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Short abstract (for submission)

We enhance a striking correlation between the paleogeography of Upper Triassic deposits and the mode of crustal stretching of the north Iberia plate during the Cretaceous transtensional event. The basins which opened during the mid-Cretaceous times along the Iberia-Eurasia plate boundary (like the emblematic Parentis basin) exhibit a peculiar synclinal-shaped profile and are devoid of prominent block faulting. The top of the basement is characterized by gentle slopes dipping symmetrically towards the basin center. Based on a comparison with rifting models established from the North Pyrenean Zone, this architecture appear to result from the thinning of the central basin continental crust under dominating-ductile deformation in greenschist facies conditions. The common character shared by all the pre-rift sequences of the studied basins is the presence of a thick low-strength Upper Triassic evaporites and clays layer belonging to the Keuper group and forming a thick pre-rift low-strength unit. Efficient décollement along this layer triggers mechanical decoupling and gliding of the pre-rift cover remaining in the basin center as the continental crust is laterally extracted. Using recent paleogeographic reconstructions, we show that the distribution of the Keuper sedeiments remarkably matches the distribution of the Pyrenean and peri-Pyrenean, Parentis-type basins. This allows for the first time to propose a genetic link between the distribution of evaporite-bearing pre-rift sedimentary formations and the development of smooth-slopes rift basins.

Abstract

This article enhances for the first time a striking correlation between the paleogeography of Upper Triassic deposits and the mode of crustal stretching around and inside the Iberia plate during the Cretaceous transtensional event. In a first step, we propose a review of the architecture of the basins which opened during the mid-Cretaceous times along the Iberia-Eurasia plate boundary. Like the emblematic Parentis basin, all these basins exhibit a peculiar synclinal-shaped profile and are devoid of prominent block faulting. The top of the basement is characterized by gentle slopes, which dip symmetrically towards the center of the basins. Based on a comparison with recent geologically-based rifting models established from the North Pyrenean Zone, we propose that this architecture results from the thinning of the central basin continental crust under dominating-ductile deformation in greenschist facies conditions. The common character shared by all the pre-rift sequences of the studied basins is the presence of a thick low-strength Upper Triassic evaporites and clays layer belonging to the Keuper group and forming a specific pre-rift salt unit. In the studied basins,

efficient décollement along the Keuper evaporites and clays triggers mechanical decoupling and gliding of the pre-rift cover that remains in the center of the basin as the continental crust is laterally extracted. Thus, during the early rifting phase, the basement undergoes thinning while the pre-rift cover remains preserved in the basin center. In response to hyper-thinning and horizontal extraction of the continental crust, hot mantle material approaches the detached pre-rift cover. The major consequences of this central basin thermal anomaly are twofolds: (i) the ductile deformation of the thinned continental crust beneath the detached pre-rift units, and (ii) the development of HT-LP metamorphic conditions in the pre-rift sediments and at the base of the syn-rift flysch levels. This thermal event is well recorded in the axial portion of the Pyrenean realm (future North Pyrenean Zone) as well as in the pre-rift sediments of the Cameros basin (northern Spain). Continental stretching is accommodated by shearing in the bulk upper and middle crust leading to the formation of thin tectonic lenses of mylonitic crustal material remaining welded on the exhuming mantle. The architecture of the smooth-slopes, Parentis-type basins studied in this article thus contrasts with the structure of the Iberia-Newfoundland Atlantic margins which are characterized by (i) top-basement detachment faults accommodating crustal extension through rotation and translation of undeformed basement blocks, and (ii) by the individualization of continental extensional allochthons lying tectonically over exhumed lower crust or mantle rocks. Finally, using recent paleogeographic reconstructions, we show that the distribution of the Keuper evaporites and clays remarkably matches the distribution of the Pyrenean and peri-Pyrenean, Parentis-type basins. This allows for the first time to propose a genetic link between the distribution of evaporite-bearing pre-rift sedimentary formations and the development of smooth-slopes rift basins.

Introduction

More than 30 years ago, important steps in our understanding of the mechanisms of continental rifting were achieved through the acquisition and interpretation of ECORS seismic reflection profiles (1983-1994) (Damotte et al., 1998). New images of crustal and Moho geometries beneath stretched continental crusts were obtained, shading light on important discrepancies between structural patterns at the base of rift systems. In particular, ECORS profiles from the Rhine graben and the Parentis basin displayed contrasting images of the thinned upper lithosphere. In the first case, the upper crust appears clearly rifted and offset by stepping normal faults (Brun et al., 1991) whilst, despite slight tectonic inversion, the second case exhibits a smooth basement top, with gentle slopes dipping symmetrically towards the basin center (Bois et al., 1997). Because only few cases of Parentis-type architecture were observed worldwide, little attention has been paid to this symmetrical, smooth-slopes type of continental rift, which apparently lacks major upper crustal faulting and block tilting. Rather, most of the current models of rift-related crustal thinning generally point to the individualization of a series of tilted continental blocks indicating that the upper crustal levels behave in a dominant brittle mode in the proximal (or continentward) as well as in the distal (or oceanward) margin domains. In such models, shallow detachment faults accommodate the upper crustal extension through the rotation and the translation of undeformed basement blocks. In the distal margin, these blocks, referred to as extensional allochthons, are covered by syn-rift and post-rift sediments and may lie tectonically over exhumed lower levels, including subcontinental mantle (Reston et al., 1995; Manatschal et al., 2001; Jammes et al., 2010c; Osmundsen and Peron-Pinvidic, 2018, and references therein).

Recent geological investigations in the northern units of the Pyrenean belt forming the North Pyrenean Zone (NPZ) as well as in the Basque-Cantabrian basin (fig. 1) show that Parentis-type basins of mid-Cretaceous age were distributed all along the boundary between the northern Iberia and southern Eurasia plates, thus introducing doubts regarding the ubiquitous character of Iberia-Newfoundland-type margins (Lagabrielle et al., 2010 ; Clerc and Lagabrielle, 2014; Teixell et al., 2016; 2018; Asti et al., 2019). In this article, we first list the main characteristics of these Parentis-type basins, based on the analysis of detailed geological reconstructions from areas exposed all along the northern flank of the Pyrenean belt. Then we review the distribution of such basins at the scale of the Iberia and Eurasia plates. We finally discuss some of the key-factors controlling the evolution of smooth-slopes basins and we evaluate how such information increases our understanding of the mechanisms of continental rifting and passive margin formation.

I. Symmetrical, smooth-slopes basins of the north Iberia margin: insights from the North Pyrenean Zone (NPZ) and the Basque-Cantabrian range

The Pyrenees and the Cantabrian mountain (fig. 1) form a narrow, N110 trending fold-and-thrust belt resulting from the collision of the northern edge of the Iberia plate (north Iberia margin) with the southern edge of the Eurasia plate during the Late Cretaceous-Tertiary (Choukroune and ECORS team, 1989; Muñoz, 1992; Deramond et al., 1993; Roure and Choukroune, 1998; Teixell, 1998; Vergés and Garcia-Senz, 2001; Pedrera et al., 2017; Teixell et al., 2018). Convergence initiated ca. 83 Ma, following an almost 40 Ma long period of transtensional motion in relation with the counterclockwise rotation of Iberia relative to Eurasia, also leading to oceanic spreading in the Bay of Biscaye between Chron M0 and A33o (ca. 125-83 Ma) (Le Pichon et al., 1971; Choukroune and Mattauer, 1978; Olivet, 1996; Sibuet et al., 2004). Convergence led to the partial or complete tectonic inversion of discontinuous Cretaceous rift basins opened along the Iberia-Eurasia plate boundary during the transtensional episode (Puigdefàbregas and Souquet, 1986; Debroas, 1990). Rotation was achieved just before the Albian according to paleomagnetic data collected onland (Gong et al., 2008). Earlier Triassic and Jurassic rifting events preceded the development of the Cretaceous rifts (Canérot, 2017, and references therein).

Along the northern flank of the Pyrenees, more than forty, up to km-sized exposures of subcontinental lherzolites are widespread within the Mesozoic pre-rift and syn-rift sediments forming the NPZ (Monchoux, 1970; Vielzeuf and Kornprobst, 1984; Fabriès *et al.*, 1991, 1998). The NPZ is bounded by two major post-metamorphic thrusts, the North Pyrenean Fault (NPF) to the South and the North Pyrenean Frontal Thrust (NPFT) to the North. The NPF represents the tectonic boundary between the NPZ and the prominent axial zone of the belt (AZ) constituted of a stack of Paleozoic basement units (Choukroune, 1976a; 1976b; 1978b).

Based on field and geophysical evidence from the central and western NPZ, exhumation of sub-continental mantle is shown to have occurred coevaly with extreme thinning of the continental crust in the Pyrenean realm during the mid-Cretaceous (Lagabrielle and Bodinier, 2008; Jammes et al., 2009; Masini et al., 2014). Therefore, mantle exhumation (locally followed by peridotite exposure up to the floor of the Pyrenean basins) is now considered as a general mechanism accounting for the presence of ultramafic material within the NPZ. It is established that the well-known regional high temperature and low pressure (HT–LP) Pyrenean metamorphism (Ravier, 1957; Azambre & Rossy, 1976; Bernus-Maury, 1984) developed along the southern NPZ in relation with continental thinning during the major Cretaceous extensional event (Vielzeuf and Kornprobst, 1984; Dauteuil and Ricou, 1989; Golberg & Leyreloup 1990; Clerc et al., 2015b; 2016). Following the early ECORS profiles (Choukroune and ECORS team, 1989), additional information on the architecture of the paleo-margin of Northern Iberia in the Pyrenees is provided by recent interpretation of tomographic data acquired during the temporary PYROPE and IBERARRAY experiments across the Pyrenees (Chevrot et al., 2015; 2018; fig. 1). Based on such data set, Wang et al. (2016) suggest the inversion of a northern Iberia margin characterized by a short necking domain and a large distal domain made of strongly attenuated crust (less than 10 km thick) overlying a large volume of subcontinental mantle. As discussed further in this article, this domain can be compared to large sheets of hyper-extended continental crust found in the distal portions of present-day passive continental margins (see section III C)

Various models of continental crust thinning and associated mantle exhumation have been proposed recently to account for geological constraints collected inside the metamorphic NPZ. In figure 2 (profiles a to e), we present a selection of reconstructions extracted from recent literature, which highlights numerous similarities between recently published models of Cretaceous NPZ basins structure (Lagabrielle et al., 2010; Clerc and Lagabrielle, 2014; Masini et al., 2014; Tugend et al., 2014; 2015; Clerc et al., 2016; Teixell et al., 2016, 2018; Corre et al., 2016; Lagabrielle et al., 2016; DeFelipe et al., 2017; Pedrera et al., 2017; Espurt et al., 2019; Saspiturry et al., 2019; Asti et al., 2019; Ducoux et al., in review). Most of these architecture models stress the role played by a major cover décollement layer during the Cretaceous crustal thinning. This weak layer corresponds to the Upper Triassic Keuper evaporites which contain clays and sands as well as minor carbonates and doleritic MORB basalts (ophites). Its maximum thickness in the Pyrenean realm reached 2.7 km, as deduced from field data in the southern Pyrenees coupled to well data in the Mauléon and Aquitaine basins and the Bay of Biscay region (James & Canérot, 1988; McClay et al., 2004; Biteau et al., 2006; Jammes et al., 2010a; 2010b; 2010c; Roca et al., 2011; Saura et al., 2016; Orti et al., 2017; Saspiturry et al., 2019). In the décollement layer now exposed in the metamorphic NPZ, the Triassic clays were transformed into talc and chlorite, and the carbonates most often suffered intense tectonic brecciation with talc, tremolite and dolomite recrystallizations (Thiébault et al., 1992; Lagabrielle et al., 2019a, 2019b). Pre-rift to syn-rift salt diapirism was also frequently observed in the non-metamorphic NPZ and in the Southern Pyrenees (e.g. Canérot, 1988; 1989; Lenoble and Canérot, 1992; Canérot and Lenoble, 1989; 1993; James and Canérot, 1999; Canérot et al., 2005; Jammes et al., 2009; Jammes et al., 2010a; 2010b; Roca et al., 2011; Saura et al., 2016; Teixell et al., 2016).

As early stated by Clerc and Lagabrielle, (2014), the main consequence of the presence of the low-strength Keuper layer along the north Iberia margin is that during the Cretaceous rifting, the pre-rift Mesozoic cover was efficiently decoupled from the Paleozoic basement along the evaporites and thus remained on top of the stretched continental lithosphere in the center of the basin. It must be noted that in the external parts of the Pyrenean rift, the borders of the subsiding Cretaceous flysch basins remain at low temperature and display classical faulted and tilted blocks (e.g. half-grabens of Quillan basin, Camarade basin, Gensac-Bonrepos basin, western border of the Mauléon basin, edges of the Gran Rieu high and Lacq basin) (Debroas, 1978; 1990; Biteau et al., 2006; Lagabrielle et al., 2010; Masini et al., 2014; Grool et al., 2018; Espurt et al., 2019).

The Cinco Villas Paleozoic massif and the Le Danois Bank (fig. 1) respectively form the eastern and western boundary of the Basque-Cantabrian basin which develops to the west of the NPZ towards the northern Iberia Peninsula. It is filled by an up to 12.5 km thick succession of Upper Jurassic-Cretaceous sediments with interlayered Aptian to Santonian basic volcanic rocks (Azambre and Rossy, 1976; Rat et al., 1983; Rat, 1988; Castañares et al., 2001; García-Mondéjar et al., 1996; 2004; Floquet, 2004) (fig. 2f-h). This basin was floored by an extremely thinned lithosphere in its central parts (Biscay Synclinorium and Nappes des Marbres) and was also affected by a Late Cretaceous thermal metamorphism (Golberg and Leyreloup, 1990; Cuevas and Tubía, 1999; Pedrera et al., 2017). A peridotite outcrop close to the Leiza fault shows that crustal thinning led to the exhumation of the upper mantle close to the floor of the basin (Mendia and Gil-Ibarguchi, 1991; deFelipe et al., 2017). The basin architecture deduced from field investigations in the eastern part of the Basque-Cantabrian basin (the “Nappe des Marbres” area) includes smooth-slopes margins with normal faults and tilted blocks restricted to the external domains (deFelipe et al., 2017; Pedrera et al., 2017; Ducoux et al., in review). These reconstructed geometries bear affinities with basin architectures deduced from geological observations in the NPZ (fig. 2f-h). Indeed, such architecture and the overall evolution deduced for this rift system implie gliding of the pre-rift sequence over its basement during crustal extension with ductile crustal thinning in its central part in a way similar to models deduced from NPZ studies (e.g. Clerc and Lagabrielle, 2014; Corre et al., 2016; Teixell et al., 2016). The Leiza détachment system of deFelipe et al. (2017) (fig. 2g) corresponds to the basal décollement allowing pre-rift sequence allochthony. The presence of a high-density mantle body beneath the Basque-Cantabrian basin has been established on the basis of lithospheric-scale gravity inversion (Pedrera et al., 2017). The association of this exhumed mantle body with rift and post-rift structural geometries suggests the activation of a major south-dipping ramp-flat-ramp extensional detachment between Valanginian and early Cenomanian times with horizontal extension of ~48 km. Interpretation of geophysical data shows that low-strength Triassic Keuper evaporites and mudstones above the basement favor the decoupling of the cover with formation of minibasins, expulsion rollovers, and diapirs (Pedrera et al., 2017).

