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# **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**

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8 **A review of Cretaceous smooth-slopes extensional basins along the Iberia-**  
9 **Eurasia plate boundary: how pre-rift salt controls the modes of continental**  
10 **rifting and mantle exhumation**  
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15 by :

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63 **34 Key words** : Smooth-slopes basins; symmetrical profile; Iberia; Eurasia; Triassic evaporites;  
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65 décollement layer; thermal anomaly; sedimentary burial; dominating-ductile tectonic  
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67 regime.

68 **37 Short abstract (for submission)**

69 We enhance a striking correlation between the paleogeography of Upper Triassic deposits  
70 and the mode of crustal stretching of the north Iberia plate during the Cretaceous  
71 transtensional event. The basins which opened during the mid-Cretaceous times along the  
72 Iberia-Eurasia plate boundary (like the emblematic Parentis basin) exhibit a peculiar  
73 synclinal-shaped profile and are devoid of prominent block faulting. The top of the basement  
74 is characterized by gentle slopes dipping symmetrically towards the basin center. Based on a  
75 comparison with rifting models established from the North Pyrenean Zone, this architecture  
76 appear to result from the thinning of the central basin continental crust under dominating-  
77 ductile deformation in greenschist facies conditions. The common character shared by all  
78 the pre-rift sequences of the studied basins is the presence of a thick low-strength Upper  
79 Triassic evaporites and clays layer belonging to the Keuper group and forming a thick pre-rift  
80 low-strength unit. Efficient décollement along this layer triggers mechanical decoupling and  
81 gliding of the pre-rift cover remaining in the basin center as the continental crust is laterally  
82 extracted. Using recent paleogeographic reconstructions, we show that the distribution of  
83 the Keuper sediments remarkably matches the distribution of the Pyrenean and peri-  
84 Pyrenean, Parentis-type basins. This allows for the first time to propose a genetic link  
85 between the distribution of evaporite-bearing pre-rift sedimentary formations and the  
86 development of smooth-slopes rift basins.  
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93 **58 Abstract**

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95 This article enhances for the first time a striking correlation between the paleogeography of  
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97 Upper Triassic deposits and the mode of crustal stretching around and inside the Iberia plate  
98 during the Cretaceous transtensional event. In a first step, we propose a review of the  
99 architecture of the basins which opened during the mid-Cretaceous times along the Iberia-  
100 Eurasia plate boundary. Like the emblematic Parentis basin, all these basins exhibit a  
101 peculiar synclinal-shaped profile and are devoid of prominent block faulting. The top of the  
102 basement is characterized by gentle slopes, which dip symmetrically towards the center of  
103 the basins. Based on a comparison with recent geologically-based rifting models established  
104 from the North Pyrenean Zone, we propose that this architecture results from the thinning  
105 of the central basin continental crust under dominating-ductile deformation in greenschist  
106 facies conditions. The common character shared by all the pre-rift sequences of the studied  
107 basins is the presence of a thick low-strength Upper Triassic evaporites and clays layer  
108 belonging to the Keuper group and forming a specific pre-rift salt unit. In the studied basins,  
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123 73 efficient décollement along the Keuper evaporites and clays triggers mechanical decoupling  
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125 74 and gliding of the pre-rift cover that remains in the center of the basin as the continental  
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127 75 crust is laterally extracted. Thus, during the early rifting phase, the basement undergoes  
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129 76 thinning while the pre-rift cover remains preserved in the basin center. In response to hyper-  
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131 77 thinning and horizontal extraction of the continental crust, hot mantle material approaches  
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133 78 the detached pre-rift cover. The major consequences of this central basin thermal anomaly  
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135 79 are twofolds: (i) the ductile deformation of the thinned continental crust beneath the  
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137 80 detached pre-rift units, and (ii) the development of HT-LP metamorphic conditions in the  
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139 81 pre-rift sediments and at the base of the syn-rift flysch levels. This thermal event is well  
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141 82 recorded in the axial portion of the Pyrenean realm (future North Pyrenean Zone) as well as  
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143 83 in the pre-rift sediments of the Cameros basin (northern Spain). Continental stretching is  
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145 84 accommodated by shearing in the bulk upper and middle crust leading to the formation of  
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147 85 thin tectonic lenses of mylonitic crustal material remaining welded on the exhuming mantle.  
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149 86 The architecture of the smooth-slopes, Parentis-type basins studied in this article thus  
150  
151 87 contrasts with the structure of the Iberia-Newfoundland Atlantic margins which are  
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153 88 characterized by (i) top-basement detachment faults accommodating crustal extension  
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155 89 through rotation and translation of undeformed basement blocks, and (ii) by the  
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157 90 individualization of continental extensional allochthons lying tectonically over exhumed  
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159 91 lower crust or mantle rocks. Finally, using recent paleogeographic reconstructions, we show  
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161 92 that the distribution of the Keuper evaporites and clays remarkably matches the distribution  
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163 93 of the Pyrenean and peri-Pyrenean, Parentis-type basins. This allows for the first time to  
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165 94 propose a genetic link between the distribution of evaporite-bearing pre-rift sedimentary  
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167 95 formations and the development of smooth-slopes rift basins.  
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183 **97 Introduction**

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185 99 More than 30 years ago, important steps in our understanding of the mechanisms of  
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187 100 continental rifting were achieved through the acquisition and interpretation of ECORS  
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189 101 seismic reflection profiles (1983-1994) (Damotte et al., 1998). New images of crustal and  
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191 102 Moho geometries beneath stretched continental crusts were obtained, shading light on  
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193 103 important discrepancies between structural patterns at the base of rift systems. In  
194  
195 104 particular, ECORS profiles from the Rhine graben and the Parentis basin displayed  
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197 105 contrasting images of the thinned upper lithosphere. In the first case, the upper crust  
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199 106 appears clearly rifted and offset by stepping normal faults (Brun et al., 1991) whilst, despite  
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201 107 slight tectonic inversion, the second case exhibits a smooth basement top, with gentle  
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203 108 slopes dipping symmetrically towards the basin center (Bois et al., 1997). Because only few  
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205 109 cases of Parentis-type architecture were observed worldwide, little attention has been paid  
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207 110 to this symmetrical, smooth-slopes type of continental rift, which apparently lacks major  
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209 111 upper crustal faulting and block tilting. Rather, most of the current models of rift-related  
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211 112 crustal thinning generally point to the individualization of a series of tilted continental blocks  
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213 113 indicating that the upper crustal levels behave in a dominant brittle mode in the proximal (or  
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215 114 continentward) as well as in the distal (or oceanward) margin domains. In such models,  
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217 115 shallow detachment faults accommodate the upper crustal extension through the rotation  
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219 116 and the translation of undeformed basement blocks. In the distal margin, these blocks,  
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221 117 referred to as extensional allochthons, are covered by syn-rift and post-rift sediments and  
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223 118 may lie tectonically over exhumed lower levels, including subcontinental mantle (Reston et  
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225 119 al., 1995; Manatschal et al., 2001; Jammes et al., 2010c; Osmundsen and Peron-Pinvidic,  
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227 120 2018, and references therein).

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229 121 Recent geological investigations in the northern units of the Pyrenean belt forming the  
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231 122 North Pyrenean Zone (NPZ) as well as in the Basque-Cantabrian basin (fig. 1) show that  
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233 123 Parentis-type basins of mid-Cretaceous age were distributed all along the boundary between  
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235 124 the northern Iberia and southern Eurasia plates, thus introducing doubts regarding the  
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237 125 ubiquitous character of Iberia-Newfoundland-type margins (Lagabrielle et al., 2010 ; Clerc  
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239 126 and Lagabrielle, 2014; Teixell et al., 2016; 2018; Asti et al., 2019). In this article, we first list  
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127 the main characteristics of these Parentis-type basins, based on the analysis of detailed  
128 geological reconstructions from areas exposed all along the northern flank of the Pyrenean

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242  
243 129 belt. Then we review the distribution of such basins at the scale of the Iberia and Eurasia  
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245 130 plates. We finally discuss some of the key-factors controlling the evolution of smooth-slopes  
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247 131 basins and we evaluate how such information increases our understanding of the  
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249 132 mechanisms of continental rifting and passive margin formation.

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252 134 **I. Symmetrical, smooth-slopes basins of the north Iberia margin: insights from the North**  
253 135 **Pyrenean Zone (NPZ) and the Basque-Cantabrian range**

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257 137 The Pyrenees and the Cantabrian mountain (fig. 1) form a narrow, N110 trending fold-and-  
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259 138 thrust belt resulting from the collision of the northern edge of the Iberia plate (north Iberia  
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261 139 margin) with the southern edge of the Eurasia plate during the Late Cretaceous-Tertiary  
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263 140 (Choukroune and ECORS team, 1989; Muñoz, 1992; Deramond et al., 1993; Roure and  
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265 141 Choukroune, 1998; Teixell, 1998; Vergés and Garcia-Senz, 2001; Pedrera et al., 2017; Teixell  
266  
267 142 et al., 2018). Convergence initiated ca. 83 Ma, following an almost 40 Ma long period of  
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269 143 transtensional motion in relation with the counterclockwise rotation of Iberia relative to  
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271 144 Eurasia, also leading to oceanic spreading in the Bay of Biscaye between Chron M0 and A33o  
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273 145 (ca. 125-83 Ma) (Le Pichon et al., 1971; Choukroune and Mattauer, 1978; Olivet, 1996;  
274  
275 146 Sibuet et al., 2004). Convergence led to the partial or complete tectonic inversion of  
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277 147 discontinuous Cretaceous rift basins opened along the Iberia-Eurasia plate boundary during  
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279 148 the transtensional episode (Puigdefàbregas and Souquet, 1986; Debroas, 1990). Rotation  
280  
281 149 was achieved just before the Albian according to paleomagnetic data collected onland (Gong  
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283 150 et al., 2008). Earlier Triassic and Jurassic rifting events preceded the development of the  
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285 151 Cretaceous rifts (Canérot, 2017, and references therein).

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287 152 Along the northern flank of the Pyrenees, more than forty, up to km-sized exposures of  
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289 153 subcontinental lherzolites are widespread within the Mesozoic pre-rift and syn-rift  
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291 154 sediments forming the NPZ (Monchoux, 1970; Vielzeuf and Kornprobst, 1984; Fabriès *et al.*,  
292  
293 155 1991, 1998). The NPZ is bounded by two major post-metamorphic thrusts, the North  
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295 156 Pyrenean Fault (NPF) to the South and the North Pyrenean Frontal Thrust (NPFT) to the  
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297 157 North. The NPF represents the tectonic boundary between the NPZ and the prominent axial  
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299 158 zone of the belt (AZ) constituted of a stack of Paleozoic basement units (Choukroune, 1976a;  
300 159 1976b; 1978b).

300 160 Based on field and geophysical evidence from the central and western NPZ, exhumation of

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303 161 sub-continental mantle is shown to have occurred coevally with extreme thinning of the  
304 162 continental crust in the Pyrenean realm during the mid-Cretaceous (Lagabrielle and  
305 163 Bodinier, 2008; Jammes et al., 2009; Masini et al., 2014). Therefore, mantle exhumation  
306 164 (locally followed by peridotite exposure up to the floor of the Pyrenean basins) is now  
307 165 considered as a general mechanism accounting for the presence of ultramafic material  
308 166 within the NPZ. It is established that the well-known regional high temperature and low  
309 167 pressure (HT-LP) Pyrenean metamorphism (Ravier, 1957; Azambre & Rossy, 1976; Bernus-  
310 168 Maury, 1984) developed along the southern NPZ in relation with continental thinning during  
311 169 the major Cretaceous extensional event (Vielzeuf and Kornprobst, 1984; Dauteuil and Ricou,  
312 170 1989; Golberg & Leyreloup 1990; Clerc et al., 2015b; 2016). Following the early ECORS  
313 171 profiles (Choukroune and ECORS team, 1989), additional information on the architecture of  
314 172 the paleo-margin of Northern Iberia in the Pyrenees is provided by recent interpretation of  
315 173 tomographic data acquired during the temporary PYROPE and IBERARRAY experiments  
316 174 across the Pyrenees (Chevrot et al., 2015; 2018; fig. 1). Based on such data set, Wang et al.  
317 175 (2016) suggest the inversion of a northern Iberia margin characterized by a short necking  
318 176 domain and a large distal domain made of strongly attenuated crust (less than 10 km thick)  
319 177 overlying a large volume of subcontinental mantle. As discussed further in this article, this  
320 178 domain can be compared to large sheets of hyper-extended continental crust found in the  
321 179 distal portions of present-day passive continental margins (see section III C)

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181 Various models of continental crust thinning and associated mantle exhumation have been  
182 proposed recently to account for geological constraints collected inside the metamorphic  
183 NPZ. In figure 2 (profiles a to e), we present a selection of reconstructions extracted from  
184 recent literature, which highlights numerous similarities between recently published models  
185 of Cretaceous NPZ basins structure (Lagabrielle et al., 2010; Clerc and Lagabrielle, 2014;  
186 Masini et al., 2014; Tugend et al., 2014; 2015; Clerc et al., 2016; Teixell et al., 2016, 2018;  
187 Corre et al., 2016; Lagabrielle et al., 2016; DeFelipe et al., 2017; Pedrera et al., 2017; Espurt  
188 et al., 2019; Saspiturry et al., 2019; Asti et al., 2019; Ducoux et al., in review). Most of these  
189 architecture models stress the role played by a major cover décollement layer during the  
190 Cretaceous crustal thinning. This weak layer corresponds to the Upper Triassic Keuper  
191 evaporites which contain clays and sands as well as minor carbonates and doleritic MORB  
192 basalts (ophites). Its maximum thickness in the Pyrenean realm reached 2.7 km, as deduced

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363 193 from field data in the southern Pyrenees coupled to well data in the Mauléon and Aquitaine  
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365 194 basins and the Bay of Biscay region (James & Canérot, 1988; McClay et al., 2004; Biteau et  
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367 195 al., 2006; Jammes et al., 2010a; 2010b; 2010c; Roca et al., 2011; Saura et al., 2016; Orti et  
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369 196 al., 2017; Saspiturry et al., 2019). In the décollement layer now exposed in the metamorphic  
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371 197 NPZ, the Triassic clays were transformed into talc and chlorite, and the carbonates most  
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373 198 often suffered intense tectonic brecciation with talc, tremolite and dolomite  
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375 199 recrystallizations (Thiébaud et al., 1992; Lagabrielle et al., 2019a, 2019b). Pre-rift to syn-rift  
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377 200 salt diapirism was also frequently observed in the non-metamorphic NPZ and in the  
378  
379 201 Southern Pyrenees (e.g. Canérot, 1988; 1989; Lenoble and Canérot, 1992; Canérot and  
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381 202 Lenoble, 1989; 1993; James and Canérot, 1999; Canérot et al., 2005; Jammes et al., 2009;  
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383 203 Jammes et al., 2010a; 2010b; Roca et al., 2011; Saura et al., 2016; Teixell et al., 2016).

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

215

216 The Cinco Villas Paleozoic massif and the Le Danois Bank (fig. 1) respectively form the  
217 eastern and western boundary of the Basque-Cantabrian basin which develops to the west  
218 of the NPZ towards the northern Iberia Peninsula. It is filled by an up to 12.5 km thick  
219 succession of Upper Jurassic-Cretaceous sediments with interlayered Aptian to Santonian  
220 basic volcanic rocks (Azambre and Rossy, 1976; Rat et al., 1983; Rat, 1988; Castañares et al.,  
221 2001; García-Mondéjar et al., 1996; 2004; Floquet, 2004) (fig. 2f-h). This basin was floored by  
222 an extremely thinned lithosphere in its central parts (Biscay Synclinorium and Nappes des  
223 Marbres) and was also affected by a Late Cretaceous thermal metamorphism (Golberg and  
224 Leyreloup, 1990; Cuevas and Tubía, 1999; Pedrera et al., 2017). A peridotite outcrop close to



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423 225 the Leiza fault shows that crustal thinning led to the exhumation of the upper mantle close  
424 226 to the floor of the basin (Mendia and Gil-Ibarguchi, 1991; deFelipe et al., 2017). The basin  
425 227 architecture deduced from field investigations in the eastern part of the Basque-Cantabrian  
426 228 basin (the “Nappe des Marbres” area) includes smooth-slopes margins with normal faults  
427 229 and tilted blocks restricted to the external domains (deFelipe et al., 2017; Pedrera et al.,  
430 230 2017; Ducoux et al., in review). These reconstructed geometries bear affinities with basin  
431 231 architectures deduced from geological observations in the NPZ (fig. 2f-h). Indeed, such  
432 232 architecture and the overall evolution deduced for this rift system implicate gliding of the pre-  
433 233 rift sequence over its basement during crustal extension with ductile crustal thinning in its  
434 234 central part in a way similar to models deduced from NPZ studies (e.g. Clerc and Lagabrielle,  
435 235 2014; Corre et al., 2016; Teixell et al., 2016). The Leiza detachment system of deFelipe et al.  
436 236 (2017) (fig. 2g) corresponds to the basal décollement allowing pre-rift sequence allochthony.  
437 237 The presence of a high-density mantle body beneath the Basque-Cantabrian basin has been  
438 238 established on the basis of lithospheric-scale gravity inversion (Pedrera et al., 2017). The  
439 239 association of this exhumed mantle body with rift and post-rift structural geometries  
440 240 suggests the activation of a major south-dipping ramp-flat-ramp extensional detachment  
441 241 between Valanginian and early Cenomanian times with horizontal extension of ~48 km.  
442 242 Interpretation of geophysical data shows that low-strength Triassic Keuper evaporites and  
443 243 mudstones above the basement favor the decoupling of the cover with formation of  
444 244 minibasins, expulsion rollovers, and diapirs (Pedrera et al., 2017).

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446 246 Finally, the presence of a thick pre-rift salt layer underlying the Mesozoic carbonates  
447 247 appears as an ubiquitous parameter to take into account when reconstructing the evolution  
448 248 of the Cantabrian-Pyrenean range. Recent models of rift development at the northern Iberia  
449 249 margin show that Triassic lithology controls the three intrinsic characteristics of the  
450 250 Pyrenean rifting which can be summarized as follows:

- 451 251 i. Tectonic juxtaposition of exhumed peridotites and pre-rift sediments. This occurs  
452 252 when the lateral extraction of the thinned continental crust is completed. In  
453 253 response to plate separation, the stretched crust is removed horizontally from the  
454 254 center of the rift and decoupling of the pre-rift cover from its basement occurs along  
455 255 the Keuper décollement. As a consequence a tectonic contact is established between  
456 256 the decoupled pre-rift sediments and the uplifted sub-continental mantle rocks

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257 (Clerc and Lagabrielle, 2014) (fig. 2e). In some locations, due to subsequent complete  
258 removal of the pre-rift cover, mantle rocks may be in turn exposed to the seafloor as  
259 observed around the Lherz, Urdach and Bestiac lherzolite bodies (Lagabrielle et al.  
260 2010; 2016; de Saint Blanquat et al., 2016).

