highs and upward to downward concave geometries (SP 800, 700 and 500 in Fig. 2D and E). The top of seismic basement separates a 5 to 6 s TWT thick crust from a 2 s TWT sedimentary cover (Fig. 2E). Although the basement is rather transparent, an outstanding set of short, high amplitude, and low frequency reflections can be traced across the Le Danois High (reflections B in Fig. 2E). This set of reflections are located at ~5 s TWT at the southern part (between SP 700 and SP 500 in Fig. 2D and E) shallowing to ~2 s TWT at the top of the high (SP 364 in Fig. 2D and E). The sediment cover includes a thick and low reflective, lower unit, which is composed of discontinuous and short reflections, and a highly reflective, upper unit, including parallel-layered and continuous reflections (Fig. 2E). A continuous, south-dipping reflection of high amplitude (reflection C in Fig. 2E) separates these two units, which are tilted towards the south. A fan-shaped and restricted unit overlies the upper parallel-layered unit. A thin flat and sub-horizontal package lays at the top of the sediment cover (Fig. 2E).

At the southern border of the Le Danois High, the top of seismic basement can be traced at 3 s TWT, overlying a 10 km wide basement block (between SP 1000 and 900 in Fig. 2E). Two discontinuous reflections of high amplitude delineate a parallel-layered unit of constant thickness on top of the block (reflections E and F in Fig. 2E). A southward-tilted wedge overlays this constant unit, showing landward dipping onlap geometries (Fig. 2E). Two south-dipping, short and discontinuous reflections of high amplitude truncate reflectivity patterns within the wedged unit (reflections H and I in Fig. 2E).

4.4 Tectono-stratigraphic architecture constrained by combined new seismic interpretations and dredging

Figure 2F displays an interpretation of the CS01-138 seismic section showing the crustal structure and the tectono-stratigraphic architecture of the Le Danois High. We interpret the reflection A delineating the top basement as a sequence of extensional detachment faults, and the overlying blocks as extensional allochthons. The highest point of each block is interpreted as the break-away of extensional detachment faults belonging to Le Danois Extensional Detachment system (LDD in Fig. 2F). The pre-rift units included in these blocks are likely to correspond to the Upper Jurassic to Lower Cretaceous shallow platform carbonates and pelagic sediments dredged at the top and along the northern slope of the Le Danois High (Boillot *et al.*, 1979; Malod *et al.*, 1982) (Fig. 2A). In our interpretation, the southward tilted set of bright reflections B corresponds to the pre-rift brittle-ductile transition (the Le Danois BDT in Fig. 2F) or, locally, pre-rift mid-crustal shear zones. The Le Danois BDT shallows northwards and pinches out at the seabed along the northern slope of the Le Danois High (Fig. 2F), where, along-strike, reworked clasts of granulites have been sampled within Aptian to Albian conglomerates (Fig. 2A and B).

Within the sedimentary cover, we interpret the thick lower reflective unit laying on top of the LDD, showing south (continental)ward dipping onlap structures onto the tilted blocks and north(ocean)ward downlapping geometries onto the top basement (Fig. 2G) as a syn-rift, syn-LDD, unit (Fig. 2F). Seismic facies correlation with borehole-constrained seismic interpretations on the Asturian Basin and on the southernmost continental platform (see Cadenas *et al.*, 2020 for further details about age constraints and well-log-based stratigraphy) enable us to suggest an Aptian to Albian age for this syn-rift unit. We propose that this unit corresponds to the dredged flysch deposits and includes the unconformable and interleaved Aptian to Albian conglomerates and breccias including clasts of granulites (*e.g.*, Capdevila *et al.*, 1974, 1980; Malod *et al.*, 1982). The upper reflective and uniform unit is interpreted as the post-rift unit (Fig. 2F). Seismic facies correlation with well-log-based stratigraphy within the Asturian Basin and the continental platform (Cadenas *et al.*, 2020) allows us to suggest an Upper Cretaceous to Paleocene age for this unit. Truncation and erosion of this unit at the southern slope explains the scarcity of Upper Cretaceous to Paleocene at the top of the Le Danois High (Boillot *et al.*, 1979) (Fig. 2F). The overlying fan-shaped unit corresponds to the syn-orogenic unit, tentatively ascribed from Eocene to Lower Miocene, and the tabular unit to the post-orogenic unit, with ages ranging from Late Miocene to Quaternary (Gallastegui *et al.*, 2002; Cadenas and Fernández-Viejo, 2017).

At the southern border of the Le Danois High, we interpret the wide block as an over-tilted break-away block (Le Danois break-away block in Fig. 2F). The block preserves a pre-rift unit that we tentatively ascribe from Jurassic to Barremian based on seismic correlation with borehole-constrained seismic interpretations (Fig. 2F). This unit possibly consists of the Late Jurassic to Barremian shallow marine carbonates and pelagic deposits sampled at the top and along the northern slope of the Le Danois High (*e.g.*, Boillot *et al.*, 1979) (Fig. 2B). We interpret the overlying wedge as a syn-rift unit with ages ranging from Aptian to Albian and the underlying reflection G as an extensional detachment surface belonging to the Llanes Extensional Detachment System (LLD) (for further details about this system, see Cadenas *et al.*, 2020) (Fig. 2F).