Finally, the presence of a thick pre-rift salt layer underlying the Mesozoic carbonates appears as an ubiquitous parameter to take into account when reconstructing the evolution of the Cantabrian-Pyrenean range. Recent models of rift development at the northern Iberia margin show that Triassic lithology controls the three intrinsic characteristics of the Pyrenean rifting which can be summarized as follows:

i. <u>Tectonic juxtaposition of exhumed peridotites and pre-rift sediments.</u> This occurs when the lateral extraction of the thinned continental crust is completed. In response to plate separation, the stretched crust is removed horizontally from the center of the rift and decoupling of the pre-rift cover from its basement occurs along the Keuper décollement. As a consequence a tectonic contact is established between the decoupled pre-rift sediments and the uplifted sub-continental mantle rocks

(Clerc and Lagabrielle, 2014) (fig. 2e). In some locations, due to subsequent complete removal of the pre-rift cover, mantle rocks may be in turn exposed to the seafloor as observed around the Lherz, Urdach and Bestiac lherzolite bodies (Lagabrielle et al. 2010; 2016; de Saint Blanquat et al., 2016).

ii. Crustal stretching under dominantly-ductile conditions. The geometry of the thinned crustal units in the distal domain of the rift margins does not correspond to a succession of triangular-shaped isolated undeformed blocks (extensional allochthons) as described along the Iberia-Newfoundland conjugate margins and along the reconstructed alpine paleomargins (Manatschal, 2001; Manatschal et al., 2001; 2006; Peron-Pinvidic and Manatschal, 2009; Mohn et al., 2010; 2012; 2015) (fig. 3). By contrast, it appears as an assemblage of very thin lenses of ductilely deformed pre-Mesozoic material, originating mainly from the middle crust, separated by anastomozing shear zones that developed in greenschist facies conditions at low pressure (e.g. Corre et al., 2016; Teixell et al., 2016; Asti et al., 2019; Espurt et al., 2019) (fig. 2b-d). This important feature occurs because stretching develops under the allochthonous pre-rift cover that maintains moderate temperature in the upper and middle crust. Microscopic study of crustal material welded on the Urdach lherzolites demonstrates that the middle crust was extracted laterally from the rift axis and deformed ductilely at temperatures between 450°C and 350°C (Asti et al., 2019). Large strains in the greenschist facies are testified by strongly elongate quartz ribbons in ortho- and para-derived mylonites with bulging recrystallization and brittle fracturing of feldspar in cataclastic flows (fig. 4a-b).

iii. Dominantly ductile deformation of the pre-rift and syn-rift sediments under HT-LP conditions. All along the rifting phase, the decoupled pre-rift cover remains in the center of the rift where the rift-related rise of the isotherms is more pronounced and where it is progressively buried under thick flysch sequence deposits. Sedimentary burial first preserves heat acquired during early rifting stages and second trigger temperature increase in the pre-rift cover. As a result, the detached pre-rift cover locally undergoes drastic syn-metamorphic ductile thinning and boudinage during continental breakup (fig. 5a-d). Such peculiar mechanical behaviour is outlined in all published rifting models (i.e. base of Nappe des Marbres basins, Leiza detachment system, base of Mauléon and Chaînons Béarnais basin infills, base of Baronnies and

Boucheville basins infill, fig. 2). Progressive rifting triggers the upward propagation of the brittle-ductile transition which may reach syn-rift sediments deposited at the early stage of the basin opening (Clerc et al., 2016). Brittle deformation dominated by cataclastic brecciation follows ductile shearing and flattening in sedimentary units accompanying final exposure of mantle rocks to the seafloor, as proposed from studies in the Lherz area (Lagabrielle et al., 2016). The ductile-brittle transition is frequently observed at the mesoscopic and microscopic scale with sets of normal faults offsetting the extensional HT foliation (fig. 5e-f, 5h). Finally, at the scale of the entire rift, extensional deformation in the lower margin is accompanied by tectonic denudation of the cover in the upper margin (Lagabrielle et al., 2010; Teixell et al., 2016, 2018).

To sum up, figure 6 presents the intrinsic characteristics of the Pyrenean rifting listed above, compiled along an idealized column of the NPZ lithologies with photographs illustrating the most emblematic deformed levels exposed along the NPZ.

II. A review of smooth-slopes basins around the Pyrenees and Cantabrian ranges

Seismic images of oceanic margins and intracontinental rifts in the close surroundings of the Pyrenees and Cantabrian ranges bear crucial information on the mode of crustal thinning along the northern Iberia margin and adjacent areas during the Cretaceous.

(1) Parentis basin (fig. 1 and 7a). First interpretations of the Parentis ECORS profile point to a symmetrical, syncline-shaped basin, with only few normal faults in the stretched crust, even in the proximal domain (Pinet et al., 1987; Bois et al., 1997). Beneath the Parentis basin fill, the crust is less than 10 km thick and decreases westward from 7 km (along the ECORS Bay of Biscay profile, fig. 1), to 6–5 km (along the MARCONI 3 profile, fig. 1) (Tomassino and Marillier, 1997; Gallart et al., 2004; Ruiz, 2007). More recently, Jammes et al. (2010a), proposed that the southern Parentis basin represents a lower plate sag basin floored by a top-basement detachment system with an asymmetrical mode of opening. These authors emphasize the presence of a thick pre-rift salt layer in the area undergoing extreme crustal thinning, forcing sub- and suprasalt layers to deform differently. Whatever the processes of

crustal thinning are favoured, both older and recent models of Parentis basin evolution highlight three major features: (1) the occurrence of symmetrical smooth-slopes gently dipping basinward; (2) the presence of a crust which thins regularly towards basin axis, without discrete steeply dipping faults, and (3) the presence of a thick pre-rift salt layer allowing décollement of the pre-rift cover from its basement (Jammes et al., 2010b, 2010c).

(2) South Bay of Biscay margin (fig. 1, fig. 7b-c). Both the northern and southern margins of the Bay of Biscay have been explored seismically. North-south transects of the Armorican margin (Norgasis profiles, fig. 1: Thinon et al., 2003; Tugend et al., 2014) reveal a short necking domain that concentrates most of the crustal deformation. Crustal thickness decreases from 35 km at the shelf break to less than 10 km at the foot of the slope. Steep rise of mantle implies the disappearance of the lower crust beneath the slope. Based on results of gravity inversion combined with seismic interpretations, Tugend et al. (2014) map a continuous domain of exhumed mantle from the Armorican basin toward the hyperthinned Parentis basin where minimum crustal thickness occurs (fig. 7a) (Pinet et al., 1987, Bois et al., 1996, Jammes et al., 2010a). According to Roca et al. (2011), the Bay of Biscay Abyssal Plain itself consists of a transitional zone formed by a thin (4–9 km) crust with riders of Mesozoic pre-rift and syn-rift sediments and continental crustal rocks that are extensionally detached over an exhumed sub-continental mantle with seismic velocities comprised between 7.2 and 8 km/s. The distal domain of the Bay of Biscay Abyssal Plain bounds to the north the North Iberian margin, an extended continental margin with Cretaceous basins (e.g. the Asturian basin, up to 10 km thick, fig. 1) and basement highs as the Le Danois Bank (Cadenas and Fernández Viejo, 2016; Teixell et al., 2018), where granulites have been dredged (Capdevila et al., 1980; Fügenschuh et al., 2003) (fig. 1).

(3) North-eastern Iberia intra-crustal basins (Iberian Chain and Valencia trough) (fig 1 and fig. 7b-d). Helpful additional information regarding the thinning modes of the northern Iberia crust can be obtained from seismic images of the Los Cameros, Maestrat and Columbrets basins now partly inverted in the Iberian Chain (fig. 1). These basins result from the distributed extension of the northern Iberia plate synchronously with the opening of the Bay of Biscay-Pyrenees in the mid-Cretaceous (Verges and Garcia-Senz, 2001; Mas et al., 2011). They represent a well-developed Mesozoic rift having similarities with the North Atlantic margins (Salas and Casas, 1993; Salas et al., 2001). In their internal parts, reconstructed

Iberian Chain basin geometries point to simple troughs exhibiting gentle slopes devoid of marked fault stepping, suggesting the absence of tilted blocks and a smooth basement top (e.g. Guimerà et al., 1995; Casas-Sainz and Gil-Imaz, 1998; Omodeo et al., 2014). The Moho generally shows an arched outline with a regular shallowing toward the basin center where the crust is reduced to some kilometers only. The Triassic evaporites play an important role during the Albian rifting in the basins of northeast Iberia. This role was recently well illustrated by interpretation of seismic reflection profiles in the Valencia trough (Etheve et al., 2018) (fig. 7b). These profiles reveal the presence of a large Albian basin, the Columbrets basin (fig. 1), filled with up to 10 km thick Mesozoic sediments over a highly extended continental basement locally only 3.5 km thick. The pre-rift and syn-rift successions form a large-scale synclinal with thinned borders, in relation with displacement along local extensional detachments. Whole deformation results of interaction between the thick pre-rift Triassic salt layer and dominantly ductile crustal thinning (Etheve et al. 2018) leading to the development of an abnormally thin continental crust (Gallart et al., 1990; Dañobeitia et al., 1992; Ayala et al., 2015). In the Cameros basin (fig. 7c-d), the pre-rift cover is decoupled on Triassic evaporites and is smeared all over the streched domain. No major offset of the top basement is attested by the syn-rift record (Casas-Sainz and Gil-Imaz, 1998; Casas-Sainz et al., 2000). A striking feature is that like in the NPZ, HT-LP metamorphism associated with crustal thinning is reported in the Cameros basin fill (Guiraud and Séguret, 1985; Goldberg et al., 1988; Rat et al., 2019).

III. Discussion

A. Smooth-slopes basins: symmetrical geometries versus asymmetrical tectonic regime

A common characteristic of the smooth-slopes basins described in this review is the lack of tilted crustal blocks and related stepping fault scarps in their central part, thus defining a dominant symmetrical smooth-slopes profile of the basement top (figs. 2 and 7). Based on field data from the NPZ, we have shown that stretching of the crustal basement occurs in a dominant ductile mode under greenschist facies conditions, since the central part of the basin remains overlain by a permanent cover of detached pre- and syn-rift sediments . An important question is now to determine whether such symmetrical shapes result from symmetrical or asymmetrical stretching processes.

The symmetry or asymmetry of the processes of lithosphere stretching and continental breakup has been largely debated over the last 30 years (i.e. Buck et al., 1988; Allemand et al., 1989; Buck, 1991; Brun, 1999, with references therein). More recently, the symmetrical character of the final architecture of passive margins has been discussed by many authors (i.e. Michon and Merle, 2003; Huismans and Beaumont, 2007; Reston et al., 1995; Sutra et al., 2013; Brune et al., 2014). Apparent symmetry does not imply dominant pure shear thinning mechanisms but may result from asymmetrical tectonic processes involving large-scale discrete extensional shear zones (simple shear) as discussed by Nagel and Buck (2004) (fig. 8a).

It is well admitted that architecture of extended crustal systems depends on the geometrical and temporal associations between simple shear and pure shear regimes. In the pure shear model of McKenzie (1978), designed to explain the evolution of sedimentary basins, the lithosphere is stretched uniformly resulting in a symmetrical basin with faulting in the brittle crust. By contrast, the simple shear model (Wernicke, 1981, 1985) points to one or few detachment faults that originate at low-angle with dips less than 30° and concentrate the entire deformation, so that, apart from the fault zones, the lithosphere is not deformed. The simple shear model has been complicated with the adjonction of sequential detachments faults (Lister and Davis, 1989). Combination of pure and simple shear model was further proposed (Lister et al., 1991). In this combination model, crustal deformation is controlled by low angle detachment faulting but thinning of the mantle lithosphere results from pure shear. By introducing time-dependant rheological changes at the lithospheric scale, Reston and Perez-Gussinye (2007) report a complex evolution from symmetric to asymmetric extension, and back to symmetric, at margins displaying exhumed mantle in the hyper-extended domain.

A laboratory model combining simple and pure shear has been realized by Brun and Beslier (1996) in order to account for the exhumation of mantle rocks at ocean-continent boundaries (fig. 8b). This model applies easily to the case of rifts with exhumed mantle such as the Pyrenean and peri-Pyrenean smooth-slopes basins. This four-layer model is composed of sand and silicone putty layers, regarded as analogues of the brittle and ductile layers of both crust and mantle. However, it does not discriminate a mid-crustal level. The lower crust deforms ductilely and the upper mantle is strong. Necking of the whole lithosphere model is nearly symmetrical (pure shear) but asymmetrical structures (simple shear) develop internally, due to boudinage and/or faulting of brittle layers. This model explains the occurrence of shear zones in the mantle lithosphere as described by Vissers et al. (1995) in the Pyrenean mantle and accounts for the ductile deformation of the crust as demonstrated by Asti et al. (2019).

In contrast with the Brun and Beslier (1996) symmetrical model, recent models of margin evolution based on the Iberian or Alpine examples have put forward asymmetric architectures resulting from the development of few major detachment faults, and promoted the use of “lower-” and “upper-plate” terminology (Manatschal, 2004; Mohn et al., 2010, 2012, 2015; Sutra et al., 2013). Mohn et al. (2012) propose a model of three-layer continental crust where the brittle upper and lower crusts are strongly decoupled by a ductile middle crust (fig. 3b). Crustal thinning, accommodated through a so-called necking zone, is the result of interplay between detachment faulting in the brittle layers and decoupling in ductile quartzo-feldspatic mid-crustal levels along localized ductile décollements. The excision of ductile mid-crustal layers and the progressive embrittlement of the crust by coupling the lower and upper crusts enable major detachment faults to cut into the underlying mantle, exhuming it to the seafloor.

In the Iberian and Alpine examples, authors envision the presence of one or few large-scale discrete detachment faults controlling the entire crustal thinning and the basin subsidence. This is also applied by Masini et al. (2014) in their model for the western NPZ where a major north-dipping detachment fault accomodates the denudation of the sub-Eurasian mantle to form the basement of the Mauléon basin (fig. 9a). Interpretation involving single detachment faults has also been retained in the preliminary reconstructions of the NPZ basins by Lagabrielle and Bodinier (2008), Lagabrielle et al. (2010) and Vauchez et al. (2013) (fig.9b, c), as well as in the reconstructed S-N transect from the Basque – Cantabrian to the Armorican margin by Roca et al. (2011) (fig. 9d). Similarly, few detachment faults are used in the Espurt et al. (2019), Saspiturry et al. (2019) and Ducoux et al. (in review) models for the Barronies, Mauléon and “Nappe des Marbres” basins respectively (fig. 2). Others models invoke deep-seated staircase extensional faults accounting for large-scale ramp-synclinal folding as documented in the Cameros and Columbrets basins (Guimerà et al., 1995; Roma et al., 2018). By contrast, models from the western NPZ by Corre et al. (2016) and Teixell et al. (2016, 2018) (fig. 2) do not favor the activation of single detachment faults alone. Rather, they involve symmetrical tectonic processes triggering a homogeneous thinning of the crust during its lateral extraction from the rift axis.

In their study of the evolution of the western Betics including the exhumation of the Ronda subcontinental mantle, Frasca et al. (2016) identify three successive steps: (i) ductile crust thinning and ascent of subcontinental mantle thanks to mid-crustal shear zone and crust-mantle shear zones acting synchronously; (ii) disappearance of the ductile crust bringing the upper crust in contact with the subcontinental mantle, (iii) complete exhumation of the mantle in the zone of localized stretching and high-angle normal faulting cutting through the Moho, with related block tilting. These steps do not completely apply to the Pyrenean case, notably because field and geophysical studies of the metamorphic NPZ never evidenced brittle faulting of the Moho during the Cretaceous rifting.

Based on these examples of recent interpretations of rifting evolution, we stress that both Alpine and Betic examples do not refer to a décollement level at the base of the pre-rift cover. They promote evolutionary models lacking allochthony of the detached pre-rift sediments, in contradiction with the examples detailed in section I and II. In addition, both Alpine and Betic models refer to a progressive embrittlement in the rift axis resulting in the complete elimination of ductile crustal layers. Again, this contrasts with the NPZ examples where thin ductile crustal layers are extracted in the distal domain and remain welded on the exhumed mantle.

B. Smooth-slopes basins: crustal shear zones and lenticular fabrics at the mesoscale.

Petrological studies of continental units exposed around the Urdach and Saraillé lherzolite bodies (western NPZ) provide information on the deformation mode associated with crustal thinning and mantle exhumation (Corre et al., 2016; Asti et al., 2019). Reconstruction of sections across the NPZ Cretaceous basins by Clerc et al. (2015b), Teixell et al. (2016), Corre et al. (2016) and Asti et al. (2019) use such ductile deformation mode having affinities with a regional-scale, uniform pure shear mechanism. It is shown that extension in the Paleozoic basement was achieved through lenticular deformation and pervasive ductile flattening with anastomosing extensional mylonitic shear zones developing at temperatures of 350-450°C. Here, during its lateral extraction from the rift axis, the crust thinned ductilely under greenschist facies P-T conditions. Stretching occurred by the mean of undulating shear contacts between tectonic lenses of flattened crustal material as described in figure 10. At the final step of the continental breakup, very thin continental crustal lenses remained welded on the exhumed mantle.

