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## The Grès Singuliers of the Mont Blanc region (France and Switzerland): stratigraphic response to rifting and crustal necking in the Alpine Tethys

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1        **The *Grès Singuliers* of the Mont Blanc region (France and Switzerland):**  
2        **Stratigraphic response to rifting and crustal necking in the Alpine Tethys**

3  
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16  
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## 27 **Abstract**

28 The Grès Singuliers unit represents an anomalous occurrence of a siliciclastic-dominated sedimentary  
29 system typifying a restricted geographic area around the Mont Blanc massif. Deposited during Early  
30 Jurassic rifting, this unit was influenced by the tectonic processes responsible for its development. This  
31 contribution integrates and reconciles sedimentological, stratigraphic and tectonic data and discusses  
32 the tectono-sedimentary evolution of the Mont Blanc basement and its autochthonous sedimentary  
33 cover. Based on depositional facies, a petrographic and detrital zircon provenance analysis, we  
34 propose that the Grès Singuliers unit is mainly derived from erosion of the local basement and pre-rift  
35 sedimentary cover. Furthermore, recognition of Jurassic cataclasites and black gouges capping the  
36 Mont Blanc basement confirms the hypothesis that the Mont Blanc domain formed an extensional  
37 core complex. The source to sink relationship between the Mont Blanc detachment system and the  
38 Grès Singuliers unit, as well as timing and location within the Alpine rift system, allows us to interpret  
39 this unit as the syn-tectonic sedimentary response to crustal necking, responsible for the onset of  
40 localized severe crustal/lithospheric thinning in the European margin of the Alpine Tethys rift system.  
41 The main result of this study was to show that the exhumation and uplift of basement during  
42 crustal/lithospheric necking produced a new source area for clastic sedimentary systems. Therefore,  
43 the local occurrence of a siliciclastic unit similar to the Grès Singuliers along passive margins may be  
44 symptomatic of necking zones in other rift systems.

45

## 46 **1. INTRODUCTION**

47 The “Grès Singuliers” were first mentioned by De Saussure (1779). In his “*Voyage dans les Alpes*”, he  
48 dedicated a paragraph entitled “Grès remarquables” to these sandstones observed across the Mont  
49 Blanc massif. A series of studies followed, mentioning the “Grès remarquables” and renaming them as  
50 “Grès Singuliers” (Favre 1867; Ritter 1897; Duparc et al. 1901). Although the term “singuliers” (English:  
51 singular/unique), referred initially to the lithofacies interpreted to result from the reworking of the

52 underlying polymetamorphic basement, eventually “singuliers” eventually denoted the stratigraphic  
53 position that subsequently attracted attention over the next 50 years (i.e. Bonhomme area, e.g.  
54 Antoine et al. 1975; Landry 1978; Eltchaninoff and Triboulet 1980; Triboulet 1980; Eltchaninoff-  
55 Lancelot et al. 1982). Indeed, the “Grès Singuliers” represents an anomalous occurrence of syn-rift  
56 clastic Jurassic sediments that formed within an otherwise carbonate dominated depositional setting  
57 at the distal proximal European margin. The uniqueness of the “Grès Singuliers” lies in the fact that  
58 this siliciclastic deposit is only observed in a very restricted paleogeographic area of the autochthonous  
59 sedimentary cover of the Mont Blanc massif.

60 The following questions arise from the study of the “Grès Singuliers”:

- 61 (i) Which type of source to sink system is responsible for the origin of the siliciclastic deposits,  
62 and how far is this system singular/unique in rift settings?
- 63 (ii) Do the “Grès Singuliers” record a particular time range in rift development?
- 64 (iii) Is the position of the “Grès Singuliers” along the margin symptomatic and/or indicative of  
65 a particular rift process and/or rift domain?
- 66 (iv) Are similar sediments observed elsewhere in the Alpine Tethys and present-day rifted  
67 margins?

68 The study presented here is based on field observations and sampling of the well-exposed remnants  
69 of a fossil rifted margin. The study aims to: (i) characterize and understand the spatial and temporal  
70 evolution of the syn-rift “Grès Singuliers” sedimentary system that was active in the late Early Jurassic  
71 between the proximal and future distal parts of the European passive margin; and (ii) highlight the  
72 tectonic significance of such a specific unit emplaced, as it will be substantiated below, during the  
73 maximum thinning phase at the transition between crustal stretching and hyper-extension. We will  
74 present new sedimentological, structural and provenance data in order to unravel the tectono-  
75 sedimentary evolution of the Mont Blanc region, which is representative of the European rifted margin  
76 (Trümpy 1980; Lemoine and Trümpy 1987). We propose that the Mont Blanc massif is a fossil

77 extensional core complex, referred to as the Mont Blanc core complex (MBCC), which was exhumed  
78 and uplifted during Early Jurassic rifting. On the basis of our original new model proposed for the Mont  
79 Blanc region, we finally discuss general implications of this study for the evaluation of syn-rift  
80 megasequences related to major crustal thinning along present-day rifted margins.

81

## 82 **2. GEOLOGICAL SETTING: THE WESTERN HELVETIC DOMAIN**

### 83 **■ Nappe stack and palinspastic reconstruction**

84 During the Jurassic, rifting led to the formation the Alpine Tethys including the Adriatic/Africa and  
85 Europe/Iberia margins and intervening Ligurian, Piedmont and Valais proto-oceanic domains (e.g.  
86 Debelmas and Lemoine 1970; Lemoine and Trümpy 1987; Schmid et al. 2004). The Alps sensu-stricto  
87 are the result of the reactivation and closure of these domains during multiple episodes of convergence  
88 with variable kinematics since the Late Cretaceous (Fig. 1; e.g. Stampfli et al. 2002; Schmid et al. 2017  
89 and references therein).

90 The external parts of the Alpine belt consist of a crystalline basement and its (para)autochthonous  
91 sedimentary cover. The former was consolidated during the Hercynian orogeny and late to post-  
92 orogenic collapse and is exposed in the External Crystalline Massifs (ECM). The late Paleozoic to  
93 Cenozoic sedimentary cover (i.e. Helvetic/Dauphinois nappe system; e.g. Trümpy 1963; Masson et al.  
94 1980) extends from the little-deformed Jura Mountains, across the foreland Molasse basin to the fold-  
95 and-thrust belt. The ECM and associated cover are overthrust along the Penninic Front or Pennine  
96 basal thrust by the Helvetic and Penninic nappes derived from more distal parts of the former  
97 European margin (Fig. 1; e.g. Schmid and Kissling 2000; Cardello et al. 2019).

98 The Helvetic nappe system is derived from the Helvetic domain, which is a part of the European  
99 proximal margin (e.g. Debelmas and Lemoine 1970; Funk et al. 1987). This domain has been subdivided  
100 into paleo-geographic sub-domains that are preserved in the Helvetic and Ultrahelvetic nappes and  
101 the underlying Infrahelvetic units. The subdivisions are sometimes arbitrary and in this study we use  
102 the subdivision proposed by Escher et al. (1993) and Pfiffner et al. (2010; 2011). The Infrahelvetic

103 complex encompasses all units beneath the basal thrust of the Helvetic nappes (Fig. 2). It consists of  
104 pre-rift sedimentary and crystalline basement rocks (i.e. Mont Blanc-Aiguilles Rouges and Gastern-Aar  
105 ECMs) and autochthonous to para-autochthonous pre-to post-rift Mesozoic and Cenozoic sediments  
106 (i.e. Morcles and Doldenhorn nappes, Fig. 2; e.g. Masson et al. 1980; Escher et al. 1993). The Helvetic  
107 nappe stack, comprising the Diablerets, Roselette, Gellihorn and Wildhorn nappes, includes  
108 allochthonous sediments that derive from a more distal part of the European proximal margin. These  
109 units were thrust during the Cenozoic toward the northwest along a basal thrust fault over distances  
110 of several tens of kilometres (i.e. Diablerets thrust or basal Helvetic thrust, Fig. 2; e.g. Masson et al.  
111 1980; Pfiffner 1993; Crespo-Blanc et al. 1995). Ultra-Helvetic nappes occur either underneath the  
112 Diablerets basal thrust of the Helvetic nappes or above the Helvetic nappes and were initially deposited  
113 on the most distal southeasternmost part of the European proximal margin (Fig. 2; e.g. Badoux 1963;  
114 Jeanbourquin and Goy-Eggenberger 1991; Escher et al. 1993; Pfiffner 2011).

115 Palinspastic reconstructions through the Helvetic domain proposed in the literature (Fig.2C; e.g.  
116 Trümpy 1980; Burkhard 1988; Wildi et al. 1989; Steck et al. 1999; Pfiffner 2011) generally indicate that  
117 the main units described in this study, from the Croix du Bonhomme and Swiss Val Ferret area (Fig.  
118 2C), belong to the autochthonous sedimentary cover of the Mont-Blanc massif (Fig. 2D). The “Grès  
119 Singuliers” however also occurs in the para-autochthonous nappes of the Infrahelvetic complex and  
120 more specifically in the Doldenhorn and Morcles nappes (Fig. 2A).

121

## 122 **Pre-rift sediments and crystalline basement rocks**

123 The Mont Blanc and Aiguilles Rouges crystalline massifs consist of a pre-Mesozoic polymetamorphic  
124 basement intruded by Variscan S- and I-type granitoids (e.g. Finger and Steyrer 1990; Von Raumer and  
125 Bussy 2004). Examples are the Vallorcine Granite in the Aiguilles Rouges massif ( $306 \pm 1.5$  Ma, Bussy  
126 et al. 2000), the Mont Blanc Granite ( $303 \pm 2$  Ma, Bussy and Von Raumer 1993) as well as the Variscan  
127 rhyolites of the Mont Blanc massif ( $307 \pm 2$  Ma, Capuzzo and Bussy 2000). The emplacement depth of  
128 the Mont Blanc granite has been estimated at 4 to 14 km (1 to 3.8 kbar; Marshall et al. 1997). The

129 rhyolitic unit was emplaced at shallower crustal levels (Von Raumer and Bussy 2004) and display  
130 textures ranging from leucocratic granites to porphyritic rhyolites (e.g. Marshall et al. 1997). The  
131 contact between the rhyolitic unit and the Mont Blanc Granite remains ambiguous (e.g. Capuzzo and  
132 Bussy 2000).

133 The Aiguilles Rouges massif includes Late Carboniferous siliciclastic sediments preserved in mildly  
134 inverted grabens (e.g. Von Raumer et al. 1993; Capuzzo and Bussy 2000). These pluri-kilometric thick  
135 basins, including the Pormenaz and Salvan-Dorénaz basins, consist of fluvial, alluvial fan and volcanic  
136 deposits (e.g. Capuzzo and Wetzel 2004).

137

138 The Triassic succession (or very locally Permian strata) unconformably covers the Carboniferous basins  
139 as well as the polymetamorphic and granitic basement rocks (e.g. Amberger 1959; Epard 1990;  
140 Wizevich et al. 2019). The succession starts with several meters of fluvial to shallow-marine sandstones  
141 overlain by vari-coloured pelites constituting the Middle to Upper Triassic Vieux Emosson Fm (Fig. 3;  
142 e.g. Epard 1990; Avanzini and Cavin 2009; Wizevich et al. 2019). Up section, the Arandellys Fm consists  
143 of dolostones locally interbedded with evaporites and overlain by the Besoëns Fm, characterized by  
144 bioclastic sandy limestones and sandstones interbedded with dark marls and shales (Fig. 3, e.g. Epard  
145 1990). This typical succession can be observed in the Emosson area and within the Morcles nappe (Fig.  
146 2A, e.g. Amberger 1959; Epard 1989; Wizevich et al. 2019). However, along the Mont Blanc massif, the  
147 pre-rift Triassic (and Early Jurassic) deposits are either lacking or represented by reduced successions  
148 (a few tens of meters locally). We will discuss whether this is due to non-deposition, erosion or if they  
149 have been tectonically removed.

150 Furthermore, the basement-cover relationships between the Mont Blanc basement and its  
151 sedimentary cover remain in places still debated in the literature. On the eastern, Italian side of the  
152 Mont Blanc massif, the basement-cover contact in the Italian Val Ferret and Val Veni (Fig. 2A) has been  
153 interpreted either as: (i) the Mont Blanc back-thrust and described as a series of steeply NW-dipping  
154 thrust faults bringing the Mont Blanc granite on top of overturned Jurassic sediments (e.g. Guermani

155 and Pennacchioni 1998; Leloup et al. 2005; Egli and Mancktelow 2013), or (ii) as the Evêque back-fold,  
156 locally overturning a primary basement-cover contact (e.g. Escher et al. 1997; Steck et al. 2001). To the  
157 south-west of the Mont Blanc massif, the basement-cover contact (i.e. Col de la Forclaz, Col de Balme,  
158 Col du Mont Lachat, Col du Tricot; Fig. 2A) is interpreted as an overturned stratigraphic contact, either  
159 involving a tectonic thrust between the Mont Blanc basement and the Mesozoic sediments (e.g.  
160 Eltchaninoff-Lancelot et al. 1982; Leloup et al. 2005; Egli and Mancktelow 2013) or without any tectonic  
161 thrust and thus preserving a primary basement-cover contact (e.g. Epard 1986). In this paper, we will  
162 describe new basement-cover contact relationships across the Mont Blanc massif from the Croix du  
163 Bonhomme area and the Swiss Val Ferret (Fig. 2).

164

### 165 **Alpine Tethys rifting and associated syn-rift stratigraphy**

166 The syn-rift megasequence (sensu Hubbard 1988) of the Alpine Tethys rifted margins developed from  
167 latest Triassic to Middle Jurassic (e.g. Lemoine and Trümpy 1987). In the study area, the early phase of  
168 rifting, Early Jurassic, is characterized by the development of numerous fault-bounded half-grabens,  
169 which are well preserved along the proximal European margin such as in the Dauphiné domain (i.e.  
170 Bourg d'Oisans, La Mure, Taillefer, e.g. Lemoine et al. 1986; Chevalier 2002) and in the Helvetic domain  
171 (i.e. Morcles and Doldenhorn nappes, e.g. Lemoine et al. 1986; Burkhard 1988; Epard 1990). The half-  
172 grabens in the Morcles and Doldenhorn nappes are filled by Hettangian to Sinemurian shales, marls  
173 and limestones (i.e. Tierces Fm, Fig. 3; Epard 1989).