5 The Labourd Massif

5.1 Generalities

The NNE-SSW trending Labourd Massif includes the Iparla-Artzamendi, the Baïgoura-Jara and the Ursuya massifs (*e.g.*, Jammes *et al.*, 2009). In contrast to the rest of the Basque Massifs, which include mainly Paleozoic metasedimentary rocks, the Labourd Massif is also characterized by a NNE-SSW trending Permian basin to the south (Bidarray basin; *e.g.* Bixel and Lucas, 1987; Saspiturry *et al.*, 2019a) and by exhumed granulite rocks within the Ursuya Massif to the north (Boissonnas *et al.*, 1974; Walgenwitz, 1976;

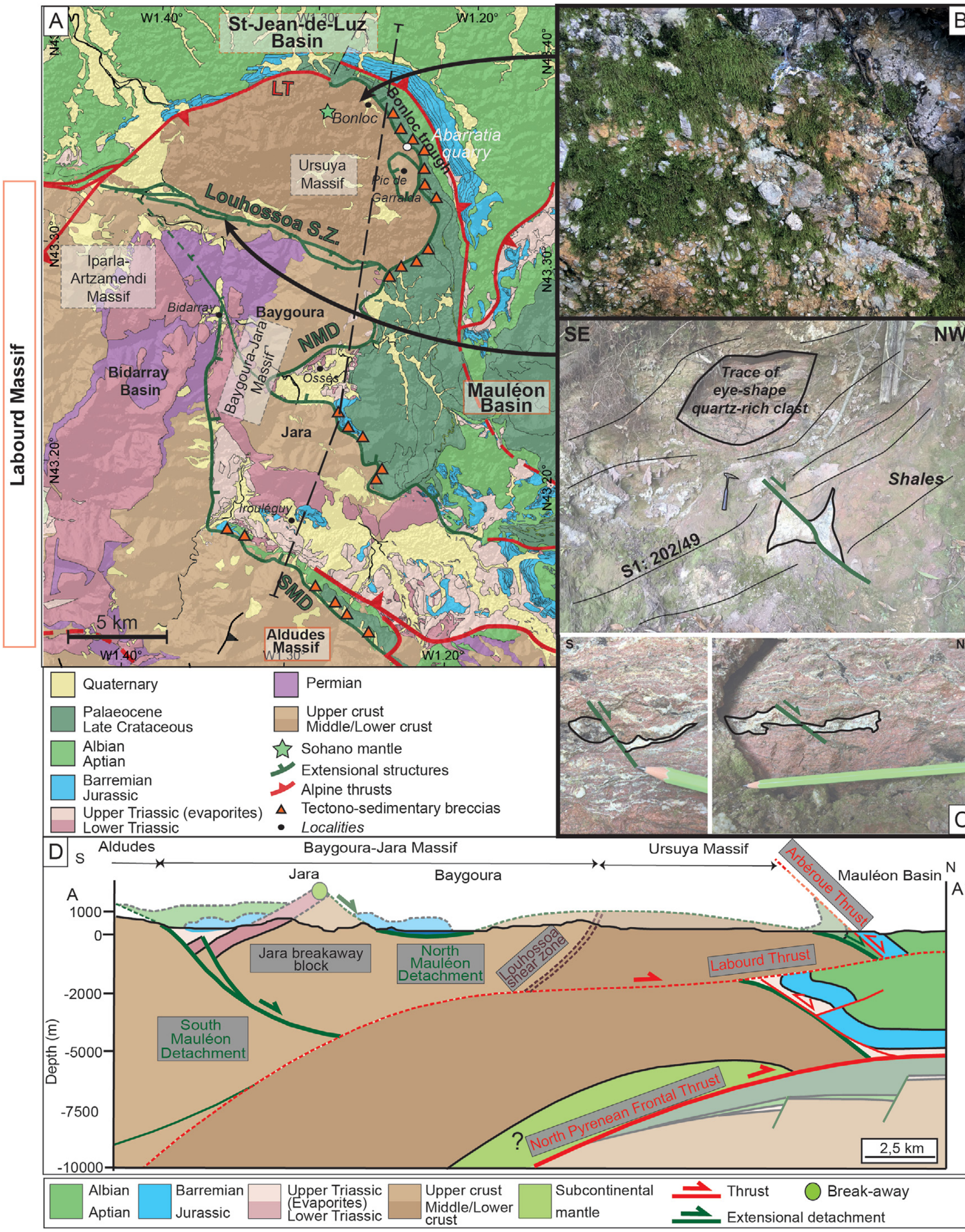

Fig. 3. **A.** Geological map of the Labourd Massif (modified after Genna, 2007), showing the main structural features and tectono-sedimentary units. Tectono-sedimentary breccias after Masini *et al.* (2014). **B.** Cataclasites affecting the Ursuya granulites, near the village of Bonloc. **C.** South-dipping foliation and boudinage related to the Louhossoa shear zone cross-cut by north-dipping extensional faults. **D.** Geological cross-section across the Labourd Massif showing the major structures and tectono-stratigraphic units (after Lescoutre *et al.*, 2021).