A very similar lenticular mode of deformation derives from investigations in the Basin and Range province. Hamilton (1987) describes tectonic lenses of middle crustal rocks that normally lie at separate levels in the crust with undulating shear contacts between them (fig. 8c). This deformation mode allows the juxtaposition of different lithologies by uplifting deeper lenses during the extensional deformation. In a different way, Gartrell (1997) propose a large scale crustal boudinage involving successive necking regions where the ductile middle crust is extremely sheared (fig. 8d). The resulting architecture is a succession of tectonic lenses that may evolve toward a large-scale lenticular geometry as proposed by Espurt et al. (2019) for the evolution of the North Pyrenean massifs (fig. 2d).

In their recent detailed study of the tectonic and metamorphic evolution of the Urdach and Saraillé mantle bodies and associated units, Lagabrielle et al. (2019a; 2019b) describe two types of low-angle shear zones that accommodated part of extension of the distal domain of the Iberia passive margin during the mid-Cretaceous (fig. 10a, b). The deepest shear zone is the crust-mantle detachment. It separates the ultramafic mantle rocks from strongly thinned continental Paleozoic rocks. It is composed of a basal 20-50 m thick lenticular layer of sheared serpentinites followed by a 10 m thick damage zone. The lenticular layer consists of ultramafic symmetrical tectonic lenses, a few meters long, separated by anastamozing serpentine-rich shear zones. The damage zone consists of an assemblage of centimeter-sized symmetrical lenses of a soft, talc-rich, sheared material, separated by conjugate shear zones. The shallowest shear zone is the cover sole décollement. It corresponds to the tectonic boundary separating the base of the detached pre-rift Mesozoic metasedimentary cover from either mantle lherzolites or continental basement rocks. It consists of a thick deformation zone (some meters to tens of meters thick) that was the locus of important metasomatic crystallizations involving notably fluids of Triassic origin (Corre et al., 2016).

Detailed structural study of the basement and mantle rocks shows that it is not easy to discriminate between dominant pure shear and dominant simple shear processes at the outcrop and regional scales (Lagabrielle et al. 2019a; 2019b). Indeed, a major detachment fault zone (typically related to regional simple shear) may contain abundant symmetrical lenses suggesting locally dominant pure shear.

Finally, in the studied smooth-slopes basins, dominant pure shear mechanisms concentrate into the strongly thinned continental tectonic lenses whereas simple shear mechanism characterize the main detachments. Pure shear mechanisms associated with overall flattening of the syn-rift and pre-rift sedimentary pile progressively develop into the basin center as represented in figure 10a. Chronological constraints have to be integrated in order to establish possible succession from simple shear-dominant toward pure shear-dominant deformation mechanisms at the scale of the entire system.

C. Smooth-slopes basins formation, insights for the evolution of passive, magma-poor continental margins.

We deduce from section B above that dominant pure shear deformation concentrates into anastomozed tectonic lenses forming the strongly stretched continental in the central region of smooth-slopes basins. In the following, we review examples of comparable uniform modes of ductile deformation worldwide.

A lenticular mode of deformation devoid of any steep normal fault is proposed at the scale of an entire passive margin by Gernigon et al., (2014) to account for the symmetrical stretching of the continental crust during the formation of the Barents margin (fig. 11a). This geometry recalls the structures proposed by Gartrell (1997) (fig. 8d). Lenticular fabric is also suggested for deep crustal units connected to tilted blocks through listric faults along the Norway margin (Osmundsen and Ebbing, 2008; fig. 11b). These structures accommodate crustal thinning to only a few kilometer thicknesses through dominant ductile mode. The symmetrical mode of stretching implying ductile thinning or boudinage of some crustal layer can be compared to processes of depth-dependent stretching or thinning (DDT and DDS) envisioned by Reston and McDermott (2014) in order to account for extensional discrepancies at some passive margins. It must be noted that according to an interpretation of deep seismic reflection profiles by Reston (1988), lens-shaped low-strain lozenges separated by high strain shear zones form the structural pattern of the lower crust beneath the United Kingdom. This overall pattern seems to be possibly applied to numerous units of stretched crust at a large scale.

Several distal domains of North Atlantic passive margins display geometries that suggest the presence of lens-shaped units of thinned to hyper-thinned continental crust detached along anastomosing shear zones and now separated by large zones exposing exhumed mantle (e.g. Labrador and West Greenland margins; Reston and Perez-Gussinyé, 2007) (fig. 11c, d). These units do not resemble extensional allochthons of the West Iberia-type margins (figs. 2 and 11e) and show geometrical affinities with crustal boudins extracted during the Pyrenean extension in the center of the Cretaceous rift (e.g. the Baronnies and Agly crustal boudins; Espurt et al., 2019; Clerc et al., 2016) (fig. 2). Such large areas of hyper-thinned continental crust possibly composed of an assemblage of heterogeneous boudins, can be viewed as sheets representing considerable volumes of sheared and flattened continental material (thickness less than 10 km, width of 100 km and length more that few 1000 km, along the margin), formed through processes of uniform pure shear at a crustal scale. We infer that the modes of deformation exhibited by the Pyrenean crustal units welded on the exhumed mantle (although at a much smaller scale) can apply to the formation of these crustal sheets, suggesting predominance of greenschists facies mylonites. Similar crustal sheets underlying sag basins are well imaged in recent numerical models of margin evolution (Brune et al., 2014 ; Huismans and Beaumont, 2011; 2014) as shown in figure 12a, b. Crustal sheets are present along the Angola margin (fig. 12d), they may be present in the very distal domain of the Gulf of Lion margin where they may originate by extraction of lower crustal material (Jolivet et al., 2017) (fig. 11f). Similar long and thin sheets are typically imaged by Wang et al. (2016) at the base of the reconstructed Iberia margin of the Mauléon basin, and by Roca et al. (2011) in their reconstruction of the north Iberia margin north of the Cantabrian coast (fig. 9d).

In their compilation of high-quality and deep penetration seismic profiles of several passive margins (Uruguay, Southern Namibia, Gabon, South China Sea and Barents Sea), Clerc et al. (2015a; 2018) suggest that the lower crust of some margins is weaker than assumed and accommodates a large part of extension by ductile shearing (fig. 8e). Boudinage appears as a recurrent deformation process accounting for the thinning of the continental crust at variable scales. This leads authors to an unorthodox vision of some type of passive margins where: (i) the lower crust is weak, (ii) boudinage controls a large part of the deformation and localization of low-angle normal faults, and (iii) these normal faults often dip toward the continent. This study highlights a crustal behavior dominated by boudinage and lenticulation, implying interplay between ductile shear zones (boudin egdes) and more resistant crustal volumes (boudin cores). As discussed above in section B, this deformation mode may apply to the thinned crustal levels in the axis of the Cretaceous Pyrenean rifts (Teixell et al. 2016, 2018; Asti et al., 2019) (fig. 10) and is supported by recent numerical models of lithospheric rifting incorporating macroscale anisotropy (Duretz et al., 2016).

In their interpretation of deep seismic profiles of the Gulf of Lion margin, Jolivet et al. (2015) point to an intense stretching of the distal margin and reveal a 80 km-wide ocean-continent transition zone that may consist of thin lower continental crust (the "Gulf of Lion metamorphic core complex") and exhumed mantle (fig. 11f). They infer an overall hot geodynamic environment with a shallow lithosphere-asthenosphere boundary able to weaken the upper mantle and the lower crust enough to make them flow south-eastward. In this example, the lower crust bears an important role, which is not fully documented by field data in the NPZ since evidence of exposure of lower crustal levels during the Cretaceous rifting event has not yet been reported with confidence. Moreover, in most of the sections of figures 3 and 7, the lower crust is considered as a high-strength layer that does not deform ductilely but tends to break into large scale boudins and to remain at depth during the rifting processes (e.g. figs. 2a, e, f, h).

D. Comparison with thermo-mechanical models of crustal hyper-extension.

The examples discussed above lead us to emphasize the frequency of lenticular fabrics at various scales reported from different studies in both the upper mantle and the crust. The formation of lenticular fabrics, necking and lateral extraction during continental rifting have been addressed in mechanical and thermo-mechanical numerical models (Duretz and Schmalholz, 2015; Duretz et al., 2016). These models emphasize the role of a pre-existing macroscopic mechanical anisotropy on the development of continental rifts. They illustrate the interplay between necking and lateral extraction of strong layers along weak décollements, thus defining a lenticular fabric and anastomosed shear zone networks at the regional scale as envisioned in the NPZ case.

Models of metamorphic core complexes (MCCs) formation generally involve a thick and hot continental crust (Brun and van den Driessche, 1994). This does not apply to the Pyrenean case but constructive inputs can be expected from a confrontation with the rheological parameters used for MCCs modeling. For instance, Tirel et al. (2008) use initial Moho temperatures of 800°C or higher, with crustal thicknesses of 45 km or greater. This is much more than what can be retained for the post-Variscan crust in the Pyrenees (thicknesses between 30 and 20 km) (Teixell et al., 2018, and references therein) and Moho temperatures lower than 800°C. In the Tirel et al. (2008) experiment, the exhumation process of the metamorphic dome results in the progressive development of a detachment zone and the Moho remains flat because the lower crust has a low viscosity and the upper mantle is weak enough. With Moho temperatures lower than 800°C, the sub-Moho mantle has high strength and effective viscosity resulting in strong Moho deflection and crustal-scale necking. These conditions (relatively cold mantle and thin crust) are reached in the Pyrenean rift explaining why the Pyrenean mantle rapidly reached the surface when it was passively mobilized in response to the drift of the Iberia plate.

A former numerical model that applies to the formation of passive continental margins suggests that the crust may be thinned by permanent pure shear both at the proximal and distal margin (Huismans and Beaumont, 2011) (fig. 12a). This scenario can apply easily to the Pyrenean case where the ductile behaviour of the middle crust is demonstrated (Asti et al., 2019). The Huismans and Beaumont (2011) model produces symmetric margins associated with distal domain characterized by large sheets of thinned crustal material, as discussed above. The symmetrical outline is well imaged by current reconstructions of the Pyrenean basins from the North Pyrenean Zone and associated examples (Parentis, Cameros and Columbrets basins, fig. 1, 2 and 7).

Brune et al. (2014) produce a different numerical model that emphasizes a rift migration accomplished by sequential upper crustal faults balanced through lower crustal flow (fig. 12b). An interesting concept is that of 'exhumation channel', a weak locus of deformation where the crust and part of the uppermost mantle are actively deformed and extremely thinned during their transfer from lower to shallower levels, over a dome of upwelling lithospheric mantle. This high strain volume is not a detachment fault and thus may bear some affinity with the lenses of crustal material exhumed with NPZ mantle and described by Asti et al. (2019). As discussed in section C above, the resulting geometry is that of areas of drastically thinned crust (named *crustal sheets* in the following) forming the distal margin domain lying over a cooled and strengthened mantle. This mantle is exposed locally at the rift axis depending on the extension rate. The final sketch derived from this model, including a dome of strong mantle rimmed in its upper part by a thin layer of mylonitic crust, is a reliable image for the geometry resulting from the Pyrenean rifting and associated basins at a lithospheric scale.

Jammes et al. (2015) and Jammes and Lavier (2016), introduced compositional complexities in the lithosphere by using an explicit bimineralic assemblage which results in the development of anastomosing shear zone. In their models, the deformation appears localized in the middle/lower crust and the upper lithospheric mantle and leads to the preservation of almost undeformed lenses of material surrounded by localized shear zones concentrating most of the deformation. Such a lenticular final geometry is also evocative of the one observed in the North Pyrenean Zone as discussed in detail by Asti et al. (2019) and illustrated in fig. 10.

To unravel the dynamic evolution of the Cretaceous Pyrenean rift, Duretz et al. (2019) carried out a set of thermo-mechanical numerical models of lithosphere-scale extension based on the available geological constraints listed above in section I. The models were used to explore the role of a km-thick basement-cover décollement layer at the base of the pre-rift sediments. These numerical experiments highlight the key-role of the décollement layer that can alone explain collectively: (i) salt tectonics deformation style and cover décollement, (ii) high temperature metamorphism of the pre-rift cover, and (iii) ductile mode of crustal thinning in the inner domain of the models. In the axis of the synclinal-shaped basin (“sag” basin in the margin literature), extreme pure shear leads to the development of a very thin basement layer, overlain by poorly-thinned pre-rift and syn-rift sediments and underlain by exhuming mantle. These models are in good agreement with the current knowledge of the architecture of the Cretaceous Pyrenean basins as exemplified by reconstructions of figs. 2 and 7, as well as with the presence of large sheets of hyper thinned crustal material (crustal sheets) in the distal part of numerous magma poor passive margins.

E. The pre-rift salt décollement layer: a mechanical key-factor in the evolution of smooth-slopes basins. Establishing a new link between Triassic paleogeography and rifting mechanisms.

As reported in section I and II, the common character between all pre-rift sequences of the aforementioned smooth-slopes basins is the presence of the thick low-strength Late Triassic evaporitic layer (Keuper). All related geological and geophysical studies highlight the importance of this décollement layer in the evolution of the rift basins under study. As detailed above, efficient décollement along the Keuper evaporites and clays triggers mechanical decoupling and gliding of the pre-rift cover that remains in the center of the basin as the crust is laterally extracted. In response to crustal hyper-thinning and horizontal crustal extraction, hot mantle material approaches the detached pre-rift cover. As a consequence, HT-LP metamorphism develops in the pre-rift sediments and at the base of the syn-rift flysch levels as recorded in the NPZ and in the pre-rift sediments of the Cameros basin. Subsequent deposition of syn-rift sediments allows preservation of the initial thermal anomaly with a major consequence on the deformation regime in the pre-rift sediments and crustal basement. Temperature increase in the NPZ basins center progressively leads to the uprise of the brittle/ductile transition avoiding the development of prominent crustal normal faults and leading to the dominantly ductile thinning of the Paleozoic basement and parts of the pre-rift and syn-rift sediments (Clerc and Lagabrielle, 2014; Clerc et al., 2015b; Asti et al., 2019; Duretz et al., 2019). We may now question the paleogeographic distribution of the Keuper group sediments at the Europa-Iberia scale in order to evaluate a possible link between modes of rift development and the occurrence of a thick Keuper layer at the base of the pre-rift sequence.

Several extensional systems interacted in the Iberia platform during the Trias, resulting in the creation of intraplate basins or troughs including the Valencian, Basque-Cantabrian, and Pyrenean basins (figs. 1 and 13). The sedimentary infill of these platform basins continued throughout the Mesozoic. Seismic, well and field data from the Bay of Biscay region, the Pyrenees and the Aquitanian Basin, suggest initial thickness of Upper Triassic formations ranging from 1000 to 2700 m (James and Canérot, 1999; Biteau et al., 2006; Jammes et al., 2010a; Roca et al., 2011; Rowan, 2014; Lopez-Mir et al., 2014; Saura et al., 2016; Soto et al., 2017; Zamora et al., 2017). The salt-rich layers generally consist of shales and evaporites including dominant gypsum and minor halite and anhydrite (figs. 13 and 14). Paleogeographic reconstructions are available for the Triassic period at the scale of the Iberia-western Europa region (Dercourt et al., 1986; 1993; Ziegler, 1988; Ortí et al., 2017; Soto et al., 2017). The distribution of Triassic shales and evaporites is contrasted around the future Iberia plate margins. This paleogeography is confirmed by a compilation of data collected independantly by D. Frizon de Lamotte (fig. 13c). Evaporites are well developed along the eastern edge of Iberia (Tethys side) and in the rift opened at the place of the future NPZ, the Basque-Cantabrian basin, the Bay of Biscaye basin and the southern part of the Armorican margin. In the place of the future North Atlantic rift system, evaporites are restricted to the Peniche, Lusitanian, Alentejo and Algarve basins along the southern half of the Portugal margin and are lacking along the northern half of the Iberia Atlantic margin. Along the conjugate north American margin, evaporites are known at the base of the Jeanne-d'Arc basin and are of restricted extension compared to the Keuper group exposed in Central Europe (fig. 13b, c).

Finally, along the western half of the Iberia-Newfounland transect, evaporitic formation are not reported, whereas thick evaporites are reported from areas characterized by Parentis-type basins. As outlined in figures 13 and 14, this paleogeography matches the distribution of the two opposite types of basins discussed in this article (Parentis type vs. Iberia-Newfoundland type). Thus, we establish a link between the presence of a pre-rift salt layer and the deep mechanisms of crustal stretching. Because they remain in the center of the basin, evaporites contribute to the preservation of a rather high thermal gradient in the axial rift allowing a dominant-ductile deformation of the basement. The lack of a major décollement level at the base of the pre-rift sequence may explain by itself why pre-rift sediments remain welded and coupled to the basement on the top of tilted blocks in the Iberia-Newfounland-type margins as illustrated in figure 3a, b. Indeed, in the Iberia as well as in Alpine margin-types, only syn-rift sediments are deposited over the exhumed lower crustal levels and subcontinental mantle (Péron-Pinvidic et al., 2007; Péron-Pinvidic and Manatschal, 2009; Mohn et al., 2012), which contrasts with the evolution of the Parentis-type basins.