174 During the Late Sinemurian–Toarcian, the western Helvetic domain records the deposition of two  
175 types of facies (Trümpy 1971): the siliciclastic “Helvetic facies” and the marly “Dauphinois facies”. The  
176 siliciclastic “Helvetic facies” are dominated by sandstones deposited above or near the ECMs, i.e.  
177 belonging, regarding the study area, to the autochthonous cover of the Mont Blanc massif and para-  
178 autochthonous cover of the Aar massif (Doldenhorn nappe; e.g. Trümpy 1971; Loup 1991). These  
179 siliciclastic facies, which include the so-called “Grès Singuliers” in France, are also referred to as the  
180 “Lotharingien” and “Domérien” sandstone units on the Swiss part of the Mont Blanc massif (i.e.



181 Catogne, Fig 2; e.g. Grasmück 1961) and in the Doldenhorn nappe and Aar massif (i.e. Torrenthorn;  
182 e.g. Loup 1991). Based on the distribution of the siliciclastic Helvetic facies above and around the ECM  
183 without any external clastic sources to produce the siliciclastic facies other than the ECM by  
184 themselves, Trümpy (1971) proposed that the Mont Blanc and Aar domains were partially emerged at  
185 that time, corresponding to “islands” during the Early Jurassic (“*île du Mont Blanc*” and “*presqu’île du*  
186 *Bietschhorn*”, respectively). For the sake of simplicity, we will use in this study the term “Grès Singuliers  
187 unit” for all the Early-Middle Jurassic siliciclastic deposits observed in the overall Mont Blanc region,  
188 then encompassing both the French Grès Singuliers Fm sensu stricto and the Swiss “Lotharingien” and  
189 “Domérien” sandstone units, as well as similar subordinate clastic horizons from the Italian side of the  
190 Mont Blanc massif. The marly “Dauphinois facies”, dominated by limestone and marls, are deposited  
191 in the surrounding areas including the Morcles, Helvetic and Ultrahelvetic nappes (Figs. 2C and 3).  
192 Locally in the Doldenhorn and Morcles nappes, the siliciclastic “Helvetic facies” is found interbedded  
193 with the marly “Dauphinois facies” (e.g. Saillon in Fig. 2); the clastic input progressively disappearing  
194 more distally in the Helvetic nappes (Fig. 2)

195

196 In the Helvetic domain, the late Early to Middle Jurassic time is characterized by the deposition of dark  
197 marls and limestone of the Toarcian Monts Rossets Fm overlain by the black lime-free Aalenian pelites  
198 of the Dugny Fm (Fig. 3; e.g. Epard 1989). Based on the recent understanding of the Southern and  
199 Northern Adriatic margin, the corresponding time interval precisely records the focusing of extension  
200 processes linked to the major crustal thinning stage of the continental crust that led to the formation  
201 of the distal European and distal Adriatic margins (i.e. Ultra-Helvetic, Lower Penninic and Lower  
202 Austroalpine nappes; e.g. Lemoine and Trümpy 1987; Berra et al. 2009; Masini et al. 2013; Ribes et al.  
203 2019b).

204 The final stage of rifting, marked by the exhumation of mantle and onset of magma activity, occurred  
205 in the Ligurian, Piedmont and Valais domains (e.g. Lemoine and Trümpy 1987; Liati et al. 2005;

206 Manatschal and Müntener 2009; Li et al. 2013). Remnants of these domains are preserved in the Lower  
207 and Upper Penninic nappes (e.g. Desmurs et al. 2001; Manatschal et al. 2006; Beltrando et al. 2012;  
208 Ribes et al. 2019c). Mantle exhumation was concomitant with the deposition of radiolarian cherts  
209 dated from the late Middle to early Late Jurassic (e.g. Bill et al. 2001; Principi et al. 2004; Baumgartner  
210 2013; Ribes et al. 2019b).

211 By comparison with the northern Adriatic margin, the deposition time of the Grès Singuliers unit (i.e.  
212 late Early to Middle Jurassic) corresponds to the moment when fault activity stops in the proximal  
213 margin and deformation starts to focalize in an area that corresponds to the futur distal margin (i.e.  
214 necking system tract sensu Ribes et al. 2019b). Furthermore, the Mont Blanc massif, where the Grès  
215 Singuliers unit is observed, is positioned at the transition between a non- to weakly-thinned  
216 continental crust to thinned continental crust (Fig. 1D; e.g. Stampfli et al. 2002; Mohn et al. 2014).  
217 Thus, the location as well as the timing relative to the margin evolution indicated that the Grès  
218 Singuliers unit should bears key information about the rift evolution of the Alpine Tethys, in particular  
219 regarding the necking system tract as defined by Ribes et al. (2019b).

220

### 221 **3. BASEMENT-COVER RELATIONSHIPS ACROSS THE MONT BLANC MASSIF**

#### 222 **Basement and Pre-rift stratigraphy**

223 Where the sedimentary autochthonous cover of the Mont Blanc ECM is preserved, the underlying  
224 basement consists of three distinct units: Variscan metamorphic rocks comprising orthogneisses and  
225 paragneisses, the Carboniferous Mont Blanc granite and a rhyolitic/porphyritic unit (Fig. 2; e.g. Von  
226 Raumer and Bussy 2004). The sedimentary interval between the Mont Blanc top basement and the  
227 Grès Singuliers unit shows a variable and reduced stratigraphic succession ranging in thickness from  
228 several tens to a few meters (Fig. 6A). This situation is distinctive if compared with facies and great  
229 thicknesses of the relatively uniform sedimentary cover of the Morcles nappe (e.g. Epard 1990) and  
230 the autochthonous sedimentary cover of the Aiguilles rouges (i.e. Emosson; Amberger 1959).

231 The sediments comprised between the Mont Blanc top basement and the Grès Singuliers unit are  
232 made up of Middle Triassic sandstones (i.e. Vieux Emosson Fm, Epard 1989; Wizevich et al. 2019)  
233 overlain by Late Triassic light brown to yellowish dolostones passing upward to dark alternating  
234 dolostones, limestones and marls (i.e. Arandellys Fm, Eltchaninoff-Lancelot 1980; Epard 1989). The last  
235 Triassic deposit is characterized by thin sandstones and shales (i.e. Besoëns Fm, Eltchaninoff-Lancelot  
236 1980; Epard 1989). Below the unconformable Grès Singuliers unit, Hettangian to early Sinemurian  
237 marls and limestones are observed (i.e. Tierces Fm, Landry 1976; Eltchaninoff-Lancelot 1980).

238

## 239 **Deformation structures**

### 240 **Croix du Bonhomme and Swiss Val Ferret (main study area)**

#### 241 • **Top basement**

242 In the Bonhomme and Swiss Val Ferret area (Fig. 4), the top basement shows a characteristic fault  
243 zonation with from base to top: (i) an undeformed host rock (i.e. gneiss or rhyolitic/porphyritic  
244 granite), (ii) a brittle damage zone with cataclasites, and (iii) a core zone that consists of black gouges.

245 The cataclasites correspond to brittle deformed basement, which in places shows a progressive change  
246 upsection from a fractured host rock to a clast-supported cataclasite. Clasts are generally angular,  
247 showing jigsaw textures at the base, yet they develop into more rounded clasts up section (Fig. 5B, C  
248 and D). The primary material derived from the gneissic host rock consists of rock fragments made of  
249 quartz and feldspars. Quartz occurs in the cataclasite as angular grains forming, together with feldspar,  
250 a clast supported framework intersected by micro-fracturing (i.e. intra- and transgranular cracks) and  
251 quartz veins (Fig. 5G). Quartz has embayments and feldspars show evidence of chemical weathering.  
252 Albitization is observed but not common. The matrix between the clasts is made of crushed fine-  
253 grained host rocks (Fig. 5G).

254 The gouges are well foliated, matrix-supported black rocks with less than 30% fragments including mm-  
255 to dm-sized clasts derived from the underlying basement, cataclasites, and more rarely “Triassic”  
256 dolostones and quartzites from the hanging wall (Fig. 5B, D and E). The black gouges occur along a

257 centimetre- to decimetre-thick core zone that tops the cataclasite (Fig. 5B and D). The contact between  
258 the black gouge and cataclasites is sharp and injection structures of the black gouge into the underlying  
259 cataclasites are found in places (Fig. 5D and F). With decreasing size, polymineralic litho-clasts become  
260 less abundant and the proportion of monomineralic clasts increases. Monomineralic clasts consist of  
261 sub-rounded quartz and remnants of feldspar grains embedded in a phyllosilicate-rich matrix. Common  
262 micro-structures in the quartz are micro-cracks and fractures. Elongated fragments show a strong  
263 preferred orientation and S±C type fabrics with the slip plane parallel to the fault-zone boundary are  
264 common (Fig. 5G). The black gouges correspond to the main zone of displacement and define a fault  
265 plane separating footwall and hanging-wall rocks (e.g. Chester and Logan 1986; Scholz 1987).

266 In the Bonhomme area, the top basement is characterized by cataclasites and locally preserved black  
267 gouges that look to be paraconformably overlain by a discontinuous sedimentary cover made up of  
268 Triassic and Lower Jurassic strata unconformably covered by the Grès Singuliers unit (Fig. 4B). In the  
269 Swiss Val Ferret area, from the Combe des Fonds to Saleinaz (Fig. 4C), the rhyolitic/porphyritic top  
270 basement is characterized by cataclasites overlain by a clast-supported conglomerates with pebbles to  
271 cobble-sized monomictic rhyolitic elements, referred to as the Amône conglomerate and attributed by  
272 Grasmück (1961) to the Aalenian. This top basement forms a corrugated (undulating) surface with  
273 corrugation wavelength of several meters. Here, intervening grooves are filled by the Amône  
274 conglomerate sealed by Aalenian dark shales (Fig. 5A and B). Toward the north, the top basement  
275 surface is overlain by discontinuous Triassic and Lower Jurassic stratigraphy reminiscent of the  
276 organisation symmetrically documented to the south in the Bonhomme area (Fig. 4C).

277

278 • **Sedimentary cover**

279 Where a Triassic to Early Jurassic succession is preserved above the top basement (i.e. Croix du  
280 Bonhomme and Swiss Val Ferret, Fig 4), it is strongly dismembered by pervasive stratal disruption  
281 resulting from extension parallel to the layering, which cannot be observed in the underlying basement  
282 rocks or Grès Singuliers unit and overlying strata (Fig. 6).

283 At the outcrop scale, extensional ramps cut the dolostone and limestone beds and flatten upwards  
284 and downwards as decollements in the marly or shaly intervals. Beds, or groups of beds, are thus  
285 truncated in lens-shaped, fault-bounded blocks of centimetric to decametric scale (Fig. 6B, C and D). A  
286 complete transition from massive well-bedded dolostone and limestone layers to monomictic breccia-  
287 like layers has been observed both in Bonhomme and Swiss Val Ferret areas. The dolostone and  
288 limestone layers are locally affected by intense silica-rich veining and fracturing, and subsidiary Ca-rich  
289 veins, that progressively merge, and the massive rocks appear to be broken into numerous centimeter-  
290 to meter-sized clasts (Fig. 6B, D and E). Because of the geometry of the deformation and of the  
291 monogenetic constitution of the succession, the breccia is interpreted to be of tectonic rather than  
292 sedimentary origin (e.g. Labaume 1987). Locally the Triassic to Lower Jurassic succession is affected by  
293 a complex array of downward-tapering sedimentary dykes and sills penetrating a few meters and filled  
294 by conglomerate and/or sand originating from the basal Grès Singuliers unit.

295

#### 296 **Italian Val Ferret and Col de Tricot**

297 From the southeastern Italian border of the Mont Blanc massif, along La Brenva Stream and at Pra-Sec  
298 in Val Veni, Elter and Elter (1964), Guermani and Pennacchioni (1998) and Leloup et al. (2005) among  
299 others mentioned at the top basement a transition from an undeformed granite to a cataclasite.  
300 Guermani (1998) also described in association with the cataclasite a dark thin layered rock with a  
301 strong foliation parallel to the shear zone boundary with clasts of rounded cataclastic granite, in which  
302 the matrix consists of fine-grained phyllosilicate and albite. By analogy with the Croix du Bonhomme  
303 observations, it is likely that these dark thin layered rocks correspond to the black gouges described in  
304 the previous section. The top basement is covered by a few meters thick succession displaying  
305 undeformed and undated sandstone beds overlain by a single limestone bed and lime-free dark shales.  
306 The latter was interpreted as representative of a thin autochthonous cover below the Diablerets thrust  
307 and the overlying Helvetic nappes (e.g. Antoine et al. 1975; Aviolat 1991; Mamin 1992). Shear criteria  
308 in the cataclasites and black gouges display a top to the SE (dip slip) (e.g. Leloup et al. 2005, Guermani,

309 1998 #4209). The shear sense has been related to back-thrusting, but, interestingly, it is also fully  
310 compatible with a top to the SE detachment system.

311 In the western part of the Mont Blanc massif, in the Col de Tricot area, Epard (1986) described at the  
312 top basement a highly deformed gneiss associated with dark thin layers consisting of phyllosilicate-rich  
313 matrix (mainly sericite) with elongated-clasts of polygonal quartz. This tectonized top basement is  
314 however overlain by a discontinuous sedimentary cover made up of Triassic and Lower Jurassic  
315 sediments, which is considered as para-autochthonous by Epard (1986). These observations are similar  
316 to our observations from the Croix du Bonhomme, Swiss Val Ferret and from the Italian Val Ferret  
317 (Guermani and Pennacchioni 1998) where top basement is characterized by cataclastic fabrics  
318 overprinting either a rhyolitic/porphyritic granite or gneissic host rock, and the occurrence of  
319 diagnostic thin foliated dark rocks that we interpret as black gouges.

320

#### 321 **■ Rift-related detachment faults: Mont Blanc detachment system?**

322 Although basement-sediment contacts along the Mont Blanc are generally interpreted as Alpine  
323 thrusts (i.e. Mont Blanc back-thrust; e.g. Leloup et al. 2005; Egli and Mancktelow 2013), we argue that  
324 these contacts that are subparallel to the overlying sediments, could be alternatively interpreted as  
325 former Jurassic extensional detachment faults that were essentially preserved and only reactivated  
326 locally as reverse faults during Alpine convergence.

327 Cataclasites and gouges, which appear paraconformable with the pre-rift stratigraphy and/or the  
328 overlying sediments, are arguably linked to extensional detachment systems. These structures and the  
329 rocks are reminiscent of the low angle detachment faults and associated products described initially  
330 by Froitzheim (1990) from the Err nappe in SE Switzerland and representing rift related detachment  
331 systems (e.g. Manatschal 1999; Masini et al. 2012; Epin and Manatschal 2018).

