BSGF - Earth Sciences Bulletin 2021, 192, 55
© G. Manatschal *et al.*, Published by EDP Sciences 2021
https://doi.org/10.1051/bsgf/2021042

BSGF
Earth Sciences Bulletin
Available online at:
www.bsgf.fr

Special Issue Orogen lifecycle: learnings and perspectives from Pyrenees, Western Mediterranean and analogues ed. O. Lacombe, S. Tavani, A. Teixell, D. Pedreira and S. Calassou (Guest editors)

OPEN ACCESS

The role of inheritance in forming rifts and rifted margins and building collisional orogens: a Biscay-Pyrenean perspective

Gianreto Manatschal[1,*], Pauline Chenin[1], Rodolphe Lescoutre[1,2], Jordi Miró[1,3], Patricia Cadenas[1,4], Nicolas Saspiturry[5], Emmanuel Masini[6,7], Sebastien Chevrot[8], Mary Ford[9], Laurent Jolivet[10], Frédéric Mouthereau[8], Isabelle Thinon[11], Benoit Issautier[11] and Sylvain Calassou[12]

[1] ITES_EOST, UMR 7063, Université de Strasbourg, CNRS, Strasbourg, France
[2] Department of Earth Sciences, Uppsala University, Uppsala, Sweden
[3] IRG, Departament de Dinàmica de la Terra, Universitat de Barcelona, City, Spain
[4] BCSI, ICM, CSIC, Barcelona, Spain
[5] EA 4592 Géoressources & Environnement, Université Bordeaux Montaigne, City, France
[6] ISTERRE, Université Grenoble Alpes, CNRS, Grenoble, France
[7] M&U SAS, Saint-Égrève, France
[8] GET-OMP, UMR 5563, Université Paul Sabatier, Toulouse, France
[9] CRPG, Université de Lorraine, Nancy, France
[10] Sorbonne Université, UMR 7193 CNRS-UPMC, Institut des Sciences de la Terre, Paris, France
[11] BRGM, GeoResources Division, Orléans, France
[12] Centre de recherches de Total, Pau, France

Received: 28 March 2021 / Accepted: 27 September 2021 / Publishing online: 4 November 2021

Abstract – A long-standing challenge in tectonics is to evaluate the role of inheritance and define the initial conditions of a geodynamic system, which are prerequisites to understand and model its evolution with some accuracy. Here we revisit the concept of "inheritance" by distinguishing "interface shape inheritance", which includes the transient thermal state and gravitational potential energy, and "persisting inheritance", which encompasses long-lasting structural and compositional inheritance. This new approach allows us to investigate, at each stage of a Wilson Cycle, the interplay between inheritance (innate/"genetic code") and the physical processes at play (extension/compression, magmatism etc.). The aim of this paper is to provide a conceptual framework that integrates the role of inheritance in the study of rifts, rifted margins and collisional orogens based on the work done in the OROGEN project, which focuses on the Biscay-Pyrenean system. The Biscay-Pyrenean rift system resulted from a multistage rift evolution that developed over a complex lithosphere pre-structured by the Variscan orogenic cycle. There is a general agreement that the Pyrenean-Cantabrian orogen resulted from the reactivation of an increasingly mature rift system along-strike, ranging from mature rifted margins in the west to an immature and segmented hyperextended rift in the east. However, different models have been proposed to explain the preceding rifting and its influence on the subsequent reactivation. Results from the OROGEN project highlight the sequential reactivation of rift-inherited decoupling horizons and identify the specific role of exhumed mantle, hyperextended and necking domains during compressional reactivation. They also highlight the contrasting fate of rift segment centres *versus* segment boundaries during convergence, explaining the non-cylindricity of internal parts of collisional orogens. Results from the OROGEN project also suggest that the role of inheritance is more important during the initial stages of collision, which may explain the higher complexity of internal parts of orogenic systems with respect to their external parts. In contrast, when the system involved in the orogeny is more mature, the orogenic evolution is mostly controlled by first-order physical processes as described in the Coulomb Wedge theory, for instance. This may account for the simpler and more continuous architecture of external parts of collisional orogens and may also explain why most numerical models can reproduce mature orogenic architectures with a better accuracy compared to those of initial collisional stages. The new concepts developed from the OROGEN research are now ready to be tested at other orogenic systems that

*Corresponding author: manat@unistra.fr

result from the reactivation of rifted margins, such as the Alps, the Colombian cordilleras and the Caribbean, Taiwan, Oman, Zagros or Timor.

Keywords: rift system / reactivation / inheritance / orogenic system / Bay of Biscay / Pyrenees

Résumé – Le rôle de l'héritage lors de la formation de rifts et marges passives, et lors d'orogenèses de collision : un aperçu du système Gascogne-Pyrénées. Un défi de longue date en tectonique consiste à évaluer le rôle de l'héritage et à définir les conditions initiales d'un système géodynamique. Ceux-ci sont en effet des prérequis pour comprendre et modéliser l'évolution d'un tel système avec une certaine précision. Nous revisitons ici le concept d'« héritage » en distinguant « l'héritage (transitoire) d'interfaces », qui comprend d'un côté l'état thermique et de l'autre l'énergie potentielle gravitationnelle, et « l'héritage persistant » qui englobe les hétérogénéités structurales et compositionnelles. Cette nouvelle approche permet d'étudier, à chaque étape du Cycle de Wilson, l'interaction entre l'héritage (inné/« code génétique » du système) et les processus physiques en jeu (extension/compression, magmatisme, etc.). Le but de cet article est de fournir un cadre conceptuel qui intègre le rôle de l'héritage dans l'étude des rifts, des marges riftées et des orogènes de collision, à partir des travaux réalisés dans le projet OROGEN dans le système Gascogne-Pyrénées. Le système de rift Gascogne-Pyrénées résulte de plusieurs épisodes extensifs qui ont successivement affecté une lithosphère déjà complexe car pré-structurée par le cycle orogénique Varisque. Il est généralement accepté que l'orogénèse pyrénéo-cantabrique a résulté de la réactivation d'un système de rift dont la maturité varie d'est en ouest, allant de marges conjuguées matures à l'ouest à un rift hyper-étiré, immature et segmenté à l'est. Cependant, différents modèles ont été proposés pour expliquer l'évolution précédant le rifting et son influence sur la réactivation ultérieure. Les résultats du projet OROGEN montrent une réactivation séquentielle des horizons de découplage hérités du rift et identifient le rôle spécifique des domaines de manteau exhumé, d'hyperextension et d'étranglement lors de la réactivation. Ils mettent également en évidence le sort contrasté des centres de segments de rifts par rapport à leurs bordures lors de l'inversion, expliquant la non-cylindricité des parties internes des orogènes de collision. Les résultats du projet OROGEN suggèrent également que le rôle de l'héritage est plus important pendant les étapes initiales de subduction et de collision, ce qui peut expliquer la plus grande complexité des parties internes des systèmes orogéniques par rapport à leurs parties externes. En revanche, quand les systèmes de rift impliqués sont plus matures, l'évolution orogénique est principalement contrôlée par des processus physiques de premier ordre, tels que ceux décrits par la théorie du Prisme de Coulomb. Ce constat pourrait expliquer l'architecture plus simple et plus continue des parties externes des orogènes de collision, et pourrait également expliquer pourquoi la plupart des modèles numériques reproduisent mieux les architectures orogéniques matures que celles des stades initiaux de collision Les nouveaux concepts développés à partir de la recherche menée lors du projet OROGEN sont désormais prêts à être testés sur d'autres systèmes orogéniques résultant de la réactivation de marges riftées, comme les Alpes, la Cordillère colombienne, les Caraïbes, Taiwan, Oman, Zagros ou encore le Timor.

Mots clés : système de rift / réactivation / héritage / système orogénique / Golfe de Gascogne / Pyrénées

1 Introduction

Writing a paper on the "role of inheritance" in forming and reactivating rifts and rifted margins and building collisional orogens may appear ambitious if one considers the disagreements and debates that exist on the descriptions of rifts, rifted margins and orogens themselves. Therefore, if we want to think about the legacy of a "rift" in an orogenic system, or of a former orogen during the formation of the rift, we need a first order understanding of rifts, rifted margins and orogens and we need to define what we mean with "inheritance". Here we revisit the concept of "inheritance" by distinguishing between "interface shape inheritance", which includes transient thermal state and gravitational potential energy, and "persisting inheritance", which encompasses long-lasting structural and compositional inheritance. This new approach allows us to define, at each stage of a Wilson Cycle, the interplay between inheritance (innate/"genetic code") and the physical processes at play (extension/compression, magmatism, etc.). This paper aims to show that understanding "inheritance" is not an option but a prerequisite for comprehending early stages of tectonic systems. Another, related question is *how* can "inheritance" be implemented in our thinking of tectonic systems? Since relatively simple numerical models can reproduce structures and architectures similar to those observed at mature rifted margins or orogenic systems, two questions arise: can natural systems be described by using only simple/generic initial conditions? And, if not, when, where and how do inherited structural, thermal and compositional complexities control the evolution of tectonic systems in a Wilson Cycle?

In order to answer to these fundamental questions, it is necessary to obtain observational constraints on how inheritance may control the evolution of tectonic systems. Here we use observations from the Biscay-Pyrenean system to investigate the role of inheritance throughout an incomplete Wilson Cycle that includes a post-Variscan collapse, a Mesozoic rifting, and an Alpine reactivation. Although the Biscay-Pyrenean system represents an incomplete Wilson

Cycle and may therefore not be representative of and/or comparable with global collisional orogens, it represents a world-class natural laboratory to study the impact of rift inheritance in the early stages of convergence (*e.g.*, nucleation of a convergent plate boundary) and building of collisional orogens.

In this paper, we commence with a historical overview of the role of inheritance in tectonic systems and summarize the state of the art on the subject. We redefine some terms and present some existing and new concepts that will be tested, improved and further discussed in following parts of the paper. We then discuss the importance of rift-inherited mechanical decoupling levels, including salt and their potential role during sequential reactivation. We address the role of rift segmentation (non-cylindricity of rifts) and the contrasting tectonic histories of reactivated segment centres compared to reactivated segment boundaries. We also try to unravel what the granulites can tell us about the pre- and syn-rift thermal state and how their presence and characteristics can help choosing between the different hyperextension models proposed in the OROGEN project. In a final part we extract and discuss some of the major learnings and develop a more generic and global perspective on how to implement "inheritance" in a workflow that can be used to describe and model the evolution of tectonic systems within a Wilson Cycle.

2 Historical overview

The understanding of geological systems evolved through the last two centuries from that of a static to a mobilistic and dynamic system. The development of new analytical, imaging, and modelling tools resulted in unprecedented progress in the comprehension of both rifted margins and orogenic systems. It enabled not only to gain insights into the temporal evolution of tectonic systems, but also to explore the physical parameters that control the related processes. Important steps forward in the understanding of tectonic systems include the discovery of nappes (Bertrand, 1884), the description of remnants of former "oceanic" sequences (ophiolites) in orogens (Steinmann, 1905), and the restoration of orogenic domains (Argand, 1924a, 1924b, 1916, 1911). This evolution was in parallel with Alfred Wegener's Continental Drift theory (Wegener, 1915) that was at the origin of a more generic and global view of the Earth evolution. Then, Arthur Holmes's mantle convection theory (Holmes, 1931), the mapping of the oceans floor (Tharp *et al.*, 1959), the first idea of seafloor spreading (Hess, 1962), the description of symmetric seafloor spreading anomalies (Vine and Matthews, 1963) and the understanding of the significance of transform faults (Tuzo Wilson, 1965) enabled to propose a uniform, coherent and generally accepted theory referred to as the *Plate Tectonic theory* (Le Pichon, 1968; Morgan, 1971; Parsons and McKenzie, 1978). Shortly after, it became generally accepted that tectonic systems are cyclic, and such a cycle was referred to as the *Wilson Cycle* (Dewey and Burke, 1974; Wilson, 1966). Although some of the pioneers had already understood that continental drift had happened several times (*e.g.*, Argand, 1924a, 1924b), the Wilson Cycle theory made it explicit that each tectonic system, except oceanic systems, overprints a former/existing system (Fig. 1a). This is where "inheritance" finds its place in the overarching Plate Tectonic model that describes the evolution of our planet Earth. However, even if the notion of "inheritance" is a fundamental and integral part of the Wilson Cycle, in the early days of Plate Tectonics and modelling experiments "inheritance" was left aside. The community was more focused on the understanding of processes and the development of a physical understanding of how the Earth works, rather than on inheritance, which is neither generic nor predictable, and was therefore seen as an obstacle to understand Plate Tectonics.

In the late 1960's and 1970's, it became clear that several observations from the Alpine-Pyrenean, Himalayan and Zagros collisional belts were not compatible with some of the first-order predictions of the Plate Tectonic theory (Jackson, 1980). While for some scientists this was the proof that Plate Tectonics did not work, others considered that these were only details of little importance. Today we understand that the Pyrenean and Alpine system in Western Europe probably neither reached mature seafloor spreading, nor subduction. This may explain on the one hand why field geologists working in these orogens who were not aware of the new geophysical and kinematic datasets coming from the oceans did neither believe the Plate Tectonics theory, nor were able to predict it (Trümpy, 2001). Conversely, it may also explain why neither Steinman's trinity (Steinmann, 1905), nor Decandia and Elter (1969) exhumed mantle theory, nor Ampferer's concept of "*subduction*" (Ampferer and Hammer, 1911; see McCarthy *et al.*, 2020 for a review), all of which were based on field observations, did not convince the protagonists of Plate Tectonics. The simple text-book Plate Tectonic model prevailed for a long time in the literature. Whatever did not fit into simple models was either ignored or interpreted as overprinted or subducted. Examples are the Bonloc syn-/post-rift polymictic breccias covering granulitic facies metamorphic basement, the reworked mantle rocks in syn-/post-rift sediments such as in the Basque Cantabrian Pyrenees (DeFelipe *et al.*, 2017), Western Pyrenees, and in the Lherz and Bestiac areas of the Central Pyrenees (*e.g.*, Fortané *et al.*, 1986; Lagabrielle and Bodinier, 2008; Debroas *et al.*, 2010; Masini *et al.*, 2014; Asti *et al.*, 2019). Another example relates to the so-called North Pyrenean Fault, which has first been introduced as a late Variscan strike-slip fault (Mattauer and Proust, 1967) and later reinterpreted as a strike-slip system to fit plate kinematic reconstructions in the Atlantic based on the work of Wilson (1965) (Choukroune and Mattauer, 1978; Le Pichon and Sibuet, 1971). The problem field geologists faced in the Pyrenees was that outcrops in the North Pyrenean Zone, the Pyrenean "suture zone", were neither compatible with such a large strike-slip fault, nor with the proposed oceanic subduction. This may explain why most of the field geologists working in the Pyrenees were reluctant to accept some of the new Plate Tectonic interpretations (for a discussion see Canérot, 2017). Today it is clear that the Pyrenean system does not violate the Plate Tectonic theory and that all tectonic systems do not necessarily go through a complete Wilson Cycle. Thus, while the Plate Tectonic theory was a huge leap forward for the understanding of global tectonic systems, its application to orogens such as the Pyrenees or the Alps was too simplistic and often model-driven. Jackson (1980) was among the first to propose that the reactivation of former rift structures may play an important role in collisional orogens, a point that

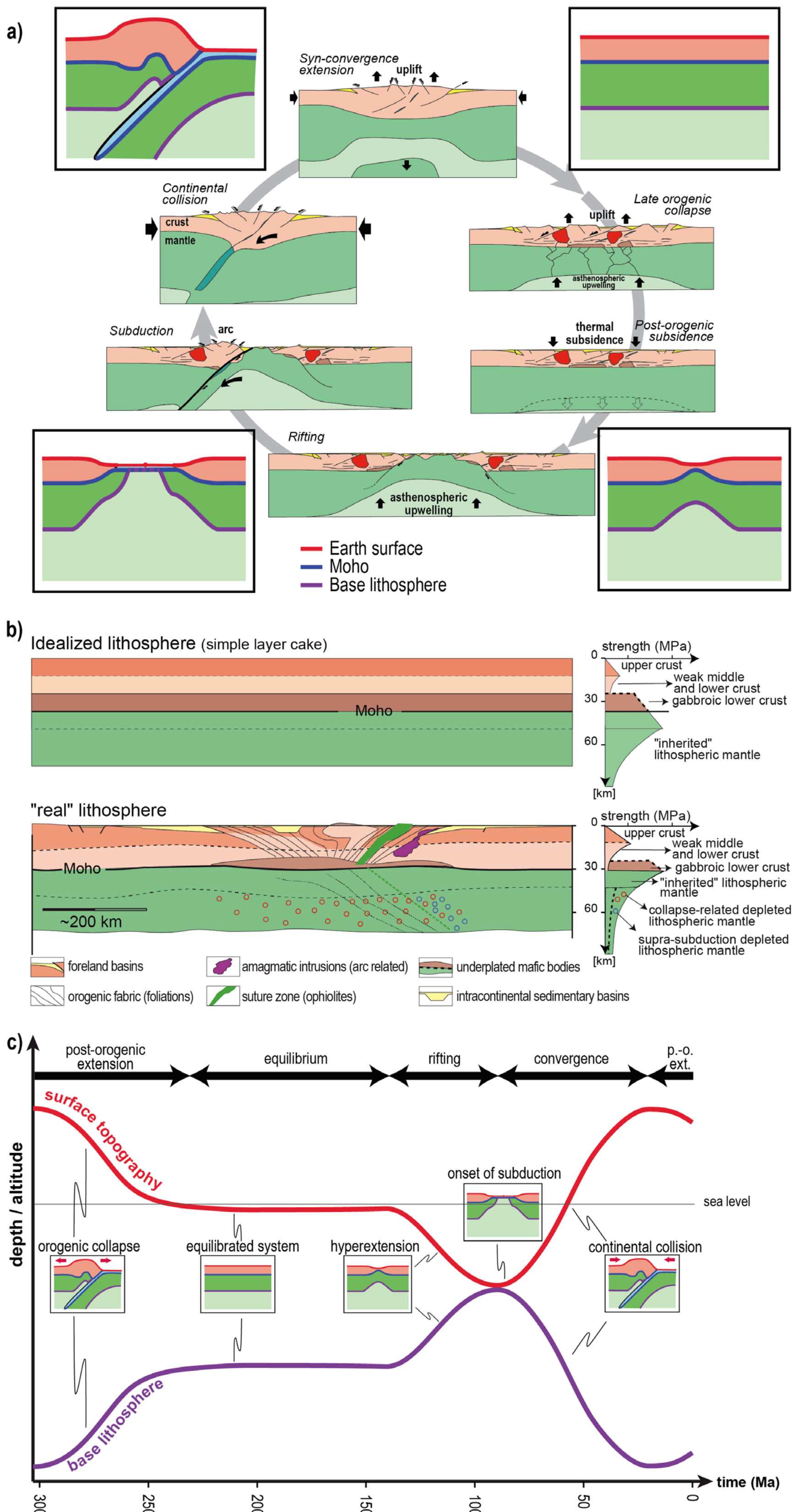

Fig. 1. (a) Main stages (rifting, seafloor spreading, subduction, and late orogenic collapse) within a Wilson Cycle are illustrated by the shapes of the three main interfaces, which are the Earth surface, the Moho and the base of the lithosphere. (b) Idealized lithosphere made of a thermally equilibrated layer cake *versus* a "real" post-orogenic lithosphere showing inherited structural and compositional complexity (modified after Manatschal *et al.*, 2015). (c) Schematic evolution of the thermal state and gravitational potential energy depicted by the base of the lithosphere (1300 °C isotherm) and the surface topography within a Wilson Cycle. p.-o. ext.: post-orogenic extension.

has been nicely demonstrated by Tavani *et al.* (2021) for the Zagros, Apennines, Oman and the Taiwan collisional belts four decades later. However, while Jackson's rifted margin model consisted of tilted blocks, Tavani *et al.* (2021) built their interpretation on a complex rift architecture, showing its importance in controlling the switch from thin- to thick-skinned thrusting.

In the late 1980's and early 1990's, serpentinized mantle rocks were drilled offshore Iberia (Boillot *et al.*, 1987) and detachment systems were described in the southwestern United States (Wernicke, 1985). These observations inspired new rift models whereby mantle was exhumed to the seafloor via detachment faults (*e.g.*, Lemoine *et al.*, 1987). The first evidence and interpretation of mantle exhumation were presented in the Apennines (Decandia and Elter, 1969). Their link to detachment faults was subsequently highlighted by Florineth and Froitzheim (1994) in the Tasna nappe in the Central Alps. Lagabrielle and Bodinier (2008) were the first to suggest that the mantle rocks exposed in the Lherz area in the Central Pyrenees were already exposed at the seafloor during Cretaceous rifting, an interpretation that was further supported by Jammes *et al.* (2009) and Lagabrielle *et al.* (2010) who suggested mantle exhumation along a detachment system in the Mauléon basin in the Western Pyrenees. Since then, many studies focused on the hyperextended rift basins exposed in the Pyrenean and Basque-Cantabrian domains. However, the application of *hyperextended margin models*, mainly developed in the Iberia-Newfoundland and fossil Alpine Tethys rifted margins to the Pyrenean system turned out not to be a simple copy-paste exercise. Indeed, the lack of good outcrops in the North Pyrenean Zone, the widespread occurrence of salt, the much higher sedimentation rates and the evidence for a high temperature/low pressure metamorphic event during rifting (Clerc and Lagabrielle, 2014; Ducoux *et al.*, 2019, 2021a) makes it difficult to compare observations from the Pyrenees with the classical examples better exposed and documented in the Alps and/or drilled and seismically imaged offshore Western Iberia. In particular the interpretation of the kinematics and vergence of extensional detachment systems remain debated in the Pyrenean and Basque-Cantabrian examples and competing interpretations continue to exist (Lagabrielle *et al.*, 2020).

3 Inheritance: concepts, definitions and methods

3.1 Inheritance: where do we come from and why is it important?

Tectonics evolved from a mainly descriptive to a more processes-oriented science focusing on a physical understanding of large-scale geodynamic systems. This evolution was paired with the development of new quantitative geological techniques, as well as imaging, analytical and modelling approaches. However, this evolution did not overcome the fact that all tectonic systems, except oceanic systems, build on their own and specific inheritance that is controlled by their geological history. Understanding how to define the initial conditions and what and how to implement it in numerical models is one of the big challenges in developing more predictive and quantitative models. To implement "inheritance" in numerical models, inheritance needs first to be defined and mapped. Secondly, as all inherited structures will not be reactivated, *what* and *under what circumstances* inheritance is reactivated need to be determined. Finally, it is necessary to identify the typical "conditions" prevailing at each tectonic stage of a Wilson cycle. These can be defined by the sum of "interface shape inheritance" and "persisting inheritance". "Interface shape inheritance" encompasses the transient thermal state and gravitational potential energy, which can be approximated by the three main interfaces defining the lithosphere, namely the earth surface, the Moho and the base of the lithosphere. "Persisting inheritance" includes lasting lithospheric structural and compositional heterogeneities (for details see Sects. 3.2–3.3).

3.2 Interface shape inheritance: the role of potential energy during a Wilson Cycle

During a Wilson cycle, tectonic systems evolve through convergent and divergent stages in which their thermal state and gravitational potential energy, expressed by the surface topography and position of the base lithosphere, are changing (Fig. 1c). In the convergent part of the cycle, excess gravitational potential energy forms as a consequence of crustal and lithospheric thickening (slab underthrusting, crustal thickening and orogenic topography), while in the divergent part of the cycle, gravitational potential energy is lost due to crustal/lithospheric thinning. The decrease in gravitational potential energy goes hand in hand with an increase in the geothermal gradient, which is largely linked to the thinning of the lithosphere and the thermal equilibration of the continental crust. This first-order evolution can be outlined in a simple way by the shape of three main interfaces, which are the Earth surface, the Moho and the base of the lithosphere (Fig. 1a, c). While in the convergent part of the cycle these interfaces diverge (surface topography and lithospheric thickness), they converge in the divergent cycle. In this intentionally first-order view, there is only one stage at which a tectonic system may reach a gravitational and thermal equilibrium (*i.e.*, all interfaces are roughly sub-horizontal), namely during the transition between a convergent and a divergent stage. Note, however, that it takes at least tens of millions of years to reach a gravitational and thermal equilibrium, and thus equilibrium may be reached only when the convergence-divergence transition is achieved on such a long (or longer) period (Fig. 1c). As each stage of a Wilson Cycle is characterized by a specific inherited gravitational potential energy and a thermal state, a key in understanding and defining the initial conditions of a tectonic system is to identify its position within the Wilson Cycle (Fig. 1a, c) and to define the extent of equilibration since the last tectonic event. This 2D view is, of course, a simplification since this problematic needs to be understood in 3D.