In this review, on the basis of examples clustering along the Iberia-Eurasia plates boudaries, we emphasize the major role played by the Upper Triassic evaporitic layer during extensional processes. In the reported smooth-slopes basin examples, cover gliding occurred on a pre-rift layer and thus contrasts with cases involving syn- to post-rift weak layers. The latter cases have been largely documented by studies of passive margins displaying thick syn-rift salt formations such as the Angola margin where the post-salt sedimentary units have glided gravitationally after the margin formation (e.g. Brun and Fort, 2011, and references therein, see also additionnal discussion relative to the pre-rift/post-rift salt effects during rifting in Jammes et al., 2010c). To sum up, the specific characters emphasized in this review are twofold : (i) the peri-Pyrenean salt is pre-rift allowing conservation of the pre-rift cover over the high-strain axial rift. Crustal faulting has not disrupted the continuity of the Triassic evaporite formation, allowing for décollement of the pre-rift sequence basinward, down to the distal margin. (ii) Consequently, the axial thermal anomaly is preserved and the dominant ductile mode of crustal deformation prevented the formation of faulting–related steps leading to smooth-slopes basin edges.

F. Time-dependent rheology during the evolution of smooth-slopes basins

From the statements listed at the end of section I as well as from the discussion above, we first stress that the models of Pyrenean Cretaceous rifting established on the basis of geological constraints from the NPZ differ significantly from the classical models of passive margin formation based on the Iberia-Newfoundland margins example (Peron-Pinvidic and Manatschal, 2009; Sutra et al., 2013; Osmundsen and Peron-Pinvidic, 2018, and references therein). The latter models involve a dominantly brittle behavior of the crust and the individualization of tilted faulted blocks bearing a concordant pre-rift cover permanently welded on their back (fig. 3). In the models based on the geology of the NPZ (e.g. models of Clerc et al., 2016; Teixell et al., 2016; Espurt et al., 2019), the external borders of the subsiding Cretaceous flysch basins remain at low temperature and display classical faulted and tilted blocks (e.g. half-grabens of Quillan basin, Camarade basin, Gensac-Bonrepos basin, western border of the Mauléon basin, Arbailles basin, edges of the Gran Rieu high and Lacq basin). By contrast, in the internal regions of the rift system (corresponding to the future metamorphic NPZ), the basement thinned in a dominant-ductile mode because temperature conditions reached 350°C to 450°C beneath the detached pre-rift cover and the syn-rift flysch.

The peculiar evolution of the NPZ basins is depicted on figure 15 based on an original model by Clerc et al., (2016). This model is strictly conceptual and was designed to account for geological constraints gathered from various sites along the NPZ. The simplified system includes the subcontinental mantle, a continental basement, a first decollement level in Triassic evaporites, a level of layered pre-rift carbonates and a cover of syn-rift flysch. The carbonates are able to deform by crystalline plasticity of calcite under HT conditions. The corresponding lithologies are illustrated and briefly described in the NPZ lithostratigraphical column of figure 5.

In order to better assess the time-dependent rheological changes that necessarily affect each geological layer involved during this three steps evolution, we provide synthetic rheological profiles and geotherms for selected parts of the basin: in the external portion representing the initial pre-extension model (fig. 15a) and in the center of the basin for the following two steps (fig. 15b and c). The data used to construct these profiles derived from the Duretz et al. (2019) model discussed in section D above.

The three steps of this conceptual evolutionary model can be described as follows:

(1) At an early rifting stage (fig. 15a) moderate extension leads to crustal thinning accommodated through normal faults in the upper crust. The rheological profile consists of a 15 km thick, cold and brittle upper crust (T > 300°C) overlying a 15 km thick ductile lower crust with Moho temperature around 550°C. The uppermost mantle is a strong 15 km thick layer. In the inner part of the system, normal faults may pass downward to ductile shear zones dipping toward the external side thus delineating a small central horst. The Triassic evaporitic layers act as a décollement layer that allows the pre-rift carbonates to remain in the most thinned and subsiding domains on both sides of the central horst while the syn-rift flysch is being deposited above. Sliding of the pre-rift carbonates in the deep domain results in the local tectonic denudation of the margins where carbonates remnants form isolated rafts tilted on listric faults.

(2) At the mid-rifting stage (fig. 15b), ductile thinning of the crust occurs in response to heating due to rapid mantle uplift. The central crustal horst starts to deform ductilely and progressively acquires a lens shape. Due to blanketing effect under the syn-rift sediments, the HT pre-rift carbonates suffer syn-metamorphic ductile deformation. Rheological profile

in the center of the basin shows the Keuper weak zone at the base of the pre-rift cover and a newly formed weak zone corresponding to the thinned crust which deforms at temperatures between 300°C and 500°C. The lower crust has been extracted laterally and the brittle mantle layer shows a decreasing thickness due to temperature increase from 400°C (step 1) to 1000°C at only 20 km depth.

(3) At the final rifting stage (fig. 15c), extreme thinning and boudinage of the crust leads to local denudation of the sub-continental mantle, which is by place in tectonic contact with the pre- or syn-rift sediments. The crust in the center of the basin has been cut into few lenses that move independently. The crust at both edges of the proximal domain thins and moves horizontally (*lateral extraction* concept of Clerc and Lagabrielle, 2014). The Triassic décollement layer undergoes drastic thickness reduction leading to boudinage in response to fluid-assisted tectonic brecciation and to metasomatic dissolution as observed in the Urdach and Saraillé massifs in the western NPZ (Lagabrielle et al., 2019a, 2019b in press). Due to their increasing plasticity, the HT marbles of the pre-rift cover progressively accommodate a large part of the deformation at the base of the basin, involving calcite plasticity and recristallization, boudinage, drag folding and low angle normal shear bands. In turn, the lower levels of the syn-rift flysch sequence are progressively affected by HT metamorphism and ductile deformation with bedding-parallel foliation and boudinage. Continuous extension of the basin floor leads also to the progressive exhumation of the metamorphic pre-rift sediments, which are progressively extracted from below the syn-rift cover (see complete description of this process in Clerc et al., 2016). In the thinnest crustal portion, the rheological profile bears similarities with that of step 2. The crustal thickness has now reduced to less than one km and the brittle/ductile transition has moved upward. The pre-rift cover, salt décollement as well as the thinned basement thus deform under dominant ductile deformation.

IV. Conclusions

Almost fourty years after the discovery of mantle exhumed at the foot of the north Iberia passive margin (Boillot et al. 1980), this review highlights the affinities between the architecture of two types of extensional basins now variously inverted in the Pyrenean orogeny. These are : (i) the extensional basins that opened during the mid-Cretaceous times along the Iberia-Eurasia plate boundary and, (ii) the intraplate basins of northern Iberia (Cameros to Columbrets basins). Taking as a reference the Parentis basin profile and on the basis of geological reconstructions of NPZ rift architecture, we have designed an idealized cross-section of a smooth-slopes basin shown in figure 16. The dominant features put forward in this cross-section relate to the basin central region which lacks stepping normal faults and large-scale tilted crustal blocks. The section shows a dominant symmetrical shape with smooth-slopes that relates to a new mode of crustal stretching during continental rifting characterized by a ductilely thinned crust in the central rift domain. This deformation mode is typically symmetrical and contrasts drastically with stretching processes described from the Iberia-Newfoundland and Alpine Tethys margins implying asymmetrical architecture and extensional detachment separating upper and lower plates having differential evolution.

The common character between all pre-rift sequences of the studied basins is the presence of the thick low-strength Late Triassic evaporitic layer (Keuper facies). Geological and geophysical studies point to the importance of this décollement layer in the evolution of these rift basins. As established by geological studies in the NPZ, efficient décollement along the Keuper evaporites and clays triggers mechanical decoupling and gliding of the pre-rift cover that remains in the center of the basin as the crust is laterally extracted. Subsequent deposition of syn-rift sediments allows preservation of the initial thermal anomaly with a major consequence on the deformation regime in the pre-rift sediments and crustal basement. The ubiquitous character of the ductilely deformed marbles in the metamorphic NPZ relates to a dominant-ductile deformation regime in the pre-rift cover during the Cretaceous extension. In these smooth-slopes basins, the ductilely stretched crust behaves homogeneoulsy at the regional scale and extensional allochthons are not individualized. A lenticular mode of homogeneous deformation is thus defined implying interplay between hectometric lenses of ductile crustal material separated by anastomozing shear zones.

Both laboratory and thermo-mechanical numerical models reproduce remarkably the mode of deformation deduced from geophysical and geological constraints compiled in the studied basins. Thus it appears that the pre-rift character of the salt layer is the key-factor of the rifting style in controlling the very early decoupling between the basement and the pre-rift cover. This strongly contrasts with the evolution of Atlantic margins where the salt is either syn-rift or post-rift. For the first time, we evidence a strong link between the occurrence of a sedimentary layer covering the future rifted region (here Keuper salt and clays deposits) and a mode of crustal thinning (here homogeneous bulk ductile deformation). Décollement along the evaporites and clays level finally favors the formation of symmetrical basins lacking numerous normal faults and related tilted blocks. This new mode of crustal deformation might not be restricted to the Pyrenean region, but may apply to all regions hosting thick pre-rift décollement series. It may have been active worldwide, in the distal portion of continental margins devoid of typical tilted blocks and extensional allochthons and where large units of extremely thinned continental crust are present.

To sum up, the specific characters of the smooth-slopes basins emphasized in this review are twofold: (i) the peri-Pyrenean salt is pre-rift allowing conservation of the pre-rift cover over the high-strain axial central region. The continuity of the Triassic evaporite formation is preserved allowing for décollement of the pre-rift sequence which remain in the basin center. (ii) Consequently, the axial thermal anomaly is preserved and the dominant ductile mode of crustal deformation prevents the formation of faulting–related steps, thus leading to smooth-slopes basin edges. Continuous sedimentation in the subsiding basin leads to progressive sedimentary burial of the prerift sequence. This in turn allows the preservation of the initial thermal anomaly that may grow during the rifting evolution.

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Figure captions

Figure 1. Location of the studied basins and their paleogeographic position during the Cretaceous at the onset of the Iberia drift.

(a) Simplified structural map of the Cantabrian-Pyrenean orogenic system and adjoining Iberia showing Eurasia deformed and undeformed domain (modifed from Verges and Garcia-Senz, 2001 and Teixell et al., 2018). (b) Hypothetical reconstruction at the onset of the Iberia drift (modified after Tugend et al., 2014).

Figure 2. A compilation of Cretaceous basins architecture from the Cantabrian-Pyrenean belt.

Reconstructions from field and geophysical data collected by various authors in the Basque-Cantabrian basin (a, b, c) and in the North Pyrenean Zone (NPZ): Mauléon basin (d), Chainons Béarnais (e, f), Baronnies basin (g) and Agly massif-Boucheville basin (h).

Figure 3. Structure and evolution of Iberia-Newfoundland-type and Alpine-type passive margins (modified from Péron-Pinvidic and Manatschal, 2009 and Mohn et al., 2012).

(a): two sketches showing the main concepts linked to Iberia-Newfoundland-type margin evolution, namely: (i) strong final asymmetry with upper and lower plates separated by a single detachment fault (HHD, Hobby High detachment), (ii) emplacement of extensional allochthons as rigid crustal blocks over the exhumed mantle. (b): strain distribution and strain partitioning during lithospheric thinning at magma-poor rifted margin, with example from the fossil Alpine Tethys margin. In this model, the pre-rift cover remains welded on the tilted crustal blocks; the middle crust is thinned to zero and the upper crust and upper mantle are juxtaposed at the break up stage. The concepts shown in (a) and (b) contrast with the concepts attached to the smooth-slopes basins evolution developed in this paper.

Figure 4. The geological record of the Cretaceous extension in the Paleozoic basement and exhumed mantle of the North Pyrenean Zone (NPZ).

The map shows the location of mantle bodies and crustal units illustrated in photographs a to k. (a): dated crustal mylonites associated with the Urdach lherzolites; thin section microphotograph (natural light) of the leucocratic gneissic mylonite exposed at Col d'Urdach and containing numerous micafishes (dating by the Ar/Ar method at 105 Ma; after Asti et al., 2019). (b): thin section of typical ultramylonite from the lenses of Paleozoic material welded on the exhumed mantle rocks of the Saraillé lherzolite (Asti et al., 2019). (c): phacoidal fabric defined by anastomozing shear zones in the mantle body of Bestiac. This fabric is typical of the lenticular layer as defined by Lagabrielle et al. (2019a, 2019b). (d): phacoidal fabric in the lenticular layer of the lherzolite body of Moncaup. (e): phacoidal fabric in the lenticular layer of the lherzolite body of Saraillé (Lagabrielle et al., 2019b). (f): curved shear zones and elongated tectonic lenses in serpentinized lherzolites of the lenticular layer in the Moncaut peridotite body. (g and h): phacoidal fabric in the lenticular layer of the lherzolite body of Urdach: h shows pervasive carbonation (Lagabrielle et al., 2019a). (i and j): thin section and outcrop of anastomozing serpentinized shear bands in the lherzolites of Etang de Lers (Lherz). (k): anastomozing serpentinized shear bands in the lherzolites of Avezac.

Figure 5. The geological record of the Cretaceous extension in the pre-rift cover of the metamorphic North Pyrenean Zone (NPZ). Some field view of outcrops showing the layer perpendicular flattening and the S0/S1 syn-metamorphic foliation.

(a): layer-parallel boudinage in the Calce quarry (Jurassic dolostones of the Agly massif cover, Eastern NPZ). (b): layer-parallel ductile stretching of the meta-laterite and carbonate breccia in the Benou quarry near Turon de la Tecouère lherzolite body (Chainons Béarnais, Western NPZ). (c): flattened fossils in the Jurassic meta-dolostones of the Saleix valley (Aulus basin, Central NPZ). (d): extreme stretching of a rudist-rich Urgonian marbles at Sarrance (Chainons Béarnais, Western NPZ) (see also fig. 6c). (e): tight normal faults affecting the early S0/S1 syn-metamorphic foliation in the pre-rift cover marbles of the Agly massif. These features characterize the ductile-brittle transition that occurred at the end of the rifting history. (f): same features as (e) but in the marbles of the detached Lherz body cover (southern side). (g): recumbent folds associated with the early ductile foliation in marbles from the detached cover of the Pays de Sault Paleozoic basement (Eastern NPZ). (h): tectonic brecciation with calcite veining marking the ductile-brittle transition in the marbles of the Lherz body cover (western side).

Figure 6 . A theoretical log of the lithological succession in the internal domain of the

Cretaceous NPZ rift basins.

The photographs illustrate the various rock-types forming the basin basement (crust and mantle) and the pre-rift and syn-rift series. (a): Chaînons Béarnais (Saraillé massif, western NPZ). (b): Boucheville basin (eastern NPZ). (c): Urgonian at Sarrance (western NPZ) (see also fig. 5d). (d): Jurassic dolomites at Calce (eastern NPZ). (e): base of pre-rift series (Bestiac, eastern NPZ). (f): base of pre-rift series (Moncaup, central NPZ). (g): crustal lenses of Saraillé massif (western NPZ). (h): lenticular layer (Urdach mantle body, western NPZ).

Figure 7. Interpretated and reconstructed profiles of peri-Pyrenean Cretaceous basins architecture.

(a): Parentis basin. (b): Columbrets basin. (c and d): Cameros basin. See location of basins in fig. 1.

Figure 8. A compilation of model results and conceptual representations of extended to hyper-extended continental crust.

This compilation aims enhancing the main mechanical concepts involved in the processes of crustal extension and how they apply or not apply to the genesis and evolution of the smooth-slopes basins defined in this article (see text for discussion).

Figure 9. A compilation of reconstructed architecture of Pyrenean Cretaceous basins and a Basque-Parentis transect.

All represented sections are based on the activation of a restricted number of detachment faults. As discussed in text, such representations do not match the newly defined smooth-slopes architecture that characterize the Pyrenean and peri-Pyrenean Cretaceous basins.