332 The top basement records systematically a brittle overprint, with in places the reworking of footwall-  
333 derived clasts and occasionally Triassic dolostone, sealed by undeformed Aalenian conglomerates  
334 and/or Aalenian dark shales. The variable and reduced Triassic to Lower Jurassic sedimentary cover

335 overlying the exhumed basement forms kilometric-scale slices. Deformation in these slices,  
336 characterised by a pervasive extensional delamination, which is not observed in the underlying  
337 basement or in the Grès Singuliers unit, is interpreted as related to the exhumation of the underlying  
338 crustal detachment during deposition of the Grès Singuliers unit. These slices of sedimentary layers  
339 predating the Grès Singuliers unit are interpreted as slivers of pre-rift/early syn-rift displaced along  
340 detachment systems. The observation that the Mont Blanc is locally capped by brittle fault rocks  
341 belonging to a pre-Alpine Jurassic detachments (for discussion see below), allows us to introduce the  
342 potential existence of the Mont Blanc detachment system. The mapping of remnants of this supposed  
343 former Jurassic detachment system in the Mont Blanc massif suggests that exhumation of the  
344 detachment footwall to the seafloor occurred throughout the Mont Blanc domain, except for the areas  
345 where the detachment was hidden by slivers of pre-rift preserved along detachment systems.

346

347 The description of the Mont Blanc top basement and associated sedimentary cover thus shows strong  
348 similarities with other rift-related detachment faults observed in remnants of the former distal Alpine  
349 Tethys rifted margin. Preserved and exposed extensional detachment faults and extensional  
350 allochthons or pre-rift slivers in the Alps were first described by Froitzheim (1990) and then recognized  
351 in several places such as the Tasna nappe (e.g. Froitzheim and Rubatto 1998; Manatschal et al. 2006;  
352 Ribes et al. 2019c), the Austroalpine nappes (e.g. Mohn et al. 2012; Incerpi et al. 2017), and in the  
353 Pyrenees (e.g. Clerc et al. 2016; Lagabrielle et al. 2016). Classically, these rift-related detachment faults  
354 are formed by tens of meter thick damage zones constituted of characteristic green cataclasites and a  
355 core zone made of black indurated fault gouges (e.g. Manatschal 1999; Manatschal et al. 2000; Mohn  
356 et al. 2011; Masini et al. 2012), which are definitely similar to what has been observed at the top of  
357 the Mont Blanc basement.

358

#### 359 **4. THE GRÈS SINGULIERS UNIT**

## 360 **Stratigraphic overview**

361 In the Croix du Bonhomme area, the Grès Singuliers unit rests on the early Sinemurian Tierces Fm  
362 (Landry 1976; Eltchaninoff-Lancelot 1980) at the Rocher du Bonhomme (Fig. 8) but unconformably  
363 overlies Triassic deposits immediately toward to northeast (Fig. 8). The top of the Grès Singuliers unit  
364 is overlain by lime-free dark shales attributed to the Aalenian Dugny Fm (Fig. 8; Epard 1990). In the  
365 Swiss Val Ferret area, the Grès Singuliers unit conformably covers early Sinemurian limestones and  
366 marls and unconformably overlies Triassic deposits and, southward, basement rocks (Fig. 9; Grasmück  
367 1961). At the top of the Grès Singuliers unit, a regional onlap is inferred considering the overlying  
368 Toarcian Monts Rossets Fm in the basinal part (Trümpy 1951) and the Aalenian Dugny Fm toward the  
369 south overlying directly the Aalenian Amône conglomerates (Fig. 9; Grasmück 1961). In the Val Veni  
370 and Italian Val Ferret, the sedimentary veneer is interpreted as a lateral equivalent of the Amône  
371 section in the Swiss Val Ferret and section E of the Croix du Bonhomme area (Fig. 8) with the quartz  
372 arenite attributed to the Grès Singuliers unit, the limestones and the overlying lime-free dark shales  
373 attributed to the Toarcian — Aalenian Monts Rossets and Dugny Fms, respectively.

374 The facies distribution around the Mont Blanc massif suggests lateral variations related to the distance  
375 from a siliciclastic source with lag deposit and coarse-grained facies evolving basinward into finer-  
376 grained facies with an increasing contribution of carbonate supply (Fig. 9; e.g. Loup 1991). The  
377 thickness of this formation thickens progressively from 0 (i.e. Amône) to 150 m in the basinal zone  
378 toward the south of the Val Ferret (i.e. Saillon, Fig. 9) and from 40 m in the south of the Bonhomme  
379 area (Fig. 8) to a few tens of meters toward the north to finally be restricted to a few decimetre thick  
380 veneer resting directly above the top basement.

381

## 382 **Facies analysis**

383 The Grès Singuliers unit is a siliciclastic-dominated sedimentary system, including clast-supported  
384 conglomerates, lithic to quartz arenites and sandy limestones that unconformably overlie either the  
385 Lower Jurassic to Triassic carbonates or the exhumed top basement (Figs 7, 8 and 9). In the following



386 paragraph, we detail the facies of the Grès Singuliers unit in the Croix du Bonhomme type area and  
387 then briefly describe those of the Swiss Val Ferret area.

388

### 389 **████████ Croix du Bonhomme**

390 The Grès Singuliers unit ranges from 8 to 35 m in thickness and consists of light yellowish  
391 conglomerates and sandstones (Fig. 7). The succession is subdivided in two parts: a poorly stratified  
392 lower subunit including conglomerates, and an upper subunit made of cross-stratified sandstones.

393

394 The lower subunit rests unconformably on an erosional surface truncating the Lower Jurassic to Middle  
395 Triassic strata. A complex of sedimentary dykes and sills including conglomerate and sandstone similar  
396 to those of the lowermost Grès Singuliers unit penetrates few meters into the underlying strata. The  
397 Grès Singuliers unit starts with meter-thick structureless, poorly graded, polymictic conglomerates  
398 composed of sub-rounded centimeter-to decimeter-sized clasts (Fig. 7A). The conglomeratic facies are  
399 overlain, above a sharp grain-size break, by a poorly sorted coarse- to medium-grained sandstone with  
400 faint primary lamination, possibly emphasised in places by subhorizontal dewatering structures.  
401 Normally graded beds with undulating lamination, 20-40 cm thick, are occasionally observed. They  
402 show ripple cross-lamination reworking the bed top, which are capped by mm-thick fine-grained  
403 intervals (Fig. 7C). A few Belemnite rostra and *Gryphea sp* have been observed. A recurrence of  
404 conglomerates is observed upward, which locally shows climbing-dune cross-stratification. Clast  
405 lithologies in both the conglomerate intervals are dominated by crystalline rocks, 90% originating from  
406 the Mont Blanc type granite and 10% from the adjacent gneissic basement, with subordinate  
407 occurrence of limestones and dolostones and rare quartzites (e.g. Eltchaninoff-Lancelot 1980).  
408 Numerous granitic clasts (80%), generally rounded to well rounded, are entirely cataclastic and  
409 resemble the deformed basement granite observed along Val Veni. Carbonate clasts are sub-rounded  
410 to angular.

411

412 The upper subunit of the Grès Singuliers unit consists of sharp-based, 1-2 m thick, medium-grained  
413 sandstone beds that generally display fining-up trends, including small gravel lags near their base (Fig.  
414 7). Sets of tangential oblique lamination are observed either isolated or amalgamated and then  
415 forming trough cross-stratified beds (Fig. 7B). A few intercalations, less than one meter thick, consist  
416 of distinctively well-sorted sandstones showing a finely defined, oblique to subhorizontal lamination,  
417 which may display thickening to fining rhythmic pattern in laminae thickness (Fig. 7E). The middle  
418 segment of the upper Grès Singuliers subunit is typified by sandstone beds showing networks of cross-  
419 cutting, 10-30 cm deep, 1-5 cm thick sand intrusions. Whether they originated from the overlying or  
420 underlying bed remains ambiguous. Intrusions are arranged in nested polygonal to rectangular cells,  
421 yet a preferential north-south orientation has been noticed (Fig. 7D). The uppermost Grès Singuliers  
422 unit is a distinctive up to 4 m thick sandstone body that shows large-scale clinoformal master beds  
423 downlapping toward the SW, and that pinches out in the opposite direction (Fig. 7F). They are  
424 truncated by an individual coarse-grained sandstone bed showing in places bioturbation in the form  
425 of U-shaped burrows (probably *Diplocraterion* and *Arenicolites*) and undefined tracks. Paleocurrent  
426 directions using mainly cross-bedded foreset dips were measured throughout the upper unit of the  
427 Grès Singuliers unit, yielding a range of paleoflow orientations from N280° to N160° with a mean vector  
428 toward N230° (SW), i.e., more or less parallel with the clinofolds observed near the top of the unit.

429

430 In thin section, the sandstone facies of the Grès Singuliers evolves from base to top and are classified  
431 as lithic arenite to quartz arenite, respectively, according to the classification of Pettijohn et al. (2012).  
432 The basal sandstones display locally a carbonate matrix-supported fabric but most of the Grès  
433 Singuliers have a grain-supported fabric with 200 µm to 1 mm sized, angular to surrounded grains  
434 (mean 0,37mm). Detrital grains are principally composed of monocrystalline and polycrystalline quartz  
435 (80-90%), weathered feldspar, cataclastic granitic grains and rare crushed mm-size clast of fine-grained  
436 material (Fig. 7G).

437

438 The lower subunit is interpreted as deposits dominated by shallow water density-flow processes. The  
439 carbonate matrix and the fossils observed in the lower subunit are interpreted as originated from the  
440 reworking of the Hettangian-Early Sinemurian limestones (i.e. Tierces Fm), probably still poorly lithified  
441 during the deposition of the Grès Singuliers unit. Graded beds with rippled tops are interpreted as  
442 high-density turbidites reworked by subsequent low-density turbidity flow processes (e.g. Talling et al.  
443 2012). The general lack of mudstone might be explained by buoyant plumes that kept the mud in  
444 suspension and carried it farther seaward out of the depositional area of the Grès Singuliers unit.  
445 The downward-tapering clastic intrusions in the pre-Grès Singuliers strata have been probably  
446 triggered by syn-sedimentary tectonic activity along the underlying detachment system (e.g. Jolly and  
447 Lonergan 2002).

448  
449 The upper subunit is interpreted as deposited under the influence of tidal currents in mud-free  
450 siliciclastic subtidal systems (e.g. Longhitano et al. 2012). Cyclic laminae thickness changes suggest the  
451 record of neap-spring tidal cycles (e.g. Kreisa and Moila 1986). The trough cross-bedding are  
452 interpreted to represent the migration of sinuous-crested dunes during dominant tidal flow and the  
453 clinofolds are interpreted as tidal bars (e.g. Olariu et al. 2012; Reynaud and Dalrymple 2012). The  
454 small sandstone dykes relate to subaqueous crack/fractures related to loading and compaction, or may  
455 be caused by seismic activity as suggested by their preferred N-S orientation. Similar features are  
456 reported in tectonically active setting (e.g. Tanner 1998; Sharp et al. 2000; Carr et al. 2003; McMahon  
457 et al. 2017).

458 In this context, the relatively uniform paleocurrents noted in the Grès Singuliers upper subunit are  
459 interpreted to reflect tidal currents with a prevailing transport direction toward the SW, which is nearly  
460 parallel to the SW-NE elongated Mont Blanc massif.

461 Furthermore, the outline of monocrystalline quartz grains commonly displays embayments and  
462 feldspars show evidence of chemical weathering, both the features being observed in the underlying  
463 basement. Crushed fine-grained grains are reminiscent of fragments originating from the

464 phyllosilicate-rich black gouges while cataclastic granitic grains may directly derived from the  
465 reworking of an exhumed top basement.

466

#### 467 **Swiss Val Ferret**

468 From the Combe des Fonds to Saleinaz, the Grès Singuliers unit corresponds to a thin (0-4 m) sandstone  
469 veneer that is overlying a cataclastic rhyolitic-porphyrific top basement. In Combe des Fonds, no  
470 sandstone was deposited. Instead, a distinctive conglomeratic horizon is observed. It consists in a  
471 monomictic rhyolitic-porphyrific conglomerate (“Amône conglomerate”, Grasmück 1961; Duparc and  
472 Pearce 1989). Clast-supported pebbles to cobbles are sub-rounded to well-rounded rhyolitic-  
473 porphyritic clasts, while the matrix is made up of coarse-grained sand. This conglomerate horizon is  
474 interpreted as a lag deposit formed by the reworking of a cataclasite derived from the nearby  
475 underlying deformed top basement. Cataclasis at the top basement, sealed by non-deformed  
476 conglomerates, indicates the that the basement-cover contact is a former detachment fault (see  
477 above), the footwall of which became available to winnowing and/or sedimentation. Historically, this  
478 facies was indeed considered as “beach facies” due to the roundness of the clasts (Trümpy 1954;  
479 Grasmück 1961). A though part of the roundness might also have been acquired during deformation  
480 processes (e.g. Chester and Logan 1986; Scholz 1987). As no gouge is observed there, it can be  
481 suspected that winnowing involved wave action and thus that initially shallow environments deepen  
482 afterwards.

483

484 At Saleinaz (Fig. 4C), the rhyolitic top basement is overlain by a 3-4 meters thick interval of Grès  
485 Singuliers that are coarse-grained and poorly sorted. Poorly defined trough cross-stratification, rippled  
486 bed tops and *diplocraterion* burrows have been observed. These characteristics are reminiscent of the  
487 tidally-influenced upper subunit of Grès Singuliers from the Bonhomme area. Here, in a shaly facies  
488 immediately above the sandstones, Grasmück (1961) found an ammonite (*Ludwigia purchisonae*) that  
489 indicates an Aalenian age.

490 Toward the north, in the Catogne area (Fig. 2), the Grès Singuliers unit dramatically thickens (Fig. 9).  
491 Here, an up to 100 m thick sandstone-dominated unit presents a very similar succession to the one  
492 observed in the Bonhomme area, including a lower conglomeratic unit and a tidally-dominated upper  
493 segment, within which tidal bars have also been identified by Loup (1991) and Grasmück (1961). The  
494 Grès Singuliers unit here also display in places carbonate matrix-supported fabrics with 250  $\mu\text{m}$  to 3  
495 mm sized, angular to surrounded grains (Loup 1991). Detrital grains are composed of 70% of  
496 monocrystalline and polycrystalline quartz, and nearly equal proportions of dolomicrites, altered K-  
497 feldspars, and fresh plagioclase and porphyric microgranite (Loup 1991).