Vielzeuf, 1984) (Fig. 3A). Currently, the Labourd Massif lays in between the Mauléon Basin to the northeast and the St-Jean-de-Luz Basin to the northwest (Heddebaut, 1973; Richard, 1986; Razin, 1989; Claude, 1990).The Labourd thrust to the north-west (Richard, 1986; Razin, 1989; Lescoutre *et al.*, 2021), and the Bonloc trough and the North Mauléon Detachment (NMD) to the east-northeast delimit the Massif at present-day (Fig. 3A). The NMD, the South Mauléon Detachment (SMD), and the Louhossoa shear zone (LSZ) constitute the major structural features affecting the massif (Jammes *et al.*, 2009; Masini *et al.*, 2014; Saspiturry *et al.*, 2019a; Lescoutre, 2019).

The Labourd Massif has been primarily interpreted as a basement klippe (*e.g.*, Viennot, 1927) or as a horst (Le Pochat, 1982), which is bounded to the west by the Pamplona transform fault (Rat, 1988; Razin, 1989; Jammes *et al.*, 2010). More recently, Lescoutre et al. (2021) interpreted the entire Basque Massifs as a crustal high in between the eastern and western terminations of the V-shaped hyperextended Basque-Cantabrian and Mauléon/St-Jean-de-Luz Basins, respectively.

5.2 The Ursuya Massif: exhumation of the granulites

The Ursuya Massif represents a dome of south-dipping foliated gneiss, including migmatites, paragneiss, metasediments and metagranulites (Boissonnas *et al.*, 1974; Vielzeuf, 1984; Cochelin *et al.*, 2017) (Fig. 3A). Peak HT/MP metamorphism occurred during the Late Variscan orogeny (295 to 274 Ma), as revealed by U-Pb dating of granulites (*e.g.*, Masini *et al.*, 2014; Hart *et al.*, 2016; Vacherat *et al.*, 2017). This peak metamorphism was associated with ductile deformation, represented by a south-dipping foliation defined by quartz ribbons, elongated feldspar, fibrolitic sillimanite and biotite. In addition, E-W trending mineral stretching lineations can be observed throughout the massif. However, to the south and approaching the LSZ, these lineations trend in a WNW-ESE to N-S direction (Boissonnas *et al.*, 1974; Saspiturry *et al.*, 2019a). Further structural analysis of the massif reveals different stages of deformation post-dating the granulitic peak. They appear as north-vergent shear zones cross-cutting the Variscan metamorphic isogrades as well as N-S striking faults affecting both the granulites and the Cretaceous sediments to the north (Boissonnas *et al.*, 1974; Vielzeuf, 1984; Petri *et al.*, 2018).

To the northeast of the Ursuya Massif, the Aptian-Cenomanian sediments of the Bonloc trough contain clasts of reworked granulites (*e.g.*, Boissonnas *et al.*, 1974; Jammes *et al.*, 2009; Masini *et al.*, 2014) (Fig. 3A). In addition, detrital zircon U-Pb ages from the Mauléon Basin show a peak of sediments sourced from the granulites during the Cenomanian (Hart *et al.*, 2016). $^{40}Ar/^{39}Ar$ ages on biotite from the granulites, interpreted as cooling ages, range between 206 and 196 Ma, suggesting that the granulites cooled below 300 °C during Late Triassic-Early Jurassic (Masini *et al.*, 2014). Hart *et al.* (2017) recovered samples of granulites within the Baygoura-Jara and Ursuya Massifs and determined ZHe cooling ages, with results ranging from 100 to 38 Ma and suggesting a Cretaceous or younger exhumation at shallow crustal depths (*e.g.*, <160–200 °C)

Two contrasting models have been proposed to explain the exhumation of the Ursuya granulites in the literature. The first scenario suggests Permian exhumation related to crustal doming and the emplacement of low-angle shear zones (*e.g.*, Louhossoa shear zone) (Saspiturry *et al.*, 2019a). The second scenario proposes Late Aptian to Cenomanian seafloor exhumation at the footwall of in-sequence, north-dipping, brittle extensional detachment faults due to their interplay with major mid-crustal shear zones (Jammes *et al.*, 2009; Masini *et al.*, 2014; Hart *et al.*, 2016, 2017; Lescoutre *et al.*, 2019).

5.3 First-order structures in the Labourd Massif

The E-W trending LSZ bounds the granulites of the Ursuya Massif towards the south (*e.g.* Jammes *et al.*, 2009; Saspiturry *et al.*, 2019a), and can be recognized at present-day by the occurrence of an E-W striking and up to ~180 m high crest in the topography. The shear zone consists mostly of Paleozoic quartzites (mostly Ordovician) and migmatitic micashists, showing a foliation and a lineation dipping towards the south (≈20 to 50°, see *e.g.*, Jammes *et al.*, 2009; Saspiturry *et al.*, 2019a). In addition, Jammes *et al.* (2009) reported sigma-clasts and shear bands that show a top-to-the-south sense of shear. The shear zone extends locally over 500 m and is mainly localized within the andalusite-biotite-staurolite zone (≈450–550 °C) (Saspiturry *et al.*, 2019a). However, thin-section analysis of carbonate rich quartzo-feldspatic metasediments from the shear zone shows dynamic recrystallization of quartz as well as recrystallized and partially annealed calcite, whereas feldspar do not show such dynamic recrystallization (Jammes *et al.*, 2009). Based on the interpretation of these microstructures, Jammes *et al.* (2009) argued that this deformation occurred under greenschist facies conditions. The foliation and metamorphic grade are abruptly decreasing down to low-grade metamorphism (anchizone; Heddebaut, 1973; Saspiturry *et al.*, 2019a) in the Paleozoic rocks of the Iparla-Artzamendi Massif.