Figure 10. Deformation regimes of the various units composing a typical smooth-slopes basin.

(a): distribution of pure shear and simple shear regimes in a simplified smooth-slopes basin system. (b): Detail of the very distal part of the hyper-extended crust (area shown in a). (b1): simplified log showing the association of metric to hectometric crustal lenses separated from the mantle rocks by the crust-mantle detachment and from the detached pre-rift cover by the cover décollement (see definition in Lagabrielle et al., 2019a, 2019b). (b2): field view of crustal sheets from the base of the Saraillé massif (western NPZ). (b3): field view of anastomozing shear zones cutting trough the serpentinized peridotite of the Saraillé body and forming the lenticular layer of the crust-mantle detachment (see also fig. 4c to k).

Figure 11. A compilation of schematic architecture of selected Atlantic and Mediterranean passive margins.

These margin profiles are selected because they offer architectures which do not fit with the Iberia-Newfoundland-type margin (see fig. 2). In particular, they show large scale crustal boudinage and lenticulation that are consistent with a ductile regime of extensional deformation. Sheets of hyper thinned crutal material is indicated by the orange arrow (see comments in text). Note that scale is similar in all profiles.

Figure 12. Three numerical models of rift development compared to the Angola-Brazil and Iberia transects.

All models highlight a mode of deformation that leads to the development of very thin and long sheets of crustal material also observed in the Angola-Campos transect but not in the Iberia transect. Such deformation necessarily imply a ductile behaviour of the crust consistent with processes acting in the central part of the smooth-slopes basins studied in this paper (see text for further comments).

Figure 13. Paleogeography of Triassic deposits and Cretaceous rifting around the Iberia plate.

(a): paleogeographic maps for the Triassic period (modified from Orti et al., 2017) and location of some further Cretaceous rifted regions. Note that by contrast to the area where Cretaceous smooth-slopes basins will open, the area corresponding to the future Iberia-Newfoundland conjugate margins are devoid of thick evaporitic series. (b): paleogeographic maps for the Ladinian and Carnian (Middle-early Late Triassic times, 242-227 Ma) modified after Scotese and Schettino (2017). (c): paleogeography of Upper Triassic deposits prepared after a compilation of unpublished data by D. Frizon de Lamotte (pers. com.) superimposed on a plate reconstruction by Olivet (1996).

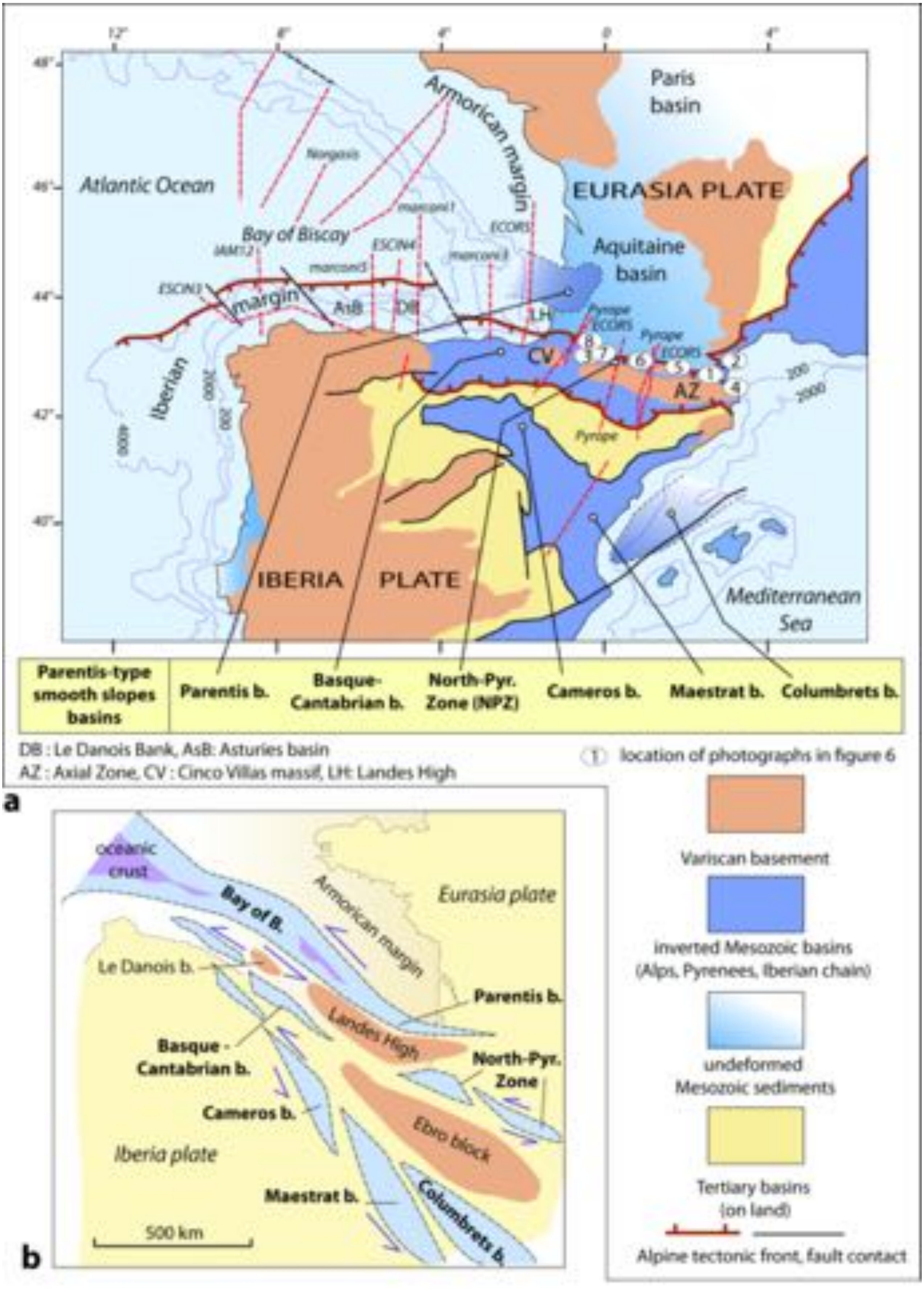
Figure 14. Correlation between the paleogeography of Triassic deposits and the mode of rifting around the Iberia plate.

(a): cartoons (a1 and a2) illustrating the contrasted rifting modes between the Iberia-Newfounland-type and the Parentis-type margins (modified from Clerc and Lagabrielle, 2014). (b): paleogeography of Triassic (Late Norian) deposits according to Marcoux et al. in the Dercourt et al. (1993) map atlas. As paleogeographic maps in fig. 13, this reconstruction points to the lack of thick evaporites deposits in the future Iberia-Newfounland rifting domain (see text for discussion).

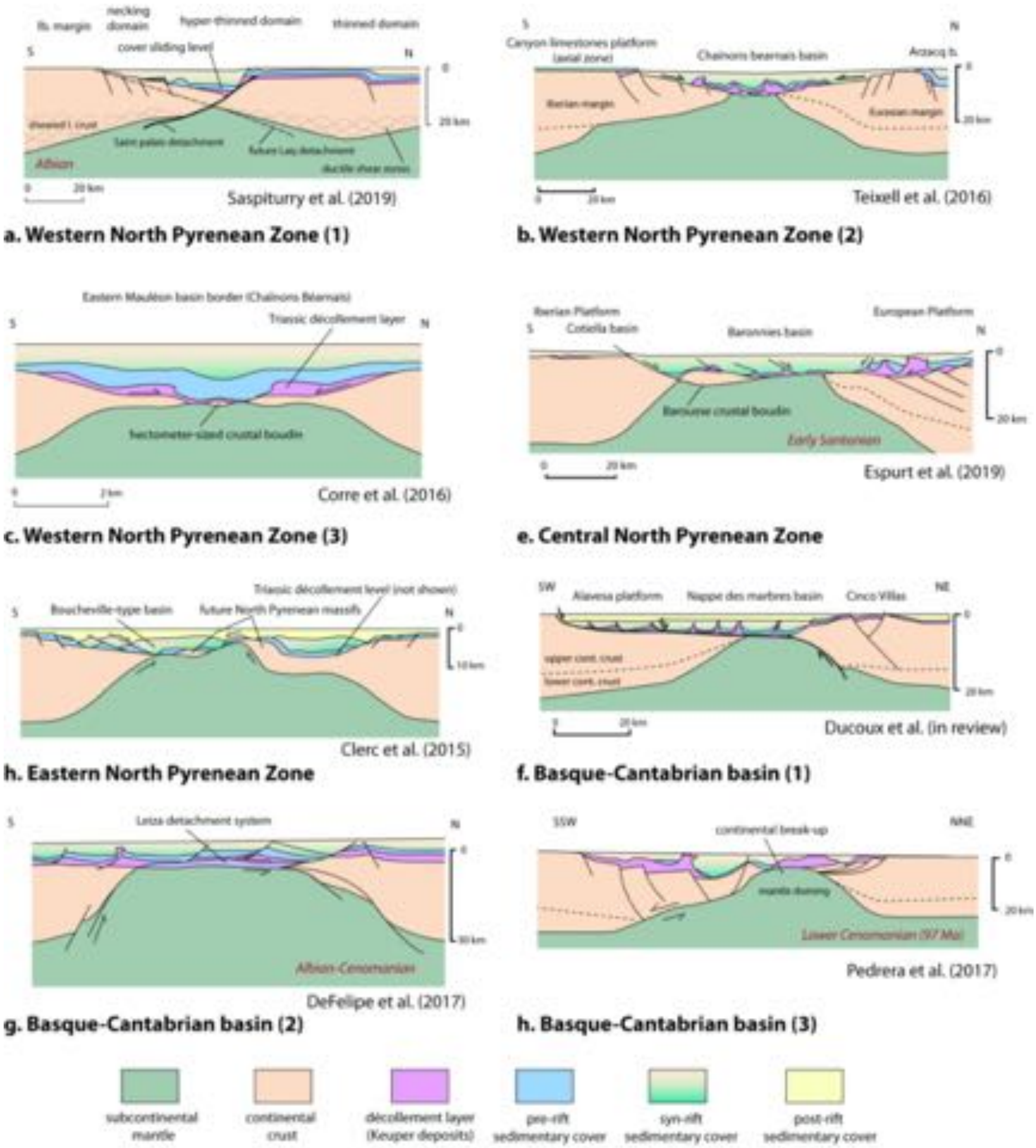
Figure 15. Time-dependent rheological evolution of the Pyrenean rifting based on geological constraints from the North Pyrenean Zone and numerical results from a thermo-mechanical numerical modeling.

Sketches depicting the geological evolution are extracted from the Clerc et al. (2016) model. Rheological profiles derive from the Duretz et al., (2019) model. They are placed at critical locations (1, 2 and 3) of the rift in order to emphasize the drastic changes in the mechanical behaviour during its evolution from limited crustal extension to local mantle exhumation (see detailed description in text).

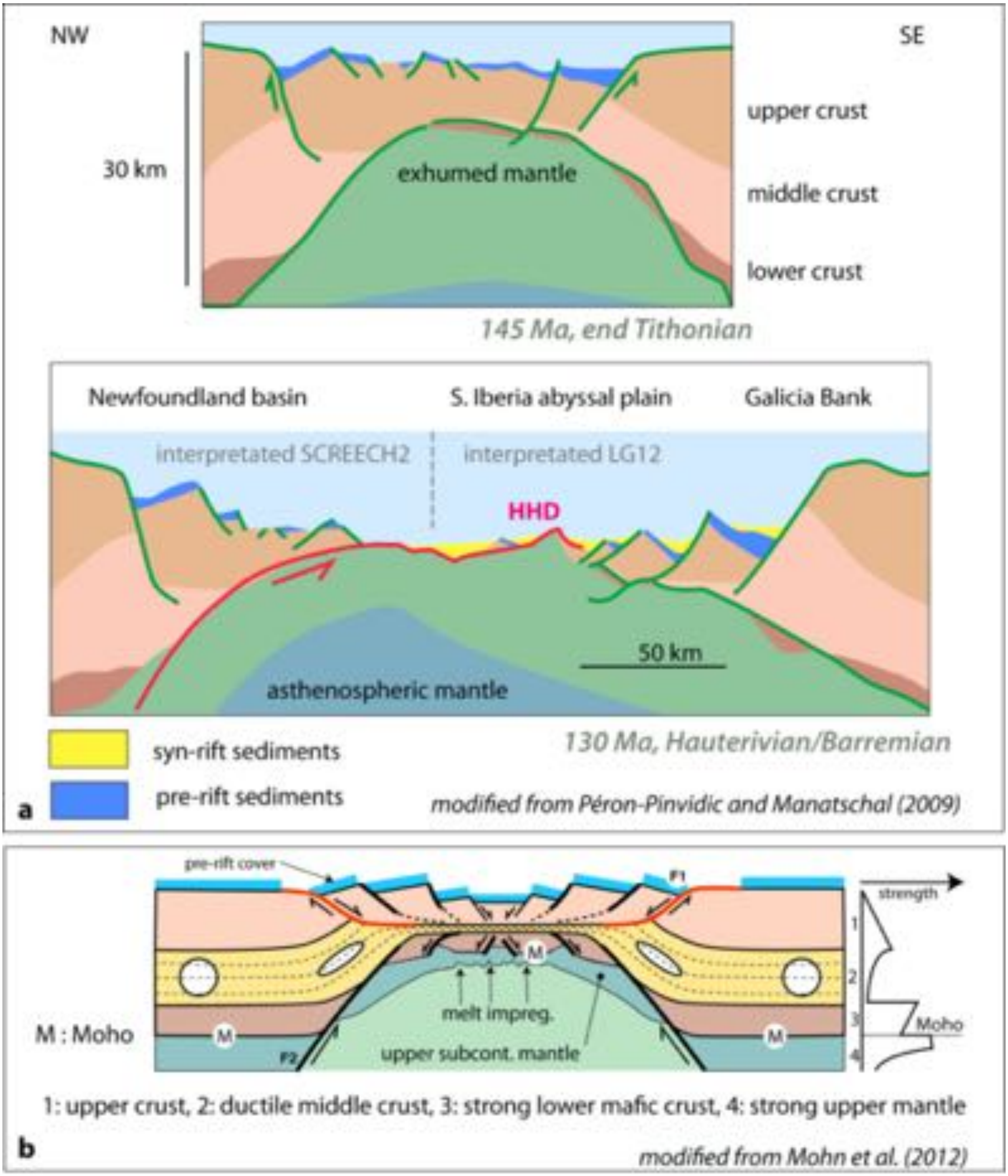
Figure 16. A theoretical structural model for the Cantabrian, Pyrenean and Iberian symmetrical smooth-slopes basins based on the features and concepts discussed in this article.