498 In the Saillon section, which is lateral or distal with respect to Catogne (Fig. 2C), two sandy units  
499 (Lotharingien & Domerien) have been traditionally distinguished, which are arguably parallelized with  
500 the basal and upper subunits of the Grès Singuliers in the Croix du Bonhomme area, yet showing an  
501 overall greater thickness (up to 150 m) and a greater contribution of the carbonate matrix. They are  
502 made up of well-sorted fine- to coarse-grained sandstones, composed of 90% of quartz in a carbonate  
503 matrix (grain size 100  $\mu\text{m}$  to 3 mm; Loup 1991). An intervening finer grained package has been  
504 deposited. It consists of alternating sandy limestone and wackstone to packstone limestones with  
505 abundant echinoderm debris, bivalves and sponge spicules and detrital grains represented by quartz  
506 and dolostone (Loup 1991). In spite of this distinctive fine-grained unit, overall stratigraphic patterns,  
507 depositional facies and ages of the Swiss Grès Singuliers unit are largely comparable to those of their  
508 French counterpart, the corresponding depositional bodies being deposited over the NE and SW tip of  
509 the Mont Blanc ECM, respectively.

510

## 511 **5. GRÈS SINGULIERS PROVENANCE : Detrital zircon analysis**

512 Detrital zircons (DZ) were separated from sandstone of the Grès Singuliers unit (samples EC16 and  
513 EC17) and Triassic quartzite (EC20) from the Bonhomme area, the Grès Singuliers unit in Catogne area  
514 (samples CR-MB-1B and CR-MB-1A) and Permo-Triassic sediments in the Sion-Courmayeur nappe

515 (Sample EC23; Fig. 2). From each sample 140-160 detrital zircon (DZ) grains were randomly chosen and  
516 analysed for U-Pb geochronology by laser ablation inductively coupled plasma mass spectrometry (LA-  
517 ICPMS). U-Pb analyses were completed using a Photon Machines Analyte G2 excimer laser with a  
518 HeLex 2-volume sample cell and a Thermo Scientific Element2 ICP-MS, following procedures outlined  
519 Hart et al. (2016). GJ1 and 91500 were used as primary and secondary zircon standards (Wiedenbeck  
520 et al. 1995; Jackson et al. 2004) for elemental and downhole fractionation correction. Raw isotopic  
521 data were reduced using the VizualAge™ workflow in the Lolite™ plugin for Igor Pro™ (Paton et al. 2011;  
522 Petrus and Kamber 2012). The  $^{206}\text{Pb}/^{238}\text{U}$  ages were plotted for all zircons  $<850$  Ma, and  
523  $^{207}\text{Pb}/^{206}\text{Pb}$  for zircon  $>850$  Ma based in analytical precision and discordance filtering. For display,  
524 data were filtered by U-Pb age precision ( $2\sigma$  error  $>10\%$ ) and discordance ( $>10\%$  between  $^{206}\text{Pb}/^{238}\text{U}$   
525 and  $^{207}\text{Pb}/^{235}\text{U}$  ages or  $>20\%$  between  $^{206}\text{Pb}/^{238}\text{U}$  age and  $^{206}\text{Pb}/^{207}\text{Pb}$ ). Filtering eliminated  $<10$   
526 % of all spot analyses. All analytical work was carried out at the UTChron laboratories of the Jacksons  
527 School of Geosciences at the University of Texas.

## 528 **Results**

529 Figure 10 synthesizes all the results obtained on DZs. Sample EC23 ( $n=118$ ), ascribed to the Permo-  
530 Triassic of the Sion-Courmayeur nappe (Fig. 2A) exhibits the youngest group of DZ ages that constraints  
531 the maximal depositional age to the Middle Permian (minimum model age:  $269 \pm 2$  Ma,  $n=3$ ). The  
532 Permo-Carboniferous group of DZ (40% Permian, 37% Late Carboniferous and 23 % Early  
533 Carboniferous) builds a wide peak centred at 315 Ma that includes 34% of the DZ population. The age  
534 range 400-500 Ma is represented by an another 31% and the so-called “Pan-African” (500 – 800 Ma)  
535 by 23% of the DZ population. The DZ ages are characterized by a large age-gap between 1050 and 2000  
536 Ma, and Tonian or older ages correspond only to the 7% of the DZ ages.

537 Sample EC20 ( $n=134$ ), ascribed to the Triassic Vieux Emosson Fm overlying the top basement in the  
538 Bonhomme area (Fig. 8C), yielded DZ U-Pb ages predominantly clustering between 400-500 Ma (66%)  
539 and a prominent age peak at 455 Ma (Ordovician). In addition, subsidiary Panafrican (500-800 Ma) and  
540 Permo-Carboniferous ( $\sim 300$  Ma) DZ age components make up 24% and 5% respectively, of the sample

541 DZ age spectrum. The DZ ages are also characterized by a large Mesoproterozoic age gap between  
542 1020 and 1960 Ma, although Paleoproterozoic and older DZ ages are very scarce.

543 Sample EC16 (n=151), collected at the base of the Grès Singuliers unit in the Bonhomme area (Fig. 8C),  
544 exhibits a complex Palaeozoic and Neoproterozoic DZ age spectrum, with 35% of the ages belonging  
545 to the Permo-Carboniferous period – specifically 13% Permian; 45% from 300-325 Ma and 42% from  
546 325-360 Ma. Another 32% of the DZ ages scatter between 395 and 500 Ma and display two age peaks  
547 at 405 Ma (9% of total DZ ages) and 460 Ma (23 %) respectively. The “Pan-African component” is  
548 represented by 30% of the DZ ages, with minor age peaks at 545 Ma, 630 Ma, 700 Ma, and 790 Ma.  
549 Only 4 DZ ages (<3 %) are older than 850 Ma and none between 1010 and 2020 Ma.

550 Sample EC17 (n=180), collected at the top of the Grès Singuliers unit in the Bonhomme area (Fig. 8C),  
551 showed U-Pb ages that fall into three main age components. In this sample, 30% of the DZ ages are  
552 Permo-Carboniferous with a dominant peak at 335 Ma. More specifically, the Permo-Carboniferous  
553 ages include 2% Permian, 28% from 299-325 Ma, and 70% from 325-360 Ma). Overall, >95 % of the  
554 Permo-Carboniferous DZ ages are older than 310 Ma. A second age component, representing 37% of  
555 the samples’ DZ age, is centred around 470 Ma, with most of the ages between 450 and 480 Ma. The  
556 “Pan-African” mode represents 26% of the DZ ages and is characterized by peaks at 540 Ma, 620 Ma,  
557 and 700 Ma. Only 6 DZ ages are older than 850 Ma and none between 990 and 1750 Ma.

558 Sample CR-MB-1B (n=148), collected at the base of the Grès Singuliers unit in the Catogne section (Fig.  
559 9), is characterized by 45% Permo-Carboniferous DZ ages that can be subdivided into 22% Permian,  
560 48% from 299-325 Ma, and 30% from 325-360 Ma). A second important age component (31%) is  
561 centred near the Silurian-Ordovician boundary, spreading from 400 to 500 Ma. “Pan-African” DZ ages  
562 cluster between 500 and 850 and comprise 16% of the total age spectra. Only 5% of the sample’s ages  
563 are >850 Ma and none are between 1200-1800 Ma.

564 Sample CR-MB-1A (n=103), collected at the top of the Grès Singuliers unit in the Catogne section (Fig.  
565 9), displayed 31% Permo-Carboniferous DZ ages that can be broken down into 13% Permian, 31% from

566 299-325 Ma, and 56% from 325-360 Ma. Another major age component (40%) clusters between 400-  
567 500 Ma with an age peak centred at 470 Ma. Lastly 21% of the ages are “Pan-African”, 8% older than  
568 850 Ma, and none between 1100 and 1800 Ma.

## 569 **Interpretation**

570 The Grès Singuliers unit in both Bonhomme and Catogne areas is characterized by very similar DZ U-  
571 Pb age spectra — a typical age-gap from 1200 to 1700 Ma, strong Early and Late Palaeozoic magmatic  
572 and metamorphic overprints— that suggest a direct or indirect provenance from Cadomian  
573 basement. This type of source is typical for the Alpine realm. The pre-Mesozoic basement of the ECMs  
574 mainly consist of Cadomian basement intruded during the Variscan by voluminous felsic plutons of  
575 mostly Carboniferous to earliest Permian age (e.g. Von Raumer et al. 2013; Grosjean et al. 2018). More  
576 specifically, the Mont Blanc - Aiguilles Rouges ECMs comprise, (1) undated Cadomian (?) gneisses, (2)  
577 Ordovician plutons, such as the Val Bérard granite ( $464 \pm 5$  Ma; Bussy et al. 2011) and the Lognan granite  
578 ( $453 \pm 3$  Ma; Bussy and Von Raumer 1993), early Carboniferous plutons, such as the Montées Pélissier  
579 and the Pormenaz granites (both dated at  $331 \pm 2$  Ma; Bussy et al. 2000), late Carboniferous- earliest  
580 Permian plutons, such as the Mont Blanc granite ( $303 \pm 2$  Ma; Bussy and Von Raumer 1993), the  
581 Morcles microgranite ( $303 \pm 2$  Ma; Grosjean et al. 2018) and the Vallorcine granite ( $306.5 \pm 1.5$  Ma;  
582 Bussy et al. 2000), and Carboniferous-earliest Permian volcanic rocks, as for example interbedded with  
583 fluvial deposits in the Salvan-Dorénaz basin (Capuzzo and Bussy 2000).

584 In light of published U-Pb ages for the Alpine basement and our new DZ U-Pb data, the Aiguilles Rouges  
585 and Mont Blanc crystalline basement appears to be the most likely provenance sources for the Late  
586 Carboniferous-early Permian DZ of the Grès Singuliers unit. However, recycling of Permo-Triassic strata  
587 (EC23) from the sedimentary cover can also have significantly contributed to the observed DZ U-Pb  
588 age signatures. A major contribution of the younger, autochthonous, Triassic strata (EC20, Triassic  
589 Vieux Emosson Fm) is unlikely, as the latter distinctively lack the Permian-Carboniferous age peak. In  
590 detail, the temporal evolution of DZ U-Pb age spectra of the Grès Singuliers unit displays subtle  
591 variations and trends observed in both localities. Within the Permo-Carboniferous age spectra, we



592 observe from the base to the top of the Grès Singuliers unit a relative decrease in Permian and  
593 Pennsylvanian-Serpukhovian ages and a concomitant increase in Early Carboniferous, mainly Viséan,  
594 DZ ages. This change however appears more pronounced in the Mt. Catogne area in the north and  
595 more subtle in the Bonhomme area in the south. Stratigraphically upsection, the peak of the early  
596 Palaeozoic DZ ages (400-500 Ma) appears to be progressively displaced toward older ages, from ~450  
597 Ma to ~470 Ma. In line with observation of a rift-related detachment fault, the DZ evolution could  
598 reflect the progressive exhumation and unroofing of the ECMs (Mont Blanc) basement sources during  
599 rifting.

600

## 601 **6. DISCUSSION**

### 602 **■ Tectono-sedimentary evolution of the Mont Blanc massif and proximal European** 603 **margin during necking**

604 During Hettangian to Early Sinemurian times numerous fault-bounded half-grabens formed, some of  
605 which are well preserved along the proximal European margin such as in the Dauphiné domain (i.e.  
606 Bourg d'Oisans, La Mure, Taillefer, e.g. Lemoine et al. 1986; Chevalier 2002) and the Helvetic domain  
607 (i.e. Morcles and Doldenhorn nappes, e.g. Lemoine et al. 1986; Burkhard 1988; Epard 1990). This first  
608 stage of rifting is dominated in the western Helvetic domain by marls and limestones (Fig. 11, i.e.  
609 Tierces Fm, Epard 1989; Loup 1991).

610 During Sinemurian-Pliensbachian time rift activity localized in areas that would evolve into the future  
611 distal domain (e.g. Lemoine et al. 1986; Chevalier et al. 2003). This evolution went along with the  
612 formation of major extensional detachment systems and related core complex described in this study.  
613 Other similar structures are the Grosina detachment system (Mohn et al. 2012) and the Gozzano-  
614 Inverio-Arona detachment system (Decarlis et al. 2017). Both the latter are located between the  
615 proximal and distal margins of the conjugate Adriatic margin and formed during Sinemurian-  
616 Pliensbachian time. As explained above on the basis of stratigraphic relationships involving the Grès

617 Singuliers unit (Figs 8 and 9), the Mont Blanc detachment system was more-or-less synchronous with  
618 them. The formation of the Mont Blanc detachment system thus corresponds to a major  
619 reorganization of the depositional systems, which is testified by the large-scale exhumation of pre-rift  
620 basement and reworking of pre-rift sedimentary cover both leading to the genesis of the Grès  
621 Singuliers unit. The appearance of a local siliciclastic source occurred within an otherwise carbonate-  
622 dominated depositional system (i.e. Mont Joly Fm, Fig. 11). Where the Grès Singuliers unit directly  
623 overlies the exhumed detachment fault, footwall-derived monomict conglomerates are observed (i.e.  
624 Amône conglomerate). This conglomerate body shows a variable thickness but can be followed over a  
625 distance of more than 10 km in the Swiss Val Ferret, and is genetically related to detachment faulting  
626 (Fig 4 and 9). Detrital zircon U-Pb age data and sandstone petrography analysis together suggest that  
627 the detritus of the Grès Singuliers unit came partly from the resedimentation of fault rocks (i.e.  
628 cataclasites and black gouges) and footwall lithologies derived from Late Carboniferous basins,  
629 polymetamorphic basement (gneiss), granite and rhyolitic rocks with a variable contribution of pre-  
630 Grès Singuliers unit carbonate lithologies (Fig. 10). The following interpretation of source regions  
631 considers the Mont Blanc massif basement (granite and gneiss) and the Late Carboniferous basins that  
632 were likely widespread along the ECMs during the time interval of interest. This shows that the  
633 detachment and its footwall became available for sedimentation and therefore presented a potential  
634 source feeding for the Grès Singuliers depositional system. In this framework, the Grès Singuliers unit  
635 represents the sedimentary response to the exhumation of the Mont Blanc basement along the rift-  
636 related Mont Blanc detachment system (i.e. syn-tectonic deposit). Their syn-tectonic character is also  
637 evidenced by a range of clastic intrusions observed beneath and within depositional body.

638 Sedimentary processes occurring during the Grès Singuliers unit deposition include shallow water  
639 density flows, which suggest the uplift and creation of (at least) one trough and adjacent palaeo-highs  
640 in the Mont Blanc domain during the late Sinemurian-Pliensbachian (Fig. 11). The formation of the  
641 palaeo-high due to footwall exhumation and uplift along the Mont Blanc detachment system explains  
642 the reworking of basement rocks. Possible mechanisms for sediment dispersal include wave action in

643 the shallower areas, the development of subaqueous sediment density flow toward the seaway axis,  
644 and tidal currents within the seaway (Fig. 11). No evidence for emersion is found. In this scheme,  
645 conglomerates in the Combe des Fonds and l'Amône represent the residual facies preserved on top of  
646 the exhuming Mont Blanc system and winnowed by marine (wave-dominated?) processes (Fig. 11).  
647 The Bonhomme and Catogne areas are probably zones of interference between gravitational and  
648 tractive flow processes as commonly observed in tectonically confined tidal seaways and straits (e.g.  
649 Longhitano and Steel 2017, Longhitano, 2013 #4215). The conglomerates in the Combe des Fonds and  
650 l'Amône could represent the residual, shallowest facies preserved on top of the exhuming Mont Blanc  
651 system and winnowed by marine (wave?) processes (Fig. 11). Along strike migrating tidal bars and  
652 ridges also characterize the syn-necking units in several rift systems such as the North Sea (e.g.  
653 Galloway 2002) or the North Atlantic in Greenland and Mid Norway during Latest Jurassic-Earliest  
654 Cretaceous (*personal communication Ian Sharp*).