To the north of the Labourd Massif and buried beneath the sediment cover, the north-vergent North Pyrenean Frontal Thrust (NPFT in Fig. 1) corresponds to a major Alpine thrust, which led to the overthrusting of the detached Mauléon Basin and the Basque massifs onto the Aquitaine Basin and the European crust, respectively (Razin, 1989; Lescoutre *et al.*, 2021). Underneath the Labourd Massif, the Labourd Thrust (Richard, 1986) has been interpreted as relay-ramp accommodating out-of-sequence deformation in the hanging wall of the NPFT. This structure is responsible for the overthrusting of the Labourd Massif onto the St. Jean de Luz and Mauléon Basins (Richard, 1986; Lescoutre *et al.*, 2021). This thrust cross-cut the south-vergent Arbéroue thrust, which displaced the detached Upper Triassic to Turonian sedimentary cover towards the south over the Labourd Massif and the Bonloc trough (Boissonnas *et al.*, 1974; Jammes *et al.*, 2009).

At two places in the north-eastern part of the Ursuya Massif (Pic de Garralda and Abarratia quarry, Fig. 3A), Jammes *et al.* (2009) described the occurrence of cataclasites and small offset normal faults affecting the top of the granulites and sealed by sediments. These sediments, likely Cenomanian in age, include turbidites and tectono-sedimentary breccias (*e. g.*, Bonloc breccias, Claude, 1990) containing clasts of granulites. These observations led to the interpretation that the basement is overlain by a brittle top basement extensional detachment. This structure has been further described by Jammes *et al.* (2009) and Masini *et al.* (2014) and referred to as the North Mauléon Detachment fault (NMD). Moreover, Masini *et al.* (2014) recognized several tectono-sedimentary breccias containing clasts of the Paleozoic basement in the mid-Cretaceous sediments along the trace of the NMD (Fig. 3A) and was able to map this structure southwards to the Jara massif. This massif represents a tilted basement block bounded to the north by the north-dipping NMD and forming the breakaway of this structure. South of the Jara Massif,