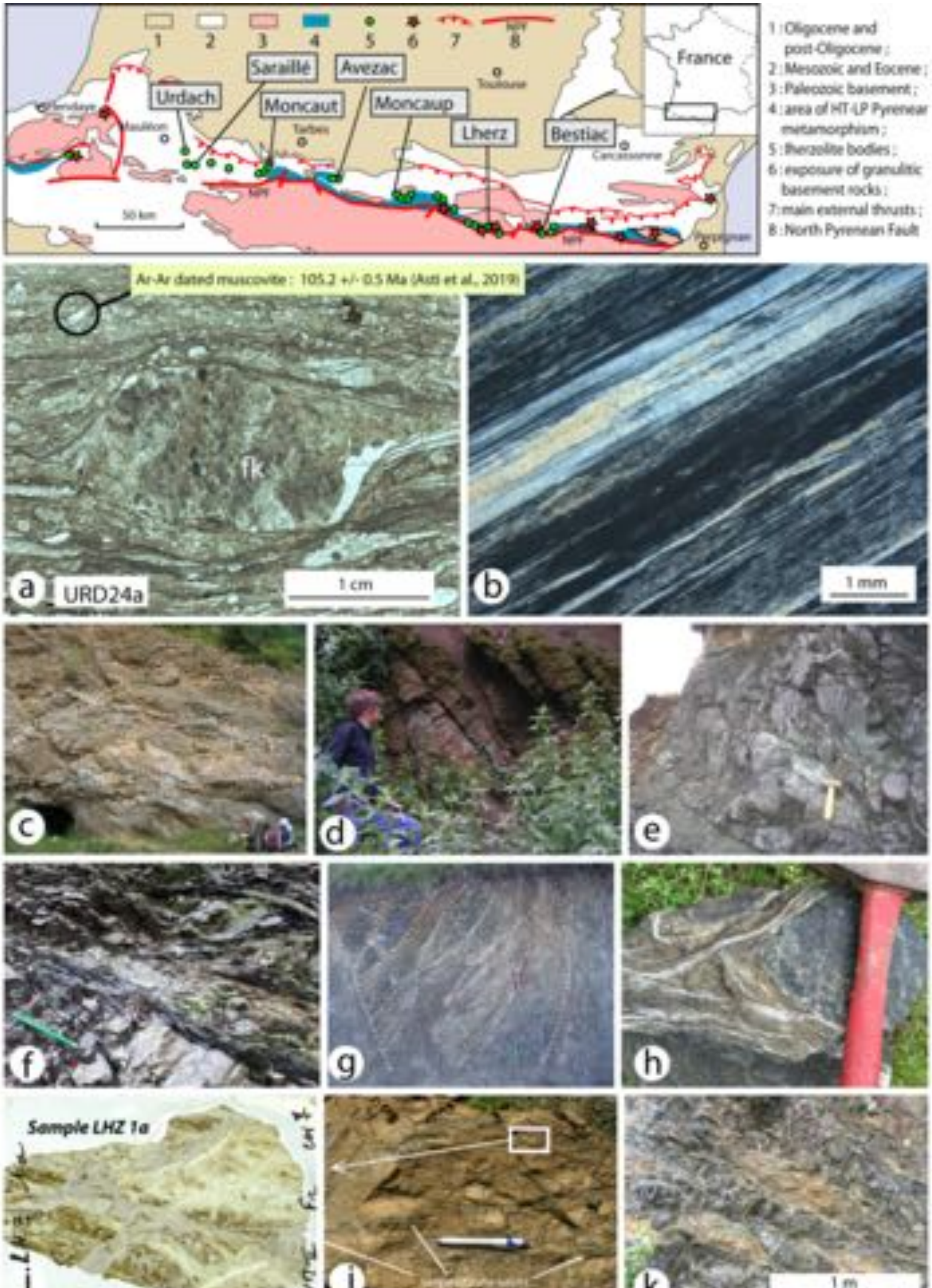
Lagabrielle et al., fig.1, ESR, submitted



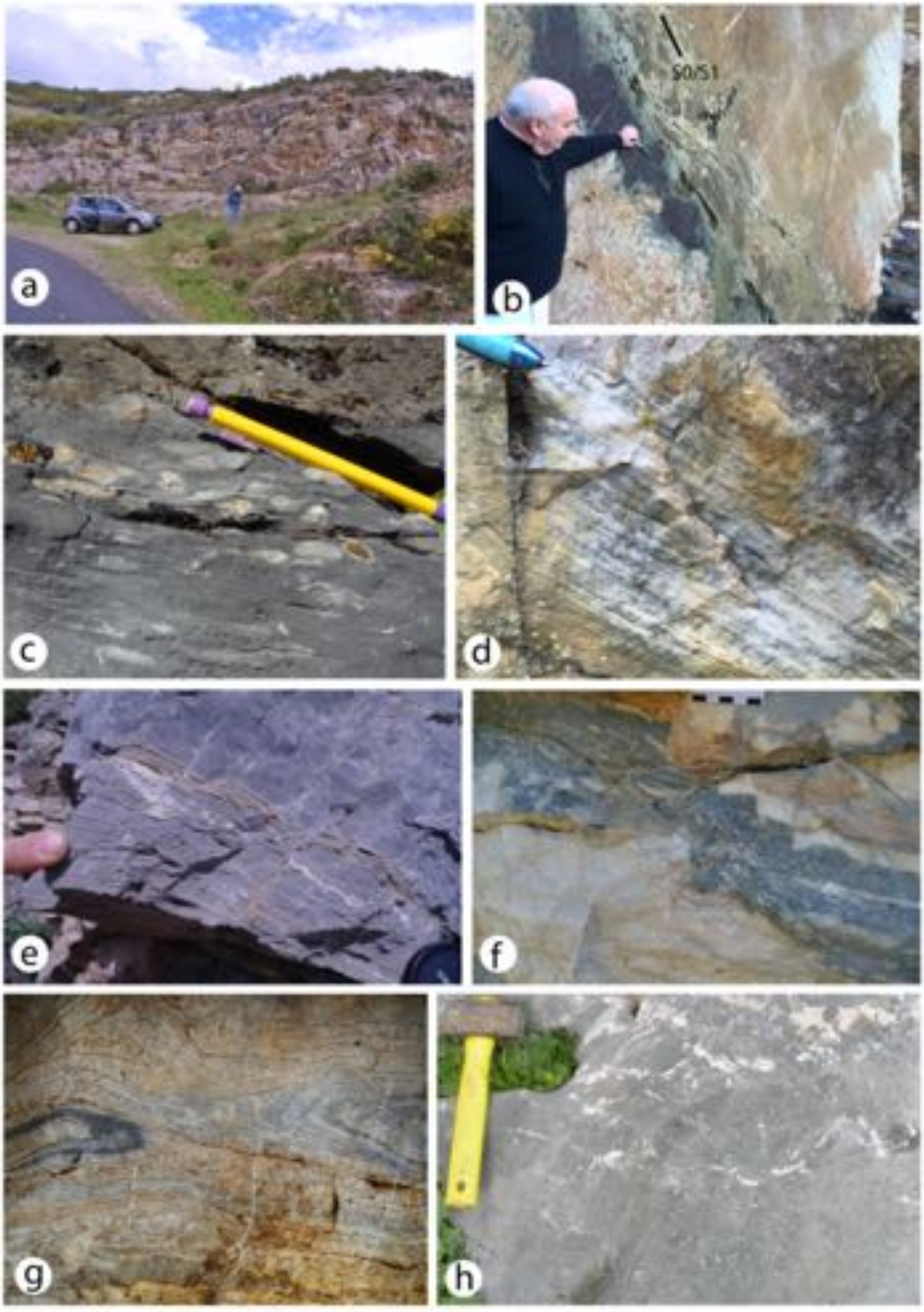
Lagabrielle et al., fig. 2, ESR, submitted



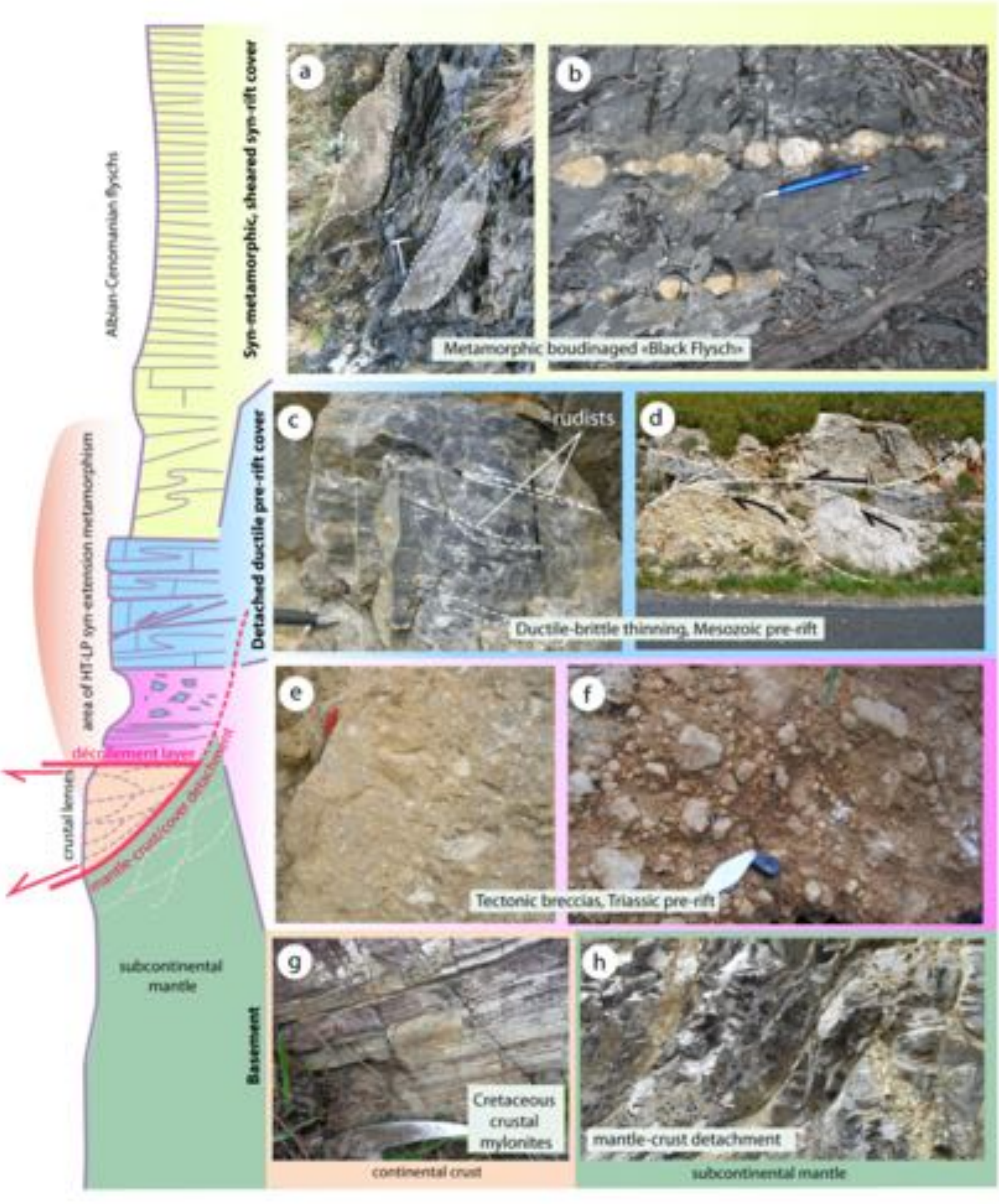
Lagabrielle et al., fig. 3, ESR, submitted



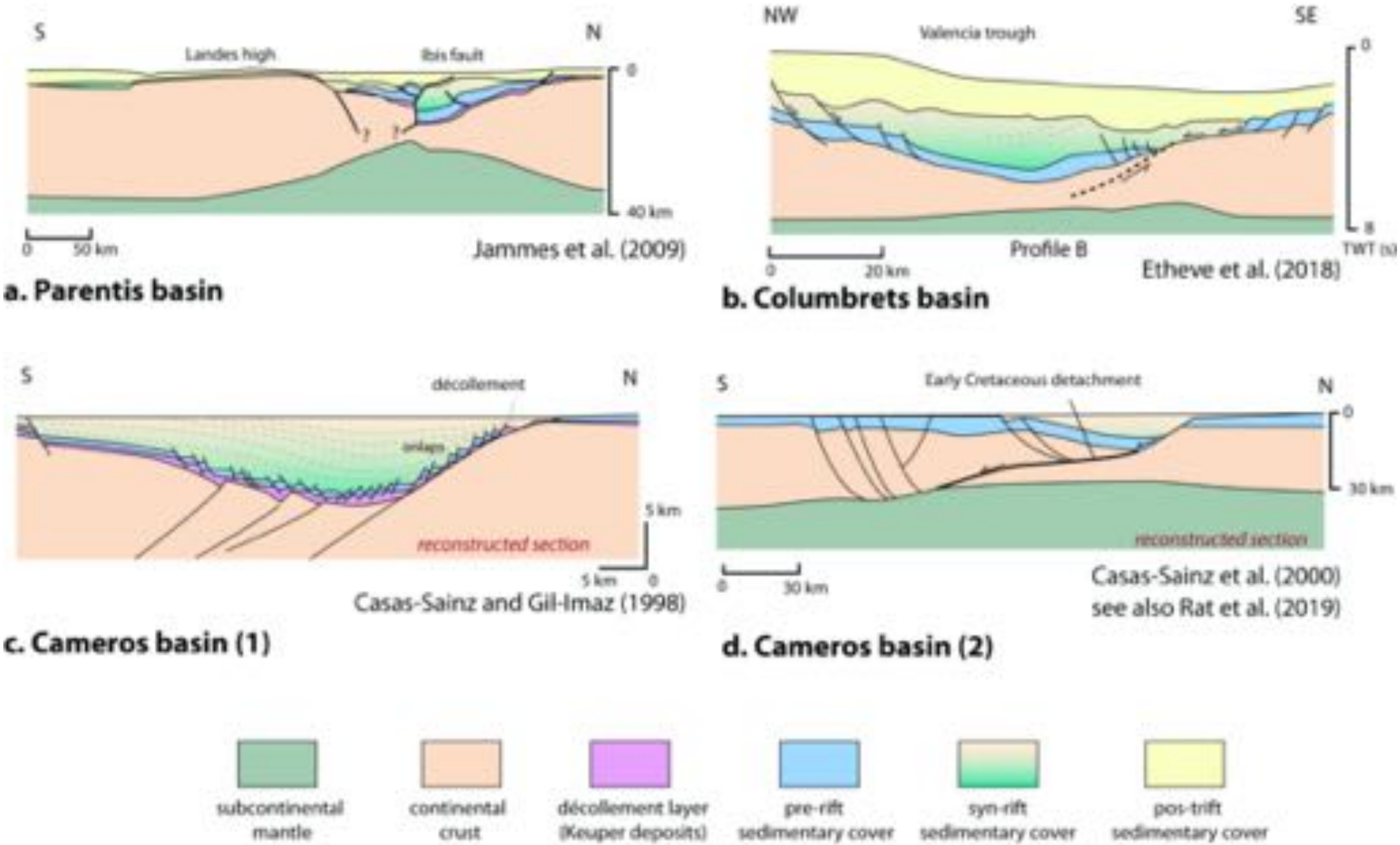
Lagabrielle et al., fig. 4, ESR, submitted



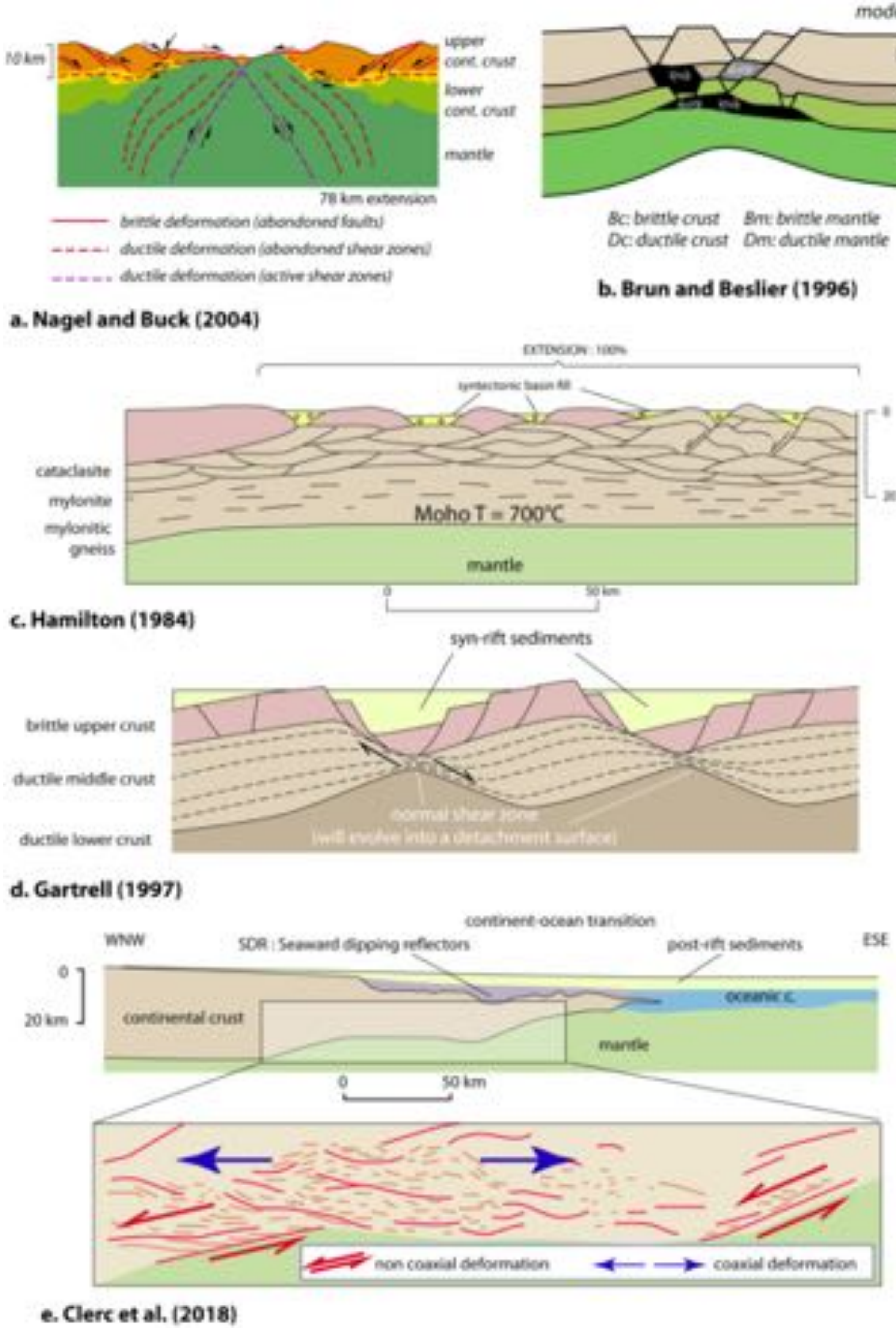
Lagabrielle et al., fig. 5, ESR, submitted