3.3 Persisting inheritance: the role of compositional and structural heterogeneities

While gravitational and/or thermal states are transient and may be equilibrated through a Wilson Cycle, structural or compositional inheritance recorded in rocks (Fig. 1b) can last

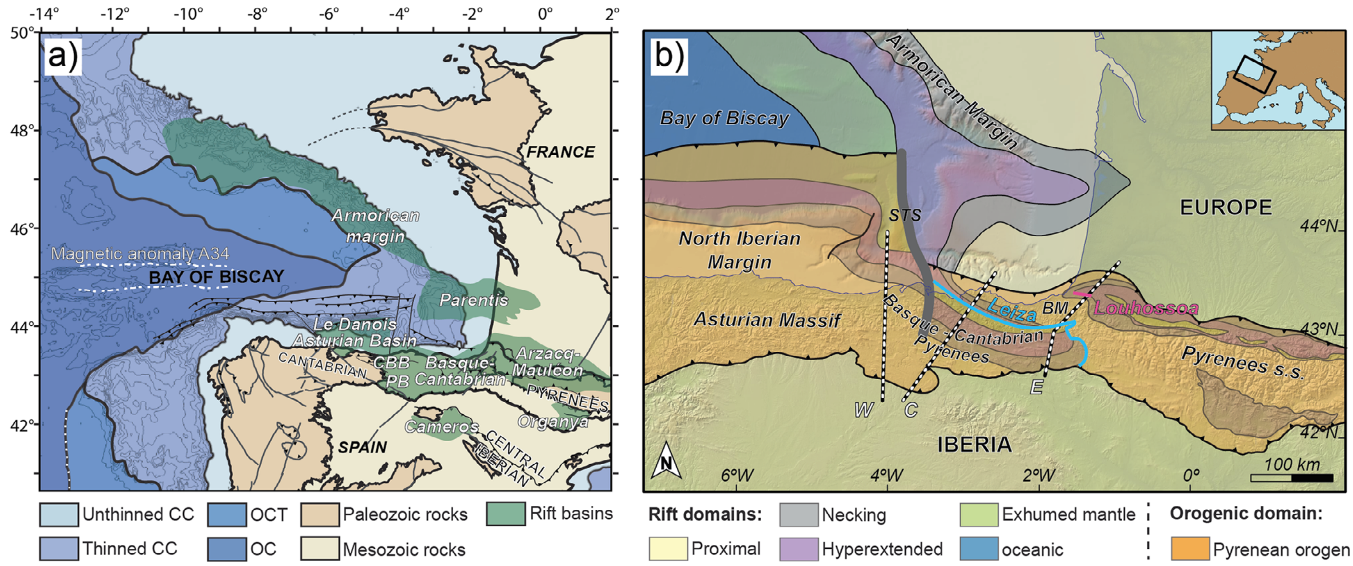

Fig. 2. (a) Map of the Mesozoic rift basins between France and Spain along the Iberian-European plate boundary. Modified after Lescoutre *et al.* (2021) and Masini *et al.* (2014). (b) Rift domain map of the Pyrenean-Cantabrian area. STS: Santander Transfer System, W: Western section, C: Central section; E: Eastern section. Modified from Tugend *et al.* (2014) and Cadenas *et al.* (2020). CC: continental crust; OC: oceanic crust; OCT: ocean-continent transition.

and leave a legacy for subsequent events. Compositional inheritance results from the juxtaposition of rocks with different properties (density, velocity, permeability, radiogenic heat production, etc.), and thus different rheologies. Yet the bulk rheological architecture and composition of the crust/lithosphere are important to determine and predict the distribution of decoupling levels, buttresses, as well as dense materials that are "subductable" *versus* buoyant materials that are difficult to subduct. Compositional inheritance is often linked to igneous and metamorphic processes or hydration reactions. In contrast, structural inheritance results either from a strong anisotropy linked to crystal or preferred shaped orientations (*e.g.*, foliation or alignments of grains or aggregates), or from mechanical discontinuities (*e.g.*, faults). Examples of systems leaving a strong inheritance (compositional and structural) in convergent systems are subduction systems with arcs/fore-arcs/back-arcs, and collisional orogens with suture zones or fold-and-thrust belts (Fig. 1b). In divergent systems, igneous processes are often linked to mafic underplating and mantle depletion and/or enrichment. Deposition and formation of low frictional materials (*e.g.*, salt, clays, or serpentine) or thick sedimentary sequences are also often linked to extensional systems. Structural and compositional inheritance cannot always be dissociated and often depend on boundary conditions (stress field, thermal state, pressure, etc.). Compositional and structural inheritance can exert a major control on strain localisation and/or distribution during subsequent reactivation.

Under some circumstances, structural and/or compositional inheritance can be wiped out. Examples are prograde metamorphic events that can dehydrate and change mineralogical compositions and/or thermally anneal microstructures (Braun *et al.*, 1999; Yamasaki *et al.*, 2006). Processes that can modify the composition of the subcontinental mantle lithosphere have been reported by Picazo *et al.* (2016). They may for instance relate to slab breakoff, which results in a lithospheric thinning and depletion linked to intense magmatic activity (*e.g.*, Permian evolution in W-Europe; Petri *et al.*, 2017). Magma infiltration and enrichment of the subcontinental mantle lithosphere during hyperextension (Müntener *et al.*, 2004) is another process that can modify the mantle lithosphere through a Wilson cycle (*e.g.*, Chenin *et al.*, 2018).

3.4 Proposed concepts to map inheritance and investigate its role within a Wilson cycle

Two geological mapping approaches have been developed in the past to investigate the role of inheritance. A first mapping approach was proposed by Tugend *et al.* (2014, 2015) who used seismic data, potential field methods and field observations to identify and locate the limits of structural entities referred to as rift domains. This approach was first applied to the Biscay-Pyrenean domain, where it enabled to map off- and onshore rift domains and to describe their reactivation during the Alpine convergence. The type of map that resulted from this approach is shown in Figure 2b. It shows the distribution of rift domains offshore and onshore the Pyrenean-Cantabrian domain. The method, developed by Tugend *et al.* (2014, 2015), enables to recognize the position of a domain in both present-day margins and remnants of former margins exposed on land, relying on first-order characteristics like the thickness of the underlying crust and the available accommodation space (offshore), and/or the lithology and type of sediments. Such information is not visible in more classical maps as that shown in Figure 2a.

Building on this approach, Chenin *et al.* (2015) undertook to assess the impact of orogenic inheritance on the architecture, timing and magmatic budget of the North Atlantic rifting. These authors defined a series of mappable first-order characteristics of orogens (suture zones, fold-and-thrust belts,

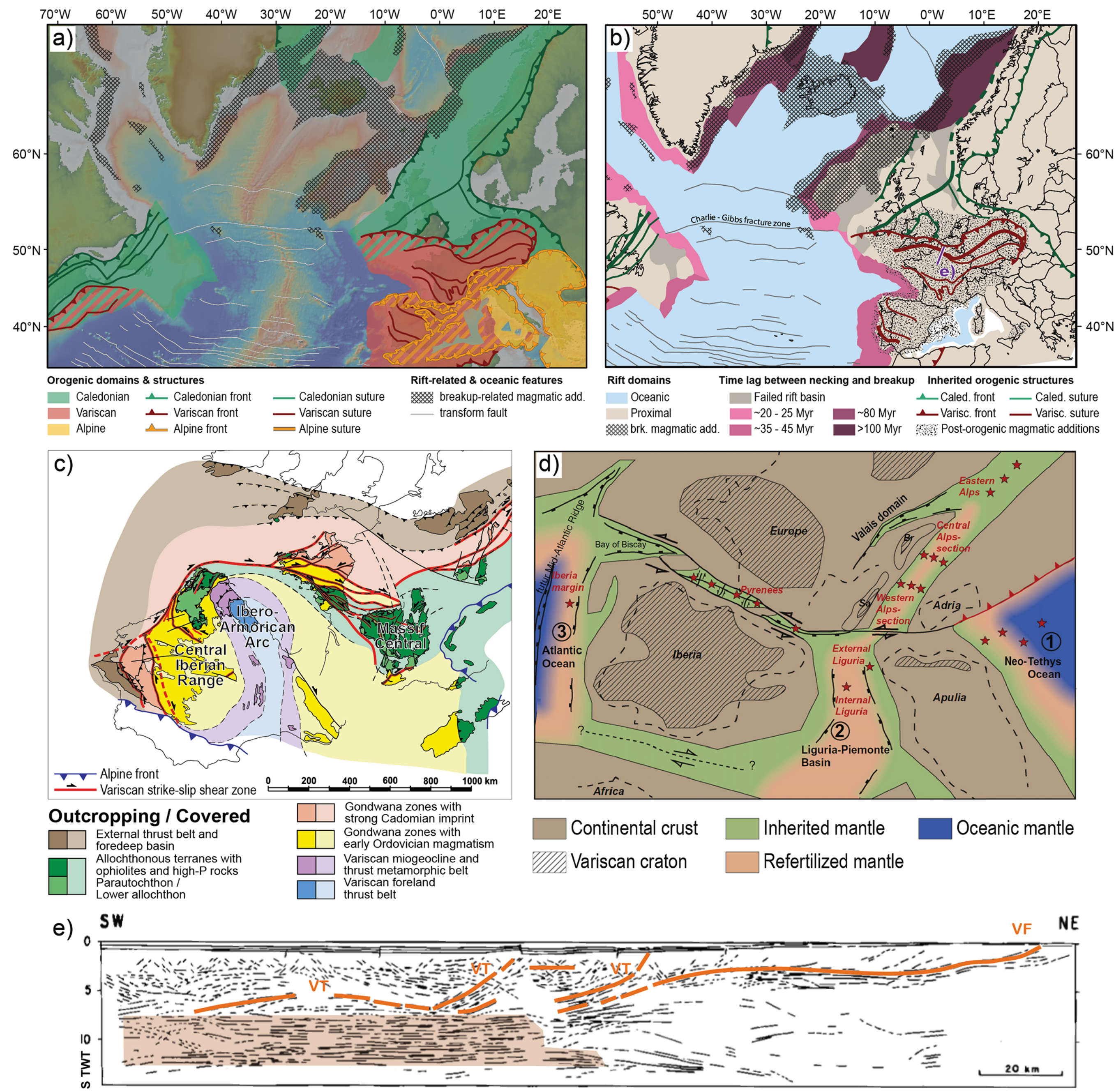

Fig. 3. (a) Major orogenic domains and structures in the North Atlantic realm (modified from Chenin *et al.*, 2015 and Chenin 2016). (b) Map showing (i) the rift domains and corresponding rifting duration (*i.e.*, the time lag between necking and breakup), as well as the distribution of breakup-related magmatic additions for the North Atlantic rift system; and (ii) orogenic inherited structures and magmatic additions onshore Western Europe and eastern N-America (from Chenin 2016). (c) Map showing the correlation of parts of the Variscan orogen across the Biscay-Pyrenean system (from Martínez Catalán *et al.*, 2007). (d) Distribution of mantle types in Europe at 110 Ma (Late Aptian) (from Picazo *et al.*, 2016). (e) Interpreted seismic section through the Variscan orogenic area (from Bois *et al.*, 1989; see map in panel b for location). VT = Variscan Thrust; VF = Variscan Front; the brown shading highlights the layered and highly reflective lower crust that is interpreted as either magmatic underplate or granulite-facies metamorphosed rocks (from Chenin *et al.*, 2019).

arcs) and compared their distribution with that of rift domains (Fig. 3a, b; for details on the mapping methodology, see Chenin *et al.*, 2015 and Chenin, 2016). Based on the mapping results they proposed that the Variscan and Caledonian orogenic domains were reactivated in a different way. While Mesozoic rifting reactivated and finally separated parts of the former Caledonian orogen, apart from few exceptions, it circumvented the Variscan domain (Fig. 3b, c). As most of the Variscan domain in Western Europe is floored by a layered and reflective lower crust (Fig. 3e) that has been interpreted as mafic underplating or granulite-facies metamorphic lower crust (*e.g.*, Rey, 1993; Bois *et al.*, 1989; for details see Sect. 5.1), Chenin *et al.* (2018) hypothesized that the different characteristics of the inherited mantle/lower crust beneath the Variscan domain, namely the large-scale underplating by mafic bodies and underlying depleted mantle had a strong impact on future rift phases, including on their magmatic budget. The impact of mafic underplating and mantle depletion on subsequent rifting was further explored using a numerical modelling approach (Chenin *et al.*, 2019). A key result of this study was that the distribution of mafic underplating and depleted mantle may have a strong impact on the strain distribution during subsequent rifting.

Thus, apart from defining and mapping inheritance, it is also important to evaluate what type of inheritance controls subsequent tectonic events. In the case of Western Europe, the inheritance that had the biggest impact on subsequent rifting may have been located in the lower lithospheric mantle. It is therefore important to understand the nature of the subcontinental mantle and its evolution through the Wilson cycle in order to evaluate its role in controlling rift distribution and/or orogenic reactivation (Chenin *et al.*, 2018, 2019). A map of the mantle domains in Western Europe was published by Picazo *et al.* (2016) (Fig. 3d) and will be further discussed later in this study.

Aside from the local/regional-scale inherited features that may survive tectonic events, various types of inheritance may be created during a tectonic event depending on the size/maturity of the system involved. For instance, Şengör (1991), Chenin *et al.* (2017) and McCarthy *et al.* (2020) proposed that the closure of wide/mature oceans differs from that of narrow/immature "oceans" not only by the existence of a "mature" oceanic crust and the type of mantle (depleted in the case of oceans, enriched or inherited in the case of margins), but also by the occurrence or absence of a magmatic arc and associated LP/HT (low pressure/high temperature) metamorphism, mantle depletion, HP/LP (high pressure/low temperature) slab metamorphism related to subduction. It appears that the closure of narrow oceans and failed hyperextended rift systems is essentially mechanical and that little or no mantle melting/depletion occurs meanwhile. These results are of particular importance for the OROGEN project because the Biscay-Pyrenean system is a type-example of a narrow/immature hyperextended rift system.

4 The Biscay-Pyrenean system: a natural laboratory to study inheritance

The Biscay-Pyrenean domain, located between the southern North Atlantic and Alpine Tethys, includes one of the best-investigated, partly reactivated magma-poor extensional systems worldwide. Moreover, it shows a transition from a slightly to completely reactivated pair of rifted margins/rift system that is well imaged by industry and academic surveys and that has been studied by several academic consortiums, including the recent OROGEN project.

In the OROGEN project, the Biscay-Pyrenean domain was chosen as a natural laboratory to investigate the role of inheritance within an incomplete Wilson Cycle. This choice was justified by: (1) the position of the Biscay-Pyrenean system between the southern N-Atlantic and Alpine Tethys systems, both belonging to the best-investigated magma-poor rift systems worldwide; (2) the access to a unique dataset that includes geophysical and geological data from both academia and industry, with a scientific community that has been investigating these sites over generations; (3) the possibility to work on one and the same tectonic system onshore and offshore; and (4) the access to different genetic stages of an incomplete Wilson Cycle that initiates after a Paleozoic orogenic cycle (Variscan), goes through a Mesozoic extensional cycle, before undergoing an Alpine reactivation during Late Cretaceous to Cenozoic.

Several studies within the OROGEN project were directly or indirectly linked to the study of inheritance and its consequences. This includes the description of multistage rift systems and the use, further development and refinement of mapping approaches that resulted in new maps and sections across the North Iberian margin and the Basque-Cantabrian and Western Pyrenean domains (Cadenas *et al.*, 2020; Lescoutre *et al.*, 2021; Miró *et al.*, 2021). It also encompasses the study of lower crustal and mantle rocks by Asti *et al.* (2019) and Saspiturry *et al.* (2019), the thermal structure of the lithosphere (Clerc and Lagabrielle, 2014; Ducoux *et al.*, 2019, 2021a; Lescoutre *et al.*, 2019; Saspiturry *et al.*, 2020b), and the role of salt (Issautier *et al.*, 2020; Saspiturry *et al.*, 2021; Ford and Vergés, 2021). A major effort was devoted to the development of new passive seismic imaging methods (Wang *et al.*, 2016; Polychronopoulou *et al.*, 2018, 2019; Chevrot *et al.*, 2015, 2018) that enabled to gain insight into the deep structure of the Pyrenean domain, as well as to resolve the local 3D architecture of a hyperextended system (Maupasacq experiment, Lehujeur *et al.*, 2021). The results of all these studies enabled to define and map the size and maturity of the Biscay-Pyrenean extensional system and to understand the role and importance of inheritance during the reactivation of the initial rift system and subsequent collision.

Despite all these benefits, the Biscay-Pyrenean system is far from being understood as demonstrated by the numerous ongoing debates that persist even after intense investigation. Lively debates concern: (1) the competing and partly diverging kinematic reconstructions between the Iberia and European plates and the ages of the related tectonic events; (2) the lithological architecture of the crust and lithosphere prior to rifting (*e.g.*, position of granulites referred in this paper to as the "granulite conundrum"); (3) the role of Triassic salt during the extensional and convergent cycles; (4) the architecture of the hyperextended rift basins, including the vergence of their main fault systems, the existence and importance of rift segmentation for subsequent reactivation; and (5) the thermal state during rifting and its importance in controlling the localization of subsequent shortening phases.

In the following, we aim to show how the Biscay-Pyrenean system can be used as a laboratory to study inheritance. We do neither aim to present a detailed description of the geological history of the Biscay-Pyrenean domain, which is the subject of other papers in this special volume, nor to list all results of the OROGEN project that are too numerous and partly already published or presented in this special volume. We rather focus on key elements that enabled us to identify compositional and structural inheritance, and on the learnings that enabled us to develop a more generic understanding of the role of inheritance in rift and orogenic systems.

5 The Biscay-Pyrenean system: evolution of an incomplete Wilson Cycle

The Biscay-Pyrenean domain (Fig. 2a) experienced a complex tectonic evolution that started in the Paleozoic with the Variscan orogeny (Martínez Catalán *et al.*, 2007; Matte, 1991). After the post-Variscan extensional collapse, multistage Triassic to Cretaceous rift events linked to the opening of the Central and North Atlantic resulted in the opening of the Bay of Biscay and extensional basins along the Iberian-European plate boundary (Roest and Srivastava, 1991; Ziegler, 1988). These basins were reactivated during the subsequent Alpine convergence that initiated in Campanian/Santonian time. In the following, we describe the geological evolution of the Biscay-Pyrenean system, focusing on the role of inheritance. For more detailed descriptions of the evolution described below see Cadenas *et al.* (2020), Issautier *et al.* (2020), Saspiturry *et al.* (2021), Lescoutre *et al.* (2021) and Miró *et al.* (2021).

5.1 Paleozoic orogenic evolution and late- to post-orogenic collapse

The Paleozoic orogenic evolution is intimately linked to the amalgamation of the Pangea supercontinent, which is documented along the N-Atlantic/Tethys system in W-Europe, and along the conjugate NW-African and N-American continent (Aguilar *et al.*, 2015; Arthaud and Matte, 1975; Cochelin, 2016; Cochelin *et al.*, 2018). The formation of the Caledonian and Variscan orogens followed the closure of the Iapetus and Rheic oceans, respectively. While the main suture zones, arcs, fold-and-thrust belts and flexural foreland basins of the Caledonides have been mapped at the scale of the N-Atlantic, the existence and location of arcs and the nature of suture zones in the Variscan system remain debated. For instance, it is still unclear how to correlate parts of the Variscan orogen across the Biscay-Pyrenean system. This uncertainty may be linked to the fact that present-day restorations of the Variscan system in the Biscay-Pyrenean system are based on kinematic restorations that are outdated and not coherent with the current knowledge of the Iberian geology. Thus, correlations of the Variscan domains across the Iberia-European plate boundaries, as shown in Figure 3c, strongly depend on the plate kinematic models that are at present still debated.

A key observation is that none of the first-order Variscan structures (sutures, arcs) correlate and/or coincide with the Mesozoic rift trends mapped in the hyperextended Biscay and Pyrenean rift systems (Figs. 2a and 3a, b). Indeed, Mesozoic rift systems are highly oblique and/or truncate most of first order Variscan structures. At a more local scale, correlations between inherited Variscan structures and younger, either Mesozoic rift structures, or Alpine structures have been proposed, but these remain often debated. Examples are the Pamplona, Leiza or Louhossoa faults (for location of the latter two see Fig. 2b), for which different interpretations still co-exist (*e.g.*, Lescoutre *et al.*, 2021; Saspiturry *et al.*, 2019) and discussion in Sect. 5.2). Depending on the authors, these structures are interpreted either as inherited and reactivated, or as rift-related, or, in the case of the Pamplona fault, as fictional. The fact that the Variscan orogen has been disrupted during the late Carboniferous to Permian orogenic collapse, the multi-stage Mesozoic rifting, and the subsequent Alpine reactivation makes it often difficult to assign structures to specific events. Therefore, rather than focusing on single structures, here we try to establish a first order understanding of the conditions that prevailed at the end of the Variscan phase, *i.e.*, to establish the initial conditions for the subsequent Mesozoic rifting. This requires determining whether or not the system went to thermal and gravitational equilibration after the Variscan orogeny (for a discussion see Sect. 7.1).

The Permo-Triassic sedimentary succession in the Biscay-Pyrenean domain shows that the first sedimentary basins over the Variscan orogenic crust formed during latest Carboniferous to Permian and remained sub-aerial. This suggests a relatively fast disappearance of the “orogenic” topography and the establishment of a Basin and Range-type morpho-tectonic evolution with the local occurrence of core complexes (López-Gómez *et al.*, 2019; Saspiturry *et al.*, 2019). The first regional marine transgression is recorded during Triassic time and is largely diachronous from east to west. Based on isostatic considerations, marine conditions can only occur over continental crust that is less than 30 ± 5 km thick in a thermally equilibrated lithosphere. Beside the lack of significant accommodation space creation until late Jurassic time, *i.e.*, over almost 100 My, and the widespread occurrence of shallow marine to sub-aerial conditions tip the scale against significant crustal thinning (*i.e.*, less than 30 ± 5 km thick). These observations indicate a general thermal and gravitational equilibrated crust and lithosphere during Triassic time. Thus, we assume that equilibrium was reached before the onset of the Mesozoic multistage rifting.

Although the tectonic system was equilibrated at a lithospheric scale, the crust and underlying mantle were complex and contained significant structural and compositional inheritance. To establish and characterize the nature of inheritance, it is necessary to reconstruct the continental crust and its underlying subcontinental mantle at Triassic time, *i.e.*, at the transition from the orogenic to the extensional cycle. Such a reconstruction is difficult to establish and needs to rely on the combination of structural and petrological data from tectonically exhumed rocks and xenoliths, as well as on geophysical data. The upper crust shows a structurally and compositionally complex “patchwork” of Cambrian to Carboniferous meta-sediments, the latter bearing the flysch-type Culm facies reminiscent of the Variscan foreland basin (Delvolvé *et al.*, 1998) that is coeval with the emplacement of granitic magmatism and HT/MP-LP metamorphism in the hinterland dated 330 to 295 Ma (Cochelin, 2016; Martínez Catalán *et al.*, 2007; Cochelin *et al.*, 2018). A significant change in magmatism occurred during the Late Permian, when alkaline magmatism became dominant (Lago *et al.*, 2004; Denèle *et al.*, 2012;). Granulite facies metamorphism affected lower structural levels of the crust (Ribeiro *et al.*, 2019). Metamorphism was coeval with a dextral strike-slip tectonic setting and with the onset of the Variscan orogen extensional collapse, and was contemporaneous to or followed by calc-alkaline plutonic and volcanic magmatism (Aguilar *et al.*, 2015; Denèle *et al.*, 2012, Petri *et al.*, 2017). At present, no basement rocks exposed in the Pyrenean belt, including granulites, show P values higher than 6 kbar (Vielzeuf and Kornprobst, 1984; Vielzeuf and Pin, 1989). Thus, the nature of the pre-rift lower crust deeper than 18 km depth is not constrained by outcrop data. However, reflection seismic data show that the present-day Iberian and European Variscan crusts are floored by a reflective, stratified and high velocity lower crust (Bois *et al.*, 1989; Alvarez-Marrón *et al.*, 1996) (Fig. 3e). ODP Sites 900 and 1067 offshore West Iberia and xenoliths in volcanic rocks over Iberia and Western Europe suggest that the lowermost crust is likely made of Permian underplated mafic bodies (Petri *et al.*, 2017). Thus, the pre-rift lower crust of the Biscay-Pyrenees realm may have been similar to the one described from the Ivrea zone in the Alpine domain (Petri *et al.*, 2019). For both the understanding of rifting and the question of pre-rift and rift inheritance, the granulites that occur throughout the Biscay-Pyrenean system are of particular importance and will be discussed in Section 10.