261 ii. Crustal stretching under dominantly-ductile conditions. The geometry of the thinned  
262 crustal units in the distal domain of the rift margins does not correspond to a  
263 succession of triangular-shaped isolated undeformed blocks (extensional  
264 allochthons) as described along the Iberia-Newfoundland conjugate margins and  
265 along the reconstructed alpine paleomargins (Manatschal, 2001; Manatschal et al.,  
266 2001; 2006; Peron-Pinvidic and Manatschal, 2009; Mohn et al., 2010; 2012; 2015)  
267 (fig. 3). By contrast, it appears as an assemblage of very thin lenses of ductilely  
268 deformed pre-Mesozoic material, originating mainly from the middle crust,  
269 separated by anastomosing shear zones that developed in greenschist facies  
270 conditions at low pressure (e.g. Corre et al., 2016; Teixell et al., 2016; Asti et al.,  
271 2019; Espurt et al., 2019) (fig. 2b-d). This important feature occurs because stretching  
272 develops under the allochthonous pre-rift cover that maintains moderate  
273 temperature in the upper and middle crust. Microscopic study of crustal material  
274 welded on the Urdach lherzolites demonstrates that the middle crust was extracted  
275 laterally from the rift axis and deformed ductilely at temperatures between 450°C  
276 and 350°C (Asti et al., 2019). Large strains in the greenschist facies are testified by  
277 strongly elongate quartz ribbons in ortho- and para-derived mylonites with bulging  
278 recrystallization and brittle fracturing of feldspar in cataclastic flows (fig. 4a-b).

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

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289 Boucheville basins infill, fig. 2). Progressive rifting triggers the upward propagation of  
290 the brittle-ductile transition which may reach syn-rift sediments deposited at the  
291 early stage of the basin opening (Clerc et al., 2016). Brittle deformation dominated by  
292 cataclastic brecciation follows ductile shearing and flattening in sedimentary units  
293 accompanying final exposure of mantle rocks to the seafloor, as proposed from  
294 studies in the Lherz area (Lagabrielle et al., 2016). The ductile-brittle transition is  
295 frequently observed at the mesoscopic and microscopic scale with sets of normal  
296 faults offsetting the extensional HT foliation (fig. 5e-f, 5h). Finally, at the scale of the  
297 entire rift, extensional deformation in the lower margin is accompanied by tectonic  
298 denudation of the cover in the upper margin (Lagabrielle et al., 2010; Teixell et al.,  
299 2016, 2018).

300

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

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

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

310

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

601  
602  
603 321 crustal thinning are favoured, both older and recent models of Parentis basin evolution  
604  
605 322 highlight three major features: (1) the occurrence of symmetrical smooth-slopes gently  
606  
607 323 dipping basinward; (2) the presence of a crust which thins regularly towards basin axis,  
608  
609 324 without discrete steeply dipping faults, and (3) the presence of a thick pre-rift salt layer  
610  
611 325 allowing décollement of the pre-rift cover from its basement (Jammes et al., 2010b, 2010c).

612  
613 326 (2) South Bay of Biscay margin (fig. 1, fig. 7b-c). Both the northern and southern margins of  
614  
615 327 the Bay of Biscay have been explored seismically. North-south transects of the Armorican  
616  
617 328 margin (Norgasis profiles, fig. 1: Thinon et al., 2003; Tugend et al., 2014) reveal a short  
618  
619 329 necking domain that concentrates most of the crustal deformation. Crustal thickness  
620  
621 330 decreases from 35 km at the shelf break to less than 10 km at the foot of the slope. Steep  
622  
623 331 rise of mantle implies the disappearance of the lower crust beneath the slope. Based on  
624  
625 332 results of gravity inversion combined with seismic interpretations, Tugend et al. (2014) map  
626  
627 333 a continuous domain of exhumed mantle from the Armorican basin toward the  
628  
629 334 hyperthinned Parentis basin where minimum crustal thickness occurs (fig. 7a) (Pinet et al.,  
630  
631 335 1987, Bois et al., 1996, Jammes et al., 2010a). According to Roca et al. (2011), the Bay of  
632  
633 336 Biscay Abyssal Plain itself consists of a transitional zone formed by a thin (4–9 km) crust with  
634  
635 337 riders of Mesozoic pre-rift and syn-rift sediments and continental crustal rocks that are  
636  
637 338 extensionally detached over an exhumed sub-continental mantle with seismic velocities  
638  
639 339 comprised between 7.2 and 8 km/s. The distal domain of the Bay of Biscay Abyssal Plain  
640  
641 340 bounds to the north the North Iberian margin, an extended continental margin with  
642  
643 341 Cretaceous basins (e.g. the Asturian basin, up to 10 km thick, fig. 1) and basement highs as  
644  
645 342 the Le Danois Bank (Cadenas and Fernández Viejo, 2016; Teixell et al., 2018), where  
646  
647 343 granulites have been dredged (Capdevila et al., 1980; Fügenschuh et al., 2003) (fig. 1).

648  
649 344 (3) North-eastern Iberia intra-crustal basins (Iberian Chain and Valencia trough) (fig 1 and fig.  
650  
651 345 7b-d). Helpful additional information regarding the thinning modes of the northern Iberia  
652  
653 346 crust can be obtained from seismic images of the Los Cameros, Maestrat and Columbrets  
654  
655 347 basins now partly inverted in the Iberian Chain (fig. 1). These basins result from the  
656  
657 348 distributed extension of the northern Iberia plate synchronously with the opening of the Bay  
658  
659 349 of Biscay-Pyrenees in the mid-Cretaceous (Verges and Garcia-Senz, 2001; Mas et al., 2011).  
660  
661 350 They represent a well-developed Mesozoic rift having similarities with the North Atlantic  
662  
663 351 margins (Salas and Casas, 1993; Salas et al., 2001). In their internal parts, reconstructed

661  
662  
663 352 Iberian Chain basin geometries point to simple troughs exhibiting gentle slopes devoid of  
664  
665 353 marked fault stepping, suggesting the absence of tilted blocks and a smooth basement top  
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667 354 (e.g. Guimerà et al., 1995; Casas-Sainz and Gil-Imaz, 1998; Omodeo et al., 2014). The Moho  
668  
669 355 generally shows an arched outline with a regular shallowing toward the basin center where  
670  
671 356 the crust is reduced to some kilometers only. The Triassic evaporites play an important role  
672  
673 357 during the Albian rifting in the basins of northeast Iberia. This role was recently well  
674  
675 358 illustrated by interpretation of seismic reflection profiles in the Valencia trough (Etheve et  
676  
677 359 al., 2018) (fig. 7b). These profiles reveal the presence of a large Albian basin, the Columbrets  
678  
679 360 basin (fig. 1), filled with up to 10 km thick Mesozoic sediments over a highly extended  
680  
681 361 continental basement locally only 3.5 km thick. The pre-rift and syn-rift successions form a  
682  
683 362 large-scale synclinal with thinned borders, in relation with displacement along local  
684  
685 363 extensional detachments. Whole deformation results of interaction between the thick pre-  
686  
687 364 rift Triassic salt layer and dominantly ductile crustal thinning (Etheve et al. 2018) leading to  
688  
689 365 the development of an abnormally thin continental crust (Gallart et al., 1990; Dañobeitia et  
690  
691 366 al., 1992; Ayala et al., 2015). In the Cameros basin (fig. 7c-d), the pre-rift cover is decoupled  
692  
693 367 on Triassic evaporites and is smeared all over the stretched domain. No major offset of the  
694  
695 368 top basement is attested by the syn-rift record (Casas-Sainz and Gil-Imaz, 1998; Casas-Sainz  
696  
697 369 et al., 2000). A striking feature is that like in the NPZ, HT-LP metamorphism associated with  
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699 370 crustal thinning is reported in the Cameros basin fill (Guiraud and Séguret, 1985; Goldberg et  
700  
701 371 al., 1988; Rat et al., 2019).

### 702 **III. Discussion**

703

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

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706 376 A common characteristic of the smooth-slopes basins described in this review is the lack of  
707  
708 377 tilted crustal blocks and related stepping fault scarps in their central part, thus defining a  
709  
710 378 dominant symmetrical smooth-slopes profile of the basement top (figs. 2 and 7). Based on  
711  
712 379 field data from the NPZ, we have shown that stretching of the crustal basement occurs in a  
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714 380 dominant ductile mode under greenschist facies conditions, since the central part of the  
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716 381 basin remains overlain by a permanent cover of detached pre- and syn-rift sediments . An  
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718 382 important question is now to determine whether such symmetrical shapes result from  
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723 383 symmetrical or asymmetrical stretching processes.  
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726  
727 385 The symmetry or asymmetry of the processes of lithosphere stretching and continental  
728 386 breakup has been largely debated over the last 30 years (i.e. Buck et al., 1988; Allemand et  
729 387 al., 1989; Buck, 1991; Brun, 1999, with references therein). More recently, the symmetrical  
730 388 character of the final architecture of passive margins has been discussed by many authors  
731 389 (i.e. Michon and Merle, 2003; Huisman and Beaumont, 2007; Reston et al., 1995; Sutra et  
732 390 al., 2013; Brune et al., 2014). Apparent symmetry does not imply dominant pure shear  
733 391 thinning mechanisms but may result from asymmetrical tectonic processes involving large-  
734 392 scale discrete extensional shear zones (simple shear) as discussed by Nagel and Buck (2004)  
735 393 (fig. 8a).

742 394

743 395 It is well admitted that architecture of extended crustal systems depends on the geometrical  
744 396 and temporal associations between simple shear and pure shear regimes. In the pure shear  
745 397 model of McKenzie (1978), designed to explain the evolution of sedimentary basins, the  
746 398 lithosphere is stretched uniformly resulting in a symmetrical basin with faulting in the brittle  
747 399 crust. By contrast, the simple shear model (Wernicke, 1981, 1985) points to one or few  
750 400 detachment faults that originate at low-angle with dips less than 30° and concentrate the  
751 401 entire deformation, so that, apart from the fault zones, the lithosphere is not deformed. The  
752 402 simple shear model has been complicated with the adjonction of sequential detachments  
753 403 faults (Lister and Davis, 1989). Combination of pure and simple shear model was further  
754 404 proposed (Lister et al., 1991). In this combination model, crustal deformation is controlled  
755 405 by low angle detachment faulting but thinning of the mantle lithosphere results from pure  
756 406 shear. By introducing time-dependant rheological changes at the lithospheric scale, Reston  
757 407 and Perez-Gussinye (2007) report a complex evolution from symmetric to asymmetric  
758 408 extension, and back to symmetric, at margins displaying exhumed mantle in the hyper-  
759 409 extended domain.

769 410

770 411 A laboratory model combining simple and pure shear has been realized by Brun and Beslier  
771 412 (1996) in order to account for the exhumation of mantle rocks at ocean-continent  
772 413 boundaries (fig. 8b). This model applies easily to the case of rifts with exhumed mantle such  
773 414 as the Pyrenean and peri-Pyrenean smooth-slopes basins. This four-layer model is composed

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782  
783 415 of sand and silicone putty layers, regarded as analogues of the brittle and ductile layers of  
784 416 both crust and mantle. However, it does not discriminate a mid-crustal level. The lower crust  
785 417 deforms ductilely and the upper mantle is strong. Necking of the whole lithosphere model is  
786 418 nearly symmetrical (pure shear) but asymmetrical structures (simple shear) develop  
787 419 internally, due to boudinage and/or faulting of brittle layers. This model explains the  
788 420 occurrence of shear zones in the mantle lithosphere as described by Vissers et al. (1995) in  
789 421 the Pyrenean mantle and accounts for the ductile deformation of the crust as demonstrated  
790 422 by Asti et al. (2019).

796 423

797 424 In contrast with the Brun and Beslier (1996) symmetrical model, recent models of margin  
798 425 evolution based on the Iberian or Alpine examples have put forward asymmetric  
799 426 architectures resulting from the development of few major detachment faults, and  
800 427 promoted the use of “lower-” and “upper-plate” terminology (Manatschal, 2004; Mohn et  
801 428 al., 2010, 2012, 2015; Sutra et al., 2013). Mohn et al. (2012) propose a model of three-layer  
802 429 continental crust where the brittle upper and lower crusts are strongly decoupled by a  
803 430 ductile middle crust (fig. 3b). Crustal thinning, accommodated through a so-called necking  
804 431 zone, is the result of interplay between detachment faulting in the brittle layers and  
805 432 decoupling in ductile quartzo-feldspatic mid-crustal levels along localized ductile  
806 433 décollements. The excision of ductile mid-crustal layers and the progressive embrittlement  
807 434 of the crust by coupling the lower and upper crusts enable major detachment faults to cut  
808 435 into the underlying mantle, exhuming it to the seafloor.

809 436 In the Iberian and Alpine examples, authors envision the presence of one or few large-scale  
810 437 discrete detachment faults controlling the entire crustal thinning and the basin subsidence.  
811 438 This is also applied by Masini et al. (2014) in their model for the western NPZ where a major  
812 439 north-dipping detachment fault accomodates the denudation of the sub-Eurasian mantle to  
813 440 form the basement of the Mauléon basin (fig. 9a). Interpretation involving single  
814 441 detachment faults has also been retained in the preliminary reconstructions of the NPZ  
815 442 basins by Lagabrielle and Bodinier (2008), Lagabrielle et al. (2010) and Vauchez et al. (2013)  
816 443 (fig.9b, c), as well as in the reconstructed S-N transect from the Basque – Cantabrian to the  
817 444 Armorican margin by Roca et al. (2011) (fig. 9d). Similarly, few detachment faults are used in  
818 445 the Espurt et al. (2019), Saspiturry et al. (2019) and Ducoux et al. (in review) models for the  
819 446 Barronies, Mauléon and “Nappe des Marbres” basins respectively (fig. 2). Others models

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842  
843 447 invoke deep-seated staircase extensional faults accounting for large-scale ramp-synclinal  
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845 448 folding as documented in the Cameros and Columbrets basins (Guimerà et al., 1995; Roma  
846  
847 449 et al., 2018). By contrast, models from the western NPZ by Corre et al. (2016) and Teixell et  
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849 450 al. (2016, 2018) (fig. 2) do not favor the activation of single detachment faults alone. Rather,  
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851 451 they involve symmetrical tectonic processes triggering a homogeneous thinning of the crust  
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853 452 during its lateral extraction from the rift axis.

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855 453 In their study of the evolution of the western Betics including the exhumation of the Ronda  
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857 454 subcontinental mantle, Frasca et al. (2016) identify three successive steps: (i) ductile crust  
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859 455 thinning and ascent of subcontinental mantle thanks to mid-crustal shear zone and crust-  
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861 456 mantle shear zones acting synchronously; (ii) disappearance of the ductile crust bringing the  
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863 457 upper crust in contact with the subcontinental mantle, (iii) complete exhumation of the  
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865 458 mantle in the zone of localized stretching and high-angle normal faulting cutting through the  
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867 459 Moho, with related block tilting. These steps do not completely apply to the Pyrenean case,  
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869 460 notably because field and geophysical studies of the metamorphic NPZ never evidenced  
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871 461 brittle faulting of the Moho during the Cretaceous rifting.

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875 463 Based on these examples of recent interpretations of rifting evolution, we stress that both  
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877 464 Alpine and Betic examples do not refer to a décollement level at the base of the pre-rift  
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879 465 cover. They promote evolutionary models lacking allochthony of the detached pre-rift  
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881 466 sediments, in contradiction with the examples detailed in section I and II. In addition, both  
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883 467 Alpine and Betic models refer to a progressive embrittlement in the rift axis resulting in the  
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885 468 complete elimination of ductile crustal layers. Again, this contrasts with the NPZ examples  
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887 469 where thin ductile crustal layers are extracted in the distal domain and remain welded on  
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889 470 the exhumed mantle.

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892  
893 472 **B. Smooth-slopes basins: crustal shear zones and lenticular fabrics at the mesoscale.**

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897 474 Petrological studies of continental units exposed around the Urdach and Sarailé lherzolite  
898  
899 475 bodies (western NPZ) provide information on the deformation mode associated with crustal  
900  
476 thinning and mantle exhumation (Corre et al., 2016; Asti et al., 2019). Reconstruction of  
477 sections across the NPZ Cretaceous basins by Clerc et al. (2015b), Teixell et al. (2016), Corre  
478 et al. (2016) and Asti et al. (2019) use such ductile deformation mode having affinities with a



901  
902  
903 479 regional-scale, uniform pure shear mechanism. It is shown that extension in the Paleozoic  
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905 480 basement was achieved through lenticular deformation and pervasive ductile flattening with  
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907 481 anastomosing extensional mylonitic shear zones developing at temperatures of 350-450°C.  
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909 482 Here, during its lateral extraction from the rift axis, the crust thinned ductilely under  
910  
911 483 greenschist facies P-T conditions. Stretching occurred by the mean of undulating shear  
912  
913 484 contacts between tectonic lenses of flattened crustal material as described in figure 10. At  
914  
915 485 the final step of the continental breakup, very thin continental crustal lenses remained  
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917 486 welded on the exhumed mantle.

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919 487 A very similar lenticular mode of deformation derives from investigations in the Basin and  
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921 488 Range province. Hamilton (1987) describes tectonic lenses of middle crustal rocks that  
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923 489 normally lie at separate levels in the crust with undulating shear contacts between them (fig.  
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925 490 8c). This deformation mode allows the juxtaposition of different lithologies by uplifting  
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927 491 deeper lenses during the extensional deformation. In a different way, Gartrell (1997)  
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929 492 propose a large scale crustal boudinage involving successive necking regions where the  
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931 493 ductile middle crust is extremely sheared (fig. 8d). The resulting architecture is a succession  
932  
933 494 of tectonic lenses that may evolve toward a large-scale lenticular geometry as proposed by  
934  
935 495 Espurt et al. (2019) for the evolution of the North Pyrenean massifs (fig. 2d).

936  
937 496 In their recent detailed study of the tectonic and metamorphic evolution of the Urdach and  
938  
939 497 Sarailé mantle bodies and associated units, Lagabrielle et al. (2019a; 2019b) describe two  
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941 498 types of low-angle shear zones that accommodated part of extension of the distal domain of  
942  
943 499 the Iberia passive margin during the mid-Cretaceous (fig. 10a, b). The deepest shear zone is  
944  
945 500 the crust-mantle detachment. It separates the ultramafic mantle rocks from strongly thinned  
946  
947 501 continental Paleozoic rocks. It is composed of a basal 20-50 m thick lenticular layer of  
948  
949 502 sheared serpentinites followed by a 10 m thick damage zone. The lenticular layer consists of  
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951 503 ultramafic symmetrical tectonic lenses, a few meters long, separated by anastomosing  
952  
953 504 serpentine-rich shear zones. The damage zone consists of an assemblage of centimeter-sized  
954  
955 505 symmetrical lenses of a soft, talc-rich, sheared material, separated by conjugate shear zones.  
956  
957 506 The shallowest shear zone is the cover sole décollement. It corresponds to the tectonic  
958  
959 507 boundary separating the base of the detached pre-rift Mesozoic metasedimentary cover  
960  
961 508 from either mantle lherzolites or continental basement rocks. It consists of a thick  
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963 509 deformation zone (some meters to tens of meters thick) that was the locus of important  
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965 510 metasomatic crystallizations involving notably fluids of Triassic origin (Corre et al., 2016).