655 The siliciclastic source of the Grès Singuliers unit is not active anymore from the Toarcian-Aalenian,  
656 which is interpreted to reflect either a cessation of footwall uplift of the Mont Blanc detachment  
657 system and or/and a subsequent drowning of the whole Helvetic domain. The Toarcian-Aalenian time  
658 interval, coeval with hyper-extension system tract in the Alpine Tethys margins (hyper-extension  
659 system tract sensu Ribes et al. 2019b), is in the Mont Blanc are characterized by the deposition of black  
660 marls and limestone of the Toarcian Monts Rossets Fm overlain by the black lime-free shales of the  
661 Dugny Fm (e.g. Epard 1989; Loreau et al. 1995). These formations observed in the overall Helvetic  
662 domain are interpreted to record a general drowning generally understood as an overall sediment  
663 starvation (e.g. Loreau et al. 1995) combined to significant carbonate switch off related to the Early  
664 Toarcian oceanic anoxic event (e.g. Fantasia et al. 2018).

665 The Toarcian-Aalenian time interval thus marks the end of tectonic activity in the Helvetic domain,  
666 which can be understood as the effect of the migration of the deformation toward more distal parts  
667 of the margin as recorded in the stratigraphic record of the distal margins (e.g. Ribes et al. 2019b).

668 Distally to the study are, syn-kinematic facies related to the hyper-extension may be represented by  
669 breccia deposit observed in the Moûtiers Unit (i.e. distal European margin, Ribes et al. 2019a),  
670 corresponding to the Dent d'Arpire Fm (Loprieno 2001) also named Brèches du Grand Fond Fm or  
671 Brèches de la Tarentaise (e.g. Antoine et al. 1972; Fudral 1973). The final stage of rifting closing the  
672 syn-rift megasequence is marked by the exhumation of mantle and onset of magma in the Valais  
673 domain (Sion-Courmayeur and Tasma nappes; Beltrando et al. 2012; Ribes et al. 2019a) and the  
674 contemporaneous deposition of the Callovo-Oxfordian "Terres Noires" in the Helvetic and Dauphinois  
675 domains (Figs 2 and 11).

676

### 677 **■ The Mont Blanc Core Complex (MBCC)**

678 The development of gravity-driven depositional systems at the base of the Grès Singuliers unit, the  
679 thinning trend of the Grès Singuliers unit toward the central part of the Mont Blanc massif, and the  
680 facies distribution along the Swiss Val Ferret suggest that the exhumed basement of the Mont Blanc  
681 massif was an elongated dome-shaped palaeo-high during the Late Early to Middle Jurassic (Fig. 11).  
682 The occurrence of such a palaeo-high was already suggested by Trümpy (1971) and Loup (1991): the  
683 "*Mont Blanc Island*". These authors, however, suggested that this high represented a relict of the  
684 Triassic paleotopography. This view is in contrasts with our interpretation proposing a true tectonic  
685 uplift during the Late Early to Middle Jurassic. The residual Triassic "island" is moreover in contradiction  
686 with the detrital zircon record indicating that the clastic source of Grès Singuliers significantly differs  
687 from that of the Triassic Vieux Emosson Fm (Fig. 10). This view is contrasts with our interpretation  
688 assuming a tectonic uplift during the Late Early to Middle Jurassic. Similar uplifts linked to crustal  
689 thinning have also been observed in several rifted margins (e.g. Pik et al. 2013; Lewis 2014) and  
690 predicted more recently by numerical modelling (Chenin et al. 2019).

691 The top basement extensional detachment fault system currently outcrops discontinuously across  
692 50km along the Mont Blanc massif, here referred to as the Mont Blanc core complex (MBCC). The

693 extensional detachment fault and associated core complex show similarities to those described from  
694 the southwestern United States and elsewhere (Wernicke 1985; Buck 1988; Lister and Davis 1989;  
695 Axen and Karner 2005; Platt et al. 2015). Its overall dome shape is reminiscent of present-day core  
696 complex (e.g. Brun et al. 2018). The domal geometry of the footwall of core complexes has been  
697 explained as resulting from a combination of isostatic/flexural uplift of the detachment when the  
698 hanging-wall rocks are extended, thinned, and denuded by rolling hinge process (e.g. Spencer 1984;  
699 Wernicke and Axen 1988; Whitney et al. 2013 references therein). Continental core complexes are  
700 typically elliptical, with a long axis of ~10–40 km; the footwall of core complexes is typically elevated  
701 above the surrounding hanging wall, creating the dome shape structure made of exhumed footwall  
702 rocks that can create up to 1–2 km of relief (e.g. Whitney et al. 2013 references therein).

703 With a rolling hinge process, the MBCC and associated detachment fault system could result from the  
704 sequential development of high-angle normal faults occurring above the Aiguilles Rouges-Mont Blanc  
705 massifs (Fig. 11). With increasing extension and footwall isostatic and flexural rebound, each new fault  
706 is rotated to a low dip then abandoned as a new fault develops in the hanging wall (e.g. Brun et al.  
707 2018 references therein).

708 An example of active detachment faults producing a metamorphic core complex related to rifting and  
709 opening of a small ocean basin has been described from the Woodlark-D'Entrecasteaux rift system  
710 (Papua New Guinea, e.g. Little et al. 2007; Daczko et al. 2009). Associated to one of these dome-shaped  
711 metamorphic core complexes, syn-kinematic (i.e. syn-detachment and syn-footwall uplift)  
712 conglomerates and sandstones derived from the exhumed footwall are observed around the  
713 Suckling- Dayman MCC (Gwoira Conglomerate and Uba Sandstone, e.g. Webber 2017; Little et al.  
714 2019). The development of these core complex-derived sediments present convincing tectono-  
715 sedimentary similarities with the Grès Singuliers unit deposited around the MBCC.

716

717  **Relics of Alpine Tethys necking zones and associated clastic units**

718 The paleographic position of the Aiguilles Rouges-Mont Blanc ECM between the proximal and distal  
719 European margins has enabled some authors to interpret it as a necking domain (e.g. Beltrando et al.  
720 2014; Mohn et al. 2014). Based on the study of present-day rifted margins, the necking domain  
721 corresponds to the region where the continental crust thins abruptly from ~30–35 to ~10 km between  
722 the proximal and distal domains (e.g. Sutra and Manatschal 2012; Peron-Pinvidic et al. 2013; Tugend  
723 et al. 2015). A necking system tract has been defined by Ribes et al. (2019), which encompasses the  
724 syn-tectonic sedimentary wedge coeval with formation of this specific domain. Extension related to  
725 the necking tectonic system tract is characterized by the localization along a few major upper and  
726 lower crustal faults exhuming basement rocks along large scale detachment faults (e.g. Mohn et al.  
727 2012; Beltrando et al. 2015). In such systems, the pre-rift succession becomes progressively  
728 delaminated along multiple detachment faults resulting in the formation of extensional allochthons  
729 and slivers overriding the top basement detachment faults (e.g. Mohn et al. 2015). The identification  
730 of the Mont Blanc core complex associated to a large detachment system and specific deformation  
731 processes (cataclasis, gouge) strengthen the interpretation of: (i) the Mont Blanc region as the  
732 breakaway of a former necking zone along the European margin, and (ii) the Grès Singuliers unit as a  
733 syn-tectonic sedimentary wedge deposited in response to the necking of the continental crust. In this  
734 scheme, the angular unconformity observed at the base of the Grès Singuliers unit is understood as  
735 the stratigraphic surface marking the onset of the necking system tract (e.g. Ribes et al. 2019b).

736 From a stratigraphic point of view, the recognition of localized, in time and space, siliciclastic facies,  
737 such as the Grès Singuliers unit, derived from an uplifted exhumed basement and reworking of its  
738 overlying pre-rift sedimentary cover during the Sinemurian-Pliensbachian is understood as an indicator  
739 of necking processes. Interestingly, during the late Early Jurassic, siliciclastic facies are observed above  
740 or near several of the Alpine ECMs while the surrounding, more proximal domains, including the  
741 Dauphinois and Helvetic domains are characterized by limestone and shale deposits (Trümpy 1971;  
742 Barfety and Mouterde 1980). In the Aar massif region, both the autochthonous sedimentary cover  
743 outcropping in the Raron syncline and the para-autochthonous sedimentary cover outcropping in the

744 Doldenhorn nappe present siliciclastic facies (Fig. 2; Loup 1991). The latter are characterized by  
745 sandstones mainly composed of angular to sub-angular quartz, altered feldspar and dolomitic grains  
746 split into two intervals, one dated from the Late Sinemurian and the second from the Pliensbachian  
747 (Loup 1991 and references therein). In the Ferden area (Fig. 2A and C), both sandstone intervals  
748 present indicators of tidal processes (herringbones cross-stratification and high-angle sigmoidal  
749 foresets, Loup 1991). The Early to Middle Jurassic lithologies and vertical succession present strong  
750 similarities with the sedimentary cover of the Mont Blanc and particularly with the Saillon section (Fig.  
751 9). The position of the Gastern-Aar massif along the European margin (e.g. hingeline of Stockmal &  
752 Beaumont (1987)), as well as the development of siliciclastic sediments around it during a specific time  
753 interval, late Sinemurian-Pliensbachian are reminiscent of what is observed in the Mont Blanc region  
754 with the Grès Singuliers unit.

755 Although an extrapolation to the other ECMs is premature and requires further investigation, we note  
756 that also in the vicinity of the Pelvoux massif, conglomerates and sandstones dated as Pliensbachian  
757 are described by Barfety and Mouterde (1980), while during that period the overall Dauphinois domain  
758 is characterized by limestone and shales (Barfety 1985). Furthermore, the description made by  
759 Wibberley (1999) of brittle damage zones with cataclasites and highly sheared black phyllosilicate-rich  
760 fault rocks in the granitic basement of the Pelvoux is similar to what has been observed from well  
761 described Jurassic extensional detachment faults (Manatschal 1999).

762 In the northern Adriatic margin, Mohn et al (2011; 2012) has identified relics of a necking zone in the  
763 Campo-Grosina nappe based on the recognition of crustal scale detachments exhuming pre-rift  
764 middle/lower crust at the seafloor during the rifting (i.e. Grosina detachment). However, no  
765 sedimentary cover has been preserved above the tectonically exhumed Grosina detachment.  
766 Recognition of crustal scale detachments exhuming pre-rift middle/lower crust have also allowed  
767 Beltrando et al. (2015) and Decarlis et al. (2017) to interpret the Gozzano-Invorio-Arona zone as the  
768 former necking zone of the southern Adriatic margin. Interestingly, siliciclastic facies are also observed

769 in this zone during the Pliensbachian to early Toarcian (i.e. Inverio Breccia and San Quirico sandstone;  
770 e.g. Berra et al. 2009; Beltrando et al. 2015; Decarlis et al. 2017). These facies that overlie  
771 unconformably karstified middle Triassic dolostone and Permian volcanic rocks are interpreted as  
772 indicative of widespread subaerial exposure of Permian volcanic rocks and metamorphic basement  
773 (Beltrando et al. 2015).

774

### 775 **■ The MBCC: a fossil analogue for necking domains in present-day rifted margins**

776 Lithospheric-scale low-angle detachment faults and associated core complexes at continental rifted  
777 margins have been first proposed by Lister et al. (1986; 1991). Thereafter, core complexes flanked by  
778 large-scale detachment structures exhuming mid crustal rocks have been recognized in the necking  
779 zone of the Iberia margin (i.e. west Galicia Bank, e.g. Peron-Pinvidic et al. 2013), the Norwegian margin  
780 (i.e. Gossa High, e.g. Osmundsen and Ebbing 2008; Osmundsen and Péron-Pinvidic 2018), the Angola  
781 margin (e.g. Unternehr et al. 2010), the Eritrea margin (i.e. Damas and Burri highs in Talbot and  
782 Ghebreab 1997) and numerically modeled (e.g. Peron-Pinvidic and Naliboff 2020). These observations  
783 at various rifted margins suggest that detachment faults and associated core complexes in necking  
784 domains of rifted margins are frequently observed. However, the MBCC is at present the only field  
785 analogue world-wide where the tectono-sedimentary evolution can be constrained and integrated into  
786 the evolution of a whole margin system (e.g. Ribes et al. 2019b).

787 The necking domain of the south Australian rifted margin, in the Great Australian Bight, shows a  
788 remarkable dome-shaped architecture and associated sequential high-angle normal faults, similar to  
789 what can be reconstructed in the Mont Blanc region (Fig. 12). This margin and its Antarctic conjugate  
790 formed during the fragmentation of Gondwanaland. The first phase of rifting probably initiated during  
791 the Triassic-Jurassic (Veevers 2012). Seismic sections across the necking area clearly show that the  
792 proximal domain is affected by several major normal faults forming half-grabens filled with wedges of  
793 syn-tectonic sediments, which have been drilled at the Jerboa-1 site (Totterdell et al. 2000). Some of  
794 the blocks appear to be overtilted (i.e. intersection of normal fault and block surface is less than 60°)



795 and a decreasing size of the faulted blocks toward the ocean is observed. The necking domain itself  
796 marks a sharp transition from a thick (30 km) to an extremely thin (less than 7.5 km) continental  
797 basement (Ball et al. 2013). The architecture and organization of the normal faults and the dome shape  
798 of the necking domain may be a modern analogue for the outer European margin preserved in the  
799 Helvetic nappes. However, an alternative interpretation could it be to consider this surface as a large  
800 footwall erosional unconformity that developed during the necking time such as suggested for the  
801 Skinna Ridge, Frøya High, Gossa High in Mid Norway (e.g. Osmundsen and Péron-Pinvidic 2018).