Mantle rocks are exposed throughout the Biscay-Pyrenean domain (Fabriès *et al.*, 1991, 1998). Lagabrielle *et al.* (2010) described two types of occurrences, namely reworked within Cretaceous sediments, and exhumed along extensional detachment faults. The best exposed examples are at Lherz and Urdach, both showing relations to surrounding crustal rocks. All mantle rocks outcropping in the Biscay-Pyrenean domain have been classified as inherited shallow subcontinental mantle (mantle type 1 of Picazo *et al.*, 2016; Fig. 3d). Infiltrated or oceanic mantle rocks (types 2 and 3 of Picazo *et al.*, 2016) have not been found, which is compatible with the lack of Cretaceous MORB basalts throughout the Pyrenean system. Thus, in contrast to the Biscay system, there is no evidence that the Pyrenean domain went to lithospheric breakup, which means that it may have never evolved into a pair of conjugate rifted margins.

5.2 Multistage Mesozoic rifting at the junction between N-Atlantic and Alpine Tethys

Rifting, defined here as the extensional process that stretches and thins the crust below 35 ± 5 km, and to less than 10 km in hyperextended examples, occurred in the southern N-Atlantic and Alpine Tethys systems from Late Triassic to late Early Cretaceous (Frizon de Lamotte *et al.*, 2015; Le Pichon *et al.*, 1977; Leleu *et al.*, 2016). During the Late Triassic and Early Jurassic, the main locus of rifting was localized along the future Central Atlantic margins and in the different branches of the Alpine Tethys realm (Fig. 4). It formed a plate boundary separating Africa/Gondwana from North America and Europe, so that Iberia was part of the European plate at that time. Around and inside Iberia, the importance of Triassic-Lower Jurassic rifting remains debated (Angrand *et al.*, 2020). Nevertheless, the occurrence of massive bodies of diabase with ophitic structures (Rossi *et al.*, 2003) throughout the Pyrenean domain suggests a significant and large-scale magmatic event. Deposition of salt occurred during the Late Triassic-Hettangian rifting, and as evaporites are efficient decoupling material, understanding their paleogeographic distribution is important to evaluate their role in controlling subsequent tectonic events (for more details see Sect. 8). In the following we refer to this Late Triassic-Hettangian extension phase as a *stretching phase sensu* Lavier and Manatschal (2006). During the late Early to Middle Jurassic, rifting culminated in the Central Atlantic with breakup and subsequent seafloor spreading, coeval with the formation of the Alpine Tethys margins separating Adria from Iberia and Europe (Angrand *et al.*, 2020). During this stage, the former Biscay-Pyrenean realm was little affected by extension as indicated by the lack of major depocenters of this age.

During the Late Jurassic to Aptian, the Atlantic rifting propagated in the southern N-Atlantic realm and resulted in hyperextension and mantle exhumation along the Iberia-Newfoundland margins (Alves *et al.*, 2009; Alves and Cunha, 2018; Soares *et al.*, 2012), as well as in the Orphan and Porcupine basins (Nirrengarten *et al.*, 2018) (Fig. 4). Several competing kinematic models exist for this time for the Biscay-Pyrenean domain. Based on the restoration of the J magnetic anomaly as an isochron, Sibuet *et al.* (2007) and Vissers *et al.* (2016) suggested the existence of an oceanic domain in the Pyrenean realm during the Aptian, which was closed by subduction during the Albian. However, neither Aptian seafloor spreading, nor Albian subduction are supported by data. Another group of kinematic models is based on the assumption that the J magnetic anomaly does not represent an oceanic magnetic anomaly and can therefore not be used as an isochron for plate kinematic reconstructions (Nirrengarten *et al.*, 2017; Angrand *et al.*, 2020; Frasca *et al.*, 2021). These kinematic models propose tight fit reconstructions for the southern N-Atlantic, which imply sinistral trans-tension along the Iberian/European plate boundary during Late Jurassic to Albian time. Angrand *et al.* (2020) and Frasca *et al.* (2021) suggested that sinistral movements were accommodated in the different branches of the Central Iberian Range, separating the Iberian plate from the European/Ebro plate (Fig. 4c). The precise location, kinematics and offset along this plate boundary remains, however, disputed. In the model of Angrand *et al.* (2020) and Frasca *et al.* (2021), it is suggested to be localized along a strike-slip corridor that linked the Asturian, Cabuérniga, Polientes, Cameros, Columbrets (for location see Fig. 2a) and other rift basins interpreted as pull-apart basins and strike-slip corridors. Such an interpretation is supported by the size, shape, bounding structures and main trend of these basins. These structures are aligned along a kinematic direction that plots on the same small circle as the Newfoundland or Flemish Pass strike-slip corridors, both of which are Late Jurassic to Aptian in age (Frasca *et al.*, 2021). Therefore, we propose that all structures may be contemporaneous and originate from the same kinematic framework. Further constraints supporting these new plate kinematic models come from Lescoutre *et al.* (2021), who showed that the Ebro block lying between the Central Iberian Range and the Pyrenees was part of the European plate until the Late Aptian. Besides, Cadenas *et al.* (2020) showed that the Asturian basin formed prior to, and independent from, the Late Aptian to Cenomanian rift event, incompatible with the models previously proposed by Sibuet *et al.* (2004) and Vissers *et al.* (2016). Thus, the results of the OROGEN project suggest that the Late Jurassic to Barremian extension phase was a distinct rift event during which most of the sinistral strike-slip movement between the Iberian and European/Ebro plates occurred, in line with the plate kinematic model proposed by Frasca *et al.* (2021).

The Late Aptian to Cenomanian rift event was, in the past, not disassociated from the Late Jurassic to Early Aptian event.

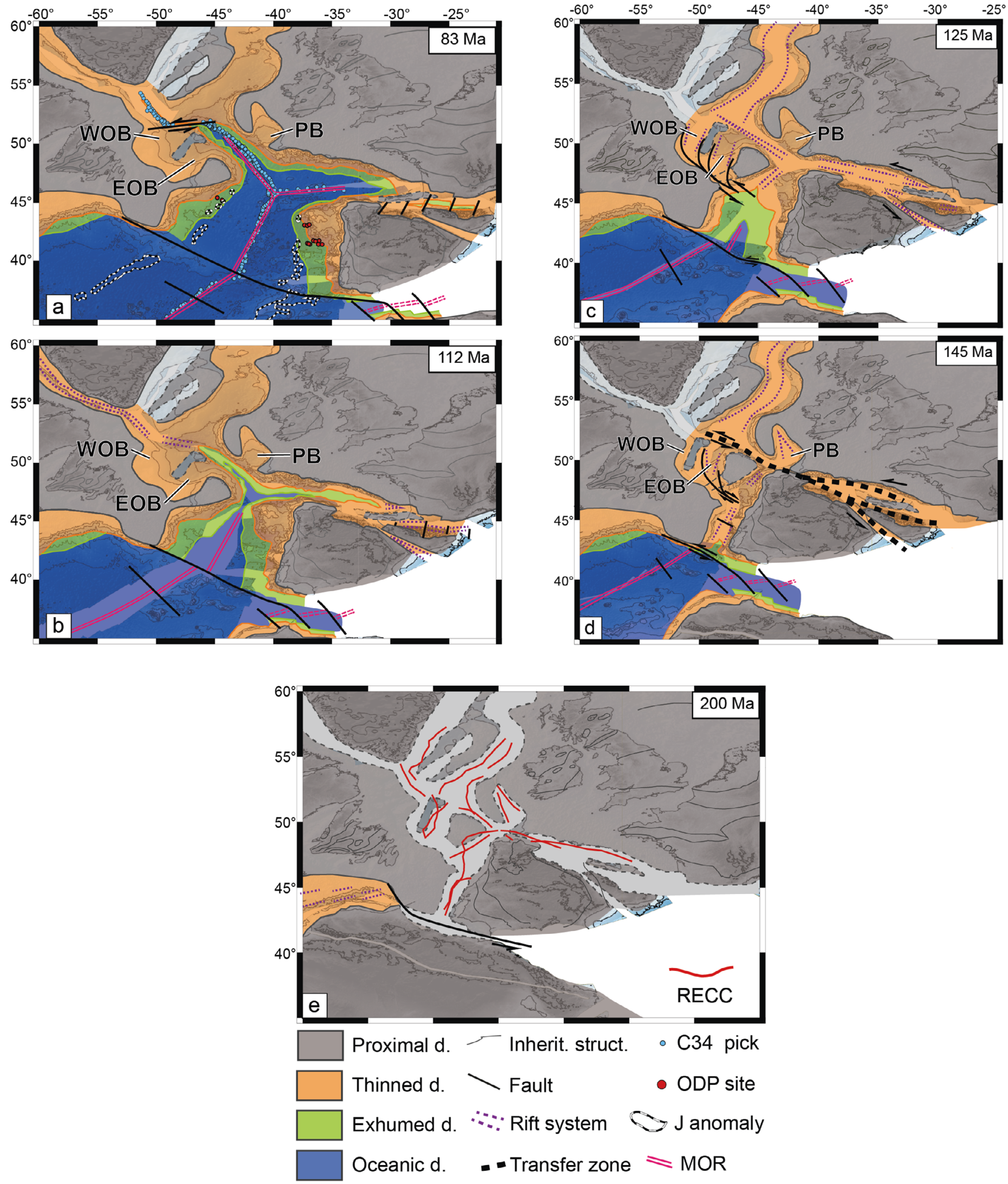

Fig. 4. Restoration of the southern North Atlantic, with North America fixed on present-day coordinates after Nirrengarten *et al.* (2018) with modifications for the Biscay Pyrenean domain based on Frasca *et al.* (2021). (a) Santonian/Campanian (83 Ma), (b) Late Aptian/Albian (112 Ma), (c) Aptian (125 Ma), (d) Late Jurassic/Early Cretaceous (145 Ma), (e) end of Triassic (200 Ma). RECC: Reconstructed Edge of the Continental Crust. d.: domain; MOR: mid-oceanic ridge; EOB: East Orphan Basin; WOB: West Orphan Basin; PB: Porcupine Basin.

Choukroune and Mattauer (1978) suggested that the Biscay-Pyrenean domain was formed by a succession of Albian pull-apart basins linked to sinistral strike-slip movements along the North Pyrenean Fault (NPF), an interpretation that was largely accepted prior to the discovery of hyperextended basins (Lagabrielle and Bodinier, 2008; Jammes *et al.*, 2009). However, neither the precise location of the NPF, nor the kinematics of this fault system were constrained in a satisfactory way. This was particularly true for the West Pyrenean-Cantabrian junction (Hall and Johnson, 1986). Classical models linked the NPF with the Leiza fault by an offset accommodated by the Pamplona transform fault (Engeser and Schwentke, 1986; Tavani *et al.*, 2018; Lescoutre *et al.*, 2021). This correlation was mainly based on the occurrence of mantle rocks, granulites and HT/LP pre-rift sediments all along this Pyrenean-Cantabrian system. However, new studies of the Pyrenean-Cantabrian junction do not support the existence of a NPF *sensu* Choukroune and Mattauer (1978). For instance, Saspiturry *et al.* (2019) demonstrated through the analysis of the Bidarray basin the impossibility to consider a large-scale sinistral strike-slip after Permian. In an alternative interpretation, Lescoutre *et al.* (2021) suggested the existence of two overlapping en-échelon hyperextended rift segments rather than two basins separated by a sharp transform fault. Further westwards, at the central North Iberian margin, Cadenas *et al.* (2020) mapped two en-échelon rift segments and described related extensional detachment faults similar to those described by Masini *et al.* (2014) from the Mauléon basin at the western termination of the Pyrenees. All these detachment systems are Aptian to Cenomanian in age are interpreted to be responsible for the exhumation of mid-crustal granulites and mantle rocks, and to show N-S directed kinematics (Cadenas *et al.*, 2021). Further evidence for a segmentation of the rift system comes from tomographic imaging by Chevrot *et al.* (2018), who suggested a deep-seated along-strike segmentation of the Pyrenean system. Evidence for N-S directed extension comes also from kinematic indicators determined from exposed exhumation faults (*e.g.*, Northern Mauléon Detachment fault; Masini *et al.*, 2014, see also Tavani et al., 2018 for further examples), from the arrangement of the overlapping segments (Lescoutre *et al.*, 2021; Cadenas *et al.*, 2020), and from the occurrence of roughly N-S directed lateral ramps surface (Masini *et al.*, 2014). All these observations cannot be satisfactorily explained by localized E–W-directed Aptian-Albian strike-slip movements in the Western Pyrenean (Canérot, 2017) and Basque-Cantabrian domains, and offshore in the North Iberian margin. Yet it is important to keep in mind that kinematic data showing E–W movements were reported from the granulites of the Basque massifs (Boissonnas *et al.*, 1974). E–W-directed lineations in these rocks formed at conditions higher than 350 °C and need therefore to be older than the lowermost Jurassic Ar/Ar ages on biotite and muscovite (Masini *et al.*, 2014). Indeed, U-Pb ages from the Ursuya massif indicate that granulites and paragneisses crystallized and were deformed between 295 and 274 Ma (Hart *et al.*, 2016; Vacherat *et al.*, 2016). Based on a structural analysis of the Ursuya granulites, Saspiturry *et al.* (2019) proposed that they underwent E-W orogen-parallel mid-crustal flow and were exhumed at the base of the upper crust, beneath Paleozoic meta-sediments. A more detailed discussion of the exhumation of the granulites and their importance in establishing the kinematics and timing of detachment faulting and related thermal structure can be found in Section 10. Kinematic data from the supra-salt cover have also been interpreted to show E-W directed movements of the supra-salt cover (Oliva-Urcia *et al.*, 2010; Ford and Vergés, 2021). However, whether the latter data can actually be used to determine the local pre-salt basement deformation as well as the larger scale plate kinematic transport directions, or are only related to salt tectonics, remains questionable.

The results of the OROGEN project allowed to establish a well-constrained kinematic framework, at least for the Western Pyrenean and Bay of Biscay domains. Moreover, it allowed to describe the rift template, including the nature of rift segments and segment boundaries, and to understand the temporal and spatial evolution of a multistage rift system that includes a Late Triassic-lowermost Jurassic stretching system, a Late Jurassic-Barremian transtensional system, and a Late Aptian to Cenomanian hyperextended system (Cadenas *et al.*, 2020). Each of these events is linked to a different kinematic setting, displays its own nature and architecture of rift basins, and its own subsidence and thermal evolution. Interestingly, although the Asturian and Cameros Late Jurassic-Barremian basins developed a significant tectonic subsidence (up to 8 km thick), no major thermal subsidence was recovered from these basins, in contrast to the later Aptian-Cenomanian rift domains (*e.g.*, Angrand *et al.*, 2018). Such an observation suggests that the lithosphere underlying these basins did not significantly thin. There is also an agreement that Iberia was not necessarily one single plate (Fig. 4). The new kinematic interpretations by Frasca *et al.* (2021) and Angrand *et al.* (2020) have important consequences for the evolution of the Biscay Pyrenean domain. If their models are correct, the main Late Jurassic to Barremian plate boundary was linking the North Atlantic with the Tethyan system through the Bay of Biscay-Central Iberian Range (*i.e.*, south of the Ebro micro-continent) and not, as previously suggested, along the Pyrenees *sensu stricto*. However, more work is necessary to confirm this assumption.

5.3 Onset of convergence

The age and the location of the onset of convergence in the Biscay-Pyrenean system are poorly constrained (Mattauer and Proust, 1967; Thinon *et al.*, 2001) but are commonly assumed to be Latest Santonian to Campanian time (anomaly 34; 84 Ma) (Andrieu *et al.*, 2021). Most evidence for onset of convergence is indirect. The problem in dating the onset of convergence is that the areas where shortening initiated are in the internal parts of the orogen (*e.g.*, Ternois *et al.*, 2019), therefore, they are either overprinted by later deformation, subducted and thus not accessible to observations, or located offshore and not drilled. Compression-like structures were interpreted to form already during the lower Cretaceous. However, the related structures were more recently re-interpreted as being linked to the interaction between normal faulting and salt tectonics (Gómez-Romeu *et al.*, 2019; Ducoux *et al.*, 2019; Izquierdo-Llavall *et al.*, 2020; Ford and Vergés, 2021). At present, many authors proposed that initial shortening was accommodated in the hyperextended and/or exhumed mantle domains. The problem is that subduction of exhumed mantle does not lead to uplift and topography, and thus is difficult to date and locate with classical methods. Although evidence for convergence is difficult to access within the highly deformed internal domains, former studies (Muñoz, 1992; Teixell, 1996) and recent work in the Pyrenees (Mencos *et al.*, 2015), on the Iberian margin (Andrieu *et al.*, 2021) and within the Aquitaine basins (Rougier *et al.*, 2016) demonstrated a change in Late Santonian time with the onset of flexural basins development. Andrieu *et al.* (2021), show a Coniacian uplift of the Iberian margin and significant subsidence similar to what is observed at the European margin. What controls this deformation is debated (far-field *versus* convergence), but a start of convergence causing lithosphere buckling cannot be excluded.

A reorganisation of the main orogenic structures occurred between 50 and 40 Ma (Eocene; Muñoz, 1992; Vergés and García-Senz, 2001; Vacherat *et al.*, 2016) and was associated with the formation of the present fold-and-thrust belt well exposed in the southern Pyrenees. The onset of this reorganization is linked to the main phase of mountain building that started when hyperextended rift basins closed and the necking domains of the former rift basins collided. Macchiavelli *et al.* (2017) reconstructed the movement of the Iberian plate relative to the European plate using the well-imaged and unquestioned magnetic anomaly 34 and younger anomalies in the southern North Atlantic. Their interpretation may be considered as the best constrained kinematic description of the convergence between the Iberian and European plates. A new compilation of the magnetic anomalies from the Bay of Biscay-West-Pyrenean domain by Le Maire *et al.* (2021) may provide further constrains for future kinematic reconstructions.

6 Restoration of crustal sections back to pre-rift stage and implications for rift models

6.1 Kinematic restoration of sections back to the pre-rift stage

To evaluate the role of inheritance during rifting and reactivation, it is critical to kinematically restore sections back to their initial pre-orogenic (*i.e.*, post-rift) and even pre-rift stages (Fig. 5). In the OROGEN project, Gómez-Romeu *et al.* (2019), Miró *et al.* (2021) and Lescoutre *et al.* (2021) proposed fully restored sections that fulfill area conservations as well as pre-rift marker horizon length conservation. The methodology of such restorations has been formulated in Chao (2021). Here we present a slightly modified version of the methodology. Requirements for an accurate kinematic restoration are that the restored section is parallel to shortening and extension direction and that the crustal area and the length of a pre-rift horizon are conserved during restoration (Dahlstrom, 1969). Restorations can be done using software such as ImageJ (freely available on the Internet: https://imagej.nih.gov/ij/) or 3DMove.

Area conservation, *i.e.*, neither addition nor loss of crust out of the section can be formulated as:

$$Ac_{initial} = Ac_{final}, \tag{1}$$

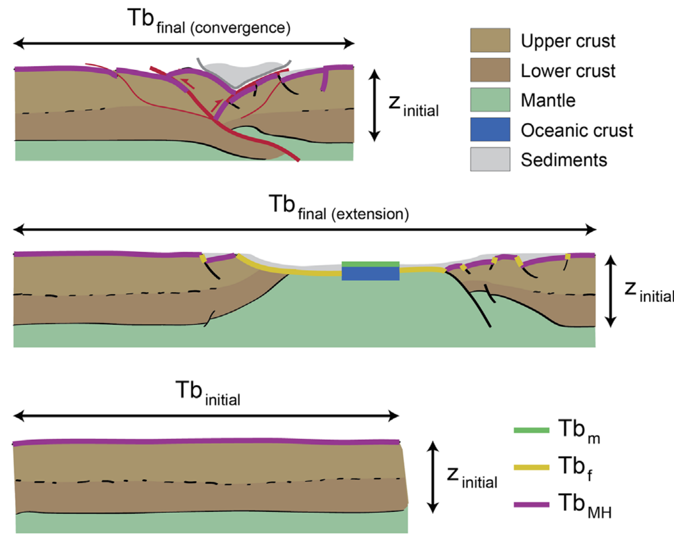

Fig. 5. Kinematic restoration of a crustal section back to the pre-rift stage with area conservation as well as pre-rift marker horizon length conservation (see text for further explanations). Tb: top basement; Tbm: magmatic top basement (neww real estate); Tbf: fault top basement (new real estate); TbMH: stratigraphic marker horizon top basement.

where $Ac_{initial}$ is the area of the crust at the pre-rift stage and Ac_{final} the area at the end of shortening. Such a reconstruction must be done at a crustal scale and needs to be based on the definition of top and base crust, which requires access to geophysical and geological data. More detailed restorations in which both the brittle and ductile crusts are restored bear the problem that the thermal evolution and/or hydration reactions may change the position of the brittle ductile transition (*e.g.*, embrittlement concept of the crust in extensional systems; Pérez-Gussinyé *et al.*, 2003). Therefore, the brittle and ductile crust areas do not remain constant and cannot be restored using the present method. Changes of the brittle and/or ductile crust area can be due to flow of ductile crust in and out of the section, magmatic additions and erosion that is mainly linked to convergence. Thus, if one of these processes occurs, they need to be quantified and can be formulated as

$$Ac_{initial} \pm Ac_{volumechange} = Ac_{final}, \tag{2}$$

A second requirement is that the length of a hypothetical pre-rift top basement marker horizon is conserved during extension and subsequent shortening. Such a pre-rift top basement marker corresponds, in an ideal case, to a continuous pre-rift stratigraphic marker horizon (*e.g.*, Buntsandstein Lower Triassic deposits in Western Europe). The length of such an idealized pre-rift Marker Horizon (MH) forming the initial top basement ($Tb_{MH\_initial}$) cannot change during the subsequent tectonic events, which can be formulated as:

$$Tb_{MHinitial} = Tb_{MHfinal}, \tag{3}$$

$$Tb_{final} = Tb_{MHinitial} + \sum Tb_f + \sum Tb_m, \tag{4}$$

where Tb_{final} is the length of top basement at the end of rifting (or convergence), Tb_f is the length of newly created top basement owing to fault play, and Tb_m is the length of new top basement made of newly formed (accreted) oceanic crust. Establishing the nature of top basement in a section through a rifted margin is challenging, in particular through the most distal parts, since it requires distinguishing between $Tb_{MH\_initial,\ Tbf}$ and Tb_m, which is often difficult and interpretative. A relation between $Tb_{MH\_initial}$ and Ac_{final} can be established through the following equation:

$$Z_{initial} \times Tb_{MHinitial} = Ac_{initial} = Ac_{final} \Leftrightarrow Tb_{MHinitial} = Ac_{final}/Z_{initial}, \qquad (5)$$

where $Z_{initial}$ is the thickness of the crust before the onset of rifting, which can be approximated by the thickness of the crust outside the areas affected by either extension or compression on either side of the restored section. Erroneous interpretations of top basement, such as the misinterpretation of an exhumation fault (Tb_f) and/or $Tb_{MH\_initial}$ and the location of first oceanic crust (Tb_m) results in gain or loss of crust during the extensional process (see Eq. (5)). Thus, for the restoration of 2D sections back to the pre-rift stage an accurate interpretation of top basement is essential.