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962  
963 511 Detailed structural study of the basement and mantle rocks shows that it is not easy to  
964  
965 512 discriminate between dominant pure shear and dominant simple shear processes at the  
966  
967 513 outcrop and regional scales (Lagabrielle et al. 2019a; 2019b). Indeed, a major detachment  
968  
969 514 fault zone (typically related to regional simple shear) may contain abundant symmetrical  
970  
971 515 lenses suggesting locally dominant pure shear.

972 516 Finally, in the studied smooth-slopes basins, dominant pure shear mechanisms concentrate  
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974 517 into the strongly thinned continental tectonic lenses whereas simple shear mechanism  
975  
976 518 characterize the main detachments. Pure shear mechanisms associated with overall  
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978 519 flattening of the syn-rift and pre-rift sedimentary pile progressively develop into the basin  
979  
980 520 center as represented in figure 10a. Chronological constraints have to be integrated in order  
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982 521 to establish possible succession from simple shear-dominant toward pure shear-dominant  
983  
984 522 deformation mechanisms at the scale of the entire system.

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986 523

987 **524 C. Smooth-slopes basins formation, insights for the evolution of passive, magma-poor**  
988  
989 **525 continental margins.**

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991 526

992 527 We deduce from section B above that dominant pure shear deformation concentrates into  
993  
994 528 anastomosed tectonic lenses forming the strongly stretched continental in the central region  
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996 529 of smooth-slopes basins. In the following, we review examples of comparable uniform  
997  
998 530 modes of ductile deformation worldwide.

999 531 A lenticular mode of deformation devoid of any steep normal fault is proposed at the scale  
1000  
1001 532 of an entire passive margin by Gernigon et al., (2014) to account for the symmetrical  
1002  
1003 533 stretching of the continental crust during the formation of the Barents margin (fig. 11a). This  
1004  
1005 534 geometry recalls the structures proposed by Gartrell (1997) (fig. 8d). Lenticular fabric is also  
1006  
1007 535 suggested for deep crustal units connected to tilted blocks through listric faults along the  
1008  
1009 536 Norway margin (Osmundsen and Ebbing, 2008; fig. 11b). These structures accommodate  
1010  
1011 537 crustal thinning to only a few kilometer thicknesses through dominant ductile mode. The  
1012  
1013 538 symmetrical mode of stretching implying ductile thinning or boudinage of some crustal layer  
1014  
1015 539 can be compared to processes of depth-dependent stretching or thinning (DDT and DDS)  
1016  
1017 540 envisioned by Reston and McDermott (2014) in order to account for extensional  
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1019 541 discrepancies at some passive margins. It must be noted that according to an interpretation  
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542 of deep seismic reflection profiles by Reston (1988), lens-shaped low-strain lozenges

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1022  
1023 543 separated by high strain shear zones form the structural pattern of the lower crust beneath  
1024  
1025 544 the United Kingdom. This overall pattern seems to be possibly applied to numerous units of  
1026  
1027 545 stretched crust at a large scale.

1028 546 Several distal domains of North Atlantic passive margins display geometries that suggest the  
1029  
1030 547 presence of lens-shaped units of thinned to hyper-thinned continental crust detached along  
1031  
1032 548 anastomosing shear zones and now separated by large zones exposing exhumed mantle (e.g.  
1033  
1034 549 Labrador and West Greenland margins; Reston and Perez-Gussinyé, 2007) (fig. 11c, d). These  
1035  
1036 550 units do not resemble extensional allochthons of the West Iberia-type margins (figs. 2 and  
1037  
1038 551 11e) and show geometrical affinities with crustal boudins extracted during the Pyrenean  
1039  
1040 552 extension in the center of the Cretaceous rift (e.g. the Baronnies and Agly crustal boudins;  
1041  
1042 553 Espurt et al., 2019; Clerc et al., 2016) (fig. 2). Such large areas of hyper-thinned continental  
1043  
1044 554 crust possibly composed of an assemblage of heterogeneous boudins, can be viewed as  
1045  
1046 555 sheets representing considerable volumes of sheared and flattened continental material  
1047  
1048 556 (thickness less than 10 km, width of 100 km and length more than few 1000 km, along the  
1049  
1050 557 margin), formed through processes of uniform pure shear at a crustal scale. We infer that  
1051  
1052 558 the modes of deformation exhibited by the Pyrenean crustal units welded on the exhumed  
1053  
1054 559 mantle (although at a much smaller scale) can apply to the formation of these crustal sheets,  
1055  
1056 560 suggesting predominance of greenschists facies mylonites. Similar crustal sheets underlying  
1057  
1058 561 sag basins are well imaged in recent numerical models of margin evolution (Brune et al.,  
1059  
1060 562 2014 ; Huisman and Beaumont, 2011; 2014) as shown in figure 12a, b. Crustal sheets are  
1061  
1062 563 present along the Angola margin (fig. 12d), they may be present in the very distal domain of  
1063  
1064 564 the Gulf of Lion margin where they may originate by extraction of lower crustal material  
1065  
1066 565 (Jolivet et al., 2017) (fig. 11f). Similar long and thin sheets are typically imaged by Wang et al.  
1067  
1068 566 (2016) at the base of the reconstructed Iberia margin of the Mauléon basin, and by Roca et  
1069  
1070 567 al. (2011) in their reconstruction of the north Iberia margin north of the Cantabrian coast  
1071  
1072 568 (fig. 9d).

1067 569 In their compilation of high-quality and deep penetration seismic profiles of several passive  
1068  
1069 570 margins (Uruguay, Southern Namibia, Gabon, South China Sea and Barents Sea), Clerc et al.  
1070  
1071 571 (2015a; 2018) suggest that the lower crust of some margins is weaker than assumed and  
1072  
1073 572 accommodates a large part of extension by ductile shearing (fig. 8e). Boudinage appears as a  
1074  
1075 573 recurrent deformation process accounting for the thinning of the continental crust at  
1076  
1077 574 variable scales. This leads authors to an unorthodox vision of some type of passive margins

1081  
1082  
1083 575 where: (i) the lower crust is weak, (ii) boudinage controls a large part of the deformation and  
1084 576 localization of low-angle normal faults, and (iii) these normal faults often dip toward the  
1085 577 continent. This study highlights a crustal behavior dominated by boudinage and  
1086 578 lenticulation, implying interplay between ductile shear zones (boudin edges) and more  
1087 579 resistant crustal volumes (boudin cores). As discussed above in section B, this deformation  
1088 580 mode may apply to the thinned crustal levels in the axis of the Cretaceous Pyrenean rifts  
1089 581 (Teixell et al. 2016, 2018; Asti et al., 2019) (fig. 10) and is supported by recent numerical  
1090 582 models of lithospheric rifting incorporating macroscale anisotropy (Duretz et al., 2016).  
1091  
1092 583 In their interpretation of deep seismic profiles of the Gulf of Lion margin, Jolivet et al. (2015)  
1093 584 point to an intense stretching of the distal margin and reveal a 80 km-wide ocean-continent  
1094 585 transition zone that may consist of thin lower continental crust (the “Gulf of Lion  
1095 586 metamorphic core complex”) and exhumed mantle (fig. 11f). They infer an overall hot  
1096 587 geodynamic environment with a shallow lithosphere-asthenosphere boundary able to  
1097 588 weaken the upper mantle and the lower crust enough to make them flow south-eastward. In  
1098 589 this example, the lower crust bears an important role, which is not fully documented by field  
1099 590 data in the NPZ since evidence of exposure of lower crustal levels during the Cretaceous  
1100 591 rifting event has not yet been reported with confidence. Moreover, in most of the sections  
1101 592 of figures 3 and 7, the lower crust is considered as a high-strength layer that does not  
1102 593 deform ductilely but tends to break into large scale boudins and to remain at depth during  
1103 594 the rifting processes (e.g. figs. 2a, e, f, h).

1117 595

#### 1119 596 **D. Comparison with thermo-mechanical models of crustal hyper-extension.**

1120 597

1121  
1122 598 The examples discussed above lead us to emphasize the frequency of lenticular fabrics at  
1123 599 various scales reported from different studies in both the upper mantle and the crust. The  
1124 600 formation of lenticular fabrics, necking and lateral extraction during continental rifting have  
1125 601 been addressed in mechanical and thermo-mechanical numerical models (Duretz and  
1126 602 Schmalholz, 2015; Duretz et al., 2016). These models emphasize the role of a pre-existing  
1127 603 macroscopic mechanical anisotropy on the development of continental rifts. They illustrate  
1128 604 the interplay between necking and lateral extraction of strong layers along weak  
1129 605 décollements, thus defining a lenticular fabric and anastomosed shear zone networks at the  
1130 606 regional scale as envisioned in the NPZ case.

1141  
1142  
1143 607 Models of metamorphic core complexes (MCCs) formation generally involve a thick and hot  
1144  
1145 608 continental crust (Brun and van den Driessche, 1994). This does not apply to the Pyrenean  
1146  
1147 609 case but constructive inputs can be expected from a confrontation with the rheological  
1148  
1149 610 parameters used for MCCs modeling. For instance, Tirel et al. (2008) use initial Moho  
1150  
1151 611 temperatures of 800°C or higher, with crustal thicknesses of 45 km or greater. This is much  
1152  
1153 612 more than what can be retained for the post-Variscan crust in the Pyrenees (thicknesses  
1154  
1155 613 between 30 and 20 km) (Teixell et al., 2018, and references therein) and Moho  
1156  
1157 614 temperatures lower than 800°C. In the Tirel et al. (2008) experiment, the exhumation  
1158  
1159 615 process of the metamorphic dome results in the progressive development of a detachment  
1160  
1161 616 zone and the Moho remains flat because the lower crust has a low viscosity and the upper  
1162  
1163 617 mantle is weak enough. With Moho temperatures lower than 800°C, the sub-Moho mantle  
1164  
1165 618 has high strength and effective viscosity resulting in strong Moho deflection and crustal-  
1166  
1167 619 scale necking. These conditions (relatively cold mantle and thin crust) are reached in the  
1168  
1169 620 Pyrenean rift explaining why the Pyrenean mantle rapidly reached the surface when it was  
1170  
1171 621 passively mobilized in response to the drift of the Iberia plate.

1168  
1169 622 A former numerical model that applies to the formation of passive continental margins  
1170  
1171 623 suggests that the crust may be thinned by permanent pure shear both at the proximal and  
1172  
1173 624 distal margin (Huisman and Beaumont, 2011) (fig. 12a). This scenario can apply easily to the  
1174  
1175 625 Pyrenean case where the ductile behaviour of the middle crust is demonstrated (Asti et al.,  
1176  
1177 626 2019). The Huisman and Beaumont (2011) model produces symmetric margins associated  
1178  
1179 627 with distal domain characterized by large sheets of thinned crustal material, as discussed  
1180  
1181 628 above. The symmetrical outline is well imaged by current reconstructions of the Pyrenean  
1182  
1183 629 basins from the North Pyrenean Zone and associated examples (Parentis, Cameros and  
1184  
1185 630 Columbrets basins, fig. 1, 2 and 7).

1184  
1185 631 Brune et al. (2014) produce a different numerical model that emphasizes a rift migration  
1186  
1187 632 accomplished by sequential upper crustal faults balanced through lower crustal flow (fig.  
1188  
1189 633 12b). An interesting concept is that of 'exhumation channel', a weak locus of deformation  
1190  
1191 634 where the crust and part of the uppermost mantle are actively deformed and extremely  
1192  
1193 635 thinned during their transfer from lower to shallower levels, over a dome of upwelling  
1194  
1195 636 lithospheric mantle. This high strain volume is not a detachment fault and thus may bear  
1196  
1197 637 some affinity with the lenses of crustal material exhumed with NPZ mantle and described by  
1198  
1199 638 Asti et al. (2019). As discussed in section C above, the resulting geometry is that of areas of

1201  
1202  
1203 639 drastically thinned crust (named *crustal sheets* in the following) forming the distal margin  
1204  
1205 640 domain lying over a cooled and strengthened mantle. This mantle is exposed locally at the  
1206  
1207 641 rift axis depending on the extension rate. The final sketch derived from this model, including  
1208  
1209 642 a dome of strong mantle rimmed in its upper part by a thin layer of mylonitic crust, is a  
1210  
1211 643 reliable image for the geometry resulting from the Pyrenean rifting and associated basins at  
1212  
1213 644 a lithospheric scale.

1214  
1215 645 Jammes et al. (2015) and Jammes and Lavier (2016), introduced compositional complexities  
1216  
1217 646 in the lithosphere by using an explicit biminerale assemblage which results in the  
1218  
1219 647 development of anastomosing shear zone. In their models, the deformation appears  
1220  
1221 648 localized in the middle/lower crust and the upper lithospheric mantle and leads to the  
1222  
1223 649 preservation of almost undeformed lenses of material surrounded by localized shear zones  
1224  
1225 650 concentrating most of the deformation. Such a lenticular final geometry is also evocative of  
1226  
1227 651 the one observed in the North Pyrenean Zone as discussed in detail by Asti et al. (2019) and  
1228  
1229 652 illustrated in fig. 10.

1230  
1231 653 To unravel the dynamic evolution of the Cretaceous Pyrenean rift, Duretz et al. (2019)  
1232  
1233 654 carried out a set of thermo-mechanical numerical models of lithosphere-scale extension  
1234  
1235 655 based on the available geological constraints listed above in section I. The models were used  
1236  
1237 656 to explore the role of a km-thick basement-cover décollement layer at the base of the pre-  
1238  
1239 657 rift sediments. These numerical experiments highlight the key-role of the décollement layer  
1240  
1241 658 that can alone explain collectively: (i) salt tectonics deformation style and cover  
1242  
1243 659 décollement, (ii) high temperature metamorphism of the pre-rift cover, and (iii) ductile  
1244  
1245 660 mode of crustal thinning in the inner domain of the models. In the axis of the synclinal-  
1246  
1247 661 shaped basin (“sag” basin in the margin literature), extreme pure shear leads to the  
1248  
1249 662 development of a very thin basement layer, overlain by poorly-thinned pre-rift and syn-rift  
1250  
1251 663 sediments and underlain by exhuming mantle. These models are in good agreement with the  
1252  
1253 664 current knowledge of the architecture of the Cretaceous Pyrenean basins as exemplified by  
1254  
1255 665 reconstructions of figs. 2 and 7, as well as with the presence of large sheets of hyper thinned  
1256  
1257 666 crustal material (crustal sheets) in the distal part of numerous magma poor passive margins.

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1259 667  
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1262  
1263 **668 E. The pre-rift salt décollement layer: a mechanical key-factor in the evolution of smooth-**  
1264 **669 slopes basins. Establishing a new link between Triassic paleogeography and rifting**  
1265 **670 mechanisms.**  
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671  
1270 672 As reported in section I and II, the common character between all pre-rift sequences of the  
1271  
1272 673 aforementioned smooth-slopes basins is the presence of the thick low-strength Late Triassic  
1273 674 evaporitic layer (Keuper). All related geological and geophysical studies highlight the  
1274  
1275 675 importance of this décollement layer in the evolution of the rift basins under study. As  
1276  
1277 676 detailed above, efficient décollement along the Keuper evaporites and clays triggers  
1278  
1279 677 mechanical decoupling and gliding of the pre-rift cover that remains in the center of the  
1280  
1281 678 basin as the crust is laterally extracted. In response to crustal hyper-thinning and horizontal  
1282  
1283 679 crustal extraction, hot mantle material approaches the detached pre-rift cover. As a  
1284  
1285 680 consequence, HT-LP metamorphism develops in the pre-rift sediments and at the base of  
1286  
1287 681 the syn-rift flysch levels as recorded in the NPZ and in the pre-rift sediments of the Cameros  
1288  
1289 682 basin. Subsequent deposition of syn-rift sediments allows preservation of the initial thermal  
1290  
1291 683 anomaly with a major consequence on the deformation regime in the pre-rift sediments and  
1292  
1293 684 crustal basement. Temperature increase in the NPZ basins center progressively leads to the  
1294  
1295 685 uprising of the brittle/ductile transition avoiding the development of prominent crustal normal  
1296  
1297 686 faults and leading to the dominantly ductile thinning of the Paleozoic basement and parts of  
1298  
1299 687 the pre-rift and syn-rift sediments (Clerc and Lagabrielle, 2014; Clerc et al., 2015b; Asti et al.,  
1300  
1301 688 2019; Duretz et al., 2019). We may now question the paleogeographic distribution of the  
1302  
1303 689 Keuper group sediments at the Europa-Iberia scale in order to evaluate a possible link  
1304  
1305 690 between modes of rift development and the occurrence of a thick Keuper layer at the base  
1306  
1307 691 of the pre-rift sequence.