802

803 The implications of this work for present-day margins are that the sediments of the necking system  
804 tract, recording the development of large-scale detachment systems, are characterized by a major  
805 reorganization of the pre-necking depositional systems typified by the development of footwall-  
806 derived clastic sedimentary systems. The recognition of these clastic sediments, which are spatially  
807 related to the necking zone and limited in time to the necking system tract, allow a better  
808 understanding of the overall rifting history, differentiating a specific time interval within the the syn-  
809 rift megasequence. The creation of a transient uplift recorded by the Mont Blanc core complex lead to  
810 the development of an unconformity at the base of the Grès Singuliers unit, which is understood as  
811 the marker for the onset of the necking. This stratigraphic surface, corresponding to the lower  
812 bounding surface, typifies a necking unconformity. It separates the sediment of the necking system  
813 tract from those belonging to the preceding stretching system tract (e.g. Ribes et al. 2019b). The top  
814 of the Grès Singuliers unit that marks the base of the post-tectonic package in the necking domain is  
815 understood as the 'onset of hyper-extension' surface.

816

## 817 **7. CONCLUSIONS**

818 The Grès Singuliers unit represents an anomalous occurrence of a clastic facies in a very limited  
819 geographic area above the Mont Blanc massif, which was emplaced during Jurassic rifting. The main  
820 aim of this contribution was to integrate and reconcile sedimentological, stratigraphic and tectonic

821 data to provide a tectono-sedimentary framework for the Mont Blanc massif and explain its evolution  
822 during Jurassic rifting.

823 The Early Jurassic rift-related structures characterized by cataclasites and black gouges observed at the  
824 top of the Mont Blanc basement highlight a detachment fault system flanking a core complex here  
825 referred to as the Mont Blanc core complex (MBCC). This system is associated with a large-scale  
826 detachment system that is located between the proximal and distal margins, supporting the idea that  
827 the Mont Blanc region hosts the breakaway area of a necking zone of the European margin.

828 The Grès Singuliers unit originated from a siliciclastic-dominated sedimentary system, including clast-  
829 supported conglomerates, lithic arenites to quartz arenites and sandy limestones that unconformably  
830 overlie the Lower Jurassic to Triassic carbonates and, in places, directly onlap the exhumed basement  
831 of the Mont Blanc massif. Based on the facies distribution, petrographic analysis and detrital zircon  
832 provenance, we have demonstrated that the Grès Singuliers unit is mainly derived from the erosion of  
833 the footwall of the Mont Blanc core complex. Depositional systems comprise density flow deposits  
834 originating from fault escarpments linked to the Mont Blanc core complex exhumation, that evolve, in  
835 time to sediments that show evidence for reworking by tidal currents.

836 The source to sink relationship between the Mont Blanc core complex and the Grès Singuliers unit  
837 allows us to consider the Grès Singuliers unit as the sedimentary response to crustal necking during  
838 rifting. They represent a syn-tectonic sediment body constituting a necking system tract within a larger  
839 scale syn-rift megasequence. The main result of this study is to show that the exhumation and uplift  
840 of basement during the necking system tract produce a new but temporary source area for rift-related  
841 clastic sedimentary systems. Thus, the position of the Grès Singuliers along the margin is symptomatic  
842 of a necking area within a wider rift domain.

843

844

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1248 **Figures caption**

1249 **Figure 1** (A) Simplified paleogeographic map of the Alps from Mohn et al. (2014). The European  
1250 external zone extends from the little-deformed Jura Mountains, across the foreland Molasse basin and  
1251 the fold-and-thrust belt of the Dauphinois nappes to the External Crystalline Massifs including the  
1252 Mont Blanc massif. The European external zone is separated from the internal zone by the Penninic  
1253 Front (P.F). The internal zone is bounded by the P.F to the WNW and by the Periadriatic Line (including  
1254 the Insubric) to the ESE. (B) Depth migration of the ECORS-CROP profile from Mohn et al. (2014)  
1255 modified after Thouvenot et al. (1996). (C) published interpretation of the ECORS-CROP profile by  
1256 Mohn et al. (2014) as a 'rift inheritance model', which combines observations of surface geology with  
1257 the geometry of present-day rifted margins. (D) Palaeo-cross-section across the Alpine Tethys margins  
1258 at the end of rifting and before onset of Alpine convergence in Late Cretaceous times. Redrawn from  
1259 Mohn et al. (2011), no scale intended. For location of cross section see (A). ECM: External Crystalline  
1260 Massifs; Aa: Aar massif; Ar: Argenteras massif; Be: Belledone; CB: Cusio Biellese; CG: Campo-Grosina  
1261 nappes; MB: Mont Blanc massif; Pe: Pelvoux; H-E: hyper-extended.

1262

1263 **Figure 2** (A) Tectonic map compiled from Burkhard (1988), Steck et al. (1989), and Leloup et al. (2005),  
1264 green stars are sample locations for detrital zircon. CR-MB-1A Top Grès Singuliers, coordinates:  
1265 46°03'23.41"N, 7°07'47.62"E; CR-MB-1B base Grès Singuliers unit, coordinates: 46°03'47.06"N,  
1266 7°07'11.67"E, EC16 base Grès Singuliers unit, coordinates: 45°43'55.30"N, 6°43'27.86"E and EC17 top  
1267 Grès Singuliers unit, coordinates: 45°43'52.87"N, 6°43'25.28"E; EC20 Triassic quartzite, coordinates:  
1268 45°43'47.17"N, 6°43'54.31"E; EC23 Permo-Triassic, coordinates: 45°41'39"N, 6°43'20."E. S-C: Sion-  
1269 Courmayeur nappe. (B) Geological section through the Helvetic basement and cover nappes in the  
1270 Mont Blanc region, redrawn from Escher (1993). (C) Palinspastic map of the Helvetic domain of western  
1271 Switzerland during the Late Jurassic based on Trümpy (1980); Burkhard (1988) and Pfiffner et al.

1272 (2011). (D) Late Jurassic Palinspastic reconstruction of the Mont Blanc and Aiguilles-Rouges basement  
1273 massifs and of Helvetic nappes redrawn from Lemoine & Trümpy (1987).

1274

1275 **Figure 3** Schematic stratigraphic succession of the dauphinois realm based on literature compilation  
1276 (Trümpy 1980; Epard 1989; Pfiffner 2011) and own observations. The four tectonic System Tracts (ST)  
1277 including stretching, necking, hyper-extension and mantle exhumation are derived from Ribes (2019b).  
1278 H. siliciclastic “Helvetic facies”, D. marly “Dauphinois facies”. The Triassic pre-rift is around 20-30m  
1279 thick, the syn-rift sediments show large variations in thickness but is around 500m thick.

1280

1281 **Figure 4** (A) Panoramic view of the Col des Fours with the Penninic Front (PF) in the south, the Diableret  
1282 Thrust (DT) and the autochthonous sedimentary cover of the Mont Blanc massif, location indicated on  
1283 (B). Distance between Tête Nord des Fours and Tête Sud des Fours: 700m. (B) Geological map of  
1284 Bonhomme area, southern border of the Mont Blanc massif, modified from (Meyer 2002). Green stars  
1285 correspond to the location of the Grès Singuliers unit samples (samples EC16 and EC17) and Triassic  
1286 quartzite sample (EC20). Location of Fig 3b shown on Fig 2. (C) Geological map of the Swiss Val Ferret,  
1287 northeastern part of the Mont Blanc massif, based on data compiled from (Grasmück 1961) and (Steck  
1288 et al. 1989). Black squares correspond to the location of the Grès Singuliers unit samples in Catogne  
1289 area (samples CR-MB-1B and CR-MB-1A).

1290

1291 **Figure 5** Fabrics and structures of the damage zone of the Mont Blanc detachment system. (A)  
1292 panoramic view of the l’Amône outcrop with the Mont Blanc detachment system. Location of B and C  
1293 indicated. (B) Cataclastic fabric overprinting the porphyritic granitic basement and black gouge  
1294 including sub-angular basement clasts, picture from l’Amône outcrop (World Geodetic System 1984  
1295 [WGS 84] coordinates: 45°56’30”N, 7°5’31”E). (C) Cataclastic fabric overprinting the porphyritic granitic

1296 basement illustrating occurrence of sub-angular to sub-rounded clasts of basement in Combe des  
1297 Fonds (coordinates: 45°55'23"N, 7°4'55"E). (D) Cataclastic fabric overprinting the Variscan  
1298 metamorphic basement and black gouge underlying covered by slice of Triassic sandstone (Vieux  
1299 Emission Fm.) and dolostones (Arandellys Fm.) picture from Nant des Lotharets (coordinates:  
1300 45°43'37"N, 6°42'40"E). (E) Black gouge with a sub-rounded clasts of Triassic dolostone, picture from  
1301 Col des Fours. (F) Black gouge with quartz veins, sample from Nant des Lotharets (coordinates:  
1302 45°44'11"N, 6°43'46"E). (G) Thin-section photomicrograph of a black gouge showing sub-rounded  
1303 clasts embedded in a phyllosilicate-rich matrix with a strong preferred orientation and S±C fabrics,  
1304 Nant des Lotharets.

1305

1306 **Figure 6** (A) Panoramic view of the autochthonous sedimentary cover of the Mont Blanc in the  
1307 Bonhomme area, Tête Nord des Fours. (B and C) pictures of an extensional allochthon made up of  
1308 Triassic Fms that shows different textures from monomict mosaic and crackle breccias with locally  
1309 clast-supported, monomict, poorly sorted breccias with sub-angular to sub-rounded clasts. The shiny  
1310 black portions are silicified matrix (Si). Pictures location indicated on Fig. 8.

1311

1312 **Figure 7** Sedimentary log of the Grès Singuliers unit in the Bonhomme area, Tête Sud des Fours  
1313 (coordinates: 45°43'55"N, 6°43'16"E). (A) Basal conglomerate unconformably overlying the Triassic  
1314 Arandellys Fm. (B) Highly amalgamated trough cross stratification. (C) Sandy high density turbidites  
1315 with traction carpet at the base and ripple crest at the top. (D) Crack morphologies forming a highly  
1316 connected network expressed on bedding planes with a preferential north-south orientation. (E)  
1317 Sigmoidal crossbedding with thinner draped bundles that represent neap-tide and thicker sets  
1318 represent spring-tide (higher tidal energy). (F) 3- to 5-meter-thick clinofolds observed at the top of  
1319 the Grès Singuliers unit. (G) Thin section photomicrograph of the Grès Singuliers unit composed of 80

1320 to 90% of monocrystalline and polycrystalline quartz and the rest of altered feldspar and rare crushed  
1321 fine-grained grains.

1322

1323 **Figure 8** Stratigraphic correlation within the sedimentary autochthonous of the southern Mont Blanc  
1324 massif, Bonhomme area. This panel summarizes the main variations in thickness, the angular  
1325 unconformity at the base of the Grès Singuliers unit, and the thin-skinned deformation observed in the  
1326 underlying Fms (Middle Triassic to Lower Jurassic Fms). The measured sections are located in Fig.3B.  
1327 Samples for detrital zircon analyses are from the Col des Fours section. Stars represent biostratigraphic  
1328 references: 1, (Eltchaninoff-Lancelot 1980); 2, (Landry 1976); 3, (Landry 1976; Eltchaninoff-Lancelot  
1329 1980); 4, (Landry 1976).

1330

1331 **Figure 9** Stratigraphic correlation within the sedimentary autochthonous cover of the north-eastern  
1332 Mont Blanc massif, Swiss Val Ferret area based on the compilation of Grasmück (1961), Loup (1991)  
1333 and own observations. This panel summarizes the main variations in thickness, the angular  
1334 unconformity at the base of the Grès Singuliers unit, and the thin-skinned deformation observed in the  
1335 underlying Fms (Middle Triassic to Lower Jurassic Fms). The measured sections are located in Fig.3C.  
1336 Samples for detrital zircon analyses are from the Catogne section, CR-MB-1A and -1B. Stars represent  
1337 biostratigraphic constraints references: 1, 2, 3, 4, 5, 6, 7 (Grasmück 1961); 4, (Trümpy 1951).

1338

1339 **Figure 10** Detrital zircon U–Pb LA-ICP-MS age distributions measured in Triassic Vieux Emosson Fm  
1340 sandstones and Grès Singuliers unit. Detrital zircons  $^{206}\text{Pb}/^{238}\text{U}$  age histograms and relative  
1341 probability curves (grey).

1342

1343 **Figure 11** (A) Reconstruction of the Helvetic margin during the Late Jurassic modified from Stampfli et  
1344 al. (2002). See text for discussion. Bo, Bonhomme area ; Di, Diablerets nappe domain; Cb, Chamonix  
1345 basin; M-C, Mont Chetif basement ; Mte L, Monte Leone nappe; S-C, zone Sion-Courmayeur; VF, Val  
1346 ferret ; Wi, Wildhorn nappe domain. (B) Three-dimensional paleogeographic-tectono-stratigraphic  
1347 diagrams of the late Early Jurassic illustrating sedimentary pattern of the Grès Singuliers unit in the  
1348 Helvetic domain. Bo, Bonhomme area; Am, Amône; Ca, Catogne; Sa, Saillon; Ar, Ardèche; Fe, Ferden  
1349 (Torrenthorn).

1350

1351 **Figure 12** Upper part: Location of the whole seismic line GA199-09 (Symonds et al. 2001) along the  
1352 south Australian rifted margin. In thick black the location of the displayed seismic section. The green  
1353 circle represents the location of the Jerboa-1 drill site. Lower part: Uninterpreted and interpreted  
1354 seismic section imaging the necking domain along line GA199-09. Normal faults are shown in red; the  
1355 interpreted detachment fault is shown in dashed violet. Copyright Commonwealth of Australia  
1356 (Geoscience Australia).