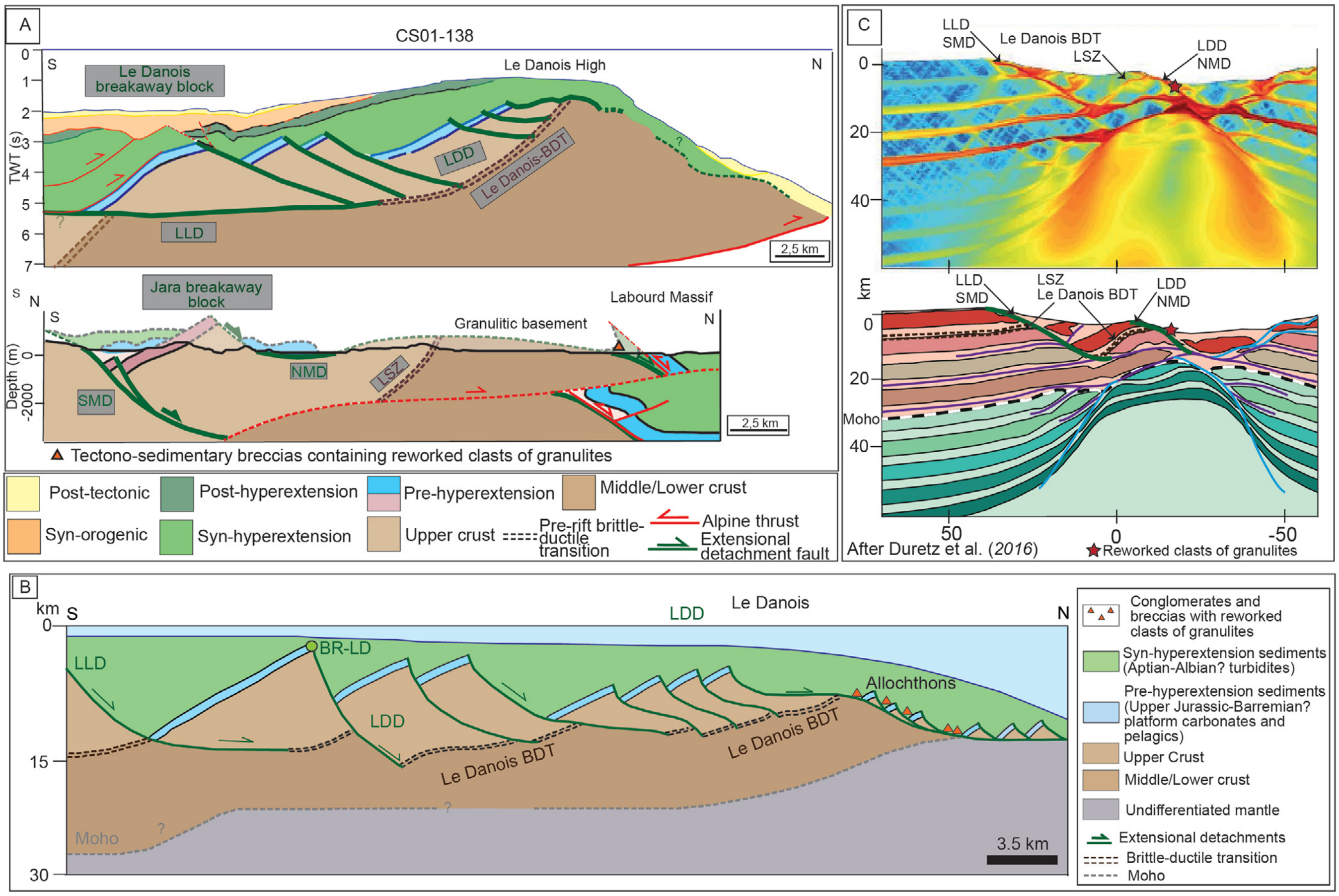

Fig. 4. A. Cross sections showing the current crustal structure and tectono-stratigraphic architecture at the Le Danois High and at the Labourd Massif. **B.** Schematic cross-section displaying an attempt of a qualitative restoration of the Le Danois High at the end of rifting. The section illustrates the geometry of the Le Danois brittle-ductile transition (Le Danois BDT), the Le Danois Extensional Detachment System (LDD) and overlying extensional allochthons, accounting for the juxtaposition and succession of discontinuous pre-rift strata onto exhumed granulites and the occurrence of conglomerates and breccias including clasts of reworked granulites downslope. **C.** 2D numerical model showing the mechanisms of crustal exhumation processes (after Duretz *et al.*, 2016). In the model, analogous structures to the NMD, SMD, LDD, and LLD extensional detachment systems, and to the LSZ and the Le Danois BDT are delineated and labelled.

Masini *et al.* (2014) further described tectono-sedimentary breccias of Late Albian to Cenomanian age (Merle, 1974), and fault gouge along the so-called South Mauléon Detachment (SMD), whose footwall exhumation was dated as Cenomanian (Hart *et al.*, 2016). As such, the NMD and the SMD have been proposed to belong to a set of north-dipping extensional detachment faults responsible for major crustal thinning from Albian to Cenomanian (Masini *et al.*, 2014; Hart *et al.*, 2016, 2017; Lescoutre *et al.*, 2019).

5.4 New field observations

Figures 3B and C show brittle deformation affecting the granulites of the Ursuya Massif and the LSZ, respectively. Figure 3D shows a cross-section (modified after Lescoutre *et al.*, 2021) crossing the Labourd Massif to the Mauléon Basin from south to north, displaying the main structures and tectono-stratigraphic units within the Jara, Baygoura and Ursuya Massifs. As proposed previously, the Jara Massif corresponds to a southward tilted crustal block, preserving a well-defined, southward tilted, and tabular pre-rift unit, highlighted by the current bedding of the Lower Triassic sandstones. The north-dipping SMD floors the crustal block while the Aldudes Massif lays at its footwall (Masini *et al.*, 2014). The southern margin of the Jara Massif is overlaid by Upper Triassic evaporites and Barremian to Cenomanian sediments. The north-dipping NMD outcrops at the northern boundary of the Ursuya and the Jara massifs (Jammes *et al.*, 2009; Masini *et al.*, 2014). It separates the Paleozoic basement from the Upper Triassic to Early Aptian shallow marine pre-rift carbonates and the thick Late Aptian to Cenomanian syn-rift flysch-type siliciclastic deep marine sediments of the Mauléon Basin (*e.g.*, Masini *et al.*, 2014). We report new evidence for brittle deformation along this section. We recognize cataclasites overprinting the granulites at an outcrop at the top of a hill near the Bonloc village (43°22’N, 1°16’E, Fig. 3A). This outcrop (Fig. 3B) is located westwards of the previously recognized brittle deformation affecting the granulites at the Abarratia quarry and Pic de Garralda (Jammes *et al.*, 2009). This observation further supports the westward continuation of the NMD over the Ursuya Massif, as previously suggested by Jammes *et al.* (2009). The brittle flat-lying deformation associated to the NMD cross-cuts the steep south-dipping syn-granulitic ductile deformation mapped on the Ursuya Massif (*e.g.*, Vielzeuf, 1984; Saspiturry *et al.*, 2019a). These observations present an additional support for the existence of a mid-Cretaceous low-angle brittle structure in the study area.

Besides, north of the Iparla-Artzamendi Massif and along the LSZ (Fig. 3A), we identified an outcrop showing the relationship between the ductile deformation of the LSZ and a subsequent brittle deformation (Fig. 3C). Such brittle deformation was already identified by Saspiturry *et al.* (2019a) and firstly reported by Lescoutre *et al.* (2019). There, Paleozoic metasediments are characterized by strongly foliated reddish shales and eye-shape quartz-rich clasts (Fig. 3C). The foliation defined by the ductilely deformed sediments is dipping towards the south and is clearly cross-cut by north-dipping, small offset normal faults. This indicates that a brittle, top-to-the-north deformation postdates the ductile deformation associated with the LSZ.

6 Discussion

6.1 Analogies between the Le Danois High and the Labourd Massif

At both, the Le Danois and Labourd areas, a major change in depositional environment occurred during the Aptian, as recorded by the transition from shallow marine platform carbonates to siliciclastic turbidites (*e.g.*, Boillot *et al.*, 1979; Masini *et al.*, 2014). The latter reveal deep depositional environments linked to high subsidence rates due to crustal thinning, resulting in the creation of large accommodation space from Aptian onwards in both areas due to rifting. The most striking tectono-stratigraphic similarity between the Le Danois High and the Labourd Massif is the presence of breccias, including reworked clasts of upper crustal Paleozoic metasediments and mid-crustal granulites, interleaved into the Aptian to Cenomanian turbidites (Fig. 4A). Both, these syn-rift Late Aptian to Cenomanian breccias and the pre-rift sedimentary cover lay unconformably on top of the basement. This suggests either a tectonic or an erosional contact between the pre- and syn-rift sediments and the underlying basement.