1308  
1309 692 Several extensional systems interacted in the Iberia platform during the Trias, resulting in  
1310  
1311 693 the creation of intraplate basins or troughs including the Valencian, Basque-Cantabrian, and  
1312  
1313 694 Pyrenean basins (figs. 1 and 13). The sedimentary infill of these platform basins continued  
1314  
1315 695 throughout the Mesozoic. Seismic, well and field data from the Bay of Biscay region, the  
1316  
1317 696 Pyrenees and the Aquitanian Basin, suggest initial thickness of Upper Triassic formations  
1318  
1319 697 ranging from 1000 to 2700 m (James and Canérot, 1999; Biteau et al., 2006; Jammes et al.,  
1320  
698 2010a; Roca et al., 2011; Rowan, 2014; Lopez-Mir et al., 2014; Saura et al., 2016; Soto et al.,  
699 2017; Zamora et al., 2017). The salt-rich layers generally consist of shales and evaporites

1321  
1322  
1323 700 including dominant gypsum and minor halite and anhydrite (figs. 13 and 14).  
1324  
1325 701 Paleogeographic reconstructions are available for the Triassic period at the scale of the  
1326  
1327 702 Iberia-western Europa region (Dercourt et al., 1986; 1993; Ziegler, 1988; Ortí et al., 2017;  
1328  
1329 703 Soto et al., 2017). The distribution of Triassic shales and evaporites is contrasted around the  
1330  
1331 704 future Iberia plate margins. This paleogeography is confirmed by a compilation of data  
1332  
1333 705 collected independantly by D. Frizon de Lamotte (fig. 13c). Evaporites are well developed  
1334  
1335 706 along the eastern edge of Iberia (Tethys side) and in the rift opened at the place of the  
1336  
1337 707 future NPZ, the Basque-Cantabrian basin, the Bay of Biscaye basin and the southern part of  
1338  
1339 708 the Armorican margin. In the place of the future North Atlantic rift system, evaporites are  
1340  
1341 709 restricted to the Peniche, Lusitanian, Alentejo and Algarve basins along the southern half of  
1342  
1343 710 the Portugal margin and are lacking along the northern half of the Iberia Atlantic margin.  
1344  
1345 711 Along the conjugate north American margin, evaporites are known at the base of the  
1346  
1347 712 Jeanne-d'Arc basin and are of restricted extension compared to the Keuper group exposed in  
1348  
1349 713 Central Europe (fig. 13b, c).  
1350  
1351 714 Finally, along the western half of the Iberia-Newfoundland transect, evaporitic formation are  
1352  
1353 715 not reported, whereas thick evaporites are reported from areas characterized by Parentis-  
1354  
1355 716 type basins. As outlined in figures 13 and 14, this paleogeography matches the distribution  
1356  
1357 717 of the two opposite types of basins discussed in this article (Parentis type vs. Iberia-  
1358  
1359 718 Newfoundland type). Thus, we establish a link between the presence of a pre-rift salt layer  
1360  
1361 719 and the deep mechanisms of crustal stretching. Because they remain in the center of the  
1362  
1363 720 basin, evaporites contribute to the preservation of a rather high thermal gradient in the axial  
1364  
1365 721 rift allowing a dominant-ductile deformation of the basement. The lack of a major  
1366  
1367 722 décollement level at the base of the pre-rift sequence may explain by itself why pre-rift  
1368  
1369 723 sediments remain welded and coupled to the basement on the top of tilted blocks in the  
1370  
1371 724 Iberia-Newfoundland-type margins as illustrated in figure 3a, b. Indeed, in the Iberia as well as  
1372  
1373 725 in Alpine margin-types, only syn-rift sediments are deposited over the exhumed lower  
1374  
1375 726 crustal levels and subcontinental mantle (Péron-Pinvidic et al., 2007; Péron-Pinvidic and  
1376  
1377 727 Manatschal, 2009; Mohn et al., 2012), which contrasts with the evolution of the Parentis-  
1378  
1379 728 type basins.  
1380  
729  
730 In this review, on the basis of examples clustering along the Iberia-Eurasia plates boudaries,  
731 we emphasize the major role played by the Upper Triassic evaporitic layer during extensional



1381  
1382  
1383 732 processes. In the reported smooth-slopes basin examples, cover gliding occurred on a pre-  
1384  
1385 733 rift layer and thus contrasts with cases involving syn- to post-rift weak layers. The latter  
1386  
1387 734 cases have been largely documented by studies of passive margins displaying thick syn-rift  
1388  
1389 735 salt formations such as the Angola margin where the post-salt sedimentary units have glided  
1390  
1391 736 gravitationally after the margin formation (e.g. Brun and Fort, 2011, and references therein,  
1392  
1393 737 see also additional discussion relative to the pre-rift/post-rift salt effects during rifting in  
1394  
1395 738 Jammes et al., 2010c). To sum up, the specific characters emphasized in this review are  
1396  
1397 739 twofold : (i) the peri-Pyrenean salt is pre-rift allowing conservation of the pre-rift cover over  
1398  
1399 740 the high-strain axial rift. Crustal faulting has not disrupted the continuity of the Triassic  
1400  
1401 741 evaporite formation, allowing for décollement of the pre-rift sequence basinward, down to  
1402  
1403 742 the distal margin. (ii) Consequently, the axial thermal anomaly is preserved and the  
1404  
1405 743 dominant ductile mode of crustal deformation prevented the formation of faulting-related  
1406  
1407 744 steps leading to smooth-slopes basin edges.

1408  
1409 745

#### 1410 746 **F. Time-dependent rheology during the evolution of smooth-slopes basins**

1411 747

1412 748 From the statements listed at the end of section I as well as from the discussion above, we  
1413  
1414 749 first stress that the models of Pyrenean Cretaceous rifting established on the basis of  
1415  
1416 750 geological constraints from the NPZ differ significantly from the classical models of passive  
1417  
1418 751 margin formation based on the Iberia-Newfoundland margins example (Peron-Pinvidic and  
1419  
1420 752 Manatschal, 2009; Sutra et al., 2013; Osmundsen and Peron-Pinvidic, 2018, and references  
1421  
1422 753 therein). The latter models involve a dominantly brittle behavior of the crust and the  
1423  
1424 754 individualization of tilted faulted blocks bearing a concordant pre-rift cover permanently  
1425  
1426 755 welded on their back (fig. 3). In the models based on the geology of the NPZ (e.g. models of  
1427  
1428 756 Clerc et al., 2016; Teixell et al., 2016; Espurt et al., 2019), the external borders of the  
1429  
1430 757 subsiding Cretaceous flysch basins remain at low temperature and display classical faulted  
1431  
1432 758 and tilted blocks (e.g. half-grabens of Quillan basin, Camarade basin, Gensac-Bonrepos  
1433  
1434 759 basin, western border of the Mauléon basin, Arbailles basin, edges of the Gran Rieu high and  
1435  
1436 760 Lacq basin). By contrast, in the internal regions of the rift system (corresponding to the  
1437  
1438 761 future metamorphic NPZ), the basement thinned in a dominant-ductile mode because  
1439  
1440 762 temperature conditions reached 350°C to 450°C beneath the detached pre-rift cover and the  
763 syn-rift flysch.

1441  
1442  
1443 764 The peculiar evolution of the NPZ basins is depicted on figure 15 based on an original model  
1444  
1445 765 by Clerc et al., (2016). This model is strictly conceptual and was designed to account for  
1446  
1447 766 geological constraints gathered from various sites along the NPZ. The simplified system  
1448  
1449 767 includes the subcontinental mantle, a continental basement, a first decollement level in  
1450  
1451 768 Triassic evaporites, a level of layered pre-rift carbonates and a cover of syn-rift flysch. The  
1452  
1453 769 carbonates are able to deform by crystalline plasticity of calcite under HT conditions. The  
1454  
1455 770 corresponding lithologies are illustrated and briefly described in the NPZ lithostratigraphical  
1456  
1457 771 column of figure 5.

1458  
1459 772 In order to better assess the time-dependent rheological changes that necessarily affect  
1460  
1461 773 each geological layer involved during this three steps evolution, we provide synthetic  
1462  
1463 774 rheological profiles and geotherms for selected parts of the basin: in the external portion  
1464  
1465 775 representing the initial pre-extension model (fig. 15a) and in the center of the basin for the  
1466  
1467 776 following two steps (fig. 15b and c). The data used to construct these profiles derived from  
1468  
1469 777 the Duretz et al. (2019) model discussed in section D above.

1470  
1471 778 The three steps of this conceptual evolutionary model can be described as follows:

1472  
1473 779 (1) At an early rifting stage (fig. 15a) moderate extension leads to crustal thinning  
1474  
1475 780 accommodated through normal faults in the upper crust. The rheological profile consists of a  
1476  
1477 781 15 km thick, cold and brittle upper crust ( $T > 300^{\circ}\text{C}$ ) overlying a 15 km thick ductile lower  
1478  
1479 782 crust with Moho temperature around  $550^{\circ}\text{C}$ . The uppermost mantle is a strong 15 km thick  
1480  
1481 783 layer. In the inner part of the system, normal faults may pass downward to ductile shear  
1482  
1483 784 zones dipping toward the external side thus delineating a small central horst. The Triassic  
1484  
1485 785 evaporitic layers act as a décollement layer that allows the pre-rift carbonates to remain in  
1486  
1487 786 the most thinned and subsiding domains on both sides of the central horst while the syn-rift  
1488  
1489 787 flysch is being deposited above. Sliding of the pre-rift carbonates in the deep domain results  
1490  
1491 788 in the local tectonic denudation of the margins where carbonates remnants form isolated  
1492  
1493 789 rafts tilted on listric faults.

1494  
1495 790 (2) At the mid-rifting stage (fig. 15b), ductile thinning of the crust occurs in response to  
1496  
1497 791 heating due to rapid mantle uplift. The central crustal horst starts to deform ductilely and  
1498  
1499 792 progressively acquires a lens shape. Due to blanketing effect under the syn-rift sediments,  
1500  
793 the HT pre-rift carbonates suffer syn-metamorphic ductile deformation. Rheological profile

1501  
1502  
1503 794 in the center of the basin shows the Keuper weak zone at the base of the pre-rift cover and a  
1504  
1505 795 newly formed weak zone corresponding to the thinned crust which deforms at temperatures  
1506  
1507 796 between 300°C and 500°C. The lower crust has been extracted laterally and the brittle  
1508  
1509 797 mantle layer shows a decreasing thickness due to temperature increase from 400°C (step 1)  
1510  
1511 798 to 1000°C at only 20 km depth.

1512  
1513 799 (3) At the final rifting stage (fig. 15c), extreme thinning and boudinage of the crust leads to  
1514  
1515 800 local denudation of the sub-continental mantle, which is by place in tectonic contact with  
1516  
1517 801 the pre- or syn-rift sediments. The crust in the center of the basin has been cut into few  
1518  
1519 802 lenses that move independently. The crust at both edges of the proximal domain thins and  
1520  
1521 803 moves horizontally (*lateral extraction* concept of Clerc and Lagabrielle, 2014). The Triassic  
1522  
1523 804 décollement layer undergoes drastic thickness reduction leading to boudinage in response  
1524  
1525 805 to fluid-assisted tectonic brecciation and to metasomatic dissolution as observed in the  
1526  
1527 806 Urdach and Sarailé massifs in the western NPZ (Lagabrielle et al., 2019a, 2019b in press).  
1528  
1529 807 Due to their increasing plasticity, the HT marbles of the pre-rift cover progressively  
1530  
1531 808 accommodate a large part of the deformation at the base of the basin, involving calcite  
1532  
1533 809 plasticity and recrystallization, boudinage, drag folding and low angle normal shear bands. In  
1534  
1535 810 turn, the lower levels of the syn-rift flysch sequence are progressively affected by HT  
1536  
1537 811 metamorphism and ductile deformation with bedding-parallel foliation and boudinage.  
1538  
1539 812 Continuous extension of the basin floor leads also to the progressive exhumation of the  
1540  
1541 813 metamorphic pre-rift sediments, which are progressively extracted from below the syn-rift  
1542  
1543 814 cover (see complete description of this process in Clerc et al., 2016). In the thinnest crustal  
1544  
1545 815 portion, the rheological profile bears similarities with that of step 2. The crustal thickness  
1546  
1547 816 has now reduced to less than one km and the brittle/ductile transition has moved upward.  
1548  
1549 817 The pre-rift cover, salt décollement as well as the thinned basement thus deform under  
1550  
1551 818 dominant ductile deformation.

#### 1547 819 **IV. Conclusions**

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1550  
1551 821 Almost fourty years after the discovery of mantle exhumed at the foot of the north Iberia  
1552  
1553 822 passive margin (Boillot et al. 1980), this review highlights the affinities between the  
1554  
1555 823 architecture of two types of extensional basins now variously inverted in the Pyrenean  
1556  
1557 824 orogeny. These are : (i) the extensional basins that opened during the mid-Cretaceous times

1561  
1562  
1563 825 along the Iberia-Eurasia plate boundary and, (ii) the intraplate basins of northern Iberia  
1564  
1565 826 (Cameros to Columbrets basins). Taking as a reference the Parentis basin profile and on the  
1566  
1567 827 basis of geological reconstructions of NPZ rift architecture, we have designed an idealized  
1568  
1569 828 cross-section of a smooth-slopes basin shown in figure 16. The dominant features put  
1570  
1571 829 forward in this cross-section relate to the basin central region which lacks stepping normal  
1572  
1573 830 faults and large-scale tilted crustal blocks. The section shows a dominant symmetrical shape  
1574  
1575 831 with smooth-slopes that relates to a new mode of crustal stretching during continental  
1576  
1577 832 rifting characterized by a ductilely thinned crust in the central rift domain. This deformation  
1578  
1579 833 mode is typically symmetrical and contrasts drastically with stretching processes described  
1580  
1581 834 from the Iberia-Newfoundland and Alpine Tethys margins implying asymmetrical  
1582  
1583 835 architecture and extensional detachment separating upper and lower plates having  
1584  
1585 836 differential evolution.

1584 837

1586 838 The common character between all pre-rift sequences of the studied basins is the presence  
1587  
1588 839 of the thick low-strength Late Triassic evaporitic layer (Keuper facies). Geological and  
1589  
1590 840 geophysical studies point to the importance of this décollement layer in the evolution of  
1591  
1592 841 these rift basins. As established by geological studies in the NPZ, efficient décollement along  
1593  
1594 842 the Keuper evaporites and clays triggers mechanical decoupling and gliding of the pre-rift  
1595  
1596 843 cover that remains in the center of the basin as the crust is laterally extracted. Subsequent  
1597  
1598 844 deposition of syn-rift sediments allows preservation of the initial thermal anomaly with a  
1599  
1600 845 major consequence on the deformation regime in the pre-rift sediments and crustal  
1601  
1602 846 basement. The ubiquitous character of the ductilely deformed marbles in the metamorphic  
1603  
1604 847 NPZ relates to a dominant-ductile deformation regime in the pre-rift cover during the  
1605  
1606 848 Cretaceous extension. In these smooth-slopes basins, the ductilely stretched crust behaves  
1607  
1608 849 homogeneously at the regional scale and extensional allochthons are not individualized. A  
1609  
1610 850 lenticular mode of homogeneous deformation is thus defined implying interplay between  
1611  
1612 851 hectometric lenses of ductile crustal material separated by anastomosing shear zones.

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1611 853 Both laboratory and thermo-mechanical numerical models reproduce remarkably the mode  
1612  
1613 854 of deformation deduced from geophysical and geological constraints compiled in the studied  
1614  
1615 855 basins. Thus it appears that the pre-rift character of the salt layer is the key-factor of the

1621  
1622  
1623 856 rifting style in controlling the very early decoupling between the basement and the pre-rift  
1624  
1625 857 cover. This strongly contrasts with the evolution of Atlantic margins where the salt is either  
1626  
1627 858 syn-rift or post-rift. For the first time, we evidence a strong link between the occurrence of a  
1628  
1629 859 sedimentary layer covering the future rifted region (here Keuper salt and clays deposits) and  
1630  
1631 860 a mode of crustal thinning (here homogeneous bulk ductile deformation). Décollement  
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1633 861 along the evaporites and clays level finally favors the formation of symmetrical basins  
1634  
1635 862 lacking numerous normal faults and related tilted blocks. This new mode of crustal  
1636  
1637 863 deformation might not be restricted to the Pyrenean region, but may apply to all regions  
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1639 864 hosting thick pre-rift décollement series. It may have been active worldwide, in the distal  
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1641 865 portion of continental margins devoid of typical tilted blocks and extensional allochthons  
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1643 866 and where large units of extremely thinned continental crust are present.

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1643  
1644 868 To sum up, the specific characters of the smooth-slopes basins emphasized in this review are  
1645  
1646 869 twofold: (i) the peri-Pyrenean salt is pre-rift allowing conservation of the pre-rift cover over  
1647  
1648 870 the high-strain axial central region. The continuity of the Triassic evaporite formation is  
1649  
1650 871 preserved allowing for décollement of the pre-rift sequence which remain in the basin  
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1652 872 center. (ii) Consequently, the axial thermal anomaly is preserved and the dominant ductile  
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1654 873 mode of crustal deformation prevents the formation of faulting-related steps, thus leading  
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1656 874 to smooth-slopes basin edges. Continuous sedimentation in the subsiding basin leads to  
1657  
1658 875 progressive sedimentary burial of the prerift sequence. This in turn allows the preservation  
1659  
1660 876 of the initial thermal anomaly that may grow during the rifting evolution.

1659 877

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2583 **1523 Figure captions**  
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2585 1524

2587 **1525 Figure 1. Location of the studied basins and their paleogeographic position during the**  
2588  
2589 **1526 Cretaceous at the onset of the Iberia drift.**

2590 1527 (a) Simplified structural map of the Cantabrian-Pyrenean orogenic system and adjoining  
2592 Iberia showing Eurasia deformed and undeformed domain (modified from Verges and Garcia-  
2593 Senz, 2001 and Teixell et al., 2018). (b) Hypothetical reconstruction at the onset of the Iberia  
2594 drift (modified after Tugend et al., 2014).  
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2597 1531

2599 **1532 Figure 2. A compilation of Cretaceous basins architecture from the Cantabrian-Pyrenean**  
2600 **1533 belt.**

2602 1534 Reconstructions from field and geophysical data collected by various authors in the Basque-  
2603 Cantabrian basin (a, b, c) and in the North Pyrenean Zone (NPZ): Mauléon basin (d),  
2604 Chainons Béarnais (e, f), Baronnies basin (g) and Agly massif-Boucheville basin (h).  
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2609 **1538 Figure 3. Structure and evolution of Iberia-Newfoundland-type and Alpine-type passive**  
2610 **1539 margins** (modified from Péron-Pinvidic and Manatschal, 2009 and Mohn et al., 2012).

2613 1540 (a): two sketches showing the main concepts linked to Iberia-Newfoundland-type margin  
2614 evolution, namely: (i) strong final asymmetry with upper and lower plates separated by a  
2615 single detachment fault (HHD, Hobby High detachment), (ii) emplacement of extensional  
2616 allochthons as rigid crustal blocks over the exhumed mantle. (b): strain distribution and  
2617 strain partitioning during lithospheric thinning at magma-poor rifted margin, with example  
2618 from the fossil Alpine Tethys margin. In this model, the pre-rift cover remains welded on the  
2619 tilted crustal blocks; the middle crust is thinned to zero and the upper crust and upper  
2620 mantle are juxtaposed at the break up stage. The concepts shown in (a) and (b) contrast with  
2621 the concepts attached to the smooth-slopes basins evolution developed in this paper.  
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2630 **1550 Figure 4. The geological record of the Cretaceous extension in the Paleozoic basement and**  
2631 **1551 exhumed mantle of the North Pyrenean Zone (NPZ).**

2633 1552 The map shows the location of mantle bodies and crustal units illustrated in photographs a  
2634 to k. (a): dated crustal mylonites associated with the Urdach Iherzolites; thin section  
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2643 1554 microphotograph (natural light) of the leucocratic gneissic mylonite exposed at Col d'Urdach  
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2645 1555 and containing numerous micafishes (dating by the Ar/Ar method at 105 Ma; after Asti et al.,  
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2647 1556 2019). (b): thin section of typical ultramylonite from the lenses of Paleozoic material welded  
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2649 1557 on the exhumed mantle rocks of the Sarailé lherzolite (Asti et al., 2019). (c): phacoidal fabric  
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2651 1558 defined by anastomosing shear zones in the mantle body of Bestiac. This fabric is typical of  
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2653 1559 the lenticular layer as defined by Lagabrielle et al. (2019a, 2019b). (d): phacoidal fabric in the  
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2655 1560 lenticular layer of the lherzolite body of Moncaup. (e): phacoidal fabric in the lenticular layer  
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2657 1561 of the lherzolite body of Sarailé (Lagabrielle et al., 2019b). (f): curved shear zones and  
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2659 1562 elongated tectonic lenses in serpentinized lherzolites of the lenticular layer in the Moncaut  
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2661 1563 peridotite body. (g and h): phacoidal fabric in the lenticular layer of the lherzolite body of  
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2663 1564 Urdach: h shows pervasive carbonation (Lagabrielle et al., 2019a). (i and j): thin section and  
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2665 1565 outcrop of anastomosing serpentinized shear bands in the lherzolites of Etang de Lers  
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2667 1566 (Lherz). (k): anastomosing serpentinized shear bands in the lherzolites of Avezac.