The restoration of compressional systems is more difficult for internal parts of orogens, where imaging methods can often not resolve the nature and location of the top and base of the crust. Moreover, collisional systems form topography that is submitted to erosion and thus changes in crustal area, in contrast to extensional systems that are largely below sea level. Thus, restorations of collisional systems are commonly less constrained than those of extensional systems. While restorations of thrust faults heaves are relatively simple in external fold and thrust belts (especially into systems without salt tectonics), such methods fail in heavily pre-structured internal parts, in particular if thrust faults reactivate former extensional detachment faults. However, in kinematic restored sections, Equation (5) needs to be fulfilled if one assumes that crust has been neither added nor removed from the section.

6.2 Implications for the rift models proposed for the Pyrenean-Cantabrian domains

Among the restorations of sections from the Basque-Cantabrian and Pyrenean domains back to the pre-rift stage presented in Lescoutre *et al.* (2021), Miró *et al.* (2021), and Saspiturry *et al.* (2020a) (see also Lagabrielle *et al.*, 2020, and sections in there), two groups of mutually exclusive interpretations can be distinguished: The first group of interpretations shows highly extended, asymmetric basins floored by detachment faults that dip to the north. In these interpretations the basin is dominantly floored by Tb_f with some extensional allochthons (*e.g.*, Ducoux *et al.*, 2019; Jammes *et al.*, 2009; Masini *et al.*, 2014; Teixell *et al.*, 2016; Lescoutre *et al.*, 2021; Miró et al., 2021). The second group of interpretations shows more symmetric hyperextended basins, bounded by south- and north-dipping faults and floored mainly by pre-rift sediments. In these interpretations the basin is dominantly floored by $Tb_{MH\_initial}$ (Corre *et al.*, 2016; DeFelipe *et al.*, 2017; Pedrera *et al.*, 2017; Saspiturry *et al.*, 2021, 2020b). While the first group of interpretations fulfils Equations (1) and (3), the second group of restorations assumes a loss of crustal area, *i.e.*, it meets Equation (2). Two hypotheses were proposed to account for this crustal loss: Corre *et al.* (2016), Lagabrielle *et al.* (2016) suggested a hot rift with a ductile crust that flowed during rifting out of the section. Asti *et al.* (2019) proposed that the crust was already thinned to 20 km in Permian time, suggesting that the crust was not equilibrated at rift onset. Thus, the two groups of interpretations require different initial conditions for the Mesozoic rifting observed in the Pyrenean-Basque-Cantabrian domain with far-reaching implications for the thermal evolution and the related rheology of the extending crust. These different models and their implications are further discussed in Section 9.

6.3 Implications for section restorations across the Pyrenean-Cantabrian domains

In Figure 6, we present three fully restored crustal-scale sections, one through the Cantabrian basin, one through the central segment of the Basque-Cantabrian basin and a last one through the en-échelon overstepping termination of the Basque-Cantabrian and Mauléon basins located in the Basque massifs, at the Pyrenean-Cantabrian junction (for original sections and explanations see Lescoutre *et al.*, 2021 and Miró *et al.*, 2021). All were interpreted based on field observations and are consistent with published geophysical and drill hole data. The three sections distinguish between $Tb_{MH\_initial}$ and Tb_f and fulfil Equations (1) and (5), assuming that no crust was gained or lost out of the section. Thus, they suggest that erosion of basement and the volume of magmatic additions in the crust were minor. Note also that they show substantial differences to previously published lines from DeFelipe *et al.* (2017), Pedrera *et al.* (2017, 2021). The restorations shown in Figure 6 assume that the main left-lateral strike-slip movement of Iberia relative to Europe was accommodated along a strike-slip corridor located along the Internal Iberian Range, as proposed by Angrand *et al.* (2020) and Frasca *et al.* (2021) and shown in Figure 4c. Moreover, they assume that the kinematic transport direction during Late Aptian to Cenomanian extension and subsequent reactivation were both approximately N-S directed (see discussion in Sect. 5.2). Thus, even if the interpretation of sections at a crustal scale can never be considered as a unique solution, the three restored sections shown in Figure 6 can at least be considered as coherent interpretations respecting a well-defined restoration method and consistent with all available geological and geophysical data. Note also that all three sections provide coherent values for crustal extension, between 60 and 90 km. Shortening in the sections is between ca. 100 km in the eastern section, >105 km in the central one and >65 km in the western one. Note however, that this method does not consider the amount of extension or shortening in the exhumed mantle domain. Yet, since the eastern section across the Mauléon-Basque/Cantabrian junction (see Fig. 6) does not show any evidence for exhumed mantle, the values obtained by its restoration of about 60 km of extension and 100 km of north-south shortening can be considered as the best constrained values for the Pyrenean system. Much more extension appears to have been

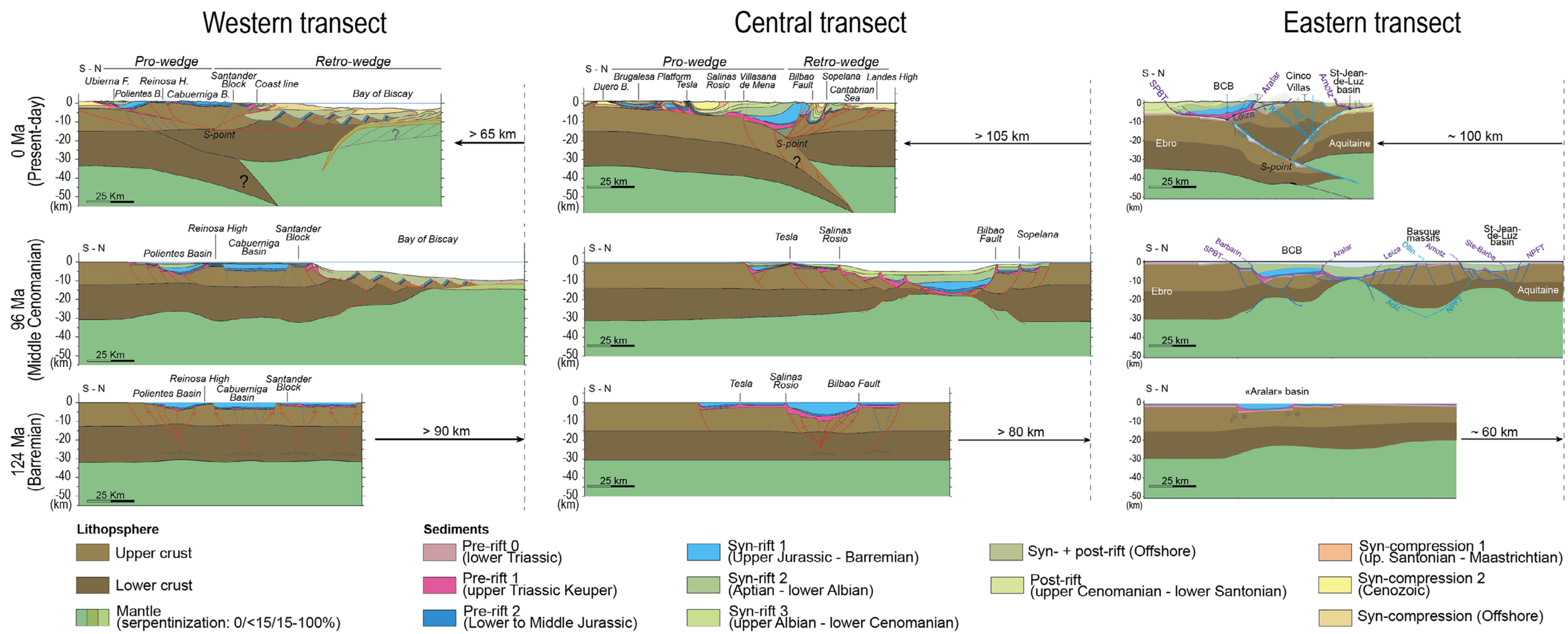

Fig. 6. Sections through the Cantabrian (Western transect) and the Basque Cantabrian Basin (Central transect) (after Miró *et al.*, 2021) and through the Mauléon-Basque massifs (Eastern section) (after Lescoutre *et al.*, 2021). Sections show the present-day situation and restorations at middle Cenomanian (96 Ma) and at Barremian (124 Ma) times. These sections are restored respecting area conservation as well as pre-rift marker horizon length conservation. See Fig. 2b for section location. B.: basin; H.: high; BCB: Basque-Cantabrian Basin; SPBT: South Pyrenean Basal Thrust; NPFT: North Pyrenean Frontal Thrust.

accommodated west of the Santander transform system, where extension also included late Jurassic to Albian sinistral strike-slip movements of the Iberian plate relative to Europe (see Fig. 4). This further supports that plate movements were partitioned during the Mesozoic rifting and that Iberia cannot be considered as one single plate (Canérot, 2017; for more details see Frasca *et al.*, 2021).

7 Assessing the role of rift inheritance in the Biscay-Pyrenean system

This section focuses on examples that have been investigated during the OROGEN project and have been either already published or are about to be published. The aim of the current section is to put the results of these studies into perspective and to discuss the potential new emerging concepts they enabled.

7.1 The role of Variscan inheritance in the Biscay-Pyrenean system

In this study, we introduced the concept of "interface shape inheritance" to describe the Biscay-Pyrenean system at the end of the Variscan cycle. Its application requires evaluating the thermal state and the residual gravitational potential energy of the system at this stage. Based on subsidence analysis, studies of depositional environments and taking isostatic considerations into account, we can assume that the thermal and gravitational potential energy was equilibrated before the onset of the Mesozoic rift events in the study area. This means that the main interfaces, *i.e.*, top basement, base of the crust and base of the lithosphere were largely parallel. In contrast, compositional and structural heterogeneities inherited from the Variscan and the post-Variscan cycle persisted in the crust and the underlying mantle. Although the detailed nature and rheological architecture of the crust, in particular of the lower crust, and the distribution of major inherited structures remain debated, it is generally accepted that main rift structures truncate Variscan structures and that, at a larger scale, the Mesozoic rift system circumvented the Variscan system (Chenin *et al.*, 2015). Thus, inherited Variscan structures appear not to have significantly controlled the subsequent Mesozoic rift system. This does not mean that inherited structures did not control extensional faults at a local scale, only that a general pattern cannot be recognized. For instance, the change in the composition of the upper crust along strike does not seem, at a first order, to control the distribution and architecture of the extensional systems. At the scale of the N-Atlantic, Chenin *et al.* (2019) suggested that the mantle composition (depleted *versus* inherited) and the occurrence or absence of underplated mafic crust formed during orogenic collapse are the main factors controlling subsequent rift location. Thus, it can be hypothesized that the nature of the mantle inherited from the orogenic evolution may have controlled the rift system at a large scale. In W-Europe, the lower lithospheric mantle inherited from the post-Variscan collapse was presumably depleted during the post-orogenic collapse (Picazo *et al.*, 2016). The existence of such a depleted mantle that was likely thermally equilibrated at the onset of rifting may explain the low volume of magma produced during Mesozoic rifting over rifted Variscan lithosphere. It could also explain that most Mesozoic rift systems circumvented the Variscan lithosphere, and that oceans formed in the southeast (Alpine Tethys) and west (North Atlantic) of the orogenic domain.

7.2 Assessing the initial conditions for the Mesozoic rifting in the Biscay-Pyrenean system

As stated in Section 6.2, two competing and mutually exclusive models have been proposed to explain hyperextension in the Pyrenean-Cantabrian junction. Here the aim is not to exclude one of the two, but to discuss the implications of these models on the "interface shape inheritance" at onset of rifting. The first model assumes an equilibrated crust and lithosphere without anomalously hot geothermal gradients at the end of the Variscan cycle, in line with the conclusions from the previous chapter and with the model of Duretz *et al.* (2019). The second model assumes either high geothermal gradients and ductile crust flow during rifting (Clerc and Lagabrielle, 2014) with the presence of salt playing an important role for controlling the high thermal gradient and ductile deformation in the crust (Lagabrielle *et al.*, 2020; Duretz *et al.*, 2019). An alternative model assumed that rifting started with an already thinned continental crust (Asti *et al.*, 2019). The latter hypothesis implies that the crust was thinned to 20 km already during Permian time. If that would have been the case, major accommodation space should have been created during Triassic and Jurassic time, except in the case of an anomalously high geothermal gradient that would have provided the necessary thermal support. Yet, on the one hand the stratigraphic record observed in the Biscay-Pyrenean domain does not display evidence for kilometre-thick Triassic or Early Jurassic depocenters; and on the other hand, massive thermal support would imply an anomalous high geothermal gradient that persisted from the Permian until the onset of major rifting in Late Jurassic time (*i.e.*, over more than 100 My). Although such a long-lasting high thermal anomaly could explain the high syn-rift thermal gradient proposed by Clerc *et al.* (2015), Lagabrielle *et al.* (2016) and Corre *et al.* (2016), it remains unclear what process(es) could prevent thermal equilibration over such a long time.

7.3 Assessing the role of rift inheritance during reactivation and collision

From a mapping point of view, there is a good correlation between rift domains and orogenic structures, as already suggested by Tugend *et al.* (2014). The results of the OROGEN project allow to distinguish between three situations: (1) reactivation of rift segment centres, (2) reactivation of rift segment boundaries, and (3) localization and subsequent stepping of shortening aside.

In all examples shown in Figure 6, reactivation initiates with soft collision in the exhumed or hyperextended domain along weak, low frictional serpentinized mantle and/or reactivation of rift inherited extensional detachments. This suggests that compositional weakening due to serpentinization may be a dominant factor controlling reactivation and may be even more important than thermal weakening for subduction initiation.

Shortening that follows mantle subduction can take different avenues. At segment centres (*e.g.*, Central section across the Basque-Cantabrian basin; Fig. 6) the collision shifted from soft to hard collision when the Coupling Point (CP) began to subduct. Here the CP refers to the location separating hyperextended, brittle, <10 km-thick crust from >10 km-thick crust that preserves inherited ductile crustal levels (*i.e.*, the necking zone and proximal domain). At that time, shortening was accommodated by ductile mid-crustal levels in the necking zone (thick-skin) and/or by low friction layers (salt or clay) at shallow levels (thin-skin). In such systems the CP corresponds to the tip of the buttress, which corresponds to the oceanward limit of the former necking zone, and becomes the S-Point (*sensu* Willett *et al.*, 1993) of the collisional system. The presence of salt can result in a complete decoupling between sub- and the supra salt levels and may create a large-scale and relatively well-preserved pop-up structure consisting of former syn- and post-rift sequences. Remnants of the former footwall may be accreted during the subduction of the former hyperextended and exhumed domains, in which case they occur in the internal parts of the orogen as shortcut tectonic slivers. However, most of the hyperextended and exhumed mantle domain is usually subducted/underthrust, so that the hyperextended crustal and exhumed mantle sections are not preserved in the central part of former rift segments.

At segment boundaries (*e.g.*, Eastern section across the Basque massifs area; Fig. 6), thrust faults that reactivate former detachment systems are forced to create shortcuts to make lateral linkage with adjacent segments. Therefore, many former rift structures escape reactivation and thus remain preserved in the orogenic wedge.

A third behaviour (*e.g.*, Western section across the Cantabrian margin; Fig. 6) shows a stop of convergence at the site of initial subduction followed by a reorganisation and localization of shortening within the proximal margin, resulting in out-of-sequence structures. This observation not only questions how shortening in the continent can compete energetically and mechanically with mantle subduction, but also what may control the stepping aside of shortening and why does the continent become the locus of shortening. A possible reason could be the onset of hard collision in the neighbouring segment to the east, which may have triggered a reorganisation of shortening.

Thus, a segmented rift template can have important consequences during shortening and may explain out-of-sequence reactivation and/or the spatial re-organisation of shortening. This shows that reactivation cannot be studied using 2D sections only. Where complex multi-stage, segmented rift systems exist, it is important to map rift domains in 3D and to analyse reactivation with a map view in mind. Indeed, rift segmentation can explain the along-strike non-cylindricity of the internal parts of the Pyrenean-Cantabrian belt. The complex structure of the internal parts contrasts with the rather continuous along strike extent of the fold-and-thrust belt in the more external parts that developed during the final stage of collision. Observations from the OROGEN project suggest that rift inheritance controls mainly the initial stages of reactivation, while later stages can be explained at a first order by Coulomb wedge theory (Willett *et al.*, 1993).

8 The role of pre-rift salt in formation and reactivation of hyperextended systems

8.1 Distribution of pre-rift salt in hyperextended systems

The behaviour of syn-rift salt during the formation of rifted margins has been widely investigated in the past (Rowan, 2014 and references in there). In the Biscay-Pyrenean domain Biteau *et al.* (2006), Canérot *et al.* (2005), Jammes *et al.* (2010), Ferrer *et al.* (2012), Issautier *et al.* (2020) and Lagabrielle *et al.* (2020) investigated the link between salt, rifting/hyperextension and the early stages of reactivation. The results of the OROGEN project shed new light on the importance of pre-rift salt during the evolution of the Biscay-Pyrenean rift system, and on its importance during subsequent compressional reactivation. Indeed, in contrast to many rift systems where salt is deposited during hyperextension (*e.g.*, Gulf of Mexico, S-Atlantic, Rowan, 2020), the main salt deposition is of Late Triassic age in the southern North Atlantic and in the Tethyan domain in Western Europe, and thus predated the main rifting event. One of the key questions relates to the presence of salt over exhumed crust and mantle: if salt was present prior to hyperextension, when and how was it emplaced over these exhumed surfaces that did not exist at the time of salt deposition (for a discussion of this problem see Jammes *et al.*, 2010; Rowan, 2014)? Answering to this question requires to understand the distribution of the Triassic mother salt (see discussion in Angrand *et al.*, 2020) and its redistribution (gravitational *versus* tectonic) during subsequent rifting and reactivation. The extent and thickness of Triassic salt appear to increase from west to east in the Biscay-Pyrenean system (Vargas *et al.*, 2009). Jammes *et al.* (2010) and Lagabrielle *et al.* (2020 and references therein) proposed that salt may have moved gravitationally during hyperextension. However, how much salt was present in the most extended and exhumed parts of the Biscay-Pyrenean hyperextended rift domain and what was its control during onset of convergence remains unclear.

8.2 Pre-rift salt in the northern Iberian hyperextended basins

Cadenas *et al.* (2020) show that evaporites and related salt tectonics occurred in Triassic basins while evidence for salt in the distal parts of the North Iberian margin are rare. Besides, the occurrence of mantle clasts in salt diapirs in the Mauléon Basin (Jammes *et al.*, 2010) and in the Basque-Cantabrian Basin (DeFelipe *et al.*, 2017) supports the idea that salt was present in the exhumed and hyperextended domains. This assumption is strengthened by recent studies for instance in the Chaînons Béarnais, where authors document not only the presence of salt onto the exhumed mantle (Asti *et al.*, 2019; Corre *et al.*, 2016), but also important metasomatism related to evaporite dissolution and remobilisation and mineralization in the Jurassic to Cretaceous sedimentary cover (Corre *et al.*, 2018).

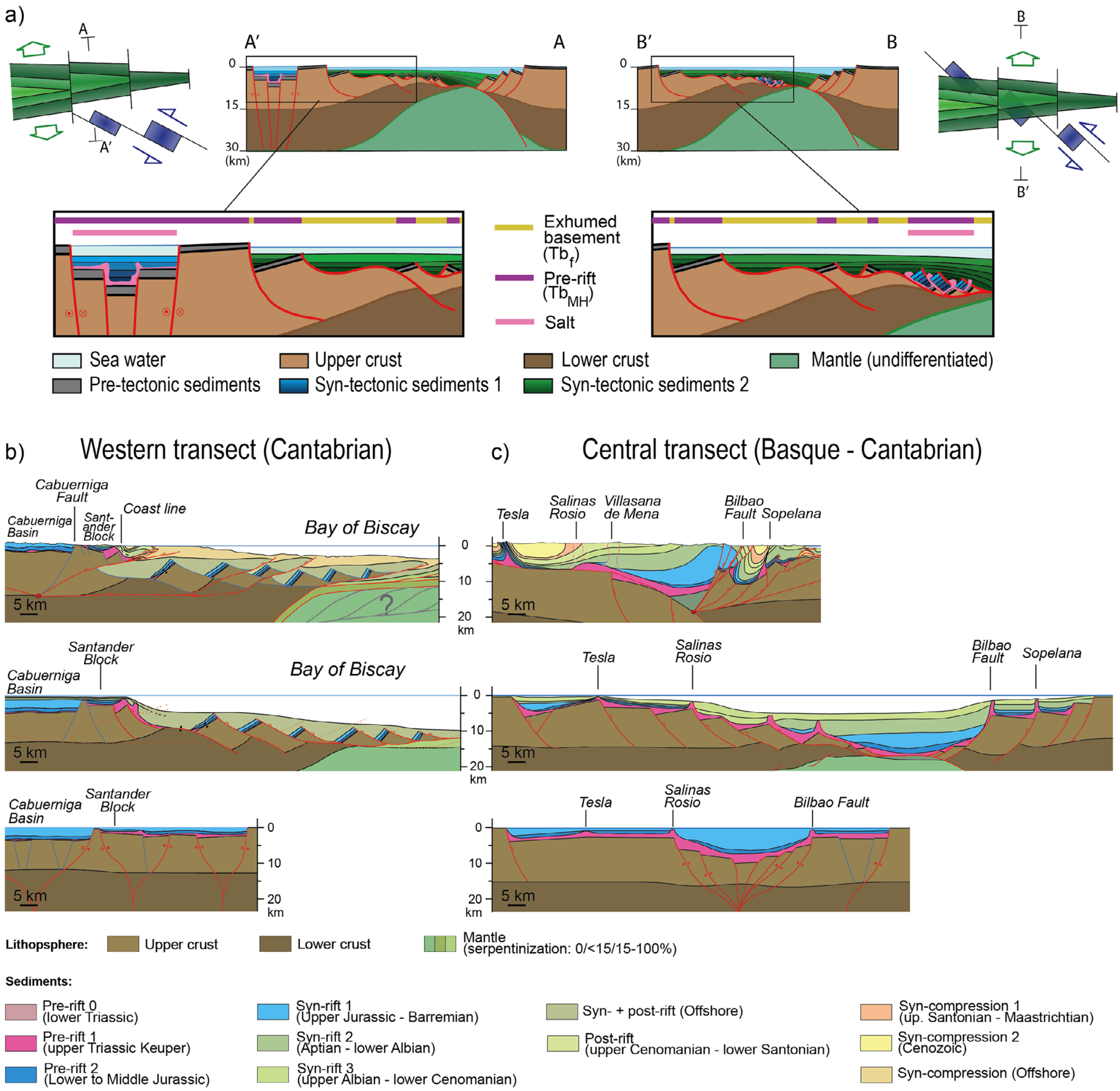

Fig. 7. (a) Schematic view of the two possible fates for Triassic (pre-hyperextension) salt in a multistage rift system: the top-left panel shows no interference/reactivation between salt bearing basins (blue) and subsequent hyperextended systems (green); the top-right panel shows full interference/overprint of salt bearing basins during later hyperextension (modified from Miró *et al.*, 2021). (b and c) Role of pre-rift salt during rifting and Alpine reactivation in the Asturias (b) and Basque-Cantabrian (c) transects (from Miró *et al.*, 2021); Note that these sections are zooms on the sections displayed in Figure 6.

In their section through the Basque-Cantabrian Basin, Miró *et al.* (2021) proposed that salt acted as a major decoupling level between the pre- and post-salt units (Fig. 7c). They suggested that salt was present in the hyperextended domain below the more than 12 km thick sedimentary infill, including thick pre-hyperextension Upper Jurassic-to Albian sediments. In contrast, in the Cantabrian section (Fig. 7b), salt does not occur in the distal hyperextended margin and only occurs in the more proximal basins and in the necking zone. Thus, while salt may occur in hyperextended domains east of the Santander system, it is not observed further to the west, suggesting that the distribution of salt may have changed along strike in the hyperextended domains. Two main processes may explain why salt does not exist along the distal western North Iberian margin and is more common in the Basque-Cantabrian basin: (1) the amount of extension, and therefore the amount of new real estate (*i.e.*, newly exhumed basement (Tb$_f$)), was significantly higher west of the Santander zone compared to the east (see Fig. 6b, c); and (2) a general decrease in salt westwards. However, these hypotheses do not explain the process by which salt can occur over hyperextended domains.