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Figure 1

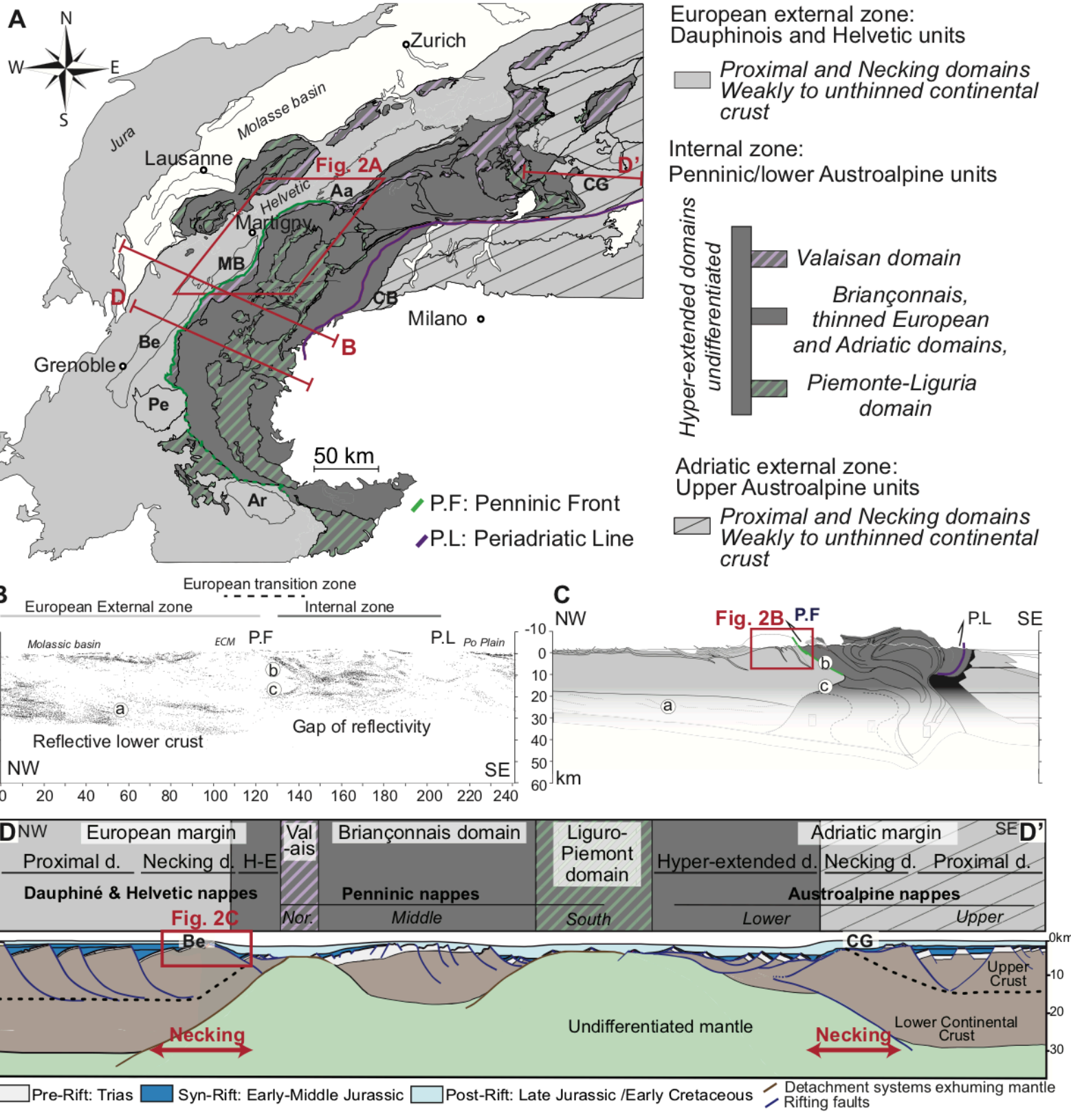




Figure 2

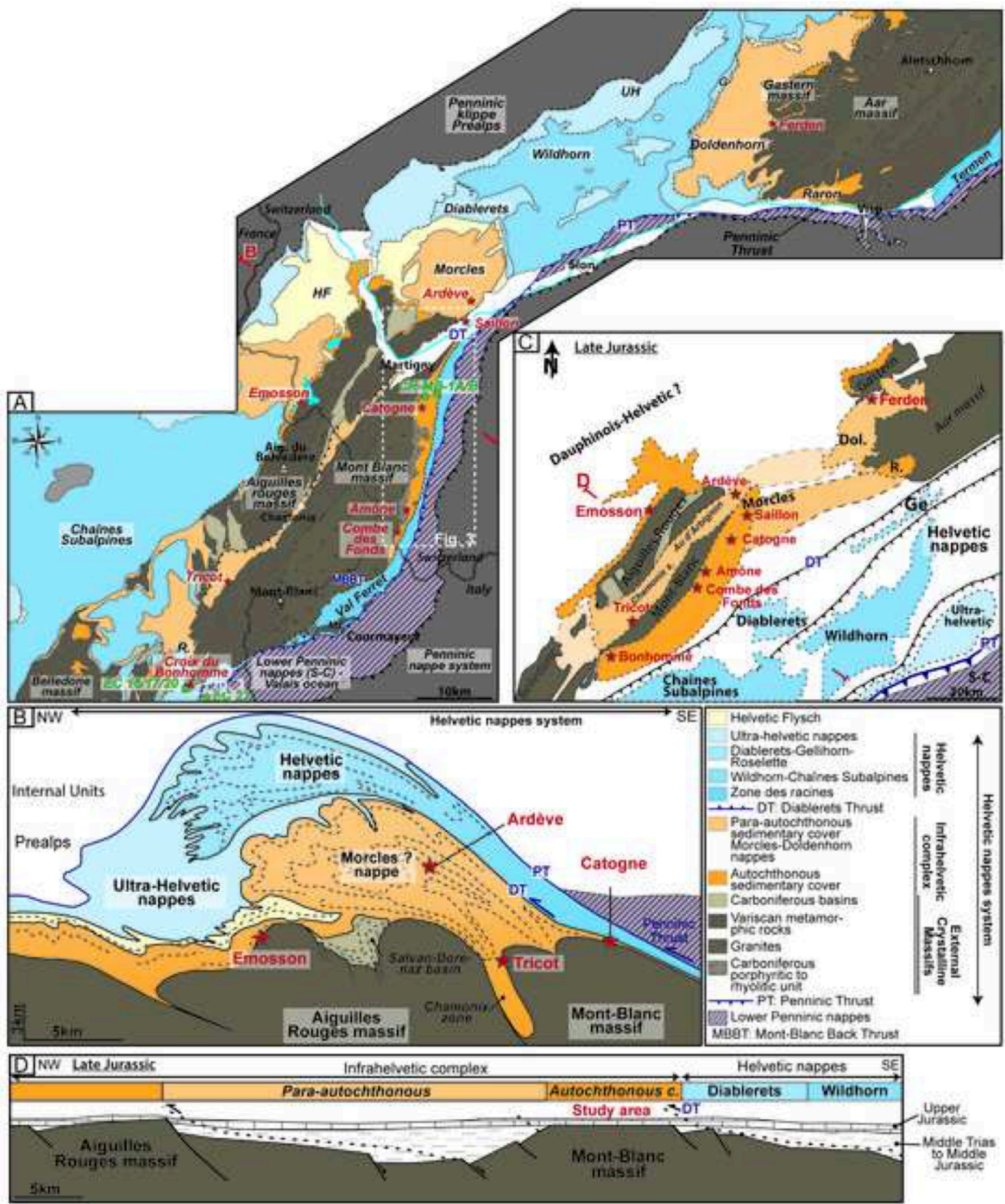


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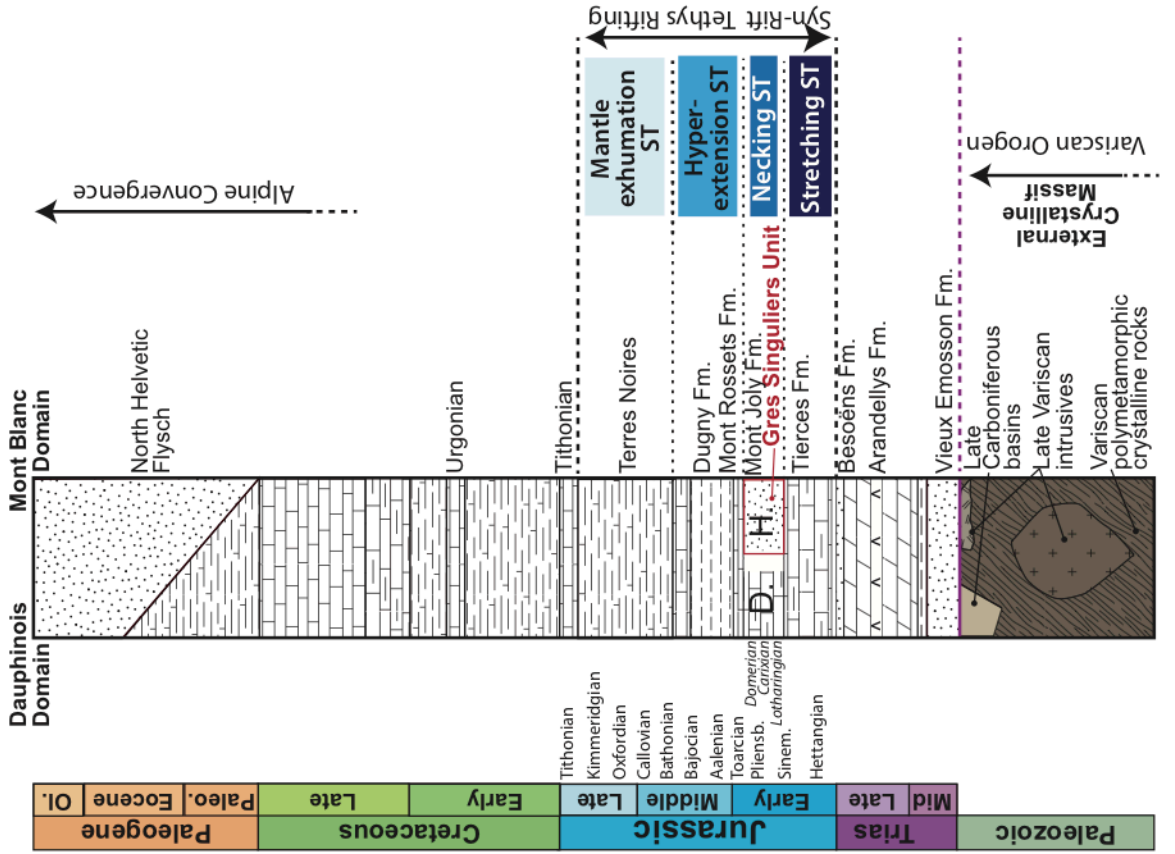


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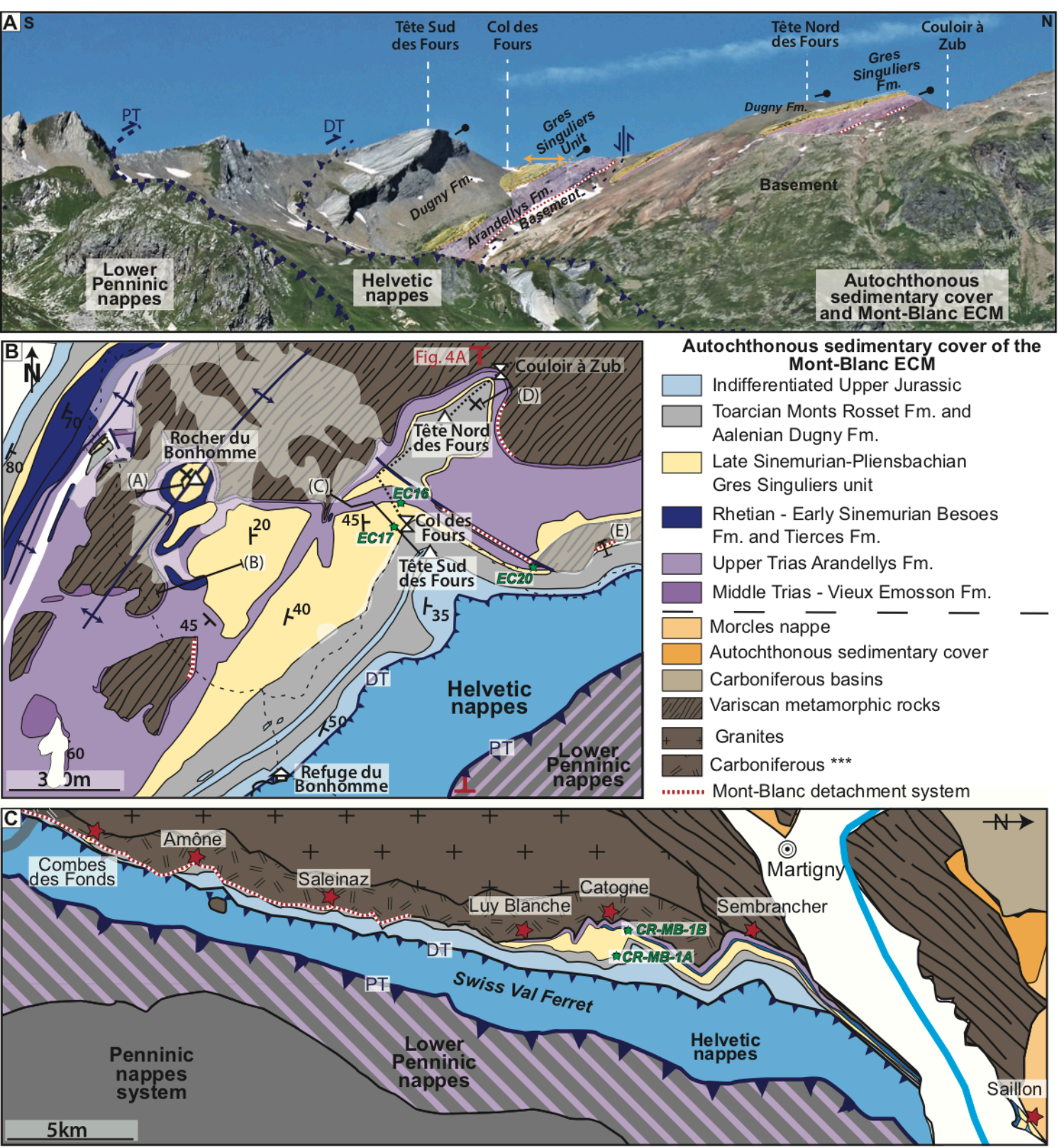