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2667 1568 **Figure 5. The geological record of the Cretaceous extension in the pre-rift cover of the**  
2668  
2669 1569 **metamorphic North Pyrenean Zone (NPZ). Some field view of outcrops showing the layer**  
2670  
2671 1570 **perpendicular flattening and the S0/S1 syn-metamorphic foliation.**

2672 1571 (a): layer-parallel boudinage in the Calce quarry (Jurassic dolostones of the Agly massif  
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2674 1572 cover, Eastern NPZ). (b): layer-parallel ductile stretching of the meta-laterite and carbonate  
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2676 1573 breccia in the Benou quarry near Turon de la Tecouère lherzolite body (Chainons Béarnais,  
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2678 1574 Western NPZ). (c): flattened fossils in the Jurassic meta-dolostones of the Saleix valley (Aulus  
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2680 1575 basin, Central NPZ). (d): extreme stretching of a rudist-rich Urgonian marbles at Sarrance  
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2682 1576 (Chainons Béarnais, Western NPZ) (see also fig. 6c). (e): tight normal faults affecting the  
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2684 1577 early S0/S1 syn-metamorphic foliation in the pre-rift cover marbles of the Agly massif. These  
2685  
2686 1578 features characterize the ductile-brittle transition that occurred at the end of the rifting  
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2688 1579 history. (f): same features as (e) but in the marbles of the detached Lherz body cover  
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2690 1580 (southern side). (g): recumbent folds associated with the early ductile foliation in marbles  
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2692 1581 from the detached cover of the Pays de Sault Paleozoic basement (Eastern NPZ). (h): tectonic  
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2694 1582 brecciation with calcite veining marking the ductile-brittle transition in the marbles of the  
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2696 1583 Lherz body cover (western side).

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2696 1585 **Figure 6 . A theoretical log of the lithological succession in the internal domain of the**

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2702  
2703 **1586 Cretaceous NPZ rift basins.**  
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2705 1587 The photographs illustrate the various rock-types forming the basin basement (crust and  
2706 1588 mantle) and the pre-rift and syn-rift series. (a): Chaînons Béarnais (Saraillé massif, western  
2707 1589 NPZ). (b): Boucheville basin (eastern NPZ). (c): Urgonian at Sarrance (western NPZ) (see also  
2710 1590 fig. 5d). (d): Jurassic dolomites at Calce (eastern NPZ). (e): base of pre-rift series (Bestiac,  
2711 1591 eastern NPZ). (f): base of pre-rift series (Moncaup, central NPZ). (g): crustal lenses of Saraillé  
2713 1592 massif (western NPZ). (h): lenticular layer (Urdach mantle body, western NPZ).  
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2717 **1594 Figure 7. Interpreted and reconstructed profiles of peri-Pyrenean Cretaceous basins**  
2718 **1595 architecture.**

2719  
2720 1596 (a): Parentis basin. (b): Columbrets basin. (c and d): Cameros basin. See location of basins in  
2721 1597 fig. 1.  
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2724  
2725 **1599 Figure 8. A compilation of model results and conceptual representations of extended to**  
2726 **1600 hyper-extended continental crust.**

2727  
2728 1601 This compilation aims enhancing the main mechanical concepts involved in the processes of  
2729 1602 crustal extension and how they apply or not apply to the genesis and evolution of the  
2730 1603 smooth-slopes basins defined in this article (see text for discussion).  
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2735 **1605 Figure 9. A compilation of reconstructed architecture of Pyrenean Cretaceous basins and a**  
2736 **1606 Basque-Parentis transect.**

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2738 1607 All represented sections are based on the activation of a restricted number of detachment  
2739 1608 faults. As discussed in text, such representations do not match the newly defined smooth-  
2740 1609 slopes architecture that characterize the Pyrenean and peri-Pyrenean Cretaceous basins.  
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2744  
2745 **1611 Figure 10. Deformation regimes of the various units composing a typical smooth-slopes**  
2746 **1612 basin.**

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2748 1613 (a): distribution of pure shear and simple shear regimes in a simplified smooth-slopes basin  
2749 1614 system. (b): Detail of the very distal part of the hyper-extended crust (area shown in a). (b1):  
2750 1615 simplified log showing the association of metric to hectometric crustal lenses separated  
2751 1616 from the mantle rocks by the crust-mantle detachment and from the detached pre-rift cover  
2752 1617 by the cover décollement (see definition in Lagabrielle et al., 2019a, 2019b). (b2): field view  
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2763 1618 of crustal sheets from the base of the Saraillé massif (western NPZ). (b3): field view of  
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2765 1619 anastomosing shear zones cutting through the serpentinitized peridotite of the Saraillé body  
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2767 1620 and forming the lenticular layer of the crust-mantle detachment (see also fig. 4c to k).

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2770 1622 **Figure 11. A compilation of schematic architecture of selected Atlantic and Mediterranean**  
2771  
2772 1623 **passive margins.**

2773 1624 These margin profiles are selected because they offer architectures which do not fit with  
2774  
2775 1625 the Iberia-Newfoundland-type margin (see fig. 2). In particular, they show large scale crustal  
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2777 1626 boudinage and lenticulation that are consistent with a ductile regime of extensional  
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2779 1627 deformation. Sheets of hyper thinned crustal material is indicated by the orange arrow (see  
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2781 1628 comments in text). Note that scale is similar in all profiles.

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2784 1630 **Figure 12. Three numerical models of rift development compared to the Angola-Brazil and**  
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2786 1631 **Iberia transects.**

2787 1632 All models highlight a mode of deformation that leads to the development of very thin and  
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2789 1633 long sheets of crustal material also observed in the Angola-Campos transect but not in the  
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2791 1634 Iberia transect. Such deformation necessarily imply a ductile behaviour of the crust  
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2793 1635 consistent with processes acting in the central part of the smooth-slopes basins studied in  
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2795 1636 this paper (see text for further comments).

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2798 1638 **Figure 13. Paleogeography of Triassic deposits and Cretaceous rifting around the Iberia**  
2799  
2800 1639 **plate.**

2801 1640 (a): paleogeographic maps for the Triassic period (modified from Orti et al., 2017) and  
2802  
2803 1641 location of some further Cretaceous rifted regions. Note that by contrast to the area where  
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2805 1642 Cretaceous smooth-slopes basins will open, the area corresponding to the future Iberia-  
2806  
2807 1643 Newfoundland conjugate margins are devoid of thick evaporitic series. (b): paleogeographic  
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2809 1644 maps for the Ladinian and Carnian (Middle-early Late Triassic times, 242-227 Ma) modified  
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2811 1645 after Scotese and Schettino (2017). (c): paleogeography of Upper Triassic deposits prepared  
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2813 1646 after a compilation of unpublished data by D. Frizon de Lamotte (pers. com.) superimposed  
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2815 1647 on a plate reconstruction by Olivet (1996).

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2823 **1649 Figure 14. Correlation between the paleogeography of Triassic deposits and the mode of**  
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2825 **1650 rifting around the Iberia plate.**

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2827 1651 (a): cartoons (a1 and a2) illustrating the contrasted rifting modes between the Iberia-  
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2829 1652 Newfoundland-type and the Parentis-type margins (modified from Clerc and Lagabrielle,  
2830  
2831 1653 2014). (b): paleogeography of Triassic (Late Norian) deposits according to Marcoux et al. in  
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2833 1654 the Dercourt et al. (1993) map atlas. As paleogeographic maps in fig. 13, this reconstruction  
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2835 1655 points to the lack of thick evaporites deposits in the future Iberia-Newfoundland rifting  
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2837 1656 domain (see text for discussion).

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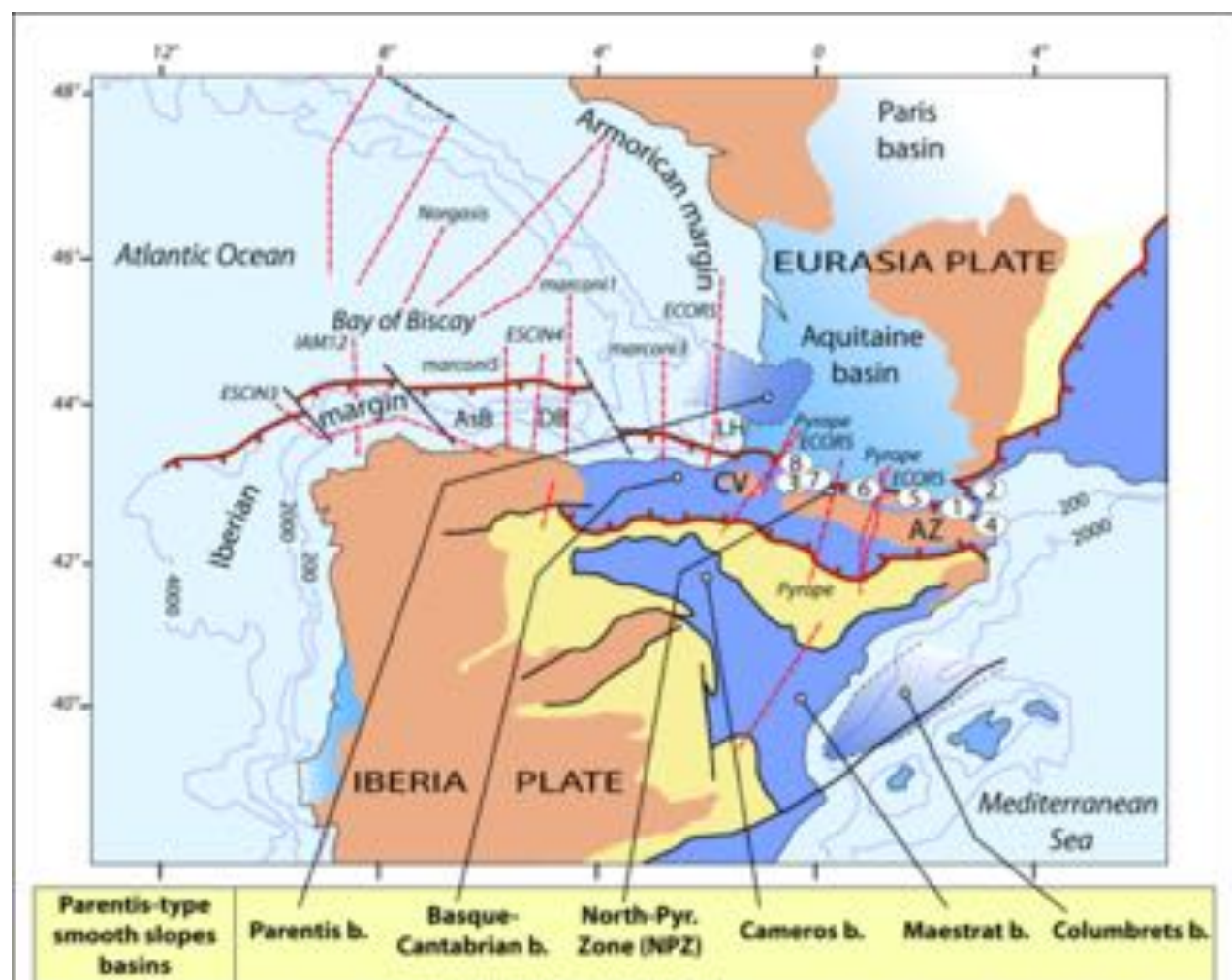
2838  
2839 **1658 Figure 15. Time-dependent rheological evolution of the Pyrenean rifting based on**  
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2841 **1659 geological constraints from the North Pyrenean Zone and numerical results from a thermo-**  
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2843 **1660 mechanical numerical modeling.**

2844 1661 Sketches depicting the geological evolution are extracted from the Clerc et al. (2016) model.  
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2846 1662 Rheological profiles derive from the Duretz et al., (2019) model. They are placed at critical  
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2848 1663 locations (1, 2 and 3) of the rift in order to emphasize the drastic changes in the mechanical  
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2850 1664 behaviour during its evolution from limited crustal extension to local mantle exhumation  
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2852 1665 (see detailed description in text).

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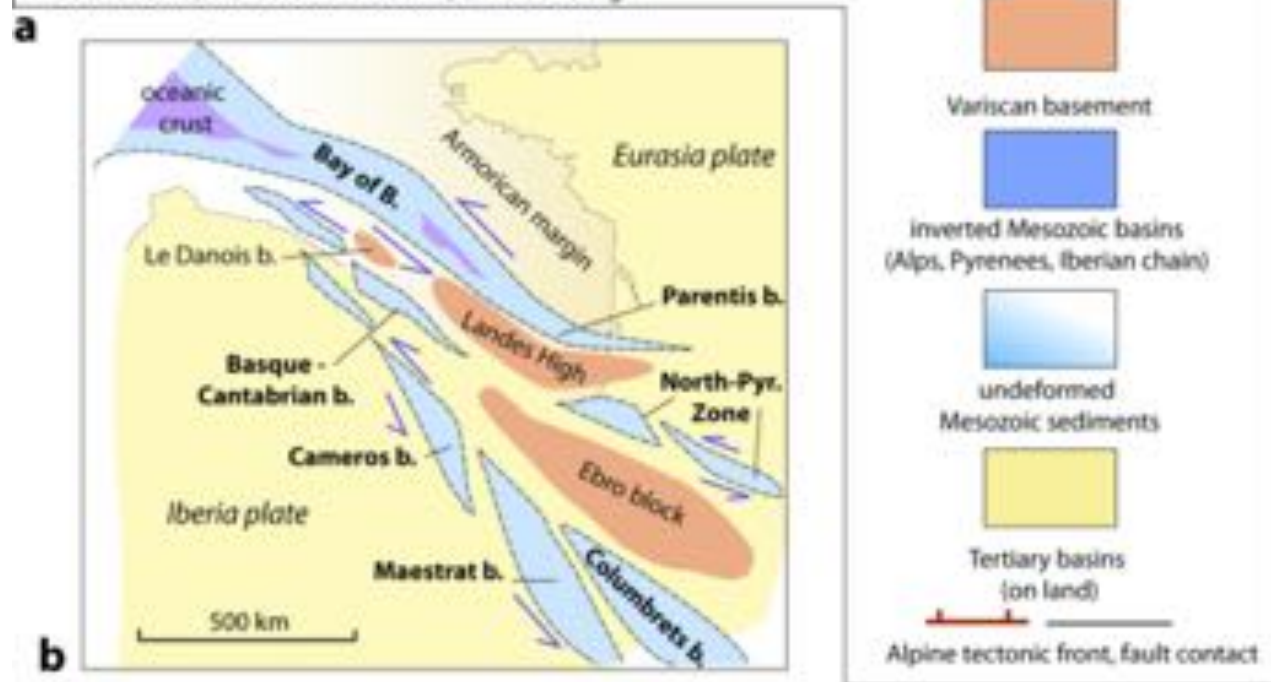
2854 **1667 Figure 16. A theoretical structural model for the Cantabrian, Pyrenean and Iberian**  
2855  
2856 **1668 symmetrical smooth-slopes basins based on the features and concepts discussed in this**  
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2858 **1669 article.**

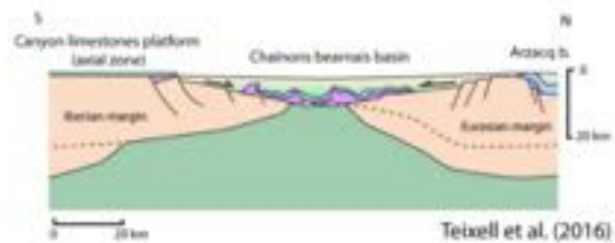
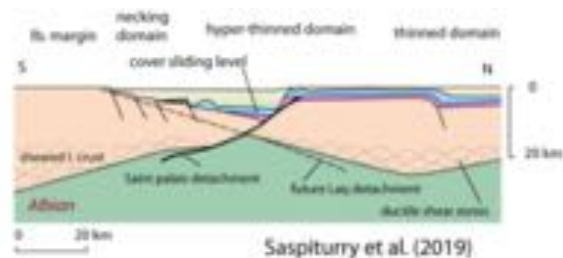
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DB : Le Danois Bank, AsB: Asturias basin  
 AZ : Axial Zone, CV : Cinco Villas massif, LH: Landes High

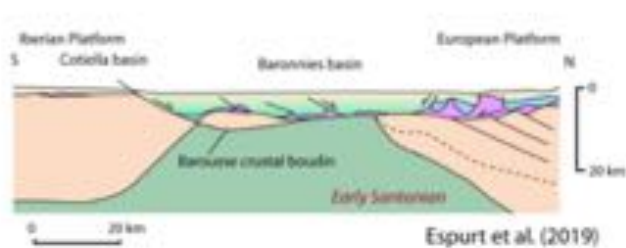
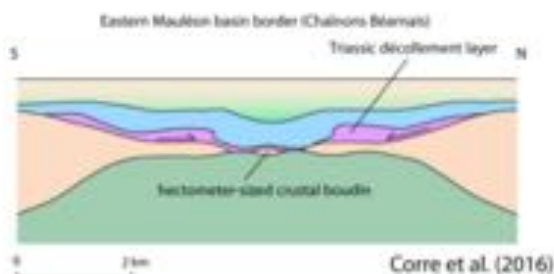
① location of photographs in figure 6





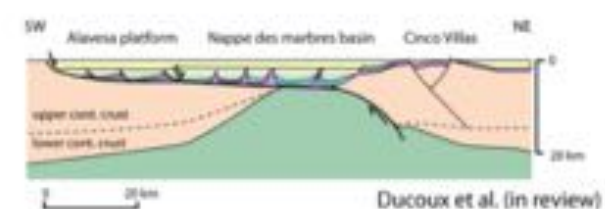
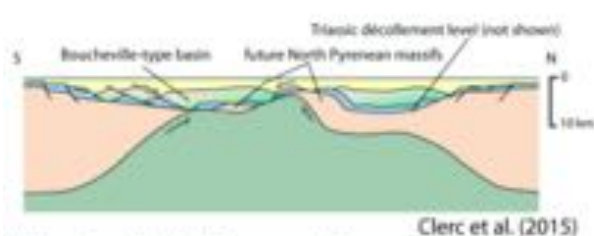
**a. Western North Pyrenean Zone (1)**

**b. Western North Pyrenean Zone (2)**



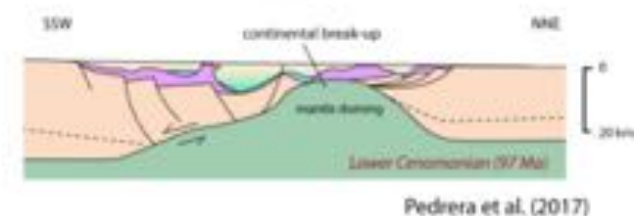
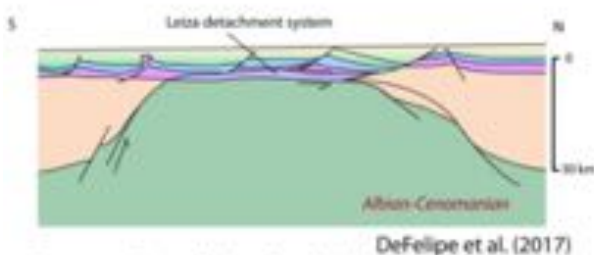
**c. Western North Pyrenean Zone (3)**