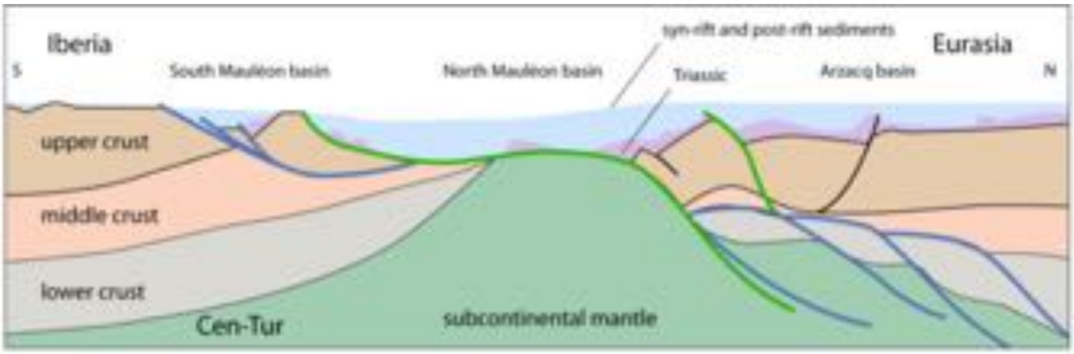
Lagabrielle et al., fig. 6, ESR, submitted



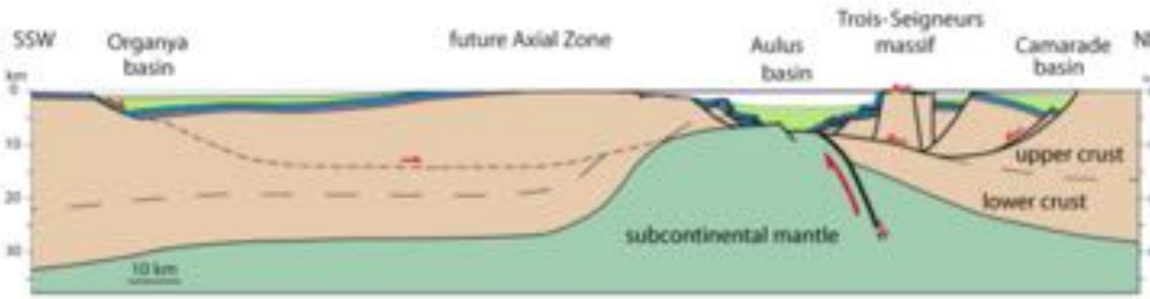
Lagabrielle et al., fig. 7, ESR, submitted



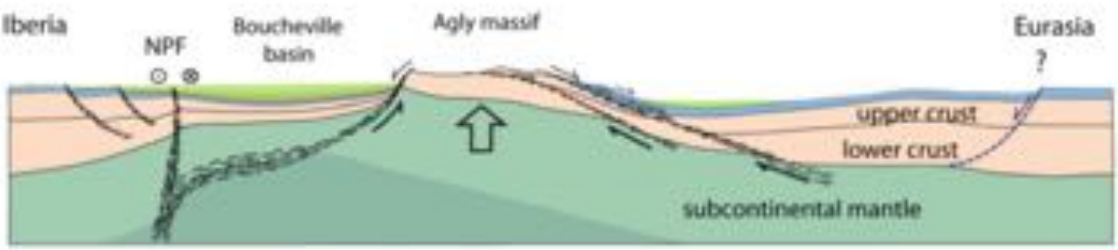
Lagabrielle et al., fig. 8, ESR, submitted



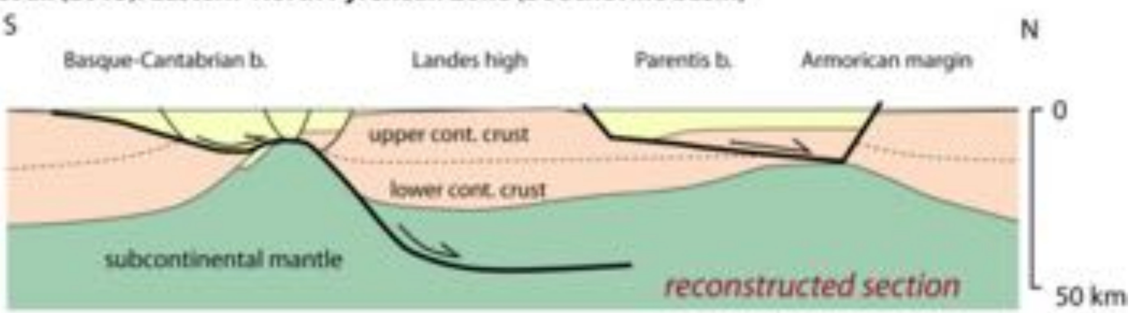
a. Masini et al. (2014): Mauléon basin



b. Lagabrielle et al. (2010): Central North Pyrenean Zone (Aulus basin, Etang de Lers)



c. Vauchez et al. (2013): Eastern North Pyrenean Zone (Boucheville basin)



d. Roca et al. (2011) : Basque-Parentis transect

Lagabrielle et al., fig. 9, ESR, submitted

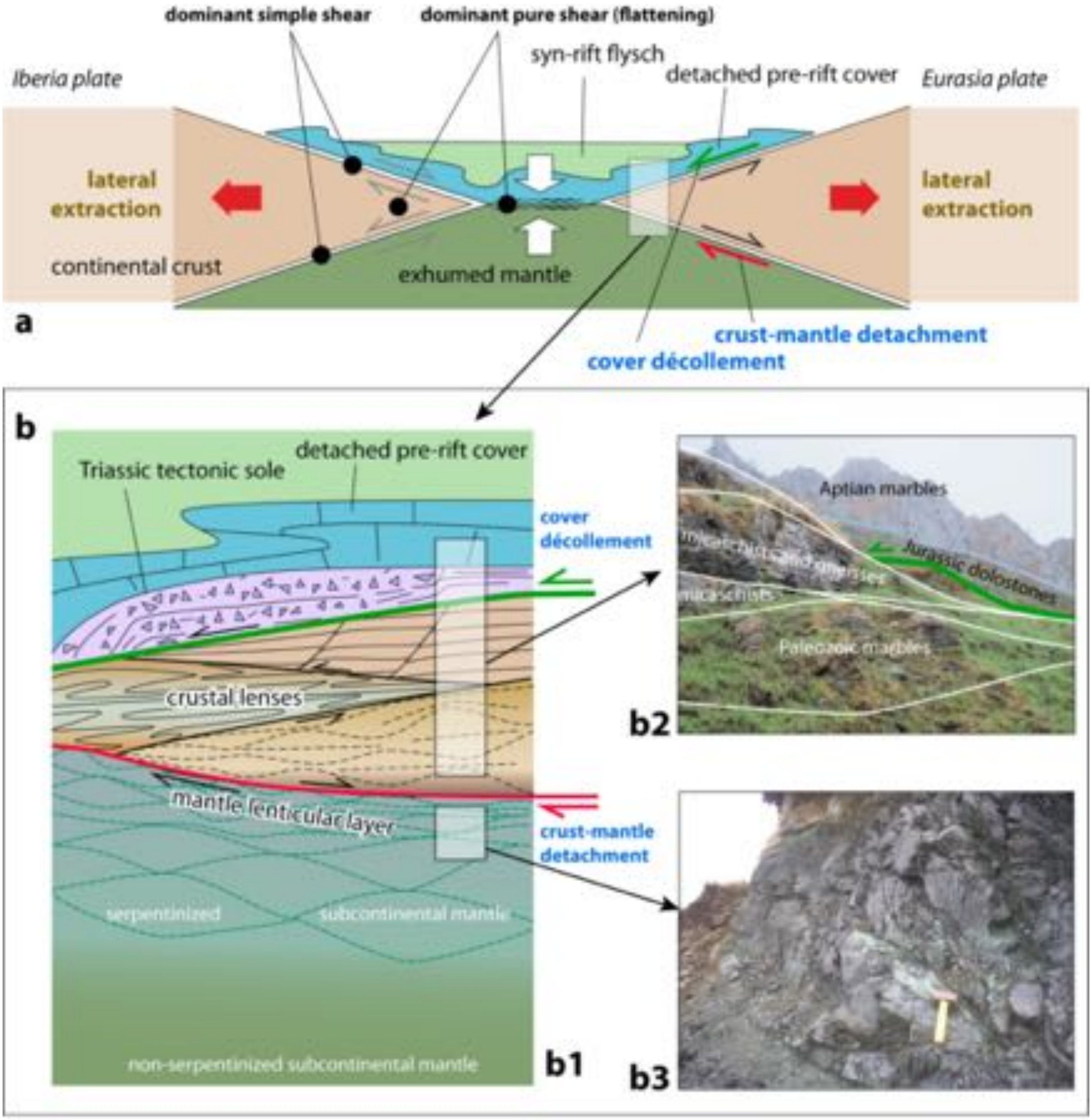
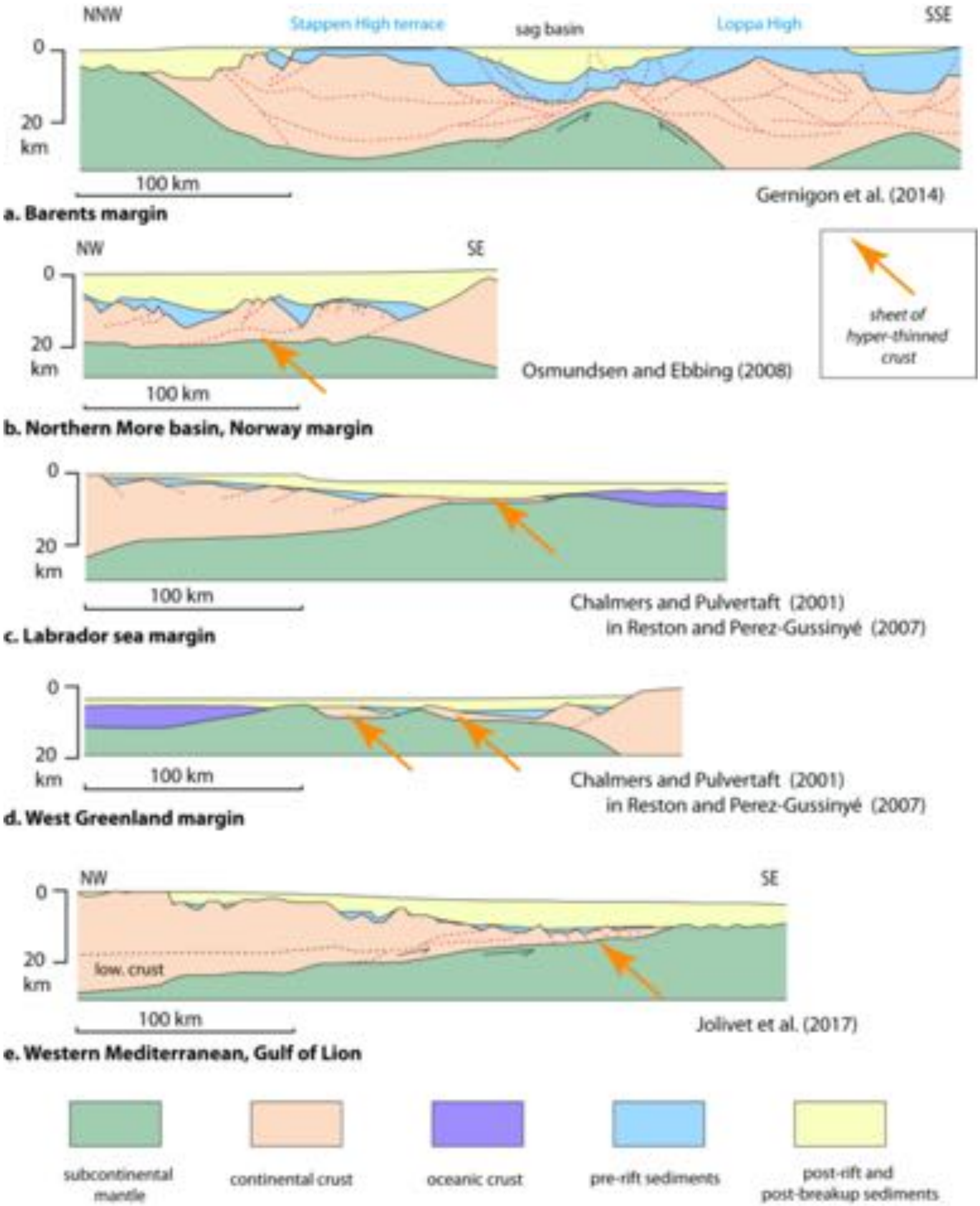
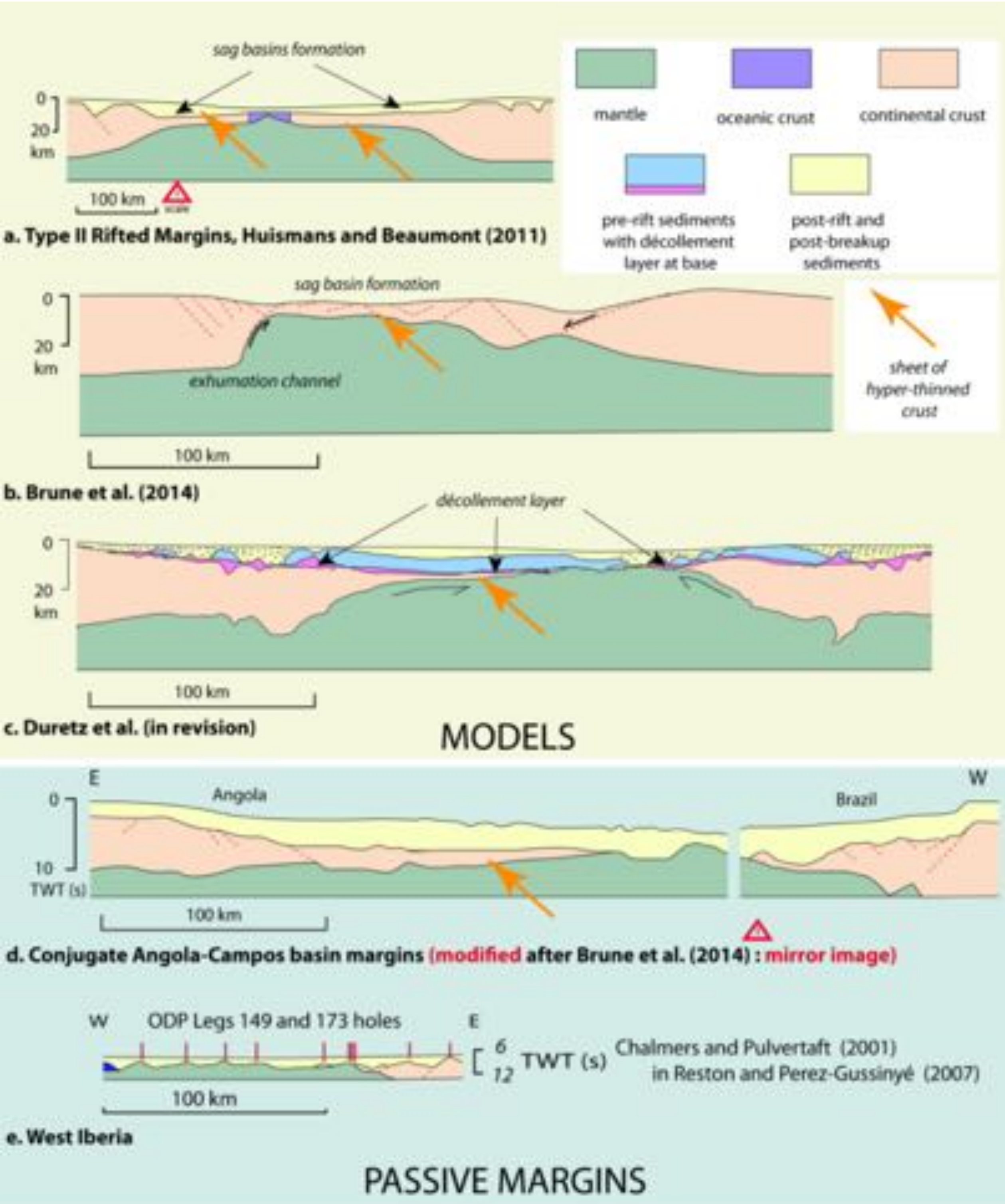