Yet, complementary observations support the tectonic nature of the basement/sediment interface at both sites. Within the Le Danois High, we interpret the prominent bright reflections describing asymmetric structural highs as the LDD. Extensional detachments show dome-shaped geometries at the footwall (*e.g.*, between SP 500 and 400 in Fig. 2E and F) and allochthonous blocks in their hanging-wall (*e.g.*, between SP 900 and 500 in Fig. 2E and F). The presence of such extensional allochthons in the hanging-wall of the LDD is in line with previous interpretations of the extensional template at Aptian time proposed by Malod *et al.* (1982), displaying successive tilted pre-rift sections downslope (*e.g.*, tilted blocks) floored by exhumed basement and separated by narrow basins along the Le Danois High. In the Labourd Massif, we report cataclasites overprinting the granulites and capping the Ursuya massif (Fig. 3B). This supports the westward continuation and the flat-lying geometry of the brittle NMD detachment recognized in the eastern part of the massif by Jammes *et al.* (2009). This flat-lying extensional detachment structure crosscuts at a high-angle the steep, south-dipping foliation related to the HT/MP fabric observed throughout the massif (Fig. 3C). At both locations, the Le Danois Break-away block (Fig. 2F) and the Jara block (Masini *et al.*, 2014) (Fig. 3C) are interpreted as break-away blocks of the LDD and the NMD respectively, preserving the Triassic to Barremian pre-rift cover on the southern side of the break-away (Fig. 4A). The Aptian to Albian syn-rift deposits show south (continent) ward onlap geometries onto the Le Danois break-away block (*e.g.*, between SP 950 and 750 in Fig. 2E and F) and onto the NMD (Masini *et al.*, 2014; NAF in Saspiturry *et al.*, 2019b). All reported observations and derived interpretations enable us to propose that the LDD and the NMD correspond to major and analogous extensional structures, active during Aptian to Cenomanian hyperextension within the Biscay and Pyrenean rift systems, respectively. These results are similar and agree well with well-known examples from highly thinned crustal domains drilled offshore in the West Iberian margin (*e.g.*, Boillot *et al.*, 1988; Pérez-Gussinyé and Reston, 2001; Lymer *et al.*, 2019) and from fossil remnants exposed in the Alps (*e.g.*, Wilson *et al.*, 2001; Epin *et al.*, 2017).

The omission of Triassic to Middle Jurassic pre-rift sediments at both, the Le Danois High and the Labourd Massif, and the discontinuous distribution of pre-rift and basement dredges along the northern slope of the Le Danois High (Fig. 2A and B) were related at both sites to uplift and erosion (Boillot *et al.*, 1979; Saspiturry *et al.*, 2019a), and/or Alpine reactivation (*e.g.*, Malod *et al.*, 1982). However, thrust tectonics and/or erosional processes alone cannot explain several first-order observations at both sites: (1) the lack of stratigraphic repetitions and omissions and/or erosional unconformities within Upper Jurassic to Lower Cretaceous marine sedimentary sequences; (2) the occurrence of reworked granulites in Apto-Albian syn-rift pre-orogenic sediments; and (3) pre-orogenic Mesozoic cooling ages of mid-crustal rocks (granulites) at the seafloor. We consider that these observations and, locally, the juxtaposition of discontinuous pre-rift strata downslope at the Le Danois High are more compatible and well explained with extensional tectonics leading to the formation of extensional detachments and overlying allochthon blocks (Fig. 4A and B).

6.2 Interplay between extensional detachments and mid-crustal shear zones

The Le Danois BDT (Fig. 2F) and the LSZ (Fig. 3D) show striking analogies. Offshore, a spatial link between the Le Danois BDT and the LDD occurs along the northern slope of the Le Danois High (Fig. 2F). Onshore, the LSZ separates the granulites from the upper crustal Paleozoic metasediments (Fig. 3A and D). The granulites, located few hundreds of meters north of the LSZ, were at mid-crustal levels during the Late Variscan (Vielzeuf, 1984) and at least up to the late Triassic-early Jurassic (*e.g.*, Ar/Ar age of sample PLB1 in Masini *et al.*, 2014). Moreover, the massifs south of the LSZ were close to the surface, as indicated by the occurrence of pre-rift sediments. This strongly argues that deformation took place across the LSZ between 200 Ma and the deposition of the onlapping mid-Cretaceous sediments onto the granulites. Considering this and the occurrence of greenschist facies deformation along the shear zone, we suggest that the LSZ was (re)-activated as a top-to-the-south ductile shear zone during the Mesozoic extension, and assisted for the exhumation of the granulites. In addition, we show that small offset north-dipping normal faults clearly cross-cut the ductile, south-dipping deformation related to the LSZ (Fig. 3C). Such small offset, north-dipping normal faults have been already described in the northern part of the Ursuya Massif, where they are sealed by mid-Cretaceous tectono-sedimentary breccias (Abarratia quarry, Fig. 3A; Jammes *et al.*, 2009). In accordance with the interpretation of Jammes *et al.* (2009), we propose that these normal faults correspond to conjugate structures in the footwall of the NMD. Their distribution, extending from the Baygoura Massif to the northern tip of the Ursuya Massif, argue in favour of the existence of a major brittle structure cross-cutting the LSZ.