The presence of salt along the Biscay-Pyrenean system is often linked to the presence of thick Late Jurassic to Early Aptian depocenters (Fig. 7a). Cadenas *et al.* (2020) and Miró *et al.* (2021) showed that, while the Late Jurassic to Barremian Asturian and Cabuérniga basins were not the locus of hyperextension, the thick Late Jurassic to Barremian depocenters in the Basque Cantabrian Basin occur over hyperextended crust. Thus, two situations can be envisaged: (1) no interference/reactivation between salt-bearing basins and hyperextended systems (*e.g.*, Cantabrian section) (Fig. 7b); or (2) full interference/overprint of salt-bearing basins during later hyperextension (*e.g.*, Basque-Cantabrian example) (Fig. 7c). While in the first case the presence of salt over exhumed domains is unlikely, in the latter case pre-rift salt can occur as allochthons in the hyperextended and exhumed domains. A likely interpretation is therefore that Triassic salt was linked to allochthons of thick pre-rift sections from Triassic and Jurassic basins that were caught up during Aptian to Cenomanian hyperextension.

9 The thermal state of hyperextended rift basins in the Biscay-Pyrenean domain

9.1 Thermal structure of hyperextended and exhumed domains

Defining the thermal structure of hyperextended and exhumed mantle domains remains one of the most challenging endeavours in extensional tectonics since, in contrast to the structural or stratigraphic record, the thermal state is transient and equilibrates after rifting. Heat flow data is usually used to assess the thermal state of a (equilibrated) margin. However, these data do not allow to retrieve the thermal state during the (transient) rifting process. Moreover, there is only little public data where heat flow is calibrated by drill holes. Studies from young, not yet thermally equilibrated rifted margins such as the Gulf of Aden (Lucazeau *et al.*, 2010) show generally high heat flow values that are, however, highly variable across the ocean continent transition. Similar observations were reported from the Red Sea (Agulles *et al.*, 2020), the Gulf of California (Neumann *et al.*, 2017) and the South China Sea. For the latter example, Nirrengarten *et al.* (2020) showed based on IODP drill hole data that pre-rift sediments were heated to temperatures as high as 200°C during the early stages of continental/lithospheric breakup, which requires a high heat flow during rifting given the relatively small sedimentary burial of the margin. In contrast, post-rift sediments have lower thermal maturities, which is likely due to a combination of a lower geothermal gradient, limited burial, and absence of late post-rift magmatism.

Data from sediment-starved Mid Ocean Ridges at magma-poor slow spreading systems show that the thermal structure is mainly controlled by hydrothermal convection linked to active faults and magma emplacement (Kelley and Shank, 2010). Here again, the thermal state is heterogeneous and very local. Measured T_{max} values at fossil rift systems can be linked to hydrothermal activity or magma emplacement, and thus can be very local and do not necessarily document an equilibrated thermal state (Lescoutre *et al.*, 2019). Therefore, such data must be combined with thermochronological data that need to be sampled in a systematic way across a basin. Both techniques have been extensively used in the Pyrenean-Cantabrian system and the results have been reviewed by Clerc and Lagabrielle (2014), Clerc *et al.* (2015), Vacherat *et al.* (2016), Ducoux *et al.* (2019) and Saspiturry *et al.* (2020b). The main result is that a HT/LP event can be linked to the hyperextension and occurred between 110 and 90 Ma. However, T_{max} values are highly variable along the Pyrenean-Basque-Cantabrian system and can be >550 °C (Clerc *et al.*, 2018). Such high T_{max} values occur, however in sediments that often occur together with granulites and/or mantle rocks and are overlain by thick syn- and post-rift sedimentary successions. Evidence for hydrothermal fluids, and to a lesser extent for magmatic activity, correlate with the distribution of high T_{max} values that occur along the so called Internal Metamorphic Zone (IMZ) in the Northern Pyrenean zone, as well as the Nappe de Marbres in the Basque-Cantabrian Basin.

9.2 The hyperextended basins in the Pyrenean-Basque-Cantabrian domain: anomalously hot?

Clerc and Lagabrielle (2014) suggested the existence of an anomalously “hot” rift segment in the eastern Pyrenees, while the lower T_{max} values in the Western Pyrenees were interpreted as a “cold” rift segment. However, Ducoux *et al.* (2019) showed that T_{max} values in the Nappe de Marbres in the west are similar to those observed in the eastern Pyrenees, questioning the postulated decreasing thermal gradient from east to west. Lescoutre *et al.* (2019), Saspiturry *et al.* (2020b) and Ducoux *et al.* (2021b) show that very high temperatures and thermal gradients can also be retrieved from the Mauléon basin, suggesting a similar thermal evolution as in the other basins further to the east and to the west, clearly arguing against the initial “hot” and “cold” rifts model. Saspiturry *et al.* (2020b) published a comprehensive summary of the thermal data from the Mauléon basin, showing a change in the thermal gradient across the basin (Fig. 8). These authors suggested that the thermal structure equilibrated quickly (*i.e.*, the isotherms in the basin were subparallel; see Figure 13 in Saspiturry *et al.*, 2021), which contrasts with the interpretation from Vacherat *et al.* (2014) who assumed that equilibration was slow and lasted until about 50 Ma. Lescoutre *et al.* (2019) proposed an alternative model that was able to predict the asymmetric thermal gradients published by Saspiturry *et al.* (2020b) and Ducoux *et al.* (2021b). In their model shown in Figure 8, the thermal state is mainly controlled by the final rise of the asthenosphere during the asymmetric hyperextension and mantle exhumation phases, resulting in a local, asymmetric thermal anomaly instead of the more regional, basin-wide thermal anomaly suggested by Saspiturry *et al.* (2020b). Thus, from the available interpretations three questions arise: (1) was the thermal event basin-wide or was it localized? (2) was it anomalous relative to other rifted margins? and (3) did the thermal state control the crustal rheology during rifting? A last question, not further discussed in this paper concerns the contradictory record of the post-rift thermal relaxation, which seems to be mid-Cenomanian from a sedimentary point of

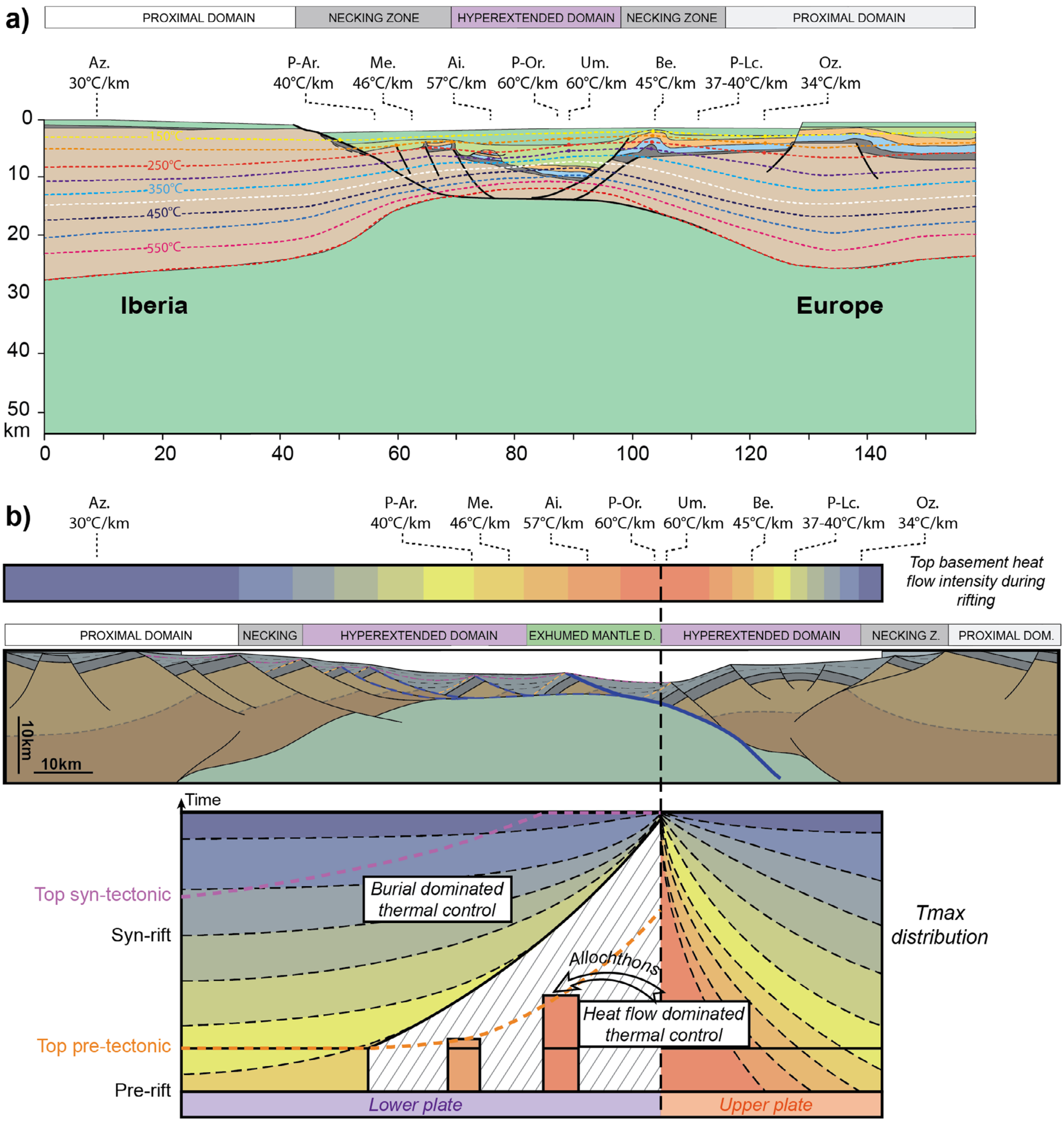

Fig. 8. Comparison of two published thermal models for the Mauléon basin: (a) the model from Saspiturry *et al.* (2020b) and (b) the model from Lescoutre *et al.* (2019). The thermal gradients at the top of the two models are from Saspiturry *et al.* (2020b) (see text for details and discussion).

view (Issautier *et al.*, 2020; Saspiturry *et al.*, 2019; Razin, 1989), and Late Cretaceous to Eocene from a thermal point of view (Saspiturry *et al.*, 2020b; Vacherat *et al.*, 2014).

The thermochronological data presented by Masini *et al.* (2014), Hart *et al.* (2016, 2017) and Odlum and Stockli (2020) showed that basement rocks derived from the hyperextended domains were not reset during rifting, suggesting that the high geothermal gradient proposed by Lagabrielle *et al.* (2016) and Corre *et al.* (2016) was late and/or local, or that these authors overestimated the thermal gradient (see Figure 11 in Lescoutre *et al.*, 2019 for an explanation). Vacherat *et al.* (2014) showed a late thermal equilibration for the most distal parts of the margin, suggesting that the thermal structure did not begin to equilibrate before 50 Ma and that the hottest geothermal gradient was localized in the hyperextended basins. Further support of a localized thermal event is the very local occurrence of the HT/LP values. However, it remains unclear whether they originate from the upper-lower plate transition as proposed by Lescoutre *et al.* (2019) or equilibrated and affected the whole basin as suggested by Saspiturry *et al.* (2020b) (Fig. 8).

Determining whether the measured T_{max} in the Pyrenean-Cantabrian domain points to an anomalously hot geothermal gradient during rifting and exhumation, or whether it can be considered as normal and comparable to that of young rifted margins is more difficult. There are two points that need to be recalled: 1) it is difficult to compare T_{max} data from the Pyrenees-Cantabrian domain with those from present-day rifted margins since few pre-rift sequences have been drilled in distal margins, and 2) T_{max} values are not allowing to determine the heat flow history of a margin, unless it can be assumed either that the margin was constantly thermally equilibrated, or that the thermal evolution was simple and controlled by depth-uniform lithospheric thinning. However, if T_{max} values are local or linked to a complex thermal evolution, including hydrothermal systems, magma and very high sedimentation rates, the values do not need to be linked to anomalous heat flow.

To evaluate whether the Pyrenean-Cantabrian domain had an anomalously hot geothermal gradient, the best places to compare with are the fossil remnants of the Alpine Tethys preserved in the Central Alps and that escaped an orogenic thermal overprint, like the Pyrenean counterparts. In the hyperextended and exhumed domains exposed in the Alps, one cannot find similar T_{max} values like those reported from the Pyrenees Incerpi *et al.* (2020b). There is, however, a fundamental difference between the distal margins in the Alps and the hyperextended basins in the Pyrenean-Cantabrian domain: while the former was sediment-starved, the latter show kilometre-thick syn-rift sequences. To explain values of 300 °C at a depth of 1 km in the absence of important sedimentary burial, the thermal gradient should be 300 °C/km, which is only possible if the heat flow is locally controlled by hydrothermal systems (see also Figure 6 in Lescoutre *et al.*, 2019). Incerpi *et al.* (2020a, 2020b) analysed the diagenesis of pre- and syn-rift sediments from both the Central Alps and the Pyrenees using fluid inclusions, isotopes and U/Pb dating of pre-hyperextension carbonates from both the distal Tethys margins exposed in the Alps and the Mauléon basin. Their results show that the fluid history as well as the related temperatures were very similar between both sites, suggesting that both sites had similar high heat flow during hyperextension and mantle exhumation. Thus, the high T_{max} values from the Pyrenean-Cantabrian domain are certainly linked to a high heat flow during hyperextension, which is to be expected in (sediment-rich) hyperextended domains and predicted by numerical modelling (*e.g.*, Lavier *et al.*, 2019; Lescoutre *et al.*, 2019; Duretz *et al.*, 2019). Thus, while the heat flow may have been similar to that of other hyperextended and exhumed mantle domains, the high T_{max} values may have been anomalous in the Biscay-Pyrenean domain. If the basal heat flow would have been anomalous, one would have expected substantial production of tholeiitic magma, which is not observed. In contrast, the high T_{max} values may best be explained by the combination of high heat flow, high sedimentation rates in combination with hydrothermal activity during hyperextension and mantle exhumation.

To answer the question if we can use the T_{max} and a paleo-geothermal gradient from the distal part of the rift basin to assess the rheology of the crust during rifting, it is important to analyse the syn-kinematic minerals and textures linked to the fault rocks accommodating extension and exhumation. In the Mauléon basin, Corre *et al.* (2016) and Saspiturry *et al.* (2021) suggested that the hyperextended domain deformed in a dominantly ductile regime. Incerpi *et al.* (2020a) described calcite mylonites of syn-rift age suggesting that deformation may have been accommodated by ductile processes in carbonate-rich lithologies. Jammes *et al.* (2009) and Masini *et al.* (2014) described cataclasites and gouges along the Northern and Southern Mauléon Detachment faults in the Mauléon basin. These fault rocks indicate that final crustal and mantle exhumation occurred in the brittle field. This is also supported by the thermochronological data of Hart *et al.* (2016, 2017), which supports that hyperextension occurred at temperatures below 300 °C within the hyperextended crust, consistent with the occurrence of serpentinites and ophicalcites and linked isotope data (Clerc, 2012; DeFelipe *et al.*, 2017). Thus, whether rifting and hyperextension occurred in the brittle or ductile regime remains at present debated. However, it is important to mention that hyperextension has been defined as the domain where the crust is in the brittle regime (Sutra *et al.*, 2013). Moreover, numerical models show that exhumation of subcontinental mantle is difficult in the presence of ductile material since it prevents faults to penetrate into the mantle and exhume it (Manatschal *et al.*, 2015). Moreover, ductile crustal rheologies and high thermal gradients tend to result in wide rift styles (Buck, 1991; Brune *et al.*, 2017), which is not observed in the Biscay-former Pyrenean system. One may also note that the rift structures preserved offshore along the northern Iberia and the conjugate Armorican margins do not show any sign of either anomalous hot or ductile crust (Montadert *et al.*, 1979; Thinon *et al.*, 2003).

10 The granulite conundrum

Among the most heavily debated topics in the OROGEN project was, and still is, the lithological architecture and thickness of the crust and lithosphere prior to rifting. The reason is that it has a major impact on the interpretation of the subsequent rifting thermal and isostatic evolution and impacts the kinematics of detachment faults. A key issue in these debates, is the crustal position of the granulites prior to rifting. Since different interpretations have been proposed, all of which have major implications on the rift evolution, we refer to this problematic as the "granulite conundrum", a topic that is in the heart of the discussion about inheritance (see also Cadenas *et al.*, 2021).

Granulites occur throughout the Biscay-Pyrenean domain. They are often linked with exhumed mantle rocks and high T/low P pre-rift sediments. Granulites can be found either as outcrops flooring thick Apto-Cenomanian syn-rift sediments, or as clasts in breccias within these sediments. There is a consensus that the granulites formed during the Carboniferous at a late stage of the Variscan orogeny (Vielzeuf and Pin, 1989), although the exact conditions and geodynamic setting of their formation remains unclear. Indeed, the crustal depth at which

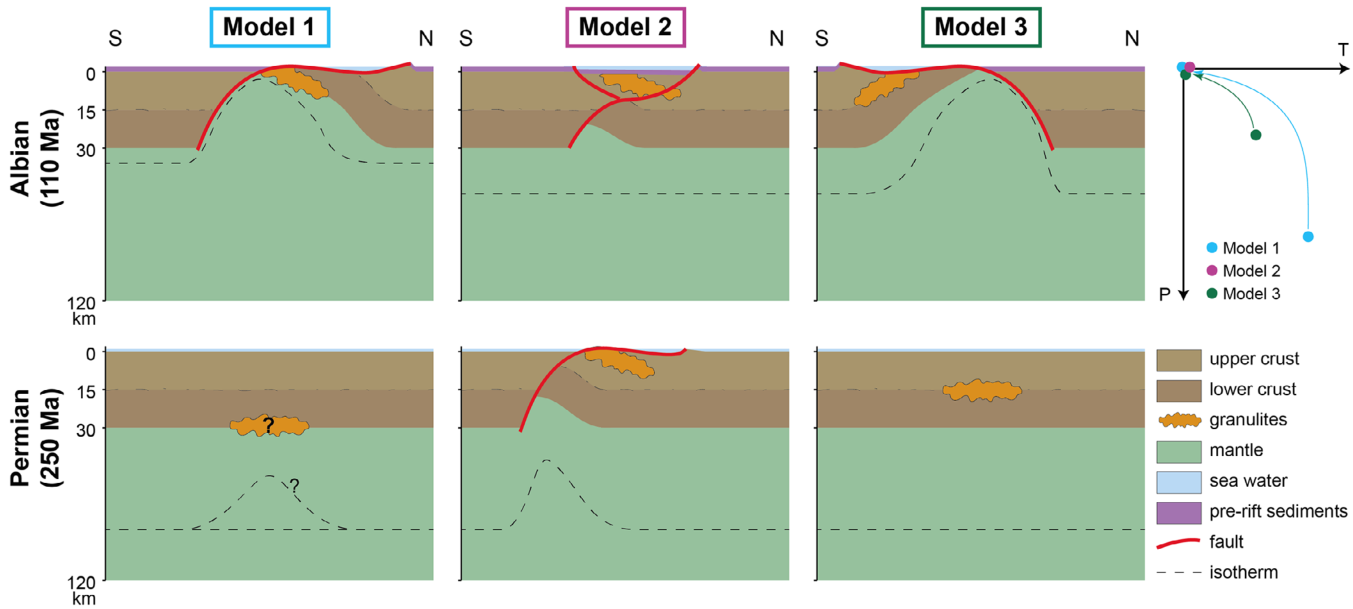

Fig. 9. Three competing models to explain the "granulite conundrum" in the Biscay-Pyrenean domain. See text for a more detailed description of the models and their implications.

the granulites were before the onset of rifting and how and when they were exhumed to the seafloor remain debated. Three different models have been proposed (Fig. 9):

- Clerc and Lagabrielle (2014) proposed a scenario (model 1 in Fig. 9) where (re)granulitisation and exhumation occurred during the Cretaceous rifting. This model was based on structural observations in the Agly massif and implies very high thermal gradients during rifting and a fast exhumation within a dominantly ductile crust.
- Saspiturry *et al.* (2019) suggested (model 2 in Fig. 9) based on observations from the Basque massifs that the granulites were exhumed to shallow levels already during the Permian via the formation of a core complex. This model was based on field observations and structural observations (see Fig. 4 (Sect. 6) and Figure 5s in Saspiturry *et al.*, 2019). In this model, the granulites can be considered as belonging to the pre-rift upper crust and do not carry any information about rifting and the related geothermal gradient.
- Jammes *et al.* (2009), Masini *et al.* (2014) and Hart *et al.* (2017) proposed (model 3 in Fig. 9) that the granulites were in the upper middle crust (at about 10–15 km assuming an equilibrated thermal gradient of 30 °C.km^{-1}) before rifting and were exhumed to the seafloor during the Cretaceous rifting via extensional detachment faults. This was based on Ar/Ar ages on biotite and other thermochronological data (Masini *et al.*, 2014; Hart *et al.*, 2017).

Models 1 and 3 imply that granulites had to be exhumed in the footwall of a rift-related exhumation fault and that their top basement corresponds to an exhumation fault (*e.g.*, Tb_f; see discussion in Sect. 6.1; Eq. (4)). The difference between models 1 and 3 is that in model 1 exhumation occurs in the ductile field, while in model 3 the granulites were already in the brittle field at the onset of rifting, as in model 2. The main difference between models 2 and 3 is that in model 2 the granulites need to be in the hanging wall of an older detachment fault thinning the crust since they were already exposed. In contrast, in model 3 they are in the footwall of a detachment fault. Although the three models are mutually exclusive for a given site, further research will be necessary to determine whether all granulites have the same origin and exhumation history at the scale of the entire Biscay-Pyrenean domain (see also Cadenas *et al.*, 2021).

Some inconsistencies appear when comparing new thermochronological data with the three models. For instance, the results of Odlum and Stockli (2020) do not support the (re) granulitisation during Cretaceous rifting in the Agly massif. The assumption that the granulites were already exhumed near the surface in a core complex-type structure in Permian time is neither supported by clasts of granulites reworked in the Triassic sandstones, nor by the thermochronological data of Hart *et al.* (2016, 2017) and Masini *et al.* (2014).

It is also interesting to compare models 2 and 3 (see Fig. 9) and to explore their implications. Both are based on observations made at the western Mauléon Basin. Model 3 assumes that the granulites were exhumed during rifting and need therefore to be in the footwall of a major north dipping extensional detachment (*e.g.*, Tb_f), which is compatible with the kinematic data determined on fault rocks from an exposed detachment fault in the Mauléon basin (Masini *et al.*, 2014). In contrast, model 2 places the granulites in the pre-rift upper crust (*e.g.*, $Tb_{MH\_initial}$), *i.e.*, in the hanging-wall of a more symmetric basin with the main detachment dipping towards the south. This explains why the two different interpretations of the pre-rift position of the granulites results in different rift models for the hyperextended Mauléon Basin.