fig. 10

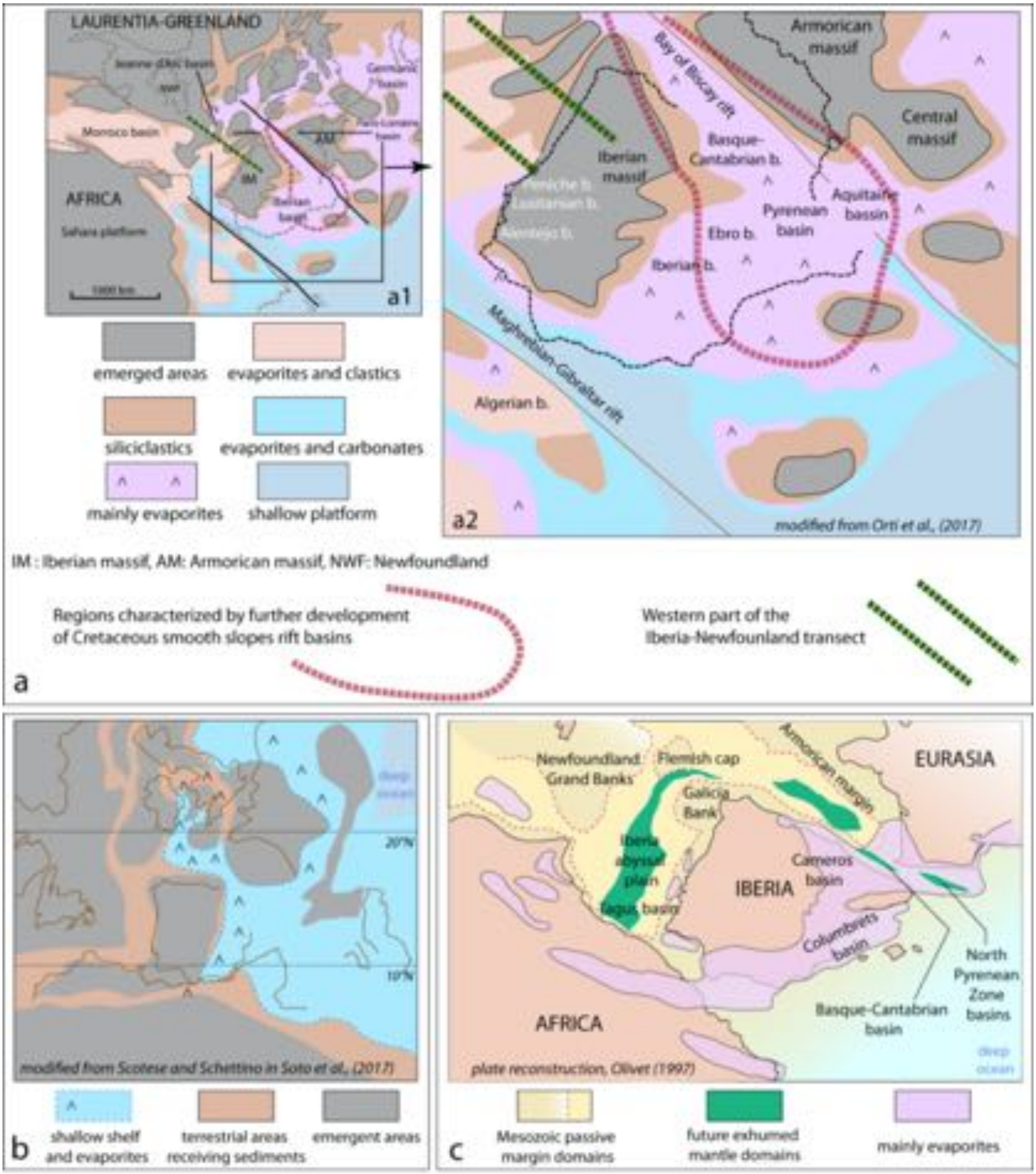
Lagabrielle et al., smooth slopes basins, submitted



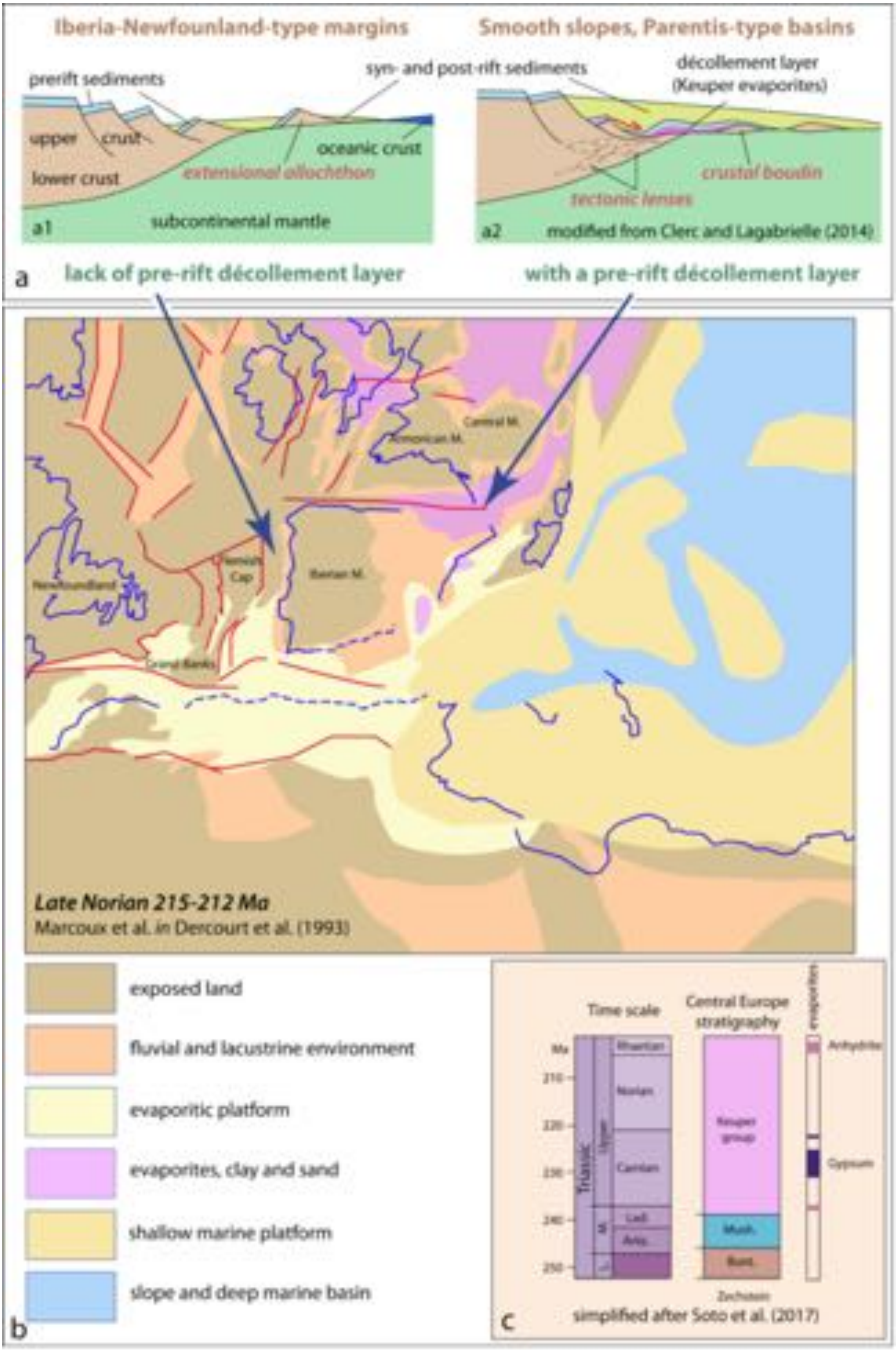
Lagabrielle et al., fig. 11, ESR, submitted



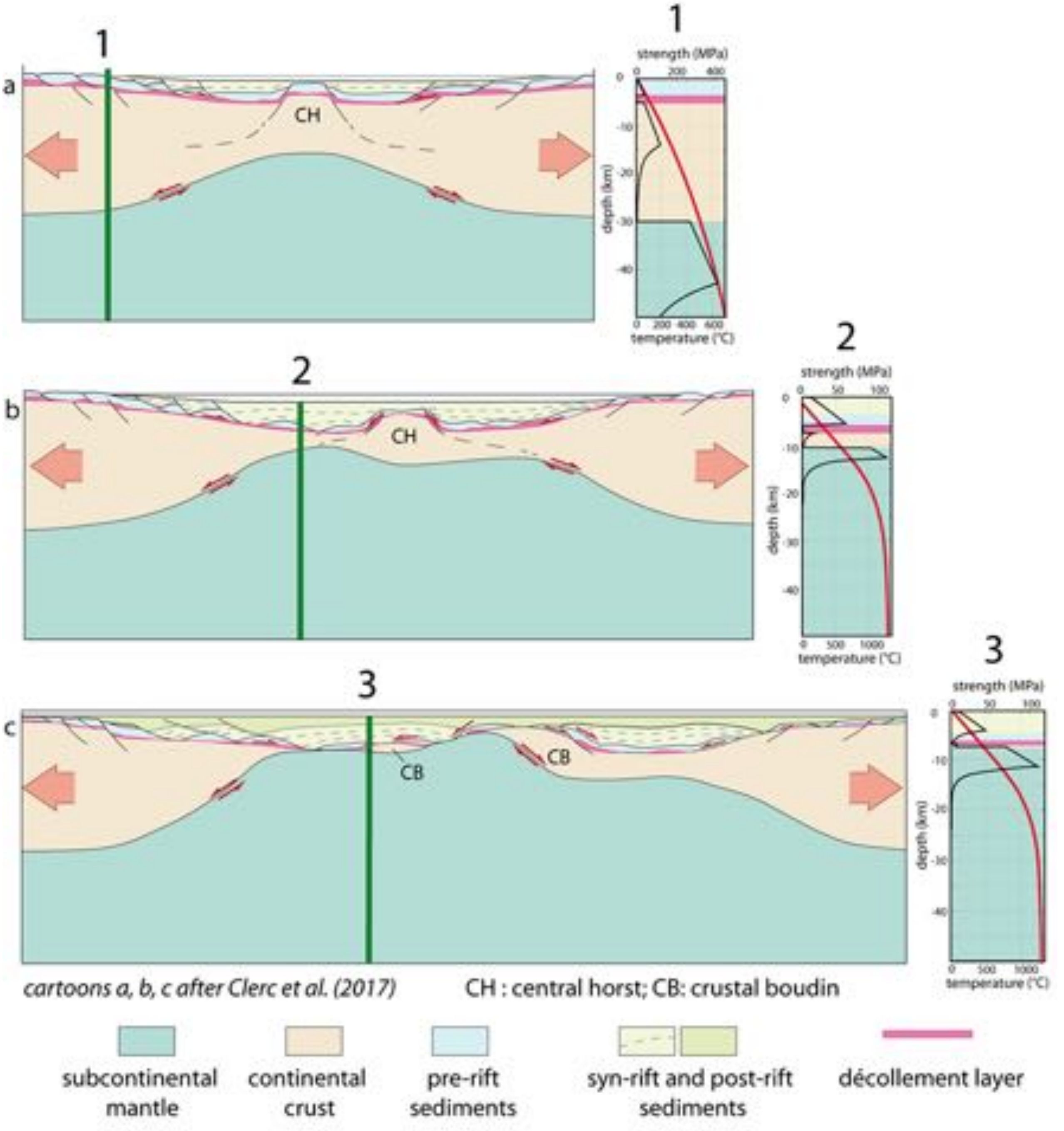
Lagabrielle et al., fig. 12, ESR, submitted



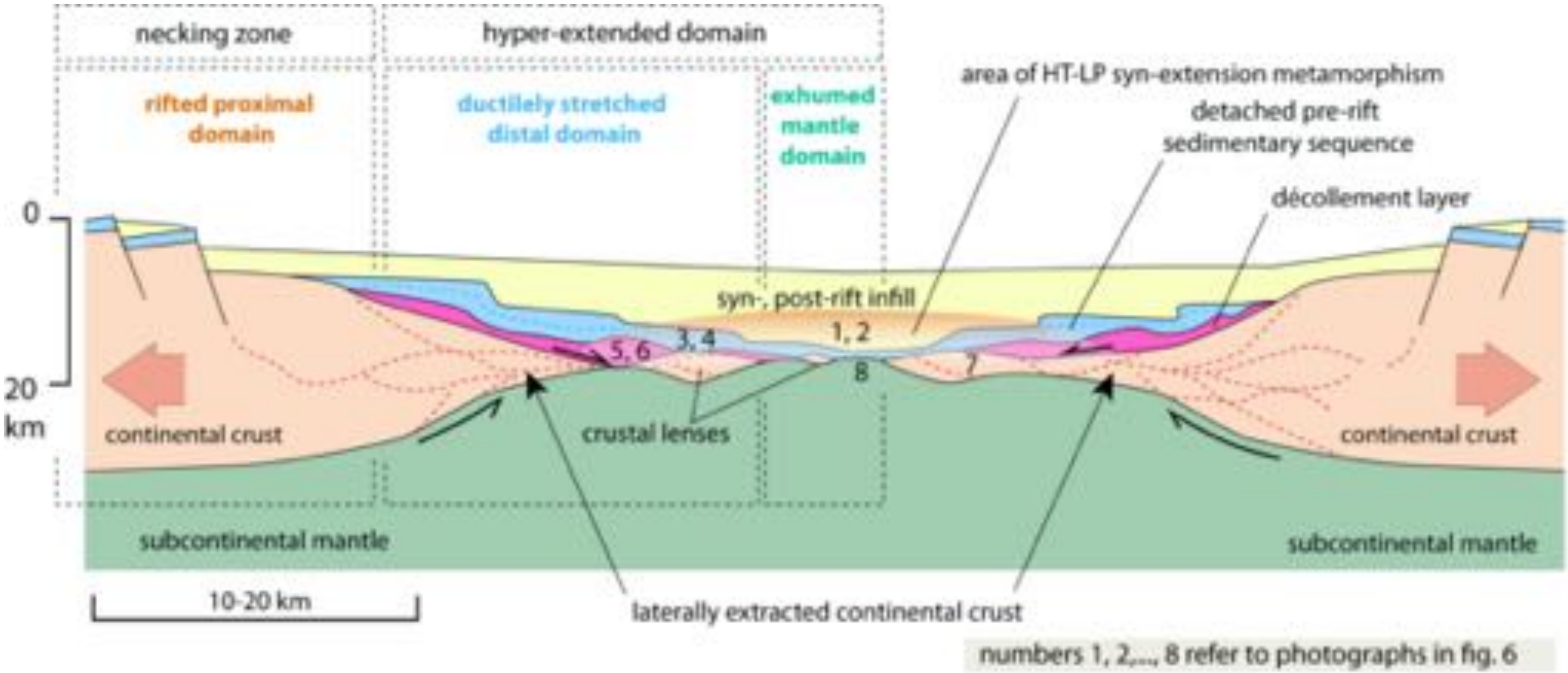
Lagabrielle et al., fig. 13, ESR, submitted



Lagabrielle et al., fig. 14, ESR, submitted



Lagabrielle et al., fig. 15, ESR, submitted



Lagabrielle et al., fig. 16, ESR, submitted