Observed cross-cutting relationships between brittle deformation related to the NMD and the LDD and ductile deformation linked with the LSZ and proposed for the Le Danois BDT show that extensional detachments penetrated and exhumed mid-crustal levels including mid-crustal shear zones. This enables us to propose that the LDD and the NMD were responsible for the seafloor exhumation of the granulites during Late Aptian to Cenomanian hyperextension. Shallow gravity anomalies modelled beneath the Le Danois High (*e.g.*, Sibuet and Le Pichon, 1971; Fernández-Viejo *et al.*, 1998; Gallastegui *et al.*, 2002) and the Labourd Massif (Casas *et al.*, 1997; Wang *et al.*, 2016), together with seismic velocity models (Fernández-Viejo *et al.*, 1998; Ruiz *et al.*, 2017) and reflection interpretations offshore (Cadenas *et al.*, 2020), and field observations onshore (*e.g.*, Masini *et al.*, 2014), support the interpretation of the presence of highly thinned crust and exhumed mantle northwards and beneath the Le Danois High (*e.g.*, Roca *et al.*, 2011; Fernández-Viejo *et al.*, 2012; Cadenas *et al.*, 2020) and the Labourd Massif (*e.g.*, Masini *et al.*, 2014; Saspiturry *et al.*, 2019b; Lescoutre *et al.*, 2021). We suggest therefore that there was a direct link between crustal thinning, granulite and mantle exhumation and the emplacement of extensional detachment faults.

These observations and interpretations allow to suggest that the LSZ and the Le Danois BDT correspond to the Upper-Middle pre-rift crustal boundary (Fig. 4A). The NMD and LDD respectively intersected these boundaries, that were back-rotated in the footwall of the two extensional detachment faults (Fig. 4A). This brittle/ductile interplay is similar to the geometrical relationships described between extensional detachment faults and mylonitic shear zones, also referred to as mylonitic front, by Lister and Davies (1989) in the Wipple Mountains (SW United States). Similar geometries have also been reproduced in 2D numerical models (Duretz *et al.*, 2016) (Fig. 4C). Such structural configurations have also been reported from fossil remnants of the Alpine Tethys margins exposed in the Central Alps, in southeastern Switzerland and northern Italy (*e.g.*, relation between mylonites of the Eita shear zone and the brittle Grosina detachment fault; see figure 14 in Mohn *et al.*, 2012).

6.3 Implications for tectonic models of the Biscay and Pyrenean hyperextended rift systems

In the Pyrenean domain, tectonic models relate crustal thinning and exhumation of mid-crustal rocks during Cretaceous extension either to ductile deformation and the formation of shear zones (*e.g.*, Corre *et al.*, 2016; Asti *et al.*, 2019; Lagabrielle *et al.*, 2020) or to brittle deformation and normal faulting (*e.g.*, Malod *et al.*, 1982; Masini *et al.*, 2014; Saspiturry *et al.*, 2019b). Alternatively, in the Labourd area, shearing, crustal doming and the formation of a metamorphic core complex have been proposed as a tectonic scenario accounting for the exhumation of mid-crustal rocks of the Ursuya Massif during the Permian (*e.g.*, Saspiturry *et al.*, 2019a). On the Le Danois area, it is widely agreed that brittle deformation accounted for high degrees of crustal thinning and basement exposure and exhumation. Postulated ages and mechanisms include Jurassic extension (*e.g.*, Boillot *et al.*, 1979), Lower Cretaceous crustal stretching (Malod *et al.*, 1982; Fügenschuh *et al.*, 2003), and post-Aptian extensional detachment faulting (Cadenas *et al.*, 2020).

Crustal thinning and lower crustal doming during Permian extension are well established throughout Western Europe (*e.g.*, Arthaud and Matte, 1977; Ziegler and Dèzes, 2006; Petri *et al.*, 2017), including the Pyrenean domain (*e.g.*, Cochelin *et al.*, 2017; Denèle *et al.*, 2014). Thermochronological data from granulitic massifs in north Iberia support that first exhumation of pre-rift mid-crustal rocks occurred in the Permian (*e.g.*, Fügenschuh *et al.*, 2003; Masini *et al.*, 2014; Hart *et al.*, 2016; Odlum and Stockli, 2019). However, questions remain concerning the depth of exhumation of granulites during the Permian post-orogenic collapse. It is, however, important to note that granulite clasts have been exclusively retrieved in syn-rift Cretaceous sediments in both study areas. Thus, combined offshore and onshore observations suggest that the final exhumation of mid-crustal granulites to the seafloor had to occur during Aptian to Cenomanian in relation with hyperextension, as suggested by Hart *et al.* (2016).