**e. Central North Pyrenean Zone**



**h. Eastern North Pyrenean Zone**

**f. Basque-Cantabrian basin (1)**

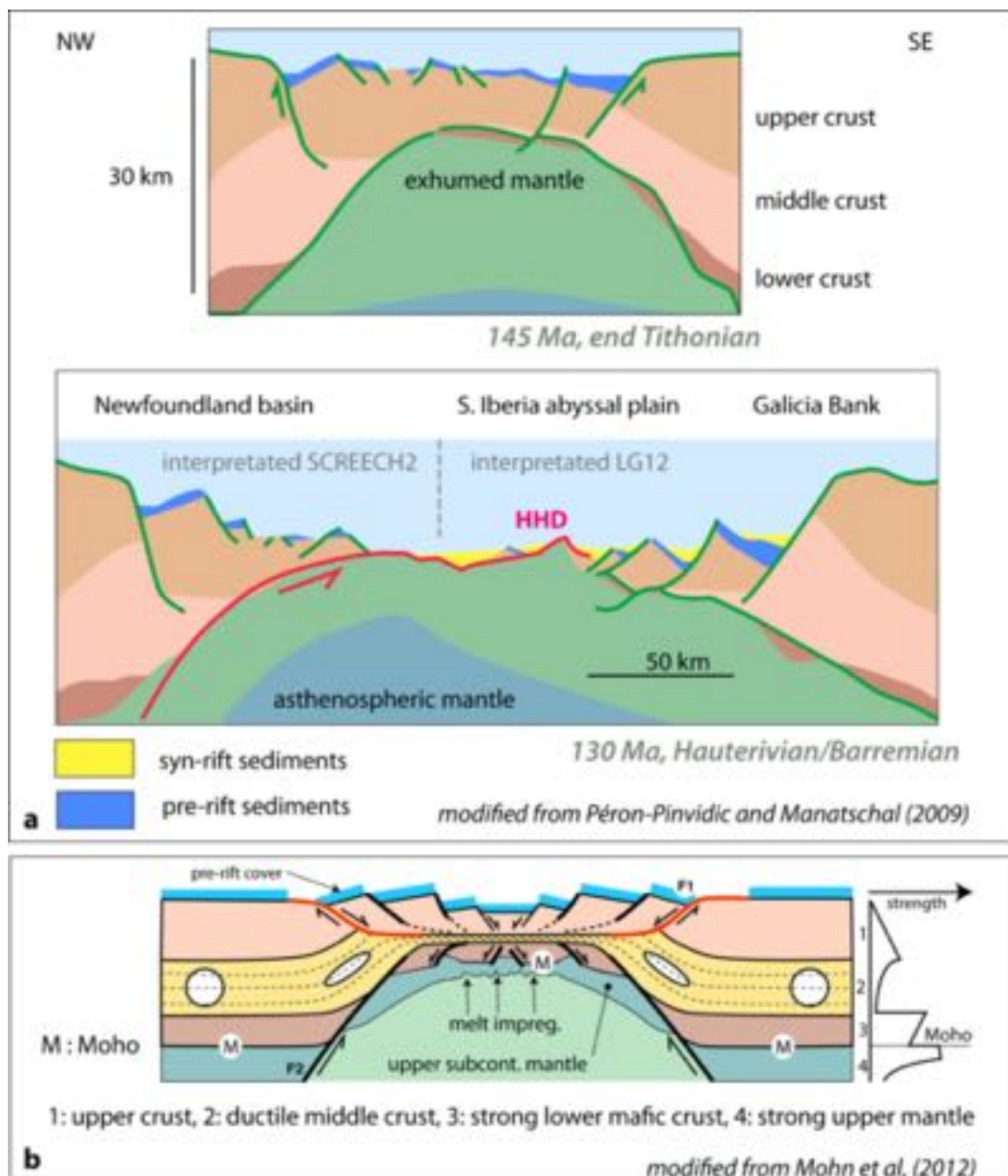


**g. Basque-Cantabrian basin (2)**

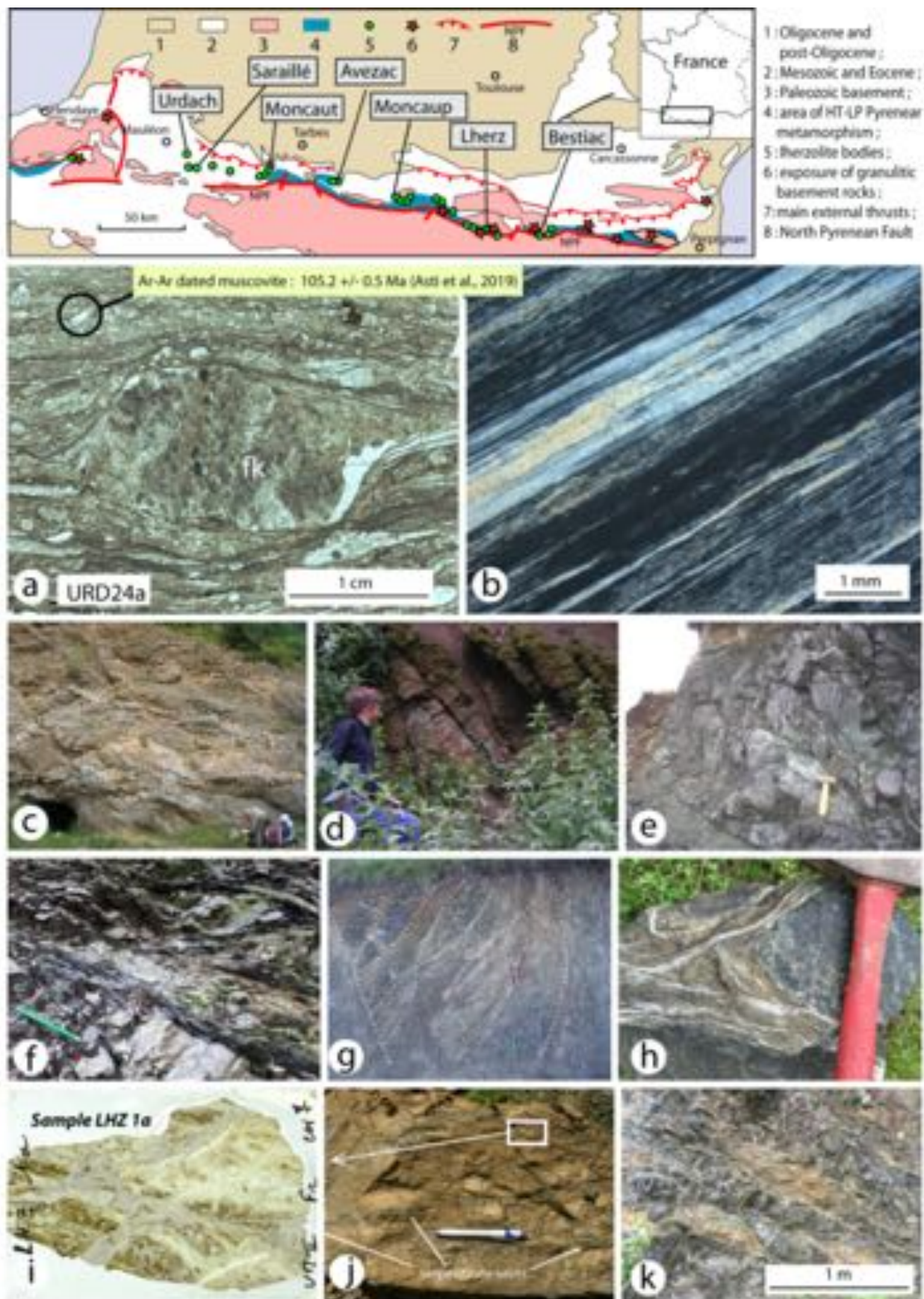
**h. Basque-Cantabrian basin (3)**



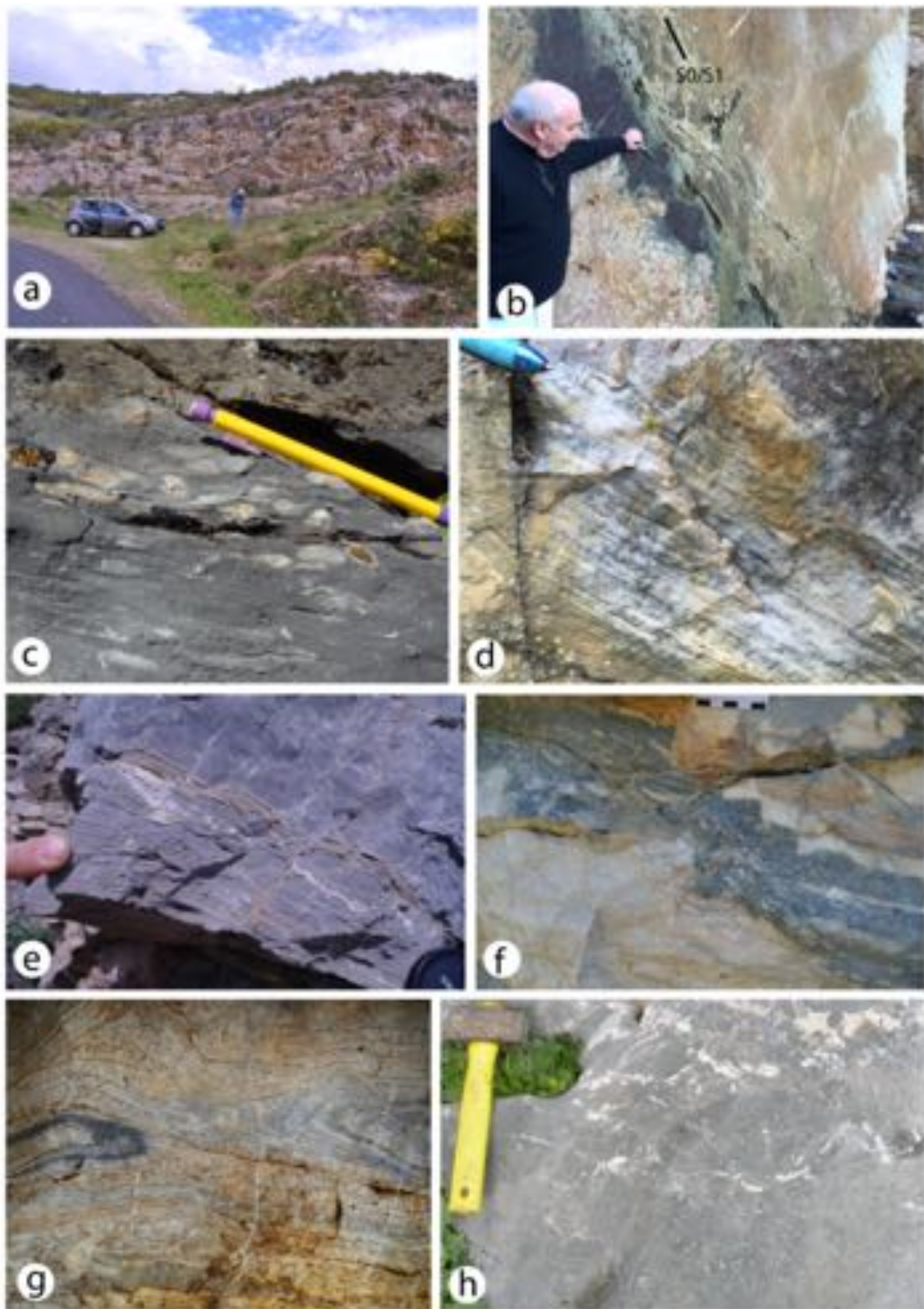
Lagabrielle et al., fig. 2, ESR, submitted



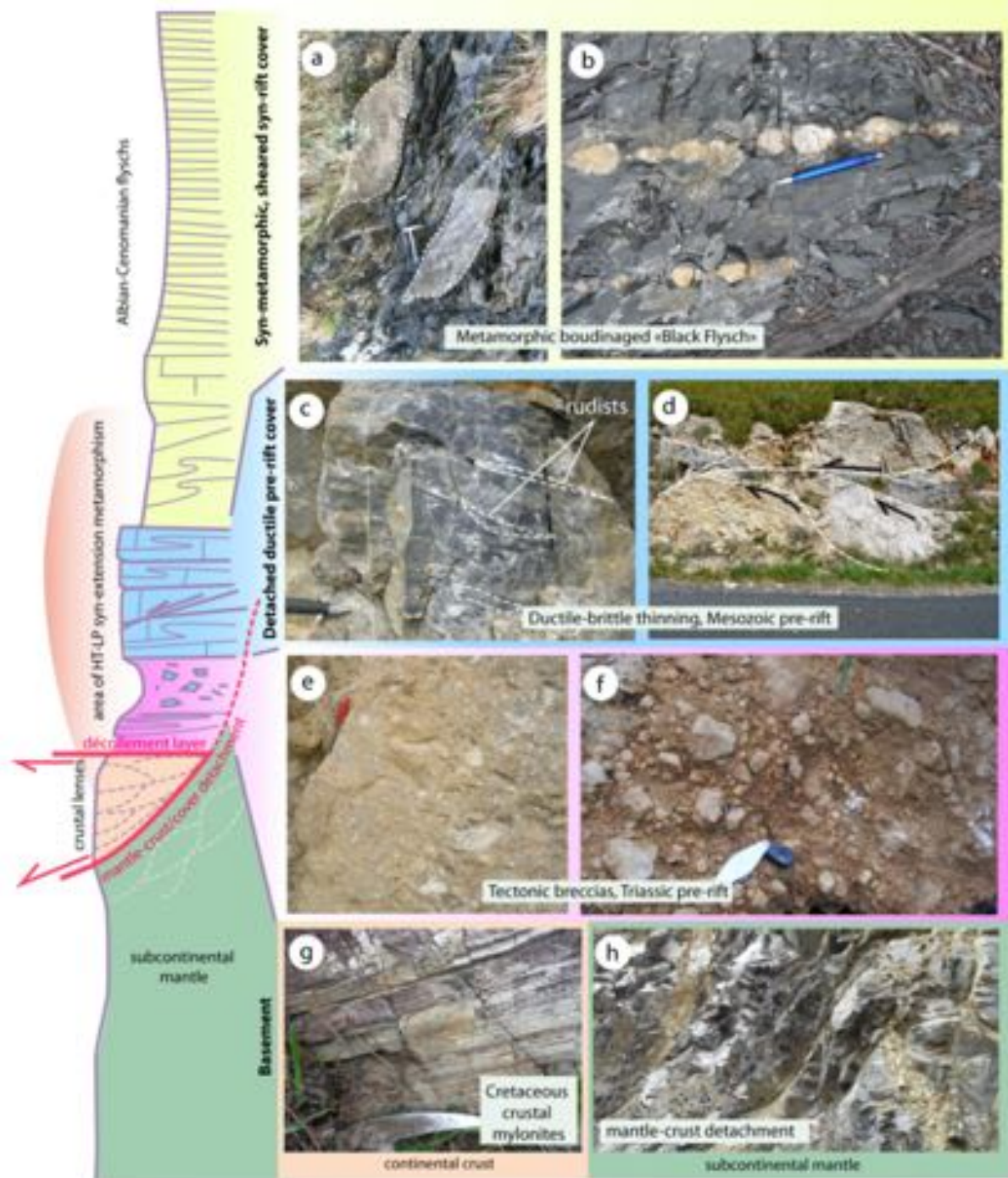
Lagabrielle et al., fig. 3, ESR, submitted



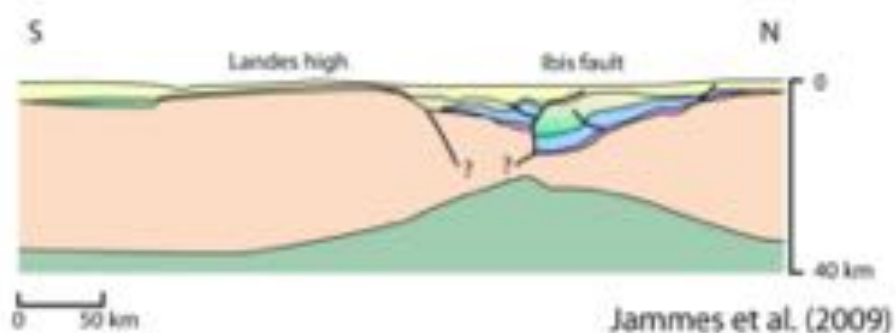
Lagabrielle et al., fig. 4, ESR, submitted



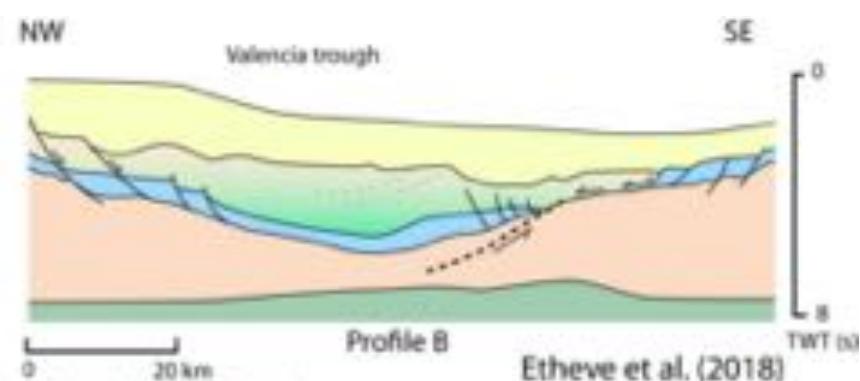
Lagabrielle et al., fig. 5, ESR, submitted



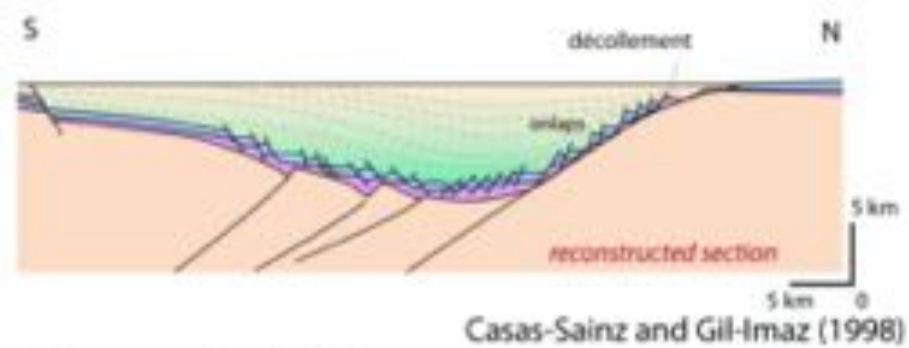
Lagabrielle et al., fig. 6, ESR, submitted