Cadenas *et al.* (2021) compared the extensional structures and the tectono-stratigraphic architecture of related syn-rift sediments exposed in the Labourd massif (Basque Massifs)

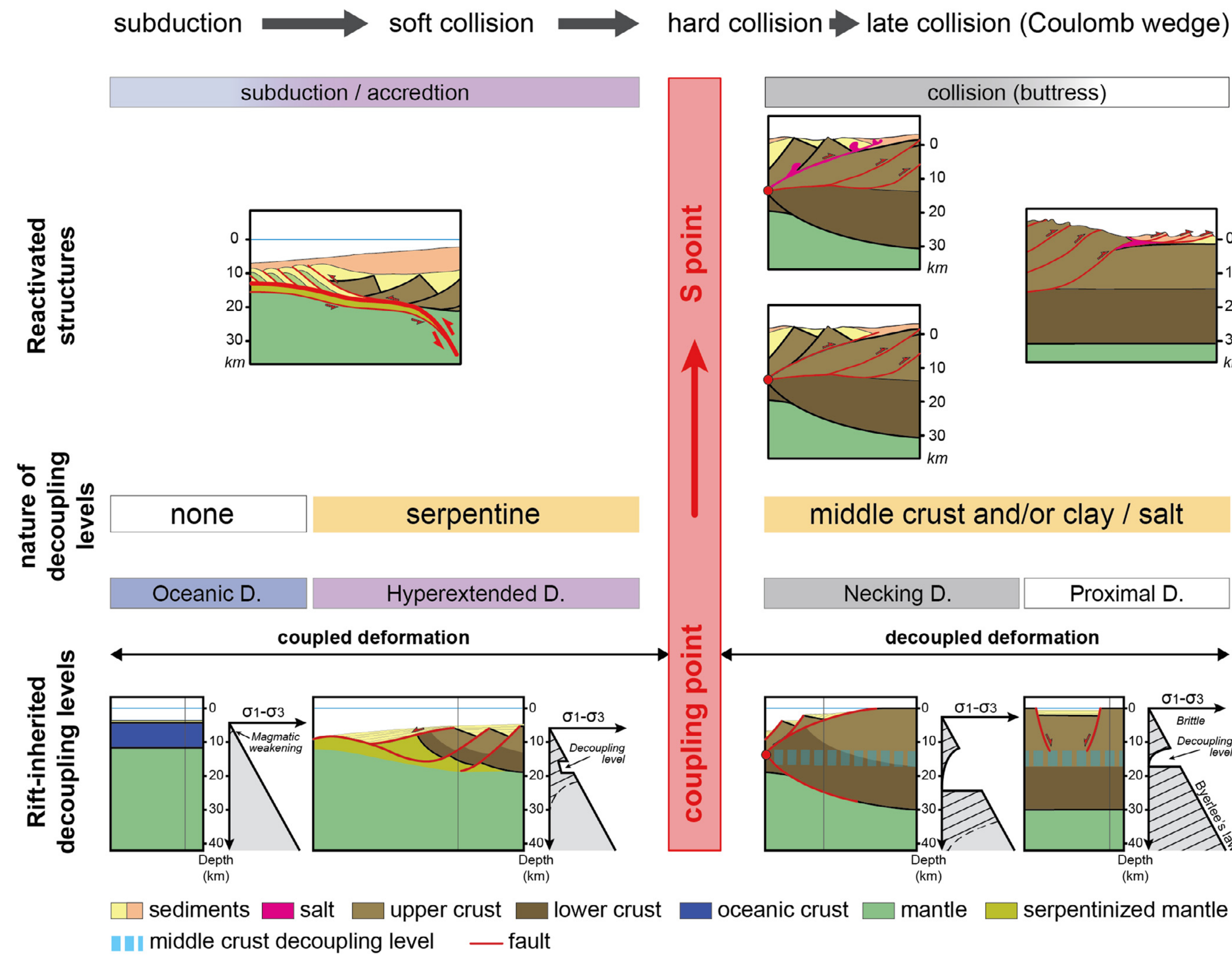

Fig. 10. Conceptual model illustrating the in-sequence reactivation of rift-inherited decoupling levels at a segment centre and explaining the transition from subduction to soft collision, to hard collision, and to final late collision (for details and discussion see text). Modified from Lescoutre and Manatschal (2020) and Miró *et al.* (2021).

with those seismically imaged and dredged offshore at the Le Danois High (central North Iberian margin). The offshore-onshore comparison shows striking similarities and is in line with an exhumation of the granulites at the Le Danois High in a brittle regime, along the footwall of a seismically imaged extensional detachment system. The authors suggest that exhumation of granulites occurred during Aptian to Cenomanian time along a north-dipping extensional detachment systems covered by syn-rift breccias at both the Biscay and the Pyrenean rift systems. Finding a definitive answer to the granulite conundrum will provide further constraints to discriminate between the two rift models and will also provide further constraints on the thermal structure of the hyperextended basins in the Biscay-Pyrenean domain.

11 Reactivation of hyperextended segmented basins: a new emerging concept

One of the main results in studying magma-poor rifted margins and hyperextended rift basins is the recognition, characterization and mapping of rift domains referred to as proximal, necking, hyperextended, exhumed and oceanic domains (Sutra *et al.*, 2013; Tugend *et al.*, 2014). Each of these domains is characterized by its crustal nature, characteristic structures, total accommodation space and rheological profile (see Fig. 10; Lescoutre and Manatschal, 2020). Tugend *et al.* (2014) and Chenin *et al.* (2017) suggested a direct link between rift and orogenic domains, an assumption that is further supported by the results of the OROGEN project.

The systematic study of the central North Iberian margin, the Basque-Cantabrian Basin and the western Mauléon Basin documented in Cadenas *et al.* (2020), Lescoutre and Manatschal (2020), Miró *et al.* (2021), and Gómez-Romeu *et al.* (2019) (Fig. 6) has enabled to describe the role of rift inheritance during reactivation of these segmented hyper-extended rift systems. Convergence at the North Iberian margin initiated in the exhumed mantle domain using a decoupling level in the serpentinized mantle. In the more reactivated domains (Basque-Cantabrian and Mauléon Basins), it is difficult to document the initial stage of convergence, in particular at segment centres. Rocks derived from the exhumed mantle and hyperextended domains, including exhumed mantle, granulites and pre-rift sediments with a HT/LP overprint, are only locally preserved in syn-rift sedimentary breccias. The occurrence of these breccias is a fingerprint that enables to argue for the presence of these domains in the former rift section. Following the inception of reactivation, shortening can take three different avenues: (1) shortening continues but the decoupling level changes (*e.g.*, central section in the Basque-Cantabrian basin; Fig. 6); (2) shortening creates new structures preserving former rift structures (*e.g.*, eastern section across the Mauléon-Basque massifs; Fig. 6) or (3) shortening jumps to a new location (*e.g.*, Cantabrian section; Fig. 6). While the last example is complex and needs further studies, the first two examples may be representative for the reactivation of segment centres and boundaries, respectively. In the next two sections we propose a conceptual model to explain the sequential reactivation of segmented rift domains that is based on the studies of Tugend *et al.* (2014), Lescoutre and Manatschal (2020) and Miró *et al.* (2021).

11.1 Rift-inherited decoupling levels and their sequential reactivation: a conceptual model

In an idealized schematic section though a magma-poor rifted margin, each rift domain is defined by a crust with a different shape, thickness, composition, and rheology (Fig. 10). The oceanic domain is made of idealized Penrose magmatic crust coupled to the underlying mantle. It terminates continent ward at the breakup point (BP), which marks the transition to the domain of exhumed mantle and hyperextended crust. The exhumed mantle-hyperextended crust domain is characterized by hydration processes that become dominant within the uppermost 3 km below seafloor and result in massive serpentinization. The effect of serpentinization results in an efficient decoupling level that is easy to reactivate. Depth and rheological characteristics of serpentinized mantle are described in Gillard *et al.* (2019). The exhumed mantle domain is characterized by a rugose top basement with basement highs and local magmatic additions, and the hyperextended domain by the occurrence of a wedge of hydrated continental crust (Nirrengarten *et al.*, 2016). The continent-ward limit of the hyperextended crust corresponds to the oceanward limit of the necking zone. It is defined to occur where the crust is ca. 10 km thick and is named the Coupling Point (CP) (Sutra *et al.*, 2013) (Fig. 10). The CP plays a key role during reactivation, since it juxtaposes crusts with different properties: On the oceanward side the crust is thin, hydrated, and brittle and it overlies serpentinized mantle. On its continent-ward side crust is thicker, includes residual ductile levels in quartz-rich layers, and is coupled to the underlying, non-serpentinized mantle. The CP marks also the limit across which potential decoupling levels are changing. While on its oceanward side serpentinized mantle or inherited low-angle extensional detachment faults can be reactivated, these decoupling levels do not exist on its continent-ward side. There, decoupling can occur either in ductile crustal levels or within the salt or clay-rich levels on top of the crust. Last but not least, the CP also juxtaposes thin crust that can be subducted against thicker, more buoyant crust.

The results of the OROGEN project support the idea that subduction initiates in the exhumed mantle domain (see also Dielforder *et al.*, 2019). Data shows that the exhumed mantle and hyperextended domains can be subducted during initial soft collision, which explains their absence (except for small blocks) in the reactivated segment centres. Since the necking domain is made of >10 km thick crust, too buoyant to be subducted, the major change in collision occurs when the CP starts to be involved in collision. This event marks the transition from soft to hard collision. In both the Basque-Cantabrian and Mauléon basins, hard collision is controlled by the necking zone that acts first as a buttress. Subsequent shortening either reactivates ductile levels within the residual continental crust, resulting in a thick-skinned reactivation, or reactivates continuous low friction levels in the sedimentary section (*e.g.*, salt), resulting in a thin-skinned reactivation. Thick-skinned reactivation results in the stacking of crustal nappes that induces crustal thickening, creation of orogenic topography, erosion and exhumation. In contrast, thin-skinned deformation results in a nappe stack that consists of supra-salt units only (Jourdon *et al.*, 2020). Combinations of thick- and thin-skinned reactivation can also be observed. Thus, the presence or absence of salt is key in controlling the reactivation during hard collision (Miró *et al.*, 2021). In the presence of salt, a complete decoupling between the supra-salt and sub-salt sequence occurs, resulting in allochthonous convergence (*e.g.*, section across the Basque-Cantabrian basin). During final collision, shortening is accommodated along thrust systems that are ramping up towards the foreland, often reactivating former exhumation faults. The occurrence of rift basins in the stretching domain can result in local complexities during final convergence, but on a first-order, final collision can be described with the Coulomb Wedge theory, indicating that rift inheritance plays at this stage a subordinate role. Collision stops and/or reorganizes either when the forces available to accommodate shortening are inferior to the bulk yield strength of the deforming lithosphere, or when the differential gravitational potential energy between the orogen and the adjacent foreland becomes too high. Both situations occur when the proximal domain starts to be involved into the collisional process. The sequential reactivation of rift domains, as discussed in this section and shown in Figure 10, can be found in segment centres (*e.g.*, section through the central Basque-Cantabrian; Fig. 6).

11.2 Reactivation of overstepping en-échelon segment boundaries

A more complex reactivation of rift domains is observed at the Pyrenean-Cantabrian junction. This domain has been re-interpreted by Lescoutre *et al.* (2021) as an en-échelon array formed by the overstepping terminations of the Basque-Cantabrian and Mauléon Basins. As shown by Lescoutre and Manatschal (2020), decoupling levels used in segment centres (see previous section) are forced to produce shortcuts at segment boundaries in order to link up with the main decoupling levels in the adjacent segment center (Fig. 11). Such shortcut structures at segment boundaries result in a change of the exhumed and hyperextended rocks from a footwall position to a hanging wall position in the main thrusts

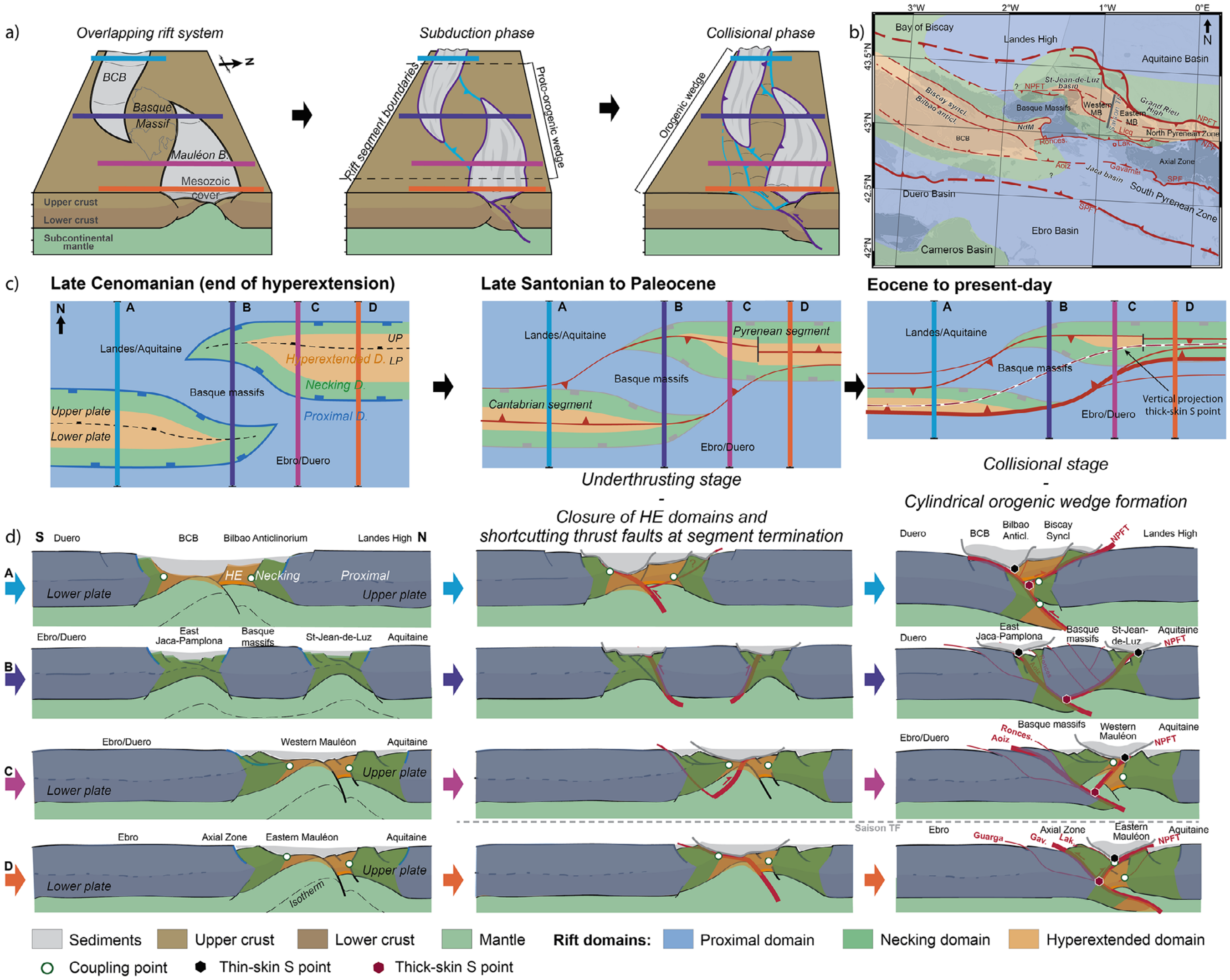

Fig. 11. Reactivation of overlapping en-echelon rift segments based on the example of the Pyrenean-Cantabrian junction showing the importance of shortcutting structures and their role in preserving rift structures (modified from Lescoutre and Manatschal, 2020). (a) Schematic 3D evolution of the Pyrenean-Cantabrian junction highlighting the structural evolution during the subduction (Late Santonian-Paleocene) and collisional (Eocene-Miocene) phases. (b) Rift domains map of the Pyrenean-Cantabrian junction. (c) Schematic kinematic restoration of the rift domains map (panel b) at Late Cenomanian (end of hyperextension), Late Santonian to Paleocene (early convergence), and Eocene to present-day (late and post convergence) stages. The locations of the cross-sections shown in panel d are represented. (d) Cross sections across the Pyrenean-Cantabrian junction (see panel c for location) showing the evolution for the Late Cenomanian (end of hyperextension), the Late Santonian to Paleocene stage (early convergence), and the Eocene to present-day (late- and post-convergence) stages. Abbreviations used in the Figures: BCB: Basque-Cantabrian Basin; MB: Mauléon Basin; SPF: South Pyrenean Fault; NdM: Nappe des Marbres; Lak: Lakoura thrust; Gav: Gavarnie thrust; Ronces: Roncesvalles thrust; NPFT: North Pyrenean Frontal Thrust; NPF: Northern Pyrenean Fault.

accommodating shortening. This explains the preservation of inherited rift structures, including detachment surfaces, exhumed crustal and mantle rocks in the nappe stack. Thus, in contrast to segment centres where rift-related detachment faults are reactivated and most of the exhumed mantle and hyperextended crust are subducted, rift structures and exhumed material are preserved during reactivation of segment boundaries. This is well documented in the Labourd massif, where rift-related detachment faults and the related crustal section are preserved (Masini *et al.*, 2014; Lescoutre *et al.*, 2019).

It is interesting to note that the preservation of the rift structures coincides with the occurrence of a high density/velocity mantle body imaged by potential field and tomographic methods (Jammes *et al.*, 2010; Martin *et al.*, 2020; Wang *et al.*, 2016). A likely interpretation is that this body corresponds to mantle rocks exhumed at or near the seafloor during hyperextension (see also results of the Maupasacq experiment; Lehujeur *et al.*, 2021). The preservation of such a high velocity body within a shallow crustal level in the orogen linked to a segment boundary is compatible with the model shown in Lescoutre and Manatschal (2020) (see also Fig. 11).

High density bodies imaged by positive gravity anomalies occur at several other places along the Biscay-Pyrenean system (*e.g.*, Parentis, Basque-Cantabrian Basin, and Saint Gaudens; Martin *et al.*, 2020) but further studies will be necessary to determine whether their presence is linked to the reactivation of rift segment boundaries.

Other observations that may help to define rift-inherited segment boundaries have been discussed in Lescoutre *et al.* (2021) and are shown in Figure 11. A striking observation at the Pyrenean-Cantabrian junction is the along-strike change of structures in the internal part of the orogenic section. While at segment centres the orogen is defined by the pull-up of the sediment infill from the former hyperextended basin (for details see previous section), at segment boundaries it is dominated by basement forming a keystone. This keystone contains preserved rift structures, and upper crustal- and locally also exhumed lower crustal rocks, both of which are bounded by symmetric retro- and pro-thrust faults. The along-strike transition between rift segment center and boundary is marked by thrusts that reactivate former extensional detachment faults. These thrusts carry sediments in their hanging wall (*e.g.*, Lakoura thrust and Licq fault) and place younger rocks on older rocks. In contrast, thrusts in the keystone such as the Roncesvalles fault (see Figure 1 in Lescoutre *et al.*, 2021) show the classical old over young relationship. Therefore, mapping and correlating thrust structures from one rift segment towards the adjacent segment is challenging. It may explain why the Pyrenean-Cantabrian junction remains one of the most debated parts in the Pyrenean system. Similar situations as that described from the Pyrenean-Cantabrian junction, may occur elsewhere in the Biscay-Pyrenean system as discussed in Cadenas *et al.* (2021).

12 The lessons learned from the OROGEN project

12.1 What's new and what remains debated?

The OROGEN project provided access to new field and seismic reflection data, better and higher resolution tomographic imaging, and new thermochronological and thermal data that enabled to propose, test and calibrate new interpretations for the tectonic evolution of the peri-Iberian system. Here we focus on the role of inheritance within the incomplete Wilson cycle recorded by the geology of the Biscay-Pyrenean system. Although at this stage the results do not allow us to unravel in detail how inheritance controlled the evolution of this system, some new ideas and concepts emerged from the OROGEN project. This includes a new definition of inheritance that includes "interface shape inheritance" and its application to the Biscay-Pyrenean system (Sect. 7). Other new results include the kinematic restoration of sections back to the pre-rift stage conserving crustal area and pre-rift marker horizons length (Sect. 6). Moreover, the in-sequence reactivation of rift inherited decoupling levels, and the antagonistic behaviour of rift segment centres and boundaries during reactivation enable to propose a refinement of previously published concepts explaining the reactivation of segmented rifted margins (Sect. 11). On a larger scale, the new interpretations of the kinematic evolution of the Europe-Iberia plate boundary across the Biscay-Pyrenean system suggest a multistage rift system. This conclusion has far-reaching implications not only for the local and regional interpretations, but also for the understanding of the Alpine and Mediterranean domains that are kinematically linked with the Atlantic system through the Iberian plate.

Although the concepts of hyperextension and mantle exhumation have been well established at present-day magma-poor rifted margins and the fossil Alpine Tethys margins, these classical models have been challenged within the OROGEN project. At present, mutually exclusive models exist to explain the hyperextended systems of the Pyrenean-Cantabrian domain (Sect. 6.2). The competing models differ in the polarity of faults, the amount of asymmetry and the style of deformation, implying different thermal and rheological evolutions that have first-order implications on the role of inheritance (Sect. 9.2). While one group of models suggests high geothermal gradients during rifting and a thermally equilibrated stage at the end of rifting, the other group of models suggests high geothermal gradients at the end of rifting (and as a result of rifting), as well as a thermal state that is asymmetric and not equilibrated at the end of rifting. At this stage it is too early to reject one of the models, especially because the existence of competing models generates debates that are necessary for prolific research. A way to test and sort between the two groups of models is to solve the granulite conundrum, *i.e.*, to understand the position and exhumation history of the granulites before and/or during rifting (Sect. 10).

12.2 Assessing the role of inheritance: what are the problems?

The Biscay-Pyrenean system is one of the few sites worldwide that allows to address the importance of inheritance at different stages within an incomplete Wilson Cycle. Advantages of this system include excellent datasets, the long history of investigation on the stacking of three main tectonic events, namely a Variscan orogenic system that has been overprinted by a multistage Mesozoic rifting, which was in turn reactivated in its easternmost parts, leading to the development of the Pyrenees. That only few Variscan structures have been used or reactivated by Mesozoic rift structures in the Pyrenean domain suggests that the former orogenic inheritance did not systematically control later rifting, contrary to common belief. While prominent first-order structures such as the Pamplona or Leiza faults have been regarded as inherited and/or reactivating Variscan and/or Permian structures in the past, new studies question the existence of the Pamplona fault and reinterpret the Leiza fault as a second-order structure (Lescoutre *et al.*, 2021). Thus, assessing the role of inheritance is complicated and cannot only rely on comparing strike directions or on geological intuition.

Another learning from the OROGEN project is that it is not only important to determine the initial conditions, *i.e.*, the genetic code of a tectonic system, but also to understand how it interacts and evolves during subsequent events. Understanding why some structures have not been reactivated is as important as understanding why other structures have been used during subsequent events. It is important to realize that structural, compositional, and thermal inheritance does not always control subsequent events, as demonstrated by the few reactivated Variscan structures in the Biscay-Pyrenean domain. Thus, defining the role of inheritance is not only about defining and mapping inheritance, but requires also determining what type of inheritance controls what, how, when, where and at what scale.

While some of the rift- or orogenic system complexities can be elegantly explained by integrating inheritance, the danger is that inheritance is used as a “deus ex machina” to explain whatever cannot be understood with classical models. Thus, the use of inheritance must be based on a foundation that is coherent with what we know of a geological system. The aim is not to find solutions by replacing unknown by inheritance. Conversely, we need to be even more aware of potential inconsistencies, incoherencies and shortcuts that may be based on the misapplication of some concepts.

12.3 Implementation of “inheritance” in conceptual, analogue, and numerical models

Numerical and analogue models commonly try to explore the physical processes of systems by defining boundary conditions and investigating the parameter space. Each model relies on initial conditions that are fundamental but difficult to define in geological systems. In most models, the initial conditions are simple layer-cakes with either one or several inherited features (*e.g.*, weak seeds). Thus, models also include “inheritance” and their initial conditions are actually not so different from those we assume for the Biscay-Pyrenean system at the onset or rifting. Thus, so-called “accordion” models presented by Jammes *et al.* (2014) may be a good way to model incomplete Wilson Cycles, since they develop more appropriate initial conditions for the orogenic reactivation, including thinned crust and lithosphere prior to convergence (*i.e.*, “interface shape inheritance”). They may also account for the main decoupling horizons such as hydrated levels, remnant ductile levels or salt (*e.g.*, Jourdon *et al.*, 2019, 2020). This may explain why 2D numerical models are able to reproduce first-order structures observed at rifted margins and orogenic systems (*e.g.*, keystone in extensional systems and orogenic prism in collisional orogens), as well as the in-sequence reactivation observed at segment centers of hyperextended basins. If one compares models using slightly different initial conditions but the same boundary conditions and physical parameters, the major differences arise at the initial stage while the final results are comparable. Thus, it appears that at a mature stage a tectonic system depends little on the initial conditions, but more on the applied boundary conditions and physical parameters. This suggests that, after an initial stage of self-organization, a tectonic system evolves into a “steady-state system”. Thus, when modelling tectonic systems, a choice may have to be made: (1) either a model tries to include acceptable initial conditions in order to test the initial stages of a system, or (2) models can only be interpreted for structures that are established at the moment when the initial conditions are not controlling anymore the model results.

Another important point when designing models is to define the controlling initial perturbance. Is it thermal, structural or compositional or a combination of the three? A viable way to test the role of inheritance may be to compare models with different initial heterogeneities (seeds) and to compare their initial evolution and to test at what stage they converge and start to resemble. This would allow to define the transition from a situation where the experiment is controlled by the initial conditions/inheritance to a stage when it is controlled by the boundary conditions and applied physical parameters. From our observations, such a stage could correspond when the Coupling Point (CP) get involved in convergence, *i.e.*, the transition from soft- to hard collision. More generally, a key question is at what stages of a Wilson Cycle what type of inheritance is the most important. The observations made in the OROGEN project suggest that the main rift inheritance controlling the reactivation of a margin relates to the distribution of decoupling levels. Reactivation initiates outboard in the hydrated mantle and migrates inboard to ductile mid crustal levels and/or weak low frictional layers in the sedimentary cover. However, in 3D, rift architecture and in particular rift segmentation appear to be a first-order control in explaining along-strike non-cylindrical structures and complexities. This suggests that integrating the third dimension in numerical models is a prerequisite to understand the tectonic evolution of convergent or divergent boundaries.