Models of ductile-governed crustal deformation during Cretaceous (Corre et al., 2016; Lagabrielle *et al.*, 2020) suggest that the Upper Triassic evaporites, acting as a decoupling level, allowed for the displacement of the pre- to syn-rift sedimentary cover over the thinned crust, which under a high thermal regime, behaved in a ductile manner. However, these ductile-governed models imply symmetrical ductile deformation of the crust during rifting (see also Duretz *et al.*, 2016). In the studied zone, only the Pyrenean domain had sufficient salt for such an evolution, while in the Le Danois High, there is no clear evidence of salt structures. Similar structural features (syn-rift exhumed granulites, north dipping extensional detachment faults, tectono-sedimentary breccias) reported from Labourd (salt-rich domain) and the Le Danois area (devoid of salt) support that brittle deformation corresponded to the key and first-order parameter controlling hyperextension along the Biscay and Pyrenean rift segments. Decoupled ductile and brittle deformation due to presence of salt, however, will be an additional parameter to account for in salt-rich domains.

Open to discussion remains the precise timing of seafloor exposure of granulites. Hart *et al.* (2016) proposed for the Labourd Massif, based on ZHe cooling ages, that seafloor exhumation of granulites had to occur during Albian to Cenomanian. The tectono-stratigraphy of the syn-rift sediments including granulite clasts retrieved in the Bonloc trough suggest a potential Cenomanian age for their denudation, but no precise dating exists. Syn-rift sequences from hyper-extended basins defined an onset of major crustal thinning in the Aptian (Masini *et al.*, 2014). In the Le Danois High, two apatite fission track-cooling ages suggest exhumation of granulites to shallow depths during Valanginian/Hauterivian and Aptian (Fügenschuh *et al.*, 2003). Syn-rift sediments overlying the LDD have been dated from Aptian onwards, based on correlation of seismic facies with borehole-calibrated seismic interpretations in the nearby Asturian Basin (Cadenas *et al.*, 2020). The sample with an apatite fission track cooling age of 120 ± 8 Ma will argue in favor of granulite exposure to shallow depths from Aptian onwards, while the sample with 138 ± 7 Ma would argue for an early exhumation and emplacement of the LDD. However, data is scarce and may not provide robust general constraints. New dating, including in-place dredges and larger datasets, are necessary to provide strong time constraints, which enable to investigate further crustal exhumation processes. Comparison between seismic and field derived observations and interpretations and available thermochronological data allow us to propose that the main stage of granulite exposure, leading to exhumation of mid- to lower crustal rocks to very shallow depths in the Biscay and Pyrenean rift systems occurred most likely from Aptian to Cenomanian under a brittle regime.

6.4 Implications for the reactivation of extensional detachment faults during convergence

The scarcity of direct observations supporting major Alpine reactivation of the LDD and the NMD is a striking similarity between the Le Danois High and the Labourd Massif. Very minor reactivation of rift-inherited interfaces can be postulated but without producing a major tectono-stratigraphic imprint (Fig. 2F). In our interpretation, the North Pyrenean Frontal Thrust (NPFT) and the Le Danois Thrust (LDT) correspond to major thrusts in the footwall of the NMD and the LDD, respectively (Figs. 2F and 3D). Thus, both the LDT and the NPFT did not use the inherited LDD and NMD extensional detachment faults. On the contrary, these thrusts truncated the LDD and the NMD during the Alpine convergence and transported them in their hanging wall northwards onto the Biscay hyperextended domains and the European crust, respectively (Figs. 2F and 3D). Overthrusting led to the currently observed uplift and southward tilting of the basement, together with the LDD and the NMD extensional detachment systems and the overlying sediment cover (Figs. 2F and 3D). Major remaining questions concern therefore the preservation of the syn-rift architecture and the absence of reactivation of the LDD and the NMD extensional detachment faults as major thrusts.

In the Labourd area, Lescoutre and Manatschal (2020) proposed that the preservation of the syn-rift structures was due to their position at the end of the overlapping Basque-Cantabrian and Pyrenean rift segments (Fig. 1). Indeed, such a rift-inherited pre-convergence setting would have forced the main thrusts at the tips of the rift segment terminations to form shortcutting structures, in order to accommodate and transfer shortening in adjacent rift segments. Interestingly, the Le Danois High also sits in between the overlapping/offset Biscay and Llanes rift segments (Cadenas *et al.*, 2020) (Fig. 1). As such, we propose that, similarly to the Labourd area, the LDD was also protected from the reactivation because it lays in between two hyperextended rift segments. Consequently, and because of their former analogue position in between rift segments, the Labourd Massif and the Le Danois High correspond to privileged areas to investigate the architecture of the Biscay and Pyrenean hyperextended rifts.

7 Conclusions

In this work, we show a detailed analysis and comparison of the Le Danois High and the Labourd Massif that are part of the Biscay and the Pyrenean rift segments, respectively. New reported seismic and field observations indicate that the north-dipping Le Danois and North Mauléon extensional detachment systems correspond to major and analogous structures, which developed from Aptian to Cenomanian, in the context of hyperextension within the Biscay and Pyrenean rifts. Seismic and field-derived interpretations, together with the integration of previous geological and thermochronological datasets suggest that these structures were responsible for crustal thinning and the exhumation of pre-rift mid-crustal rocks to the seafloor. This combined offshore-onshore study supports granulite exhumation in a brittle regime during Aptian to Cenomanian. Our interpretations suggest that the position of the North Mauléon and the Le Danois extensional detachments systems in between hyperextended rift segments allowed for their preservation into the hanging-wall of major Alpine thrusts, whose emplacement is responsible for their current uplift and southward tilting.

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