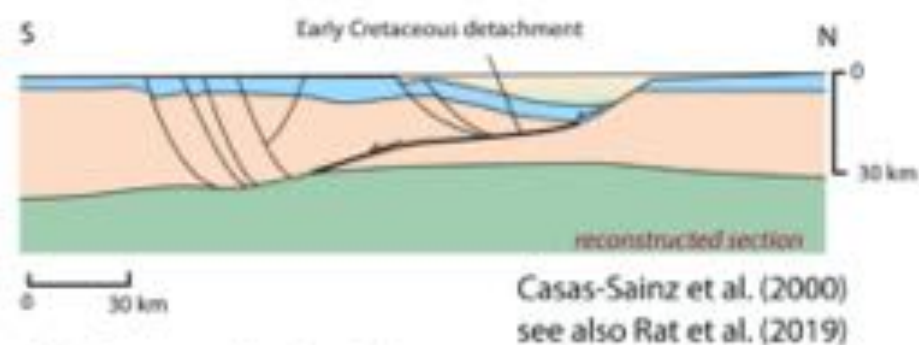
**a. Parentis basin**



**b. Columbrets basin**



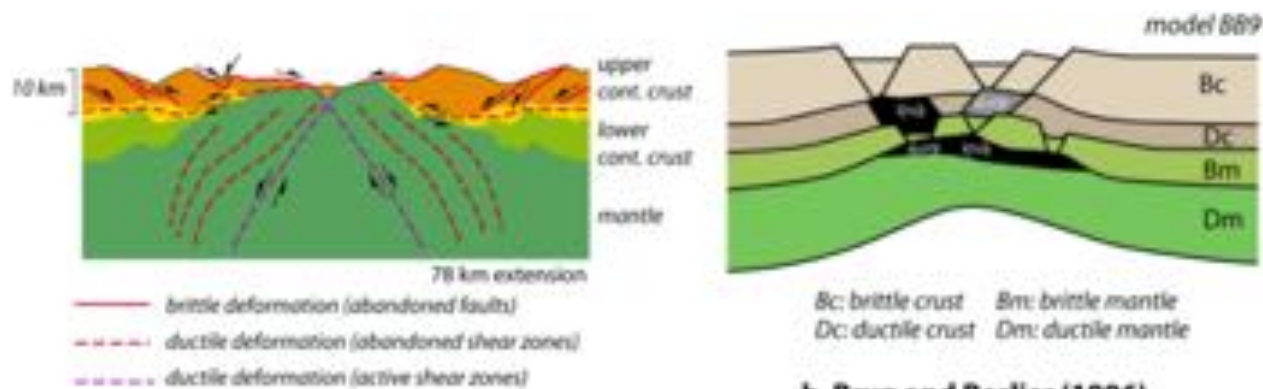
**c. Cameros basin (1)**



**d. Cameros basin (2)**

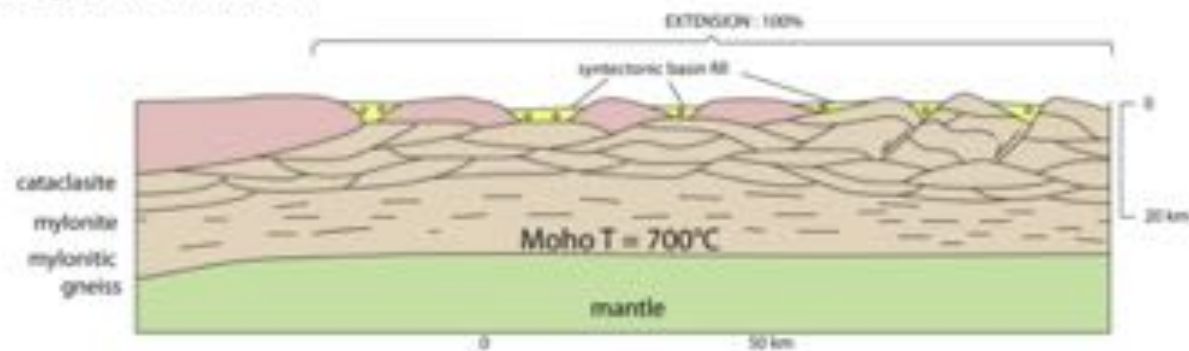




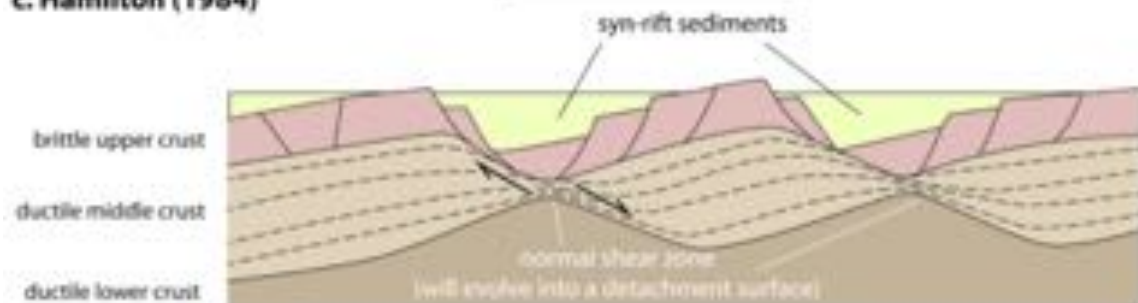


**a. Nagel and Buck (2004)**

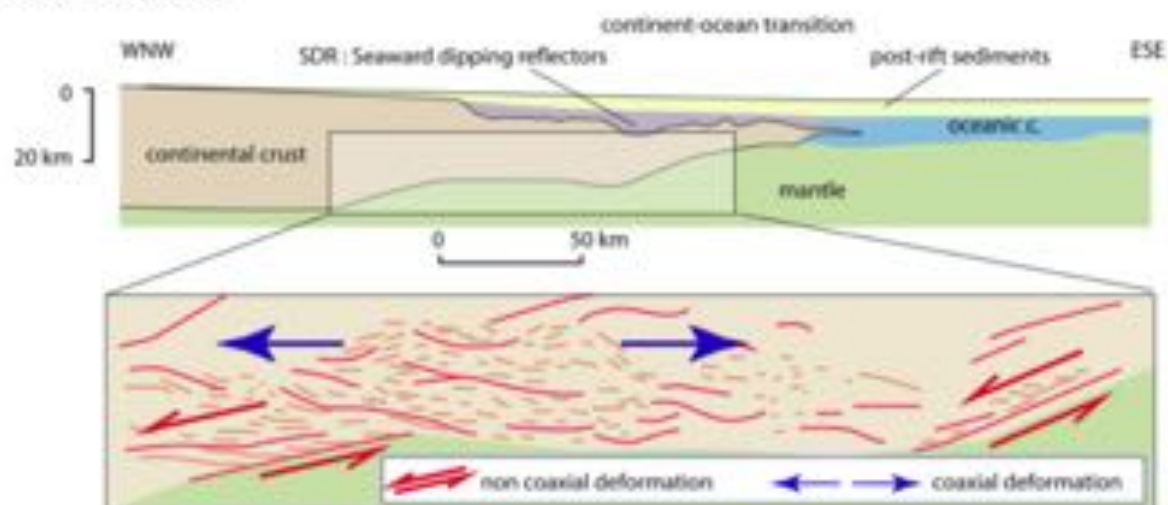
**b. Brun and Beslier (1996)**



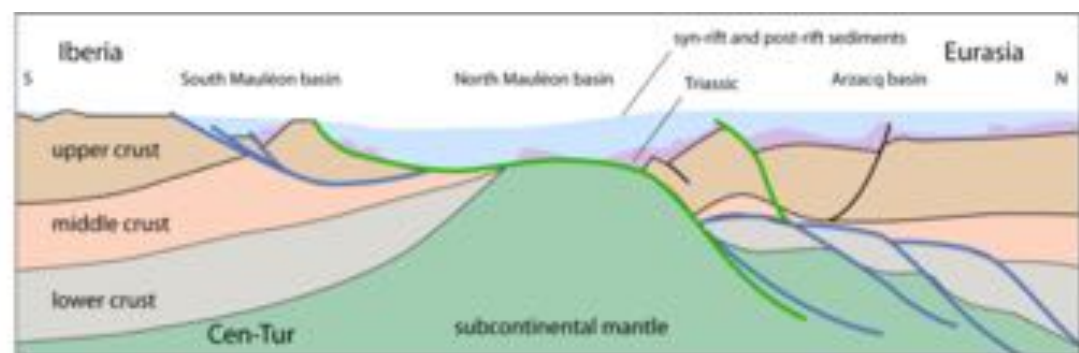
**c. Hamilton (1984)**



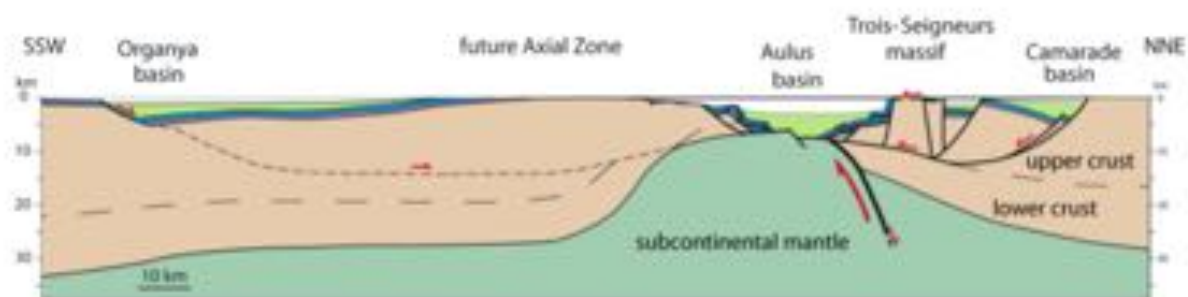
**d. Gartrell (1997)**



**e. Clerc et al. (2018)**



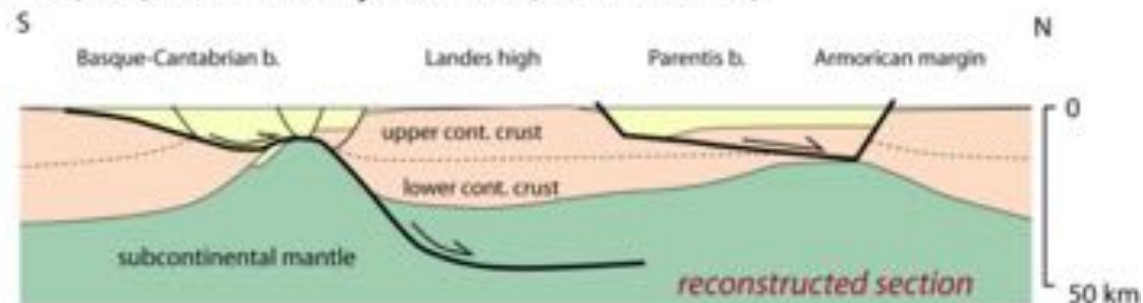
**a. Masini et al. (2014): Mauléon basin**



**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**

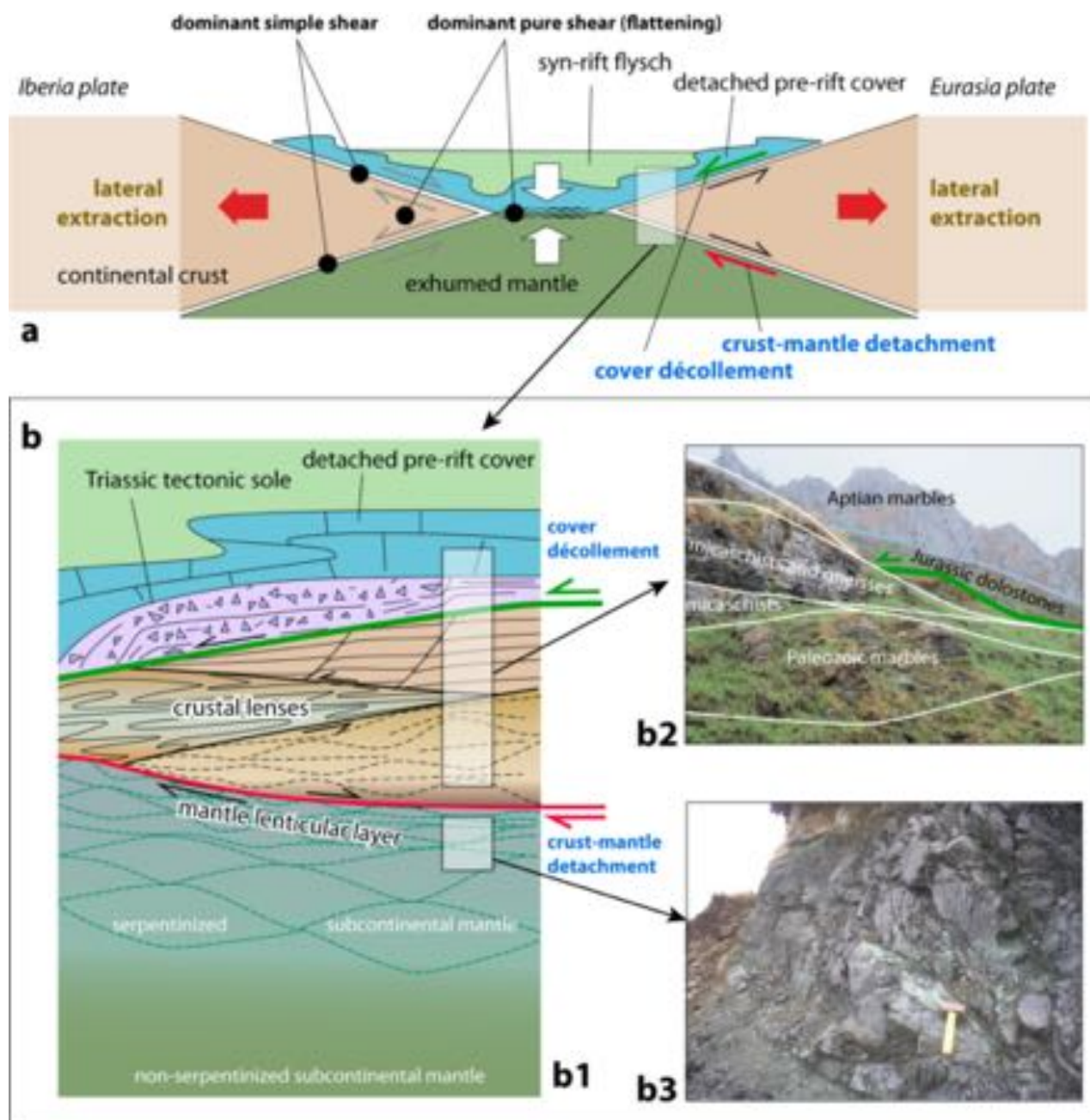
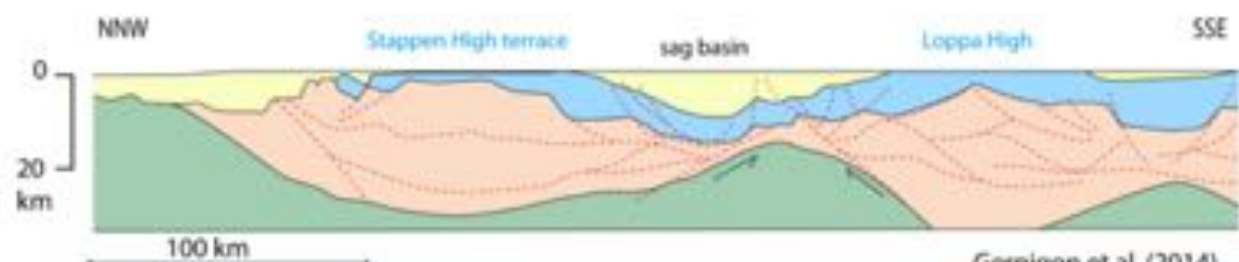
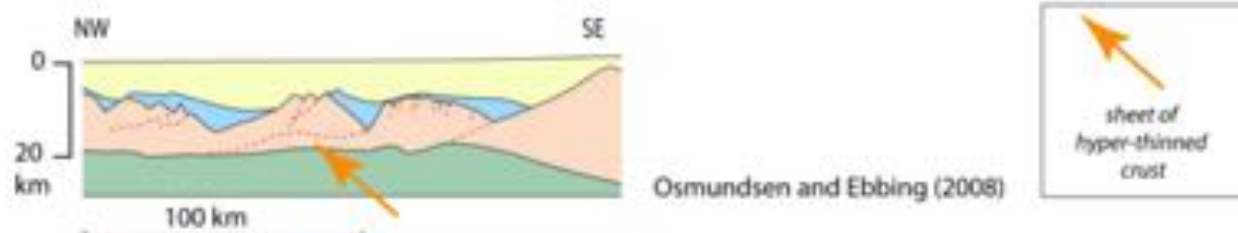


fig. 10

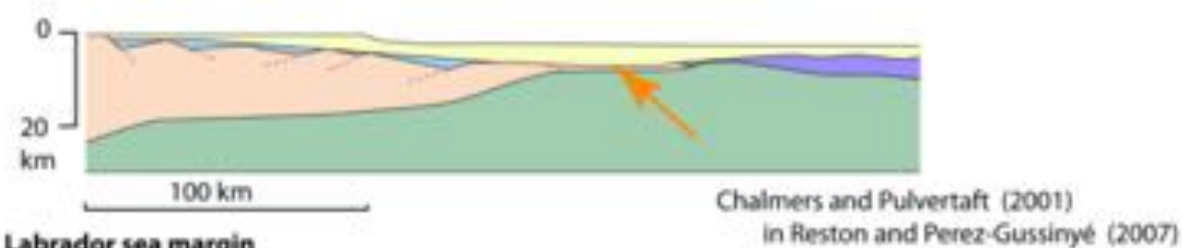
Lagabrielle et al., smooth slopes basins, submitted



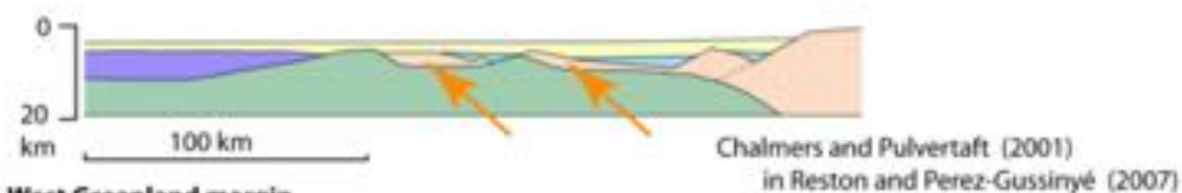
**a. Barents margin**



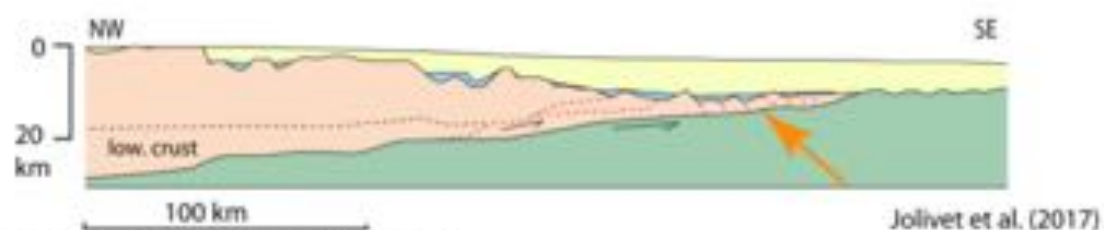
**b. Northern More basin, Norway margin**