12.4 Emerging concepts and applicability to global systems

It is likely that the orogenic evolution of systems that went through a full Wilson Cycle, *i.e.*, the closure of a mature and wide oceanic system, is controlled by long-lasting subduction-related magmatic arc systems and slab dynamics and cannot be compared with the Biscay-Pyrenean system. Thus, what can we learn from orogens that result from incomplete Wilson Cycles, *i.e.*, the closure of narrow/immature hyperextended domain, and how can these learnings be applied to the mature orogenic systems? One of the major learnings is that in the Biscay-Pyrenean system we can mainly observe the initial stages of subduction and collision. Since all orogens, even the mature ones, had to initiate, these are precisely these early stages, often neither defined nor observed or understood that are important and where our learnings can be applied. For orogens where collision occurs after a mature, long-lasting subduction, the hanging wall may be completely obliterated by arc magmatism, while such a system does not exist in a Pyrenean-type system. However, the incoming lower-plate margin may be reactivated under similar conditions like those observed at the Biscay-Pyrenean system. Thus, some of the learnings from the OROGEN project, such as the in-sequence reactivation of rift-inherited decoupling levels or the role of segment centers *versus* boundaries may be applicable to more mature systems. This is well shown by Tavani *et al.* (2021) who successfully applied the in-sequence concept initially proposed by Tugend *et al.* (2014) and Lescoutre and Manatschal (2020) to the Apennine, Oman, Zagros and Taiwan. Other examples where the learnings of the OROGEN project may be applied are the Alps in Western Europe and the Oriental Cordillera in Colombia.

12.5 Recognizing remnants of former rifts and rifted margins in orogens

Our study shows that a prerequisite to investigate the role of rift inheritance and predict its effects is the mapping of rift domains and its comparison with the along strike variability and/or non-cylindricity of internal parts of orogens. Two cases may be found: at former segment centres a complete reactivation of the former margin is likely, and most of the former distal margin is subducted. In such systems it is important to evaluate the decoupling levels and to see if their sequential reactivation can be observed. Key questions that need to be addressed include: Are there hints for exhumed mantle and/or lower crust material reworked in syn-rift breccias? Are there decoupling levels, or remnants of characteristic fault rocks such as gouges or cataclasites related to such structures? Is the accretionary prism formed by syn-rift sediments that contain tectono-sedimentary breccias sampling remnants of the former distal margin? Moreover, can a change in the nature of the decoupling level be observed at the transition from soft- of hard collision and is shortening focused in the ductile crust and/or in the low-friction sediment layers?

In contrast, at potential segment boundaries one would expect the preservation of rift inherited basement structures, including lower crustal and mantle rocks remaining in the nappe stack. In such examples one can expect the preservation of exhumation faults and related diagnostic fingerprints, which are exhumed basement overlain by tectono-sedimentary breccias reworking the underlying footwall (see Epin *et al.*, 2017). The along-strike changes may be abrupt and difficult to map and understand. Thrusts may appear to stop abruptly and/or show a change from old over young polarity to young over old along one and the same thrust plane. Structures where sediments are transported along thrusts over basement, including tectono-sedimentary breccias reworking the underlying basement at their base are reminiscent of reactivated detachment faults. Examples have been described by Epin *et al.* (2017) from the Alps. The local geological complexity due to reactivation of former rift structures, in particular of extensional detachment systems, is difficult to understand, since it is local and only occurring in the more internal parts of orogenic systems. In contrast, at external parts structures appear to be more cylindric. In the Pyrenean example, such local complexities have either been ignored or interpreted as Variscan, post-Variscan or Alpine structures. Only very recently, such structures have been related to the former Mesozoic rifting. Most geologists working in orogens still have problems in defining rift-related inheritance and in particular former, often reactivated extensional detachment faults. In the Alps, Beltrando *et al.* (2014) and Epin *et al.* (2017) defined diagnostic "fingerprints" to identify such structures and discussed how they are reactivated. Many present-day debates in the Pyrenees are linked to the non-recognition or erroneous interpretation of inherited structures. Although it is important to be careful and not to use and abuse inheritance, ignoring it does not make interpretations better. Missing inherited structures and interpreting them as Alpine structures results in erroneous interpretations. In most cases, recognizing rift-inherited structures makes the apparently complex orogenic structures simpler (*e.g.*, Beltrando *et al.*, 2014). A key is to understand that hyperextended systems cannot be approximated by simple layer cakes, as was often done in the past.

13 Concluding remarks

Even if the main aim of this paper was to define the role of inheritance in the Biscay-Pyrenean system, the results are of broader importance and the ultimate aim is to transfer the learnings established in the OROGEN project to other, less explored hyperextended rift systems, magma-poor rifted margins and Alpine-type collisional mountain belts. The main lessons learnt from the Biscay-Pyrenean system that may be applied elsewhere include:

- the sequential reactivation of rift-inherited decoupling levels;
- the importance of the Coupling Point as a main, mappable boundary that may become the S-point *sensu* Willett *et al.* (1993) of a collisional system at the transition from soft- to hard collision;
- distinguishing between competing decoupling systems (salt/clay *versus* middle crust) that are at the origin of thin- *versus* thick-skinned reactivation;
- complexities at segment boundaries creating non-cylindrical structures in internal parts of orogens;
- along-strike variations from inherited reactivated structures to newly formed structures with changing hanging-wall and footwall.

It appears that the thermal state of a margin is less important than previously thought for the localization of subduction but may control the flexural behaviour of the lithosphere during collision (Mouthereau *et al.*, 2013). In contrast, it seems that serpentinized mantle is a key in controlling onset of subduction. This may be explained by the low friction at its top contrasting with the strength of the underlying non-serpentinized mantle, and its high density comparing to the surrounding crustal rocks.

Last but not least, trying to integrate the role of rift inheritance in the understanding of orogens may also imply to change the approach used in the field and in interpreting datasets. While detailed structural analysis assuming layer cake geology may work for post-rift sequences/at external parts of the orogen, such methods are more difficult to use in distal margins/internal parts of orogens, where the inherited geological template is more complex.

Acknowledgments. This study was funded by the Orogen project, a tripartite joint academic-industry research program between the CNRS, BRGM, and Total R&D Frontier Exploration program. We thank Tiago Alves and an anonymous reviewer for their very constructive comments that helped to improve the manuscript as well as the Associate Guest Editor Stefano Tavani and the Guest Editor Olivier Lacombe for handling the manuscript.

References

Aguilar C, Liesa M, Štípská P, Schulmann K, Muñoz JA, Casas JM. 2015. P–T–t–d evolution of orogenic middle crust of the Roc de Frausa Massif (Eastern Pyrenees): a result of horizontal crustal flow and Carboniferous doming? *J Metamorph Geol* 33: 273–294. https://doi.org/10.1111/jmg.12120.

Agulles M, Jordà G, Jones B, Agustí S, Duarte CC. 2020. Temporal evolution of temperatures in the red sea and the gulf of aden based on in situ observations (1958–2017). *Ocean Sci* 16: 149–166. https://doi.org/10.5194/os-16-149-2020.

Alvarez-Marrón J, Pérez-Estaún A, Danñobeitia JJ, Pulgar JA, Martínez JR, Marcos A, *et al.* 1996. Seismic structure of the northern continental margin of Spain from ESCIN deep seismic profiles. *Tectonophysics* 264(1–4): 153–174.

Alves TM, Moita C, Cunha T, Ullnaess M, Myklebust R, Monteiro JH, *et al.* 2009. Diachronous evolution of Late Jurassic-Cretaceous continental rifting in the northeast Atlantic (west Iberian margin). *Tectonics* 28(4).

Alves TM, Cunha TA. 2018. A phase of transient subsidence, sediment bypass and deposition of regressive-transgressive cycles during the breakup of Iberia and Newfoundland. *Earth and Planetary Science Letters* 484: 168–183.

Ampferer O, Hammer W. 1911. Geologischer Querschnitt durch die Ostalpen vom Allgäu zum Gardasee. *Jahrbuch der Kaiserlich-Königlichen Geologischen Reichsanstalt* 61(3/4): 532–710.

Andrieu S, Saspiturry N, Lartigau M, Issautier B, Angrand P, Lasseur E. 2021. Large-scale vertical movements on Cenomanien to Santonian carbonate platforms in Iberia: a marker for a Coniacian Pyrenean convergence initiation? *Bulletin de la Société géologique de France* 192(1): 19. https://doi.org/10.1051/bsgf/2021011.

Angrand P, Ford M, Watts AB. 2018. Lateral variations in foreland flexure of a rifted continental margin: The Aquitaine Basin (SW France). *Tectonics* 37(2): 430–449.

Angrand P, Mouthereau F, Masini E, Asti R. 2020. A reconstruction of Iberia accounting for Western Tethys-North Atlantic kinematics since the late-Permian-Triassic. *Solid Earth* 11: 1313–1332. https://doi.org/10.5194/se-11-1313-2020.

Argand E. 1924a. La tectonique de l'Asie. In: 13th International Geological Congress. Brussel, pp. 171–372.

Argand E. 1924b. Les Alpes et l'Afrique. *Bulletin Société vaudoise des Sciences naturelles* 55: 233–236.

Argand, E. 1916. Sur l'arc des Alpes occidentales. Bridel G.

Argand E, Bloesch E, Heim A, Heim A. 1911. I. Les nappes de recouvrement des Alpes pennines et leurs prolongements structuraux (No. 31-33). In: Kommission bei A. Francke (vorm. Schmid & Francke).

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

Asti R, Lagabrielle Y, Fourcade S, Corre B, Monié P. 2019. How do continents deform during mantle exhumation? Insights from the northern Iberia inverted paleopassive margin, western Pyrenees (France). *Tectonics* 38(5): 1666–1693.

Beltrando M, Manatschal G, Mohn G, Dal Piaz GV, Vitale Brovarone A, Masini E. 2014. Recognizing remnants of magma-poor rifted margins in high-pressure orogenic belts: The Alpine case study. *Earth-Science Rev* 131: 88–115. https://doi.org/10.1016/j.earscirev.2014.01.001.

Bertrand M. 1884. Rapports de structure des Alpes de Glaris et du bassin houiller du Nord. *Bull Soc Géol Fr* 3: 318–330.

Biteau J-J, Le Marrec A, Le Vot M, Masset J-M. 2006. The Aquitaine Basin. *Pet Geosci* 12: 247–273. https://doi.org/10.1144/1354-079305-674.

Boillot G, Recq M, Winterer EL, Meyer AW, Applegate J, Baltuck M, *et al.* 1987. Tectonic denudation of the upper mantle along passive margins: a model based on drilling results (ODP leg 103, western Galicia margin, Spain). *Tectonophysics* 132: 335–342. https://doi.org/10.1016/0040-1951(87)90352-0.

Bois C, Pinet B, Roure F. 1989. Dating lower crustal features in France and adjacent areas from deep seismic profiles. In: Mereu RF, *et al.* eds. Properties and Processes of Earth's Lower Crust. *American Geophysical Union Geophysical Monograph* 51: 17–31. https://doi.org/10.1029/GM051p0017.

Boissonnas J, Destombes JP, Heddebaut C, Le Pochat G, Lorsignol S, Roger P, *et al.* 1974. Feuille de Iholdy (1027), Carte géologique de la France, scale 1/50,000. Bureau de Recherche Géologique et Minières.

Braun J, Chéry J, Poliakov A, Mainprice D, Vauchez A, Tomassi A, *et al.* 1999. A simple parameterization of strain localization in the ductile regime due to grain size reduction: A case study for olivine. *J Geophys Res* 104: 25,167–25,181.

Brune S, Heine C, Clift PD, Pérez-Gussinyé M. 2017. Rifted margin architecture and crustal rheology: Reviewing IberiaNewfoundland, Central South Atlantic, and South China Sea. *Marine and Petroleum Geology* 79: 257–281. https://doi.org/10.1016/j.marpetgeo.2016.10.018.

Buck WR. 1991. Modes of continental lithospheric extension. *J Geophys Res* 96: 20,161–20,178.

Cadenas P, Lescoutre R, Manatschal G, Fernández-Viejo G. 2021. 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. *Bulletin de la Société géologique de France*. https://doi.org/10.1051/bsgf/2021045.

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

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

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

Chao P. 2021. Tectono-sedimentary and magmatic evolution of rifting and early seafloor spreading in the NW propagator to the South China Sea. PhD. University of Strasbourg.

Chenin P. 2016. Unravelling the impact of inheritance on the Wilson Cycle: A combined mapping and numerical modelling approach applied to the North Atlantic rift system. Doctoral dissertation, Strasbourg.

Chenin P, Jammes S, Lavier LL, Manatschal G, Picazo S, Müntener O, *et al.* 2019. Impact of mafic underplating and mantle depletion on subsequent rifting: a numerical modeling study. *Tectonics* 38: 2185–2220. https://doi.org/10.1029/2018TC005318.

Chenin P, Manatschal G, Lavier LL, Erratt D. 2015. Assessing the impact of orogenic inheritance on the architecture, timing and magmatic budget of the North Atlantic rift system: a mapping approach. *J Geol Soc Lond* 172: 711–720. https://doi.org/10.1144/jgs2014-139.

Chenin P, Manatschal G, Picazo S, Müntener O, Karner GD, Johnson C, *et al.*2017. Influence of the architecture of magma-poor hyperextended rifted margins on orogens produced by the closure of narrow versus wide oceans. *Geosphere* 13: 1–18. https://doi.org/10.1130/GES01363.1.

Chenin P, Picazo S, Jammes S, Manatschal G, Müntener O, Karner G. 2018. Potential role of lithospheric mantle composition in the Wilson cycle: a North Atlantic perspective. In: Wilson RW, Houseman GA, McCaffrey KJW, Doré AG, Buiter SJH, eds. Fifty Years of the Wilson Cycle Concept in Plate Tectonics. *Geological*

Society, London, Special Publications 470. https://doi.org/10.1144/SP470.10.

Chevrot S, Sylvander M, Diaz J, Martin R, Mouthereau F, Manatschal G, *et al.* 2018. The non-cylindrical crustal architecture of the Pyrenees. *Sci Rep* 8: 1–8. https://doi.org/10.1038/s41598-018-27889-x.

Chevrot S, Sylvander M, Diaz J, Ruiz M, Paul A, Cougoulat G, *et al.* 2015. The Pyrenean architecture as revealed by teleseismic P-to-S converted waves recorded along two dense transects. *Geophys J Int* 200: 1096–1107. https://doi.org/10.1093/gji/ggu400.

Choukroune P, Mattauer M. 1978. Tectonique des plaques et Pyrenees; sur le fonctionnement de la faille transformante nord-pyreneenne ; comparaisons avec des modeles actuels. *Bull Soc Geol Fr* 7: 689–700.

Clerc C. 2012. Évolution du domaine nord-pyrénéen au Crétacé. Amincissement crustal extrême et thermicité élevée : Un analogue pour les marges passives. Université Pierre et Marie Curie-Paris VI.

Clerc C, Jolivet L, Ringenbach JC. 2015. Ductile extensional shear zones in the lower crust of a passive margin. *Earth Planet Sci Lett* 431: 1–7. https://doi.org/10.1016/j.epsl.2015.08.038.

Clerc C, Lagabrielle Y. 2014. Thermal control on the modes of crustal thinning leading to mantle exhumation: Insights from the Cretaceous Pyrenean hot paleomargins. *Tectonics* 33: 1340–1359. https://doi.org/10.1002/2013TC003471.

Clerc C, Ringenbach JC, Jolivet L, Ballard JF. 2018. Rifted margins: Ductile deformation, boudinage, continentward-dipping normal faults and the role of the weak lower crust. *Gondwana Res* 53: 20–40. https://doi.org/10.1016/j.gr.2017.04.030.

Cochelin B. 2016. Champ de déformation du socle paléozoïque des Pyrénées. Université Toulouse 3 Paul Sabatier.

Cochelin B, Lemirre B, Denèle Y, de Saint Blanquat M, Lahfid A, Duchêne S. 2018. Structural inheritance in the Central Pyrenees: the Variscan to Alpine tectonometamorphic evolution of the Axial Zone. *Journal of the Geological Society* 175(2): 336–351.

Corre B, Lagabrielle Y, Labaume P, Fourcade S, Clerc C, Ballèvre M. 2016. Deformation associated with mantle exhumation in a distal, hot passive margin environment: New constraints from the Saraillé Massif (Chaînons Béarnais, North-Pyrenean Zone). *C R Geosci* 348: 279–289. https://doi.org/10.1016/j.crte.2015.11.007.

Corre B, Boulvais P, Boiron MC, Lagabrielle Y, Marasi L, Clerc C. 2018. Fluid circulations in response to mantle exhumation at the passive margin setting in the north Pyrenean zone, France. *Mineralogy and Petrology* 112(5): 647–670.

Dahlstrom CDA. 1969. Balanced cross sections. *Canadian Journal of Earth Sciences* 6(4): 743–757.

Debroas EJ, Bilotte M, Canérot J, Astruc G. 2010. Réinterprétation des brèches de la Faille nord-pyrénéenne ariégeoise (France). *Bull Soc Hist Nat Toulouse* 146: 77–88.

Decandia FA, Elter P. 1969. Riflessioni sul problema delle ofioliti nell'Appennino settentrionale (nota preliminare). *Atti della Soc Toscana di Sci Nat*.

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

Delvolvé JJ, Vachard D, Souquet P. 1998. Stratigraphic record of thrust propagation, Carboniferous foreland basin, Pyrenees, with emphasis on Pays-de-Sault (France/Spain). *Geol Rundschau* 87: 363–372. https://doi.org/10.1007/s005310050215.

Denèle Y, Paquette J-L, Olivier P, Barbey P. 2012. Permian granites in the Pyrenees: the Aya pluton (Basque Country). *Terra Nova* 24: 105–113. https://doi.org/10.1111/j.1365-3121.2011.01043.x.

Dewey JF, Burke K. 1974. Hot spots and collisional break-up: Implications for collisional orogeny. *Geology* 2: 57–60. https://doi.org/10.1130/0091-7613(1974)2<57:HSACBI>2.0.CO;2.

Dielforder A., Frasca G., Brune S., Ford M. 2019. Formation of the Iberian-European Convergent Plate Boundary Fault and Its Effect on Intraplate Deformation in Central Europe. *Geochemistry Geophysics Geosystems* 20(5): 2395–2417. https://doi.org/10.1029/2018GC007840.

Ducoux M, Jolivet L, Callot JP, Aubourg C, Masini E, Lahfid A, *et al.* 2019. The Nappe des Marbres Unit of the Basque-Cantabrian Basin: The Tectono-thermal Evolution of a Fossil Hyperextended Rift Basin. *Tectonics* 38: 3881–3915. https://doi.org/10.1029/2018TC005348.

Ducoux M, Jolivet L, Cagnard F, Baudin T. 2021a. Basement-cover decoupling during the inversion of a hyperextended basin: Insights from the Eastern Pyrenees. *Tectonics* 40: e2020TC006512. https://doi.org/10.1029/2020TC006512.

Ducoux M, Jolivet L, Masini E, Augier R, Lahfid A, Bernet M, *et al.* 2021b. Distribution and intensity of High-Temperature Low-Pressure metamorphism across the Pyrenean-Cantabrian belt: constraints on the thermal record of the pre-orogenic hyperextension rifting. *BSGF - Earth Sciences Bulletin* 192: 43. https://doi.org/10.1051/bsgf/2021029.

Duretz T, Asti R, Lagabrielle Y, Brun JP, Jourdon A, Clerc C, *et al.* 2019. Numerical modelling of Cretaceous Pyrenean Rifting: The interaction between mantle exhumation and syn-rift salt tectonics. *Basin Res* 32(4): 652–667. https://doi.org/10.1111/bre.12389.

Engeser T, Schwentke W. 1986. Towards a new concept of the tectogenesis of the Pyrenees. *Tectonophysics* 129(1–4): 233–242.

Epin ME, Manatschal G, Amann M. 2017. Defining diagnostic criteria to describe the role of rift inheritance in collisional orogens: the case of the Err-Platta nappes (Switzerland). *Swiss J Geosci* 110: 419–438. https://doi.org/10.1007/s00015-017-0271-6.

Fabriès J, Lorand JP, Bodinier JL, Dupuy C. 1991. Evolution of the upper mantle beneath the Pyrenees: evidence from orogenic spinel lherzolite massifs. *Journal of Petrology* (2): 55–76.

Fabriès J, Lorand JP, Bodinier JL. 1998. Petrogenetic evolution of orogenic lherzolite massifs in the central and western Pyrenees. *Tectonophysics* 292(1–2): 145–167.

Ferrer O, Jackson MPA, Roca E, Rubinat M. 2012. Evolution of salt structures during extension and inversion of the Offshore Parentis Basin (Eastern Bay of Biscay). *Geol Soc Spec Publ* 363: 361–380. https://doi.org/10.1144/SP363.16.

Florineth D, Froitzheim N. 1994. Transition from continental to oceanic basement in the Tasna Nappe: evidence for Early Cretaceous opening of the Valais Ocean. *Schweiz Miner Petrogr Mitt* 74: 437–448.

Ford M, Vergés J. 2021. Evolution of a salt-rich transtensional rifted margin, eastern North Pyrenees, France. *J Geol Soc Lond* 178: jgs2019-157. https://doi.org/10.1144/jgs2019-157.

Fortané A, Duée G, Lagabrielle Y, Coutelle A. 1986. Lherzolites and the western "Chainons béarnais"(French Pyrenees): Structural and paleogeographical pattern. *Tectonophysics* 129(1–4): 81–98.

Frasca G, Manatschal G, Cadenas P, Miró J, Lescoutre R. 2021. Restoring deformable microplates with intracontinental strike-slip corridors: hints from Iberia. *Terra Nova* 00: 1–9. https://doi.org/10.1111/ter.12549.

Frizon de Lamotte D, Fourdan B, Leleu S, Leparmentier F, Clarens P. 2015. Style of rifting and the stages of Pangea breakup. *Tectonics* 34: 1–21. https://doi.org/10.1002/2014TC003760.

Gillard M, Tugend J, Müntener O, Manatschal G, Karner GD, Autin J, *et al.* 2019. The role of serpentinization and magmatism in the formation of decoupling interfaces at magma-poor rifted margins. *Earth Sci Rev* 196: 102882. https://doi.org/10.1016/j.earscirev.2019.102882.

Gómez-Romeu J, Masini E, Tugend J, Ducoux M, Kusznir N. 2019. Role of rift structural inheritance in orogeny highlighted by the Western Pyrenees case-study. *Tectonophysics* 766: 131–150. https://doi.org/10.1016/j.tecto.2019.05.022.

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

Hart NR, Stockli DF, Hayman NW. 2016. Provenance evolution during progressive rifting and hyperextension using bedrock and detrital zircon U-Pb geochronology, Mauléon Basin, western Pyrenees. *Geosphere* 12: 1166–1186. https://doi.org/10.1130/GES01273.1.

Hart NR, Stockli DF, Lavier LL, Hayman NW. 2017. Thermal evolution of a hyperextended rift basin, Mauléon Basin, western Pyrenees. *Tectonics* 36: 1103–1128. https://doi.org/10.1002/2016TC004365.

Hess HH. 1962. History of ocean basins. In: Engel AEJ, James HL, Lonard BF, eds. Petrologic Studies: A Volume to Honor A.F. Buddington. New York: Geological Society of America, pp. 599–620.

Holmes A. 1931. Radioactivity and Earth Movements. In: Transactions of the Geological Society of Glasgow. Geological Society of London, pp. 559–606. https://doi.org/10.1144/transglas.18.3.559.

Incerpi N, Manatschal G, Martire L, Bernasconi SM, Gerdes A, Bertok C. 2020a. Characteristics and timing of hydrothermal fluid circulation in the fossil Pyrenean hyperextended rift system: new constraints from the Chaînons Béarnais (W Pyrenees). *Int J Earth Sci* 109: 1071–1093.