**c. Labrador sea margin**

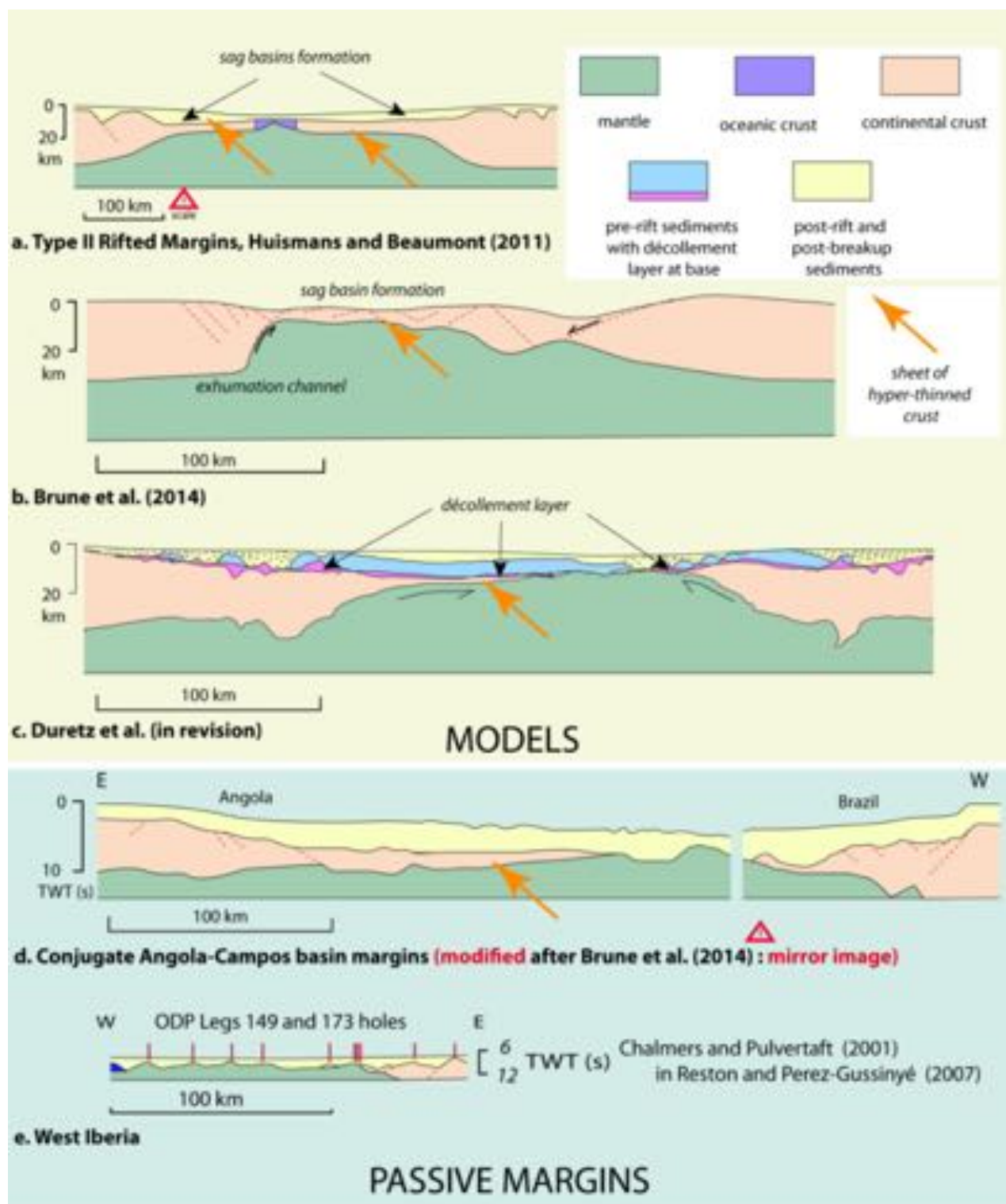


**d. West Greenland margin**

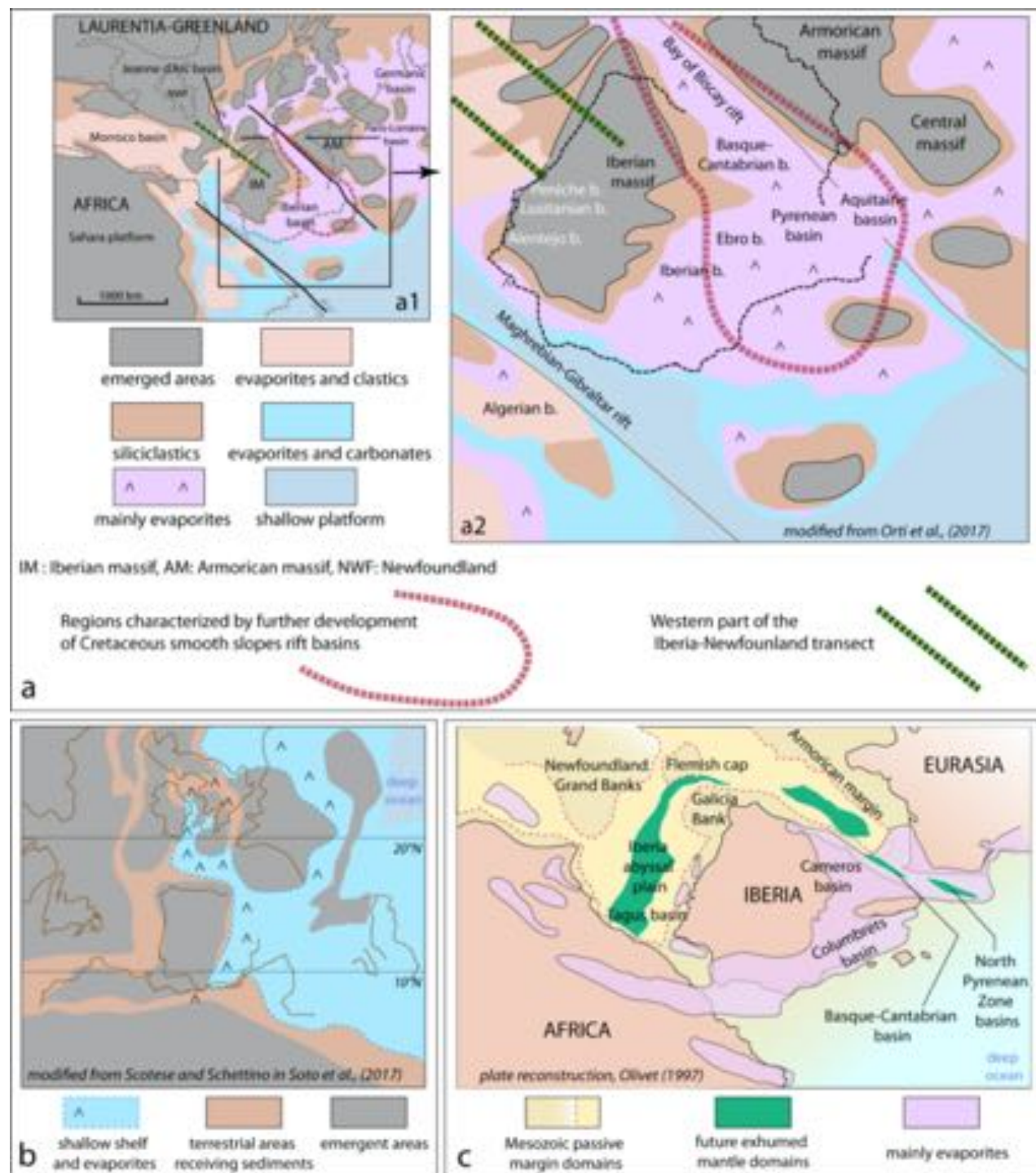


**e. Western Mediterranean, Gulf of Lion**

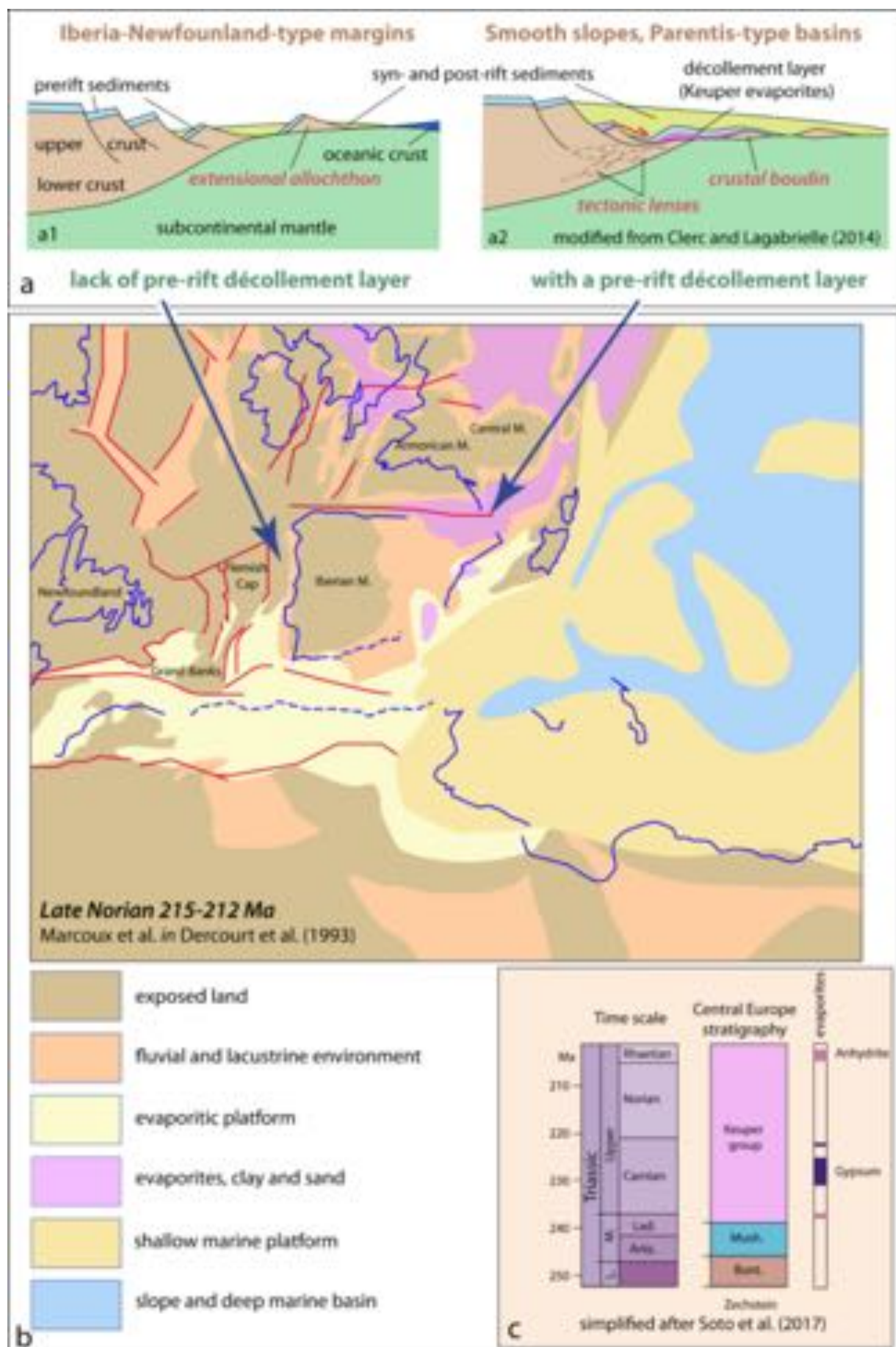


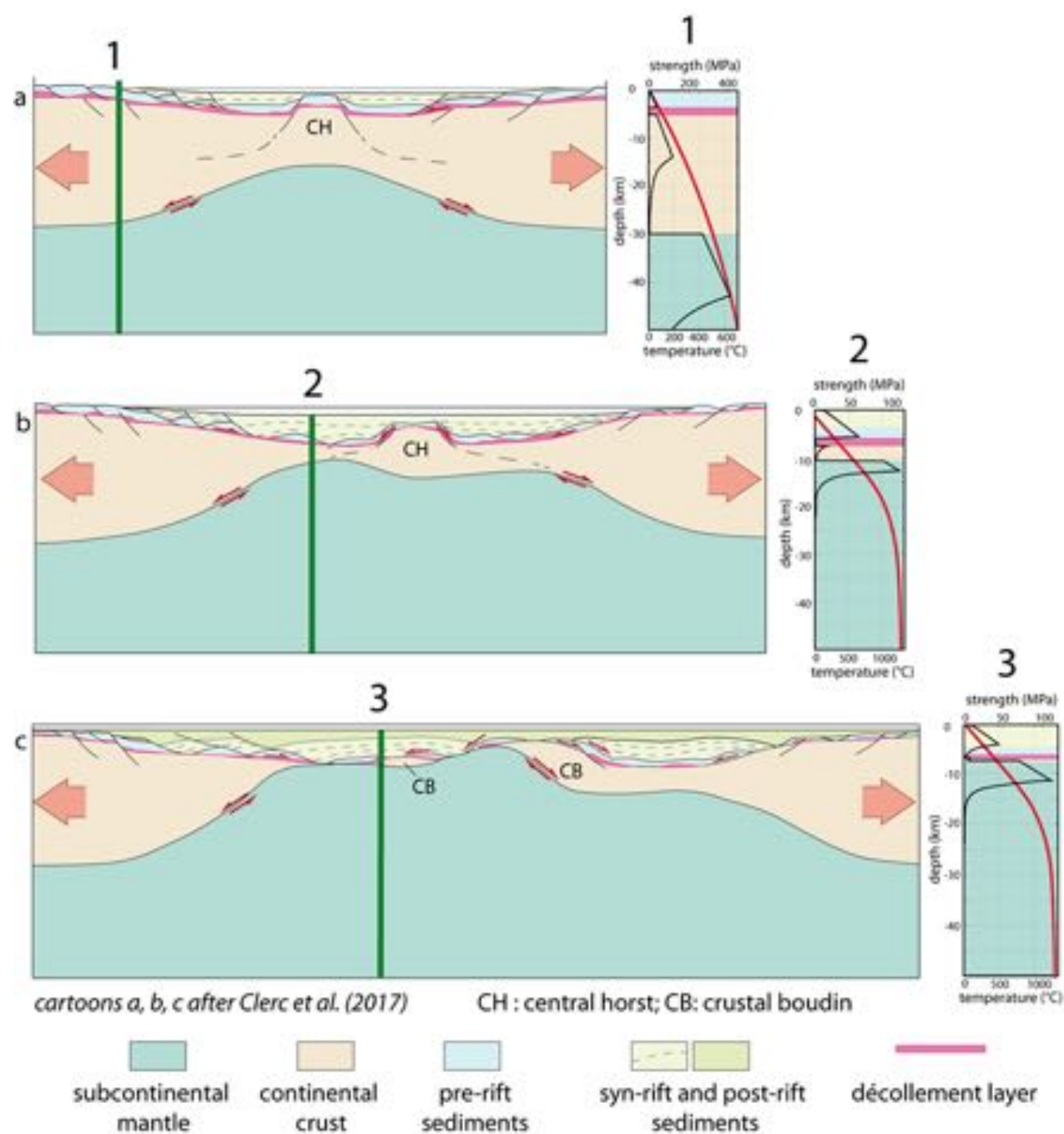


Lagabrielle et al., fig. 12, ESR, submitted



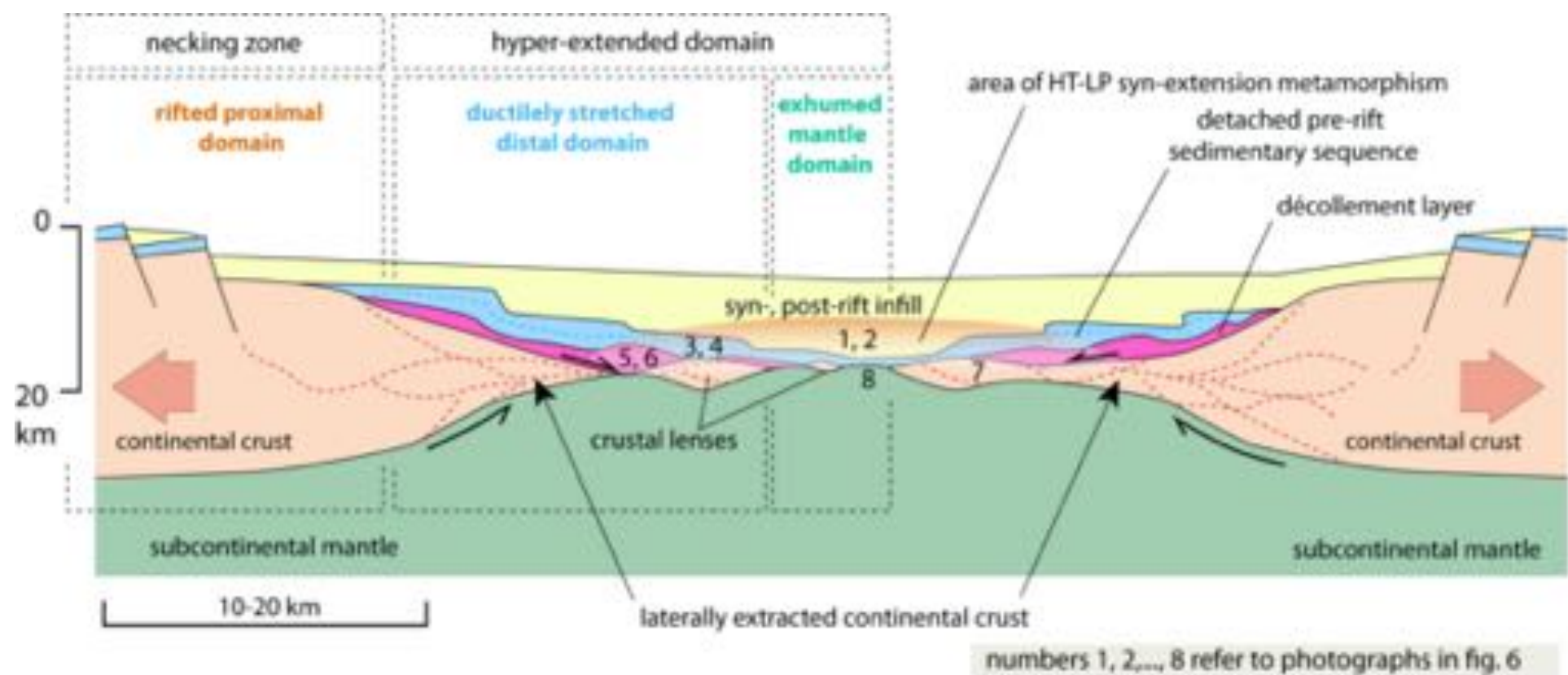
Lagabrielle et al., fig. 13, ESR, submitted





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





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