Incerpi N, Martire L, Manatschal G, Bernasconi SM, Gerdes A, Czuppon G, *et al.* 2020b. Hydrothermal fluid flow associated to the extensional evolution of the Adriatic rifted margin: Insights from the pre- to post-rift sedimentary sequence (SE Switzerland, N Italy). *Basin Res* 32: 91–115. https://doi.org/10.1111/bre.12370.

Issautier B, Saspiturry N, Olivier S. 2020. Role of structural inheritance and salt tectonics in the formation of pseudosymmetric continental rifts on the european margin of the hyperextended Mauléon basin (Early Cretaceous Arzacq and Tartas Basins). *Mar Pet Geol* 118: 104395. https://doi.org/10.1016/j.marpetgeo.2020.104395.

Izquierdo-Llavall E, Menant A, Aubourg C, Callot J-P, Hoareau G, Camps P, *et al.* 2020. Preorogenic folds and syn-orogenic basement tilts in an inverted hyperextended margin: The Northern Pyrenees case study. *Tectonics* 39: e2019TC005719. https://doi.org/10.1029/2019TC005719.

Jackson JA. 1980. Reactivation of basement faults and crustal shortening in orogenic belts. *Nature* 283: 343–346.

Jammes S, Huismans RS, Muñoz JA. 2014. Lateral variation in structural style of mountain building: Controls of rheological and rift inheritance. *Terra Nova* 26: 201–207. https://doi.org/10.1111/ter.12087.

Jammes S, Manatschal G, Lavier L. 2010. Interaction between prerift salt and detachment faulting in hyperextended rift systems: The example of the Parentis and Mauléon basins (Bay of Biscay and western Pyrenees). *Am Assoc Pet Geol Bull* 94: 957–975. https://doi.org/10.1306/12090909116.

Jammes S, Manatschal G, Lavier L, Masini E. 2009. Tectonosedimentary evolution related to extreme crustal thinning ahead of a propagating ocean: Example of the western Pyrenees. *Tectonics* 28: TC4012. https://doi.org/10.1029/2008TC002406.

Jourdon A, Mouthereau F, Le Pourhiet L, Callot J. 2020. Topographic and Tectonic Evolution of Mountain Belts Controlled by Salt Thickness and Rift Architecture. *Tectonics* 39: e2019TC005903. https://doi.org/10.1029/2019TC005903.

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

Kelley DS, Shank TM. 2010. Hydrothermal systems: A decade of discovery in slow spreading environments. *Geophys Monogr Ser* 188: 369–407. https://doi.org/10.1029/2010GM000945.

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

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

Lagabrielle Y, Clerc C, Vauchez A, Lahfid A, Labaume P, Azambre B, *et al.* 2016. Very high geothermal gradient during mantle exhumation recorded in mylonitic marbles and carbonate breccias from a Mesozoic Pyrenean palaeomargin (Lherz area, North Pyrenean Zone, France). *C R Geosci* 348: 290–300. https://doi.org/10.1016/j.crte.2015.11.004.

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

Lago M, Arranz E, Pocoví A, Galé C, Gil-Imaz A. 2004. Permian magmatism and basin dynamics in the southern Pyrenees: A record of the transition from late Variscan transtension to early Alpine extension. *Geol Soc Spec Publ* 223: 439–464. https://doi.org/10.1144/GSL.SP.2004.223.01.19.

Lavier LL, Ball PJ, Manatschal G, Heumann MJ, MacDonald J, Matt VJ, *et al.* 2019. Controls on the Thermomechanical Evolution of Hyperextended Lithosphere at Magma-Poor Rifted Margins: The Example of Espirito Santo and the Kwanza Basins. *Geochem Geophys Geosyst* 20: 5148–5176. https://doi.org/10.1029/2019GC008580.

Lavier LL, Manatschal G. 2006. A mechanism to thin the continental lithosphere at magma-poor margins. *Nature* 440: 324–328. https://doi.org/10.1038/nature04608.

Le Maire P, Thinon I, Tugend J, Issautier B, Martelet G, Paquet F, *et al.* 2021. New Magnetic compilation of the Bay of Biscay and surrounding continental shelves. *Bulletin de la Société Géologique de France* 68: 1989–1997.

Lehujeur S, Chevrot A, Villasenor E, Masini N, Saspiturry R, Lescoutre M, *et al.* 2021. Three-dimensional shear velocity structure of the Mauleon and Arzacq basins (Western Pyrenees). *BSGF - Earth Sciences Bulletin* 192: 47. https://doi.org/10.1051/bsgf/2021039.

Le Pichon X. 1968. Sea-floor spreading and continental drift. *J Geophys Res* 73: 3661–3697. https://doi.org/10.1029/jb073i012p03661.

Le Pichon X, Sibuet JC. 1971. Western extension of boundary between European and Iberian plates during the Pyrenean orogeny. *Earth Planet Sci Lett* 12: 83–88. https://doi.org/10.1016/0012-821X(71)90058-6.

Le Pichon X, Sibuet JC, Francheteau J. 1977. The fit of the continents around the North Atlantic Ocean. *Tectonophysics* 38: 169–209. https://doi.org/10.1016/0040-1951(77)90210-4.

Leleu S, Hartley AJ, van Oosterhout C, Kennan L, Ruckwied K, Gerdes K. 2016. Structural, stratigraphic and sedimentological characterisation of a wide rift system: The Triassic rift system of the Central Atlantic Domain. *Earth Sci Rev* 158: 89–124. https://doi.org/10.1016/j.earscirev.2016.03.008.

Lemoine M, Tricart P, Boillot G. 1987. Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Apennines): In search of a genetic imodel. *Geology* 15: 622–625. https://doi.org/10.1130/0091-7613(1987)15.

Lescoutre R, Manatschal G. 2020. Role of rift-inheritance and segmentation for orogenic evolution: example from the Pyrenean-Cantabrian system. *Bulletin de la Société géologique de France* 191(1).

Lescoutre R, Tugend J, Brune S, Masini E, Manatschal G. 2019. Thermal Evolution of Asymmetric Hyperextended Magma-Poor Rift Systems: Results From Numerical Modeling and Pyrenean Field Observations. *Geochem Geophys Geosyst* 20: 4567–4587. https://doi.org/10.1029/2019GC008600.

Lescoutre R, Manatschal G, Muñoz JA. 2021. Nature, origin, and evolution of the Pyrenean-Cantabrian junction. *Tectonics* 40: e2020TC006134. https://doi.org/10.1029/2020TC006134.

López-Gómez J, Alonso-Azcárate J, Arche A, Arribas J, Fernández Barrenechea J, Borruel-Abadía V, *et al.* 2019. Permian-Triassic Rifting Stage. In: Regional Geology Reviews. Springer, Cham, pp. 29–112. https://doi.org/10.1007/978-3-030-11295-0_3.

Lucazeau F, Leroy S, Rolandone F, d'Acremont E, Watremez L, Bonneville A, *et al.* 2010. Heat-flow and hydrothermal circulation at the ocean-continent transition of the eastern gulf of Aden. *Earth Planet Sci Lett* 295: 554–570. https://doi.org/10.1016/j.epsl.2010.04.039.

Macchiavelli C, Vergés J, Schettino A, Fernàndez M, Turco E, Casciello E, *et al.* 2017. A New Southern North Atlantic Isochron Map: Insights Into the Drift of the Iberian Plate Since the Late Cretaceous. *J Geophys Res Solid Earth* 122: 9603–9626. https://doi.org/10.1002/2017JB014769.

Manatschal G, Lavier LL, Chenin P. 2015. The role of inheritance in structuring hyperextended rift systems: Some considerations based on observations and numerical modeling. *Gondwana Res* 27: 140–164. https://doi.org/10.1016/j.gr.2014.08.006.

Martin R, Giraud J, Ogarko V, Chevrot S, Beller S, Gégout P, *et al.* 2021. Three-dimensional gravity anomaly inversion in the Pyrenees using compressional seismic velocity model as structural similarity constraints. *Geophys J Int* 225(2): 1063–1085. https://doi.org/10.1093/gji/ggaa414.

Martínez Catalán JR, Arenas R, Díaz García F, Cuadra PG, Gómez-Barreiro J, Abati J, *et al.* 2007. Space and time in the tectonic evolution of the northwestern Iberian Massif: Implications for the Variscan belt. In: Hatcher RD, Carlson MP, McBride JH, Martínez Catalán JR, eds. Space and Time in the Tectonic Evolution of the North-Western Iberian Massif: Implications for the Variscan Belt. *The Gological Society of America Memoir* 200: 403–423. https://doi.org/10.1130/2007.1200(21).

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

Mattauer M, Proust F. 1967. L'évolution structurale de la partie Est du domaine pyrénéo-provençal au Crétacé et au Paléogène. In: Extrait des Comptes rendus du colloque sur la Biogéographie du Crétacé-éocène de la France Méridionale. Travaux de Laboratoire de Géochimie de la Biosphère, École Pratique des Hautes Études, vol. 310, pp. 9–20.

Matte P. 1991. Accretionary history and crustal evolution of the Variscan belt in Western Europe. *Tectonophysics* 196: 309–337.

McCarthy A, Tugend J, Mohn G, Candioti L, Chelle-Michou C, Arculus R, *et al.* 2020. A case of Ampferer-type subduction and consequences for the Alps and the Pyrenees. *Am J Sci* 320: 313–372. https://doi.org/10.2475/04.2020.01.

Mencos J, Carrera N, Muñoz JA. 2015. Influence of rift basin geometry on the subsequent postrift sedimentation and basin inversion: The Organyà Basin and the Bóixols thrust sheet (south central Pyrenees). *Tectonics* 34(7): 1452–1474.

Miró J, Manatschal G, Cadenas P, Muñoz JA. 2021. Reactivation of a hyperextended rift system: The Basque–Cantabrian Pyrenees case. *Basin Research* 00: 1–25. https://doi.org/10.1111/bre.12595.

Montadert L, de Charpal O, Roberts D, Guennoc P, Sibuet J-C. 1979. Northeast Atlantic passive continental margins: Rifting and subsidence processes. In: Talwani M, Hay W, Ryan WBF, eds. Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment, Volume 3. American Geophysical Union (AGU), pp. 154–186. https://doi.org/10.1029/me003p0154.

Morgan WJ. 1971. Convection Plumes in the Lower Mantle. *Nature* 230: 42–43. https://doi.org/10.1038/230042a0.

Mouthereau F, Watts AB, Burov E. 2013. Structure of orogenic belts controlled by lithosphere age. *Nat Geosci* 6: 785–789. https://doi.org/10.1038/ngeo1902.

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

Müntener O, Pettke T, Desmurs L, Meier M, Schaltegger U. 2004. Refertilization of mantle peridotite in embryonic ocean basins: trace element and Nd isotopic evidence and implications for crust-mantle relationships. *Earth Planet Sci Lett* 221: 293–308. https://doi.org/10.1016/S0012-821X(04)00073-1.

Neumann F, Negrete-Aranda R, Harris RN, Contreras J, Sclater JG, González-Fernández A. 2017. Systematic heat flow measurements across the Wagner Basin, northern Gulf of California. *Earth Planet Sci Lett* 479: 340–353. https://doi.org/10.1016/j.epsl.2017.09.037.

Nirrengarten M, Mohn G, Schito A, Corrado S, Gutiérrez-García L, Bowden SA, *et al.* 2020. The thermal imprint of continental breakup during the formation of the South China Sea. *Earth Planet Sci Lett* 531: 115972. https://doi.org/10.1016/j.epsl.2019.115972.

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

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

Nirrengarten M, Manatschal G, Yan X, Kusznir N, Millot B. 2016. Application of the critical Coulomb wedge theory to hyper-extended, magma-poor rifted margins. *Earth Planet Sci. Lett* 442: 121–132.

Odlum ML, Stockli DF. 2020. Geochronologic constraints on deformation and metasomatism along an exhumed mylonitic shear zone using apatite U-Pb, geochemistry, and microtextural analysis. *Earth Planet Sci Lett* 538: 116177. https://doi.org/10.1016/j.epsl.2020.116177.

Oliva-Urcia B, Casas AM, Pueyo EL, Román-Berdiel T, Geissman JW. 2010. Paleomagnetic evidence for dextral strike-slip motion in the Pyrenees during alpine convergence (Mauléon basin, France). *Tectonophysics* 494(3–4): 165–179.

Parsons B, McKenzie D. 1978. Mantle convection and the thermal structure of the plates. *J Geophys Res* 83: 4485. https://doi.org/10.1029/JB083iB09p04485.

Pedrera A, García-Senz J, Ayala C, Ruiz-Constán A, Rodríguez-Fernández LR, Robador A, *et al.* 2017. Reconstruction of the Exhumed Mantle Across the North Iberian Margin by Crustal-Scale 3-D Gravity Inversion and Geological Cross Section. *Tectonics* 36: 3155–3177. https://doi.org/10.1002/2017TC004716.

Pedrera A, García-Senz J, Peropadre C, Robador A, López-Mir B, Díaz-Alvarado J, *et al.* 2021. The Getxo crustal-scale cross-section: Testing tectonic models in the Bay of Biscay-Pyrenean rift system. *Earth Sci Rev*: 103429. https://doi.org/10.1016/j.earscirev.2020.103429.

Pérez-Gussinyé M, Ranero CR, Reston TJ. 2003. Mechanisms of extension at nonvolcanic margins: Evidence from the Galicia interior basin, west of Iberia. *J Geophys Res* 108. https://doi.org/10.1029/2001JB000901.

Petri B, Duretz T, Mohn G, Schmalholz SM, Karner GD, Müntener O. 2019. Thinning mechanisms of heterogeneous continental lithosphere. *Earth Planet Sci Lett* 512: 147–162. https://doi.org/10.1016/J.EPSL.2019.02.007.

Petri B, Skrzypek E, Mohn G, Mateeva T, Galster F, Manatschal G. 2017. U–Pb geochronology of the Sondalo gabbroic complex (Central Alps) and its position within the Permian post-Variscan extension. *Int J Earth Sci* 106: 2873–2893. https://doi.org/10.1007/s00531-017-1465-x.

Picazo S, Müntener O, Manatschal G, Bauville A, Karner GD, Johnson C. 2016. Mapping the nature of mantle domains in Western and Central Europe based on clinopyroxene and spinel chemistry: evidence for mantle modification during an extensional cycle. *Lithos* 266: 233–263. https://doi.org/10.1016/j.lithos.2016.08.02.

Polychronopoulou K, Lois A, Martakis N, Calassou S, Draganov D. 2019. Earthquake-based passive seismic exploration techniques. In: SEG Technical Program Expanded Abstracts 2019. Society of Exploration Geophysicists, pp. 5393–5397.

Polychronopoulou K, Lois A, Martakis N, Chevrot S, Sylvander M, Diaz J, *et al.* 2018. Broadband, short-period or geophone nodes? Quality assessment of Passive Seismic signals acquired during the Maupasacq experiment. *First Break* 36(4): 71–76.

Ribeiro ML, Reche J, López-Carmona A, Aguilar C, Bento dos Santos T, Chichorro M, *et al.* 2019. Variscan Metamorphism. In: Regional Geology Reviews. Springer, Cham, pp. 431–495. https://doi.org/10.1007/978-3-030-10519-8_12.

Razin P. 1989. Évolution tecto-sédimentaire alpine des Pyrénées Basques à l'Ouest de la transformante de Pamplona (province du Labourd). Doctoral dissertation.

Roest WR, Srivastava SP. 1991. Kinematics of the plate boundaries between Eurasia, Iberia, and Africa in the North Atlantic from the Late Cretaceous to the present. *Geology* 19: 613–616. https://doi.org/10.1130/0091-7613(1991)019<0613:KOTPBB>2.3.CO;2.

Rougier G, Ford M, Christophoul F, Bader AG. 2016. Stratigraphic and tectonic studies in the central Aquitaine Basin, northern Pyrenees: Constraints on the subsidence and deformation history of a retro-foreland basin. *Comptes Rendus Geoscience* 348(3–4): 224–235.

Rowan MG. 2020. The south atlantic and gulf of mexico salt basins: Crustal thinning, subsidence and accommodation for salt and presalt strata. In: Geological Society Special Publication. Geological Society of London, pp. 333–363. https://doi.org/10.1144/SP476.6.

Rowan MG. 2014. Passive-margin salt basins: hyperextension, evaporite deposition, and salt tectonics. *Basin Res* 26: 154–182. https://doi.org/10.1111/bre.12043.

Saspiturry N, Issautier B, Razin P, Baudin T, Asti R, Lagabrielle Y, *et al.* 2021. Review of Iberia-Eurasia plate-boundary basins: Role of sedimentary burial and salt tectonics during rifting and continental breakup. *Basin Res* 33(2): 1626–1661. https://doi.org/10.1111/bre.12529.

Saspiturry N, Allanic C, Razin P, Issautier B, Baudin T, Lasseur E, *et al.* 2020a. Closure of a hyperextended system in an orogenic lithospheric pop-up, Western Pyrenees: The role of mantle buttressing and rift structural inheritance. *Terra Nova* 32: 253–260. https://doi.org/10.1111/ter.12457.

Saspiturry N, Lahfid A, Baudin T, Guillou-Frottier L, Razin P, Issautier B, *et al.* 2020b. Paleogeothermal gradients across an inverted hyperextended rift system: example of the Mauléon fossil rift (Western Pyrenees). *Tectonics* 39(10): e2020TC006206.

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

Şengör AMC. 1991. Orogenic architecture as a guide to size of ocean lost in collisional mountain belts. *Bull Tech Univ Istanbul* 44: 43–74.

Sibuet JC, Srivastava SP, Enachescu M, Karner GD. 2007. Early Cretaceous motion of Flemish Cap with respect to North America: implications on the formation of Orphan Basin and SE Flemish Cap–Galicia Bank conjugate margins. In: Karner GD, Manatschal G, Pinhiero LM, eds. Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup, Geological Society, London, Special Publications, 282. The Geological Society of London, pp. 59–72. https://doi.org/10.1144/SP282.4.

Sibuet J-C, Srivastava SP, Spakman W. 2004. Pyrenean orogeny and plate kinematics. *J Geophys Res* 109: B08104. https://doi.org/10.1029/2003JB002514.

Soares DM, Alves TM, Terrinha P. 2012. The breakup sequence and associated lithospheric breakup surface: Their significance in the context of rifted continental margins (West Iberia and Newfoundland margins, North Atlantic). *Earth and Planetary Science Letters* 355: 311–326.

Steinmann G. 1905. Geologische Beobachtungen in den Alpen. Wagners Universitäts-Buchdruckereis.

Sutra E, Manatschal G, Mohn G, Unternehr P. 2013. Quantification and restoration of extensional deformation along the Western Iberia and Newfoundland rifted margins. *Geochem Geophys Geosyst* 14: 2575–2597. https://doi.org/10.1002/ggge.20135.

Tavani S, Granado P, Corradetti A, Camanni G, Vignaroli G, Manatschal G, *et al.* 2021. Rift inheritance controls the switch from thin- to thick-skinned thrusting and basal décollement re-localization at the subduction-to-collision transition. *GSA Bulletin* 133(9–10): 2157–2170. https://doi.org/10.1130/B35800.1.

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

Teixell A. 1996. The Ansó transect of the southern Pyrenees: Basement and cover thrust geometries. *J Geol Soc Lond* 153: 301–310.

Teixell A, Labaume P, Lagabrielle Y. 2016. The crustal evolution of the west-central Pyrenees revisited: Inferences from a new kinematic scenario. *C R Geosci* 348: 257–267. https://doi.org/10.1016/j.crte.2015.10.010.

Ternois S, Odlum M, Ford M, Pik R, Stockli D, Tibari B, *et al.* 2019. Thermochronological evidence of early orogenesis, eastern Pyrenees, France. *Tectonics* 38(4): 1308–1336.

Tharp M, Heezen BC, Ewing M. 1959. The floors of the oceans: I. The North Atlantic. 65. Geological Society of America. https://doi.org/10.1130/SPE65-p1.

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

Thinon I, Fidalgo-González L, Réhault JP, Olivet JL. 2001. Déformations pyrénéennes dans le golfe de Gascogne. *Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary Science* 332(9): 561–568.

Trümpy R. 2001. Why plate tectonics was not invented in the Alps. *Int J Earth Sci* 90: 477–483. https://doi.org/10.1007/s005310000175.

Tugend J, Manatschal G, Kusznir N. 2015. Spatial and temporal evolution of hyperextended rift systems: implication for the nature, kinematics and timing of the Iberian-European plate boundary. *Geology* 43: 15–18.

Tugend J, Manatschal G, Kusznir NJ, Masini E. 2014. Characterizing and identifying structural domains at rifted continental margins: application to the Bay of Biscay margins and its Western Pyrenean fossil remnants. *Geol Soc Lond Spec Publ* 413: SP413–3. https://doi.org/10.1002/2014TC003529.

Tuzo Wilson J. 1965. Transform faults, oceanic ridges, and magnetic anomalies Southwest of Vancouver Island. *Science* 150: 482–485. https://doi.org/10.1126/science.150.3695.482.

Vacherat A, Mouthereau F, Pik R, Bellahsen N, Gautheron C, Bernet M, *et al.* 2016. Rift-to-collision transition recorded by tectonothermal evolution of the northern Pyrenees. *Tectonics* 35: 907–933. https://doi.org/10.1002/2015TC004016.

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

Vargas H, Gaspar-Escribano JM, López-Gómez J, Van Wees JD, Cloetingh S, de La Horra R, *et al.* 2009. A comparison of the Iberian and Ebro Basins during the Permian and Triassic, eastern Spain: A quantitative subsidence modelling approach. *Tectonophysics* 474: 160–183. https://doi.org/10.1016/j.tecto.2008.06.005.

Vergés J, García-Senz J. 2001. Mesozoic evolution and Cainozoic inversion of the Pyrenean rift. *Mémoires du Muséum national d'histoire naturelle (1993)* 186: 187–212.

Vielzeuf D, Kornprobst J. 1984. Crustal splitting and the emplacement of Pyrenean lherzolites and granulites. *Earth and Planetary Science Letters* 67: 87–96. https://doi.org/10.1016/0012821X(84)90041-4.

Vielzeuf D, Pin C. 1989. Geodynamic implications of granulitic rocks in the Hercynian belt. *Geol Soc Spec Publ* 43: 343–348. https://doi.org/10.1144/GSL.SP.1989.043.01.29.

Vine FJ, Matthews DH. 1963. Magnetic anomalies over oceanic ridges. *Nature* 199: 947–949. https://doi.org/10.1038/199947a0.

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

Wang Y, Chevrot S, Monteiller V, Komatitsch D, Mouthereau F, Manatschal G, *et al.* 2016. The deep roots of the western Pyrenees revealed by full waveform inversion of teleseismic P waves. *Geology* 44: 475–478. https://doi.org/10.1130/G37812.1.

Wegener A. 1915. Die Entstehung der Kontinente und Ozeane. Braunschweig.

Wernicke B. 1985. Uniform-sense normal simple shear of the continental lithosphere. *Can J Earth Sci* 22: 108–125. https://doi.org/10.1139/e85-009.

Willett S, Beaumont C, Fullsack P. 1993. Mechanical model for the tectonics of doubly vergent compressional orogens. *Geology* 21: 371–374. https://doi.org/10.1130/0091-7613(1993)021<0371:MMFTTO>2.3.CO.

Wilson JT. 1966. Did the Atlantic close and then re-open? *Nature* 211: 676–681. https://doi.org/10.1038/211676a0.

Yamasaki T, O'Reilly B, Readman P. 2006. A rheological weak zone intensified by post-rift thermal relaxation as a possible origin of simple shear deformation associated with reactivation of rifting. *Earth Planet Sci Lett* 248: 119–131. https://doi.org/10.1016/j.epsl.2006.05.019.

Ziegler PA. 1988. Evolution of the Arctic-North Atlantic and the Western Tethys. *Am Assoc Pet Geol Mem* 43: 164–196.

Cite this article as: Manatschal G, Chenin P, Lescoutre R, Miró J, Cadenas P, Saspiturry N, Masini E, Chevrot S, Ford M, Jolivet L, Mouthereau F, Thinon I, Issautier B, Calassou S. 2021. The role of inheritance in forming rifts and rifted margins and building collisional orogens: a Biscay-Pyrenean perspective, *BSGF - Earth Sciences Bulletin* 192: 55.