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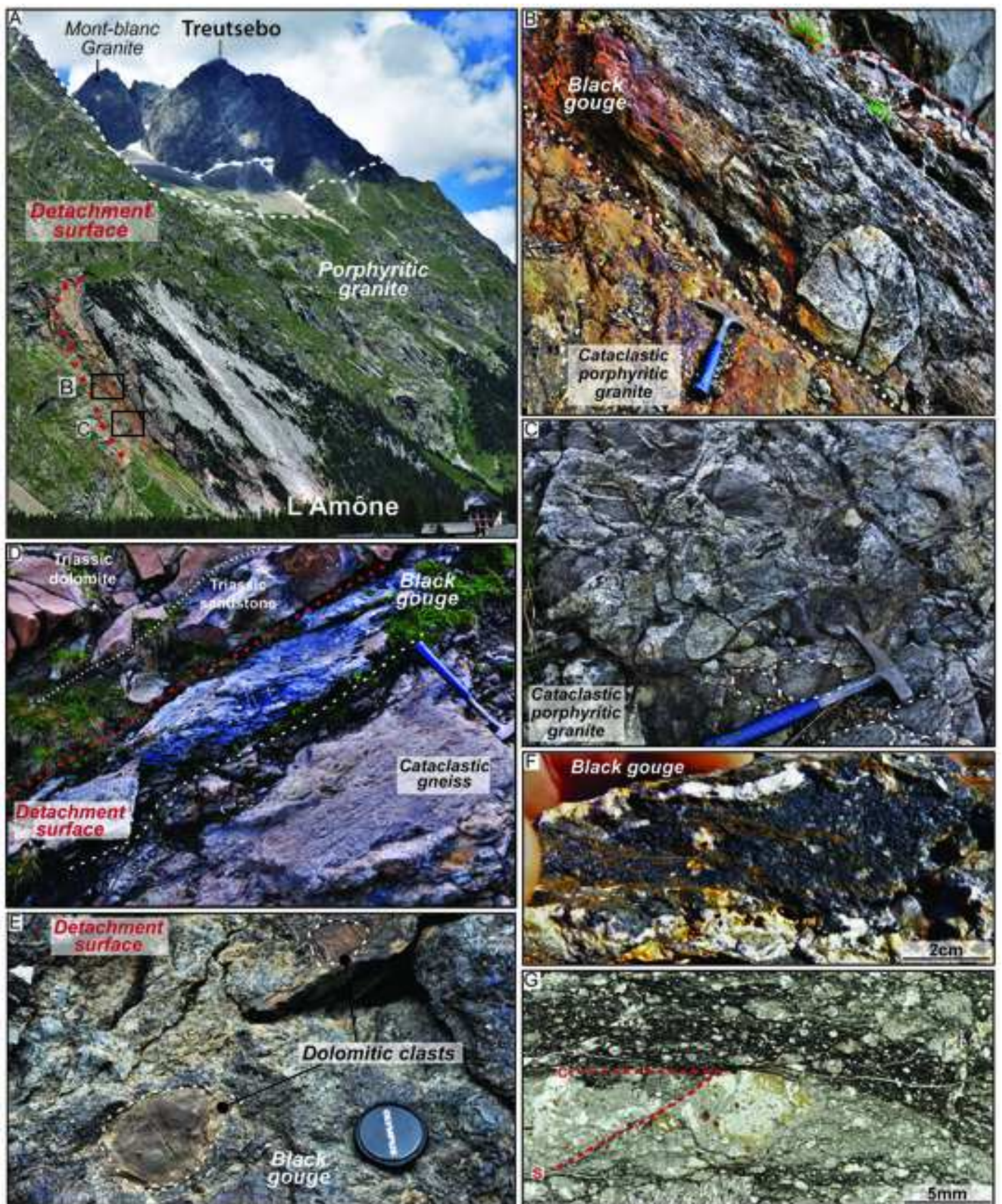


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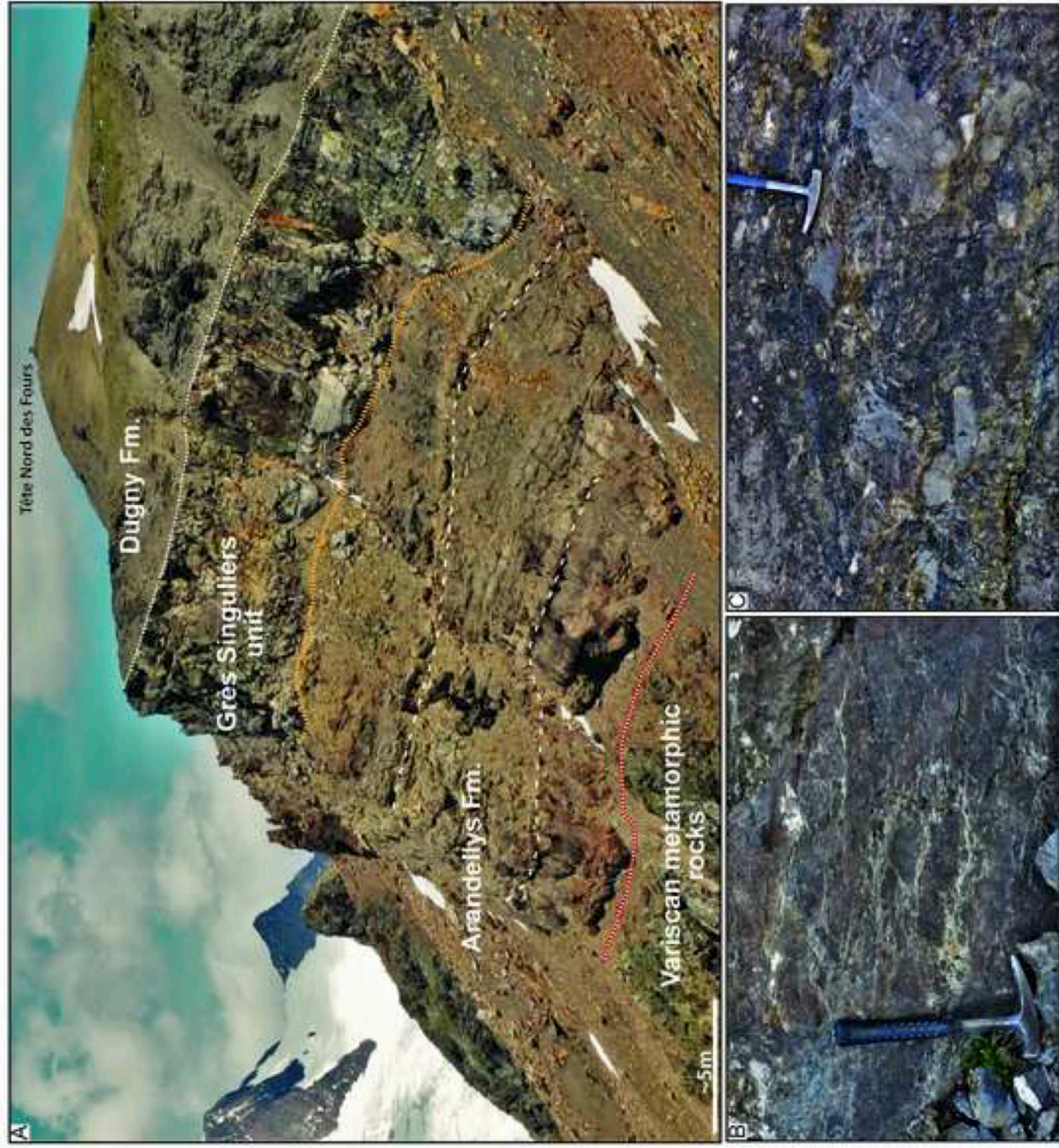


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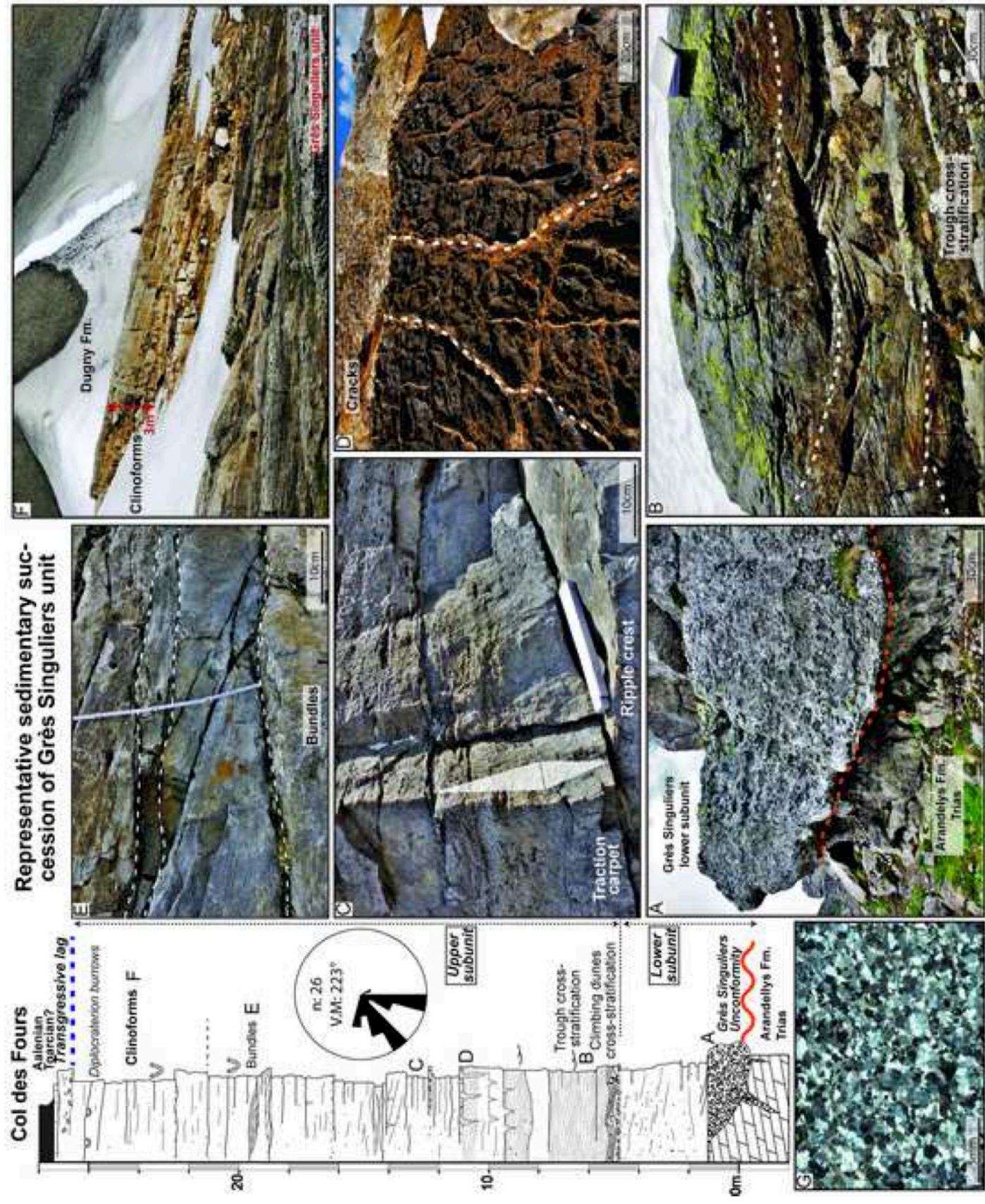
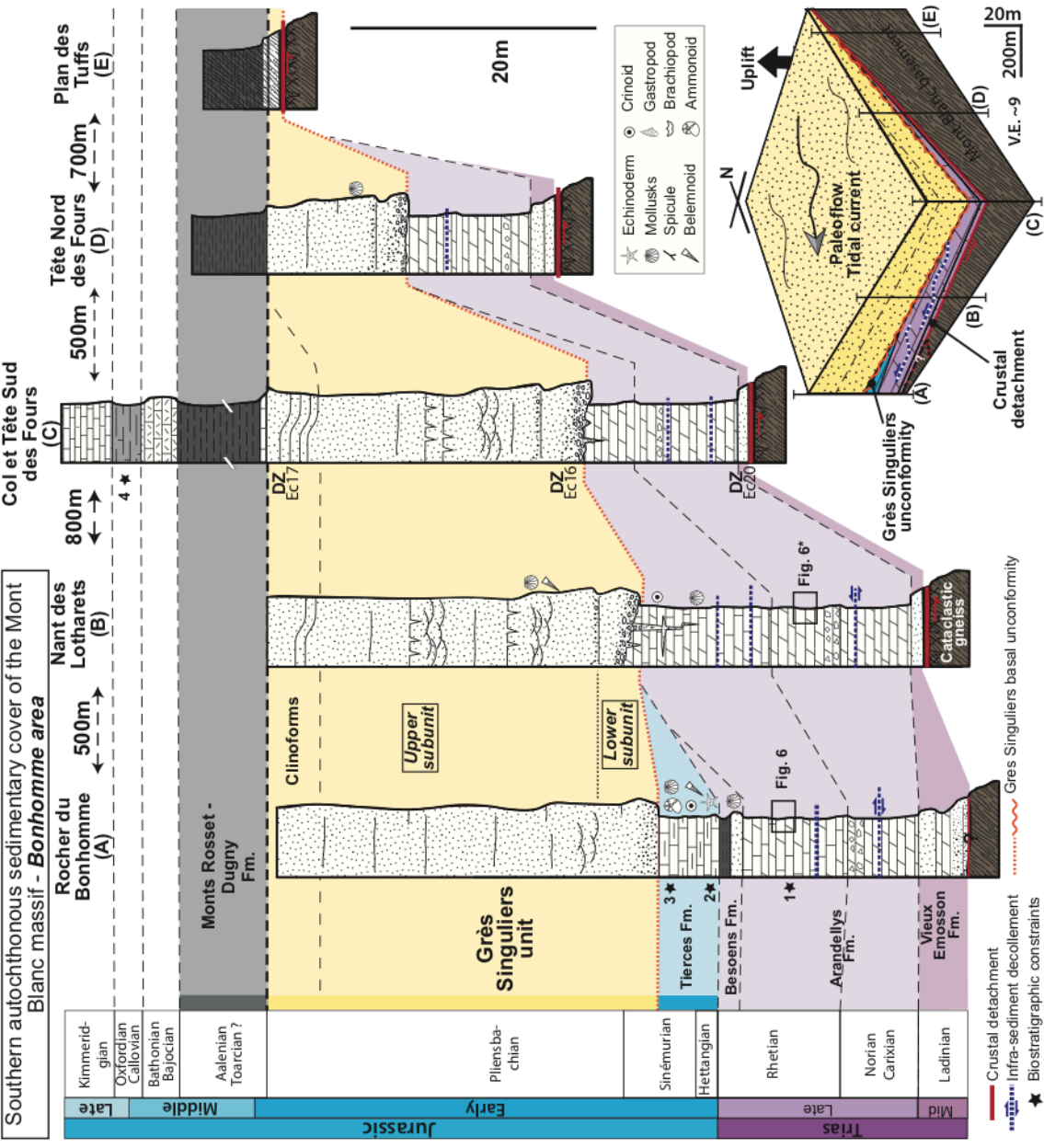


Figure 8



Crustal detachment

Infra-sediment decollement

Biostratigraphic constraints

Crinoid

Gastropod

Brachiopod

Ammonoid

Echinoderm

Mollusks

Spicule

Belemnoid

Kimmeridgian

Oxfordian

Callovian

Bathonian

Bajocian

Aalenian

Toarcian?

Pliensbachian

Sinemurian

Hettangian

Rhetian

Norian

Carixian

Ladinian

Jurassic

Trias

Monts Rosset - Dugny Fm.

Grès Singuliers unit

Cliniforms

Upper subunit

Lower subunit

Tierces Fm.

Besoens Fm.

Argandellys Fm.

Vieux Emosson Fm.

Figure 9

**Northeastern autochthonous sedimentary cover of the Mont Blanc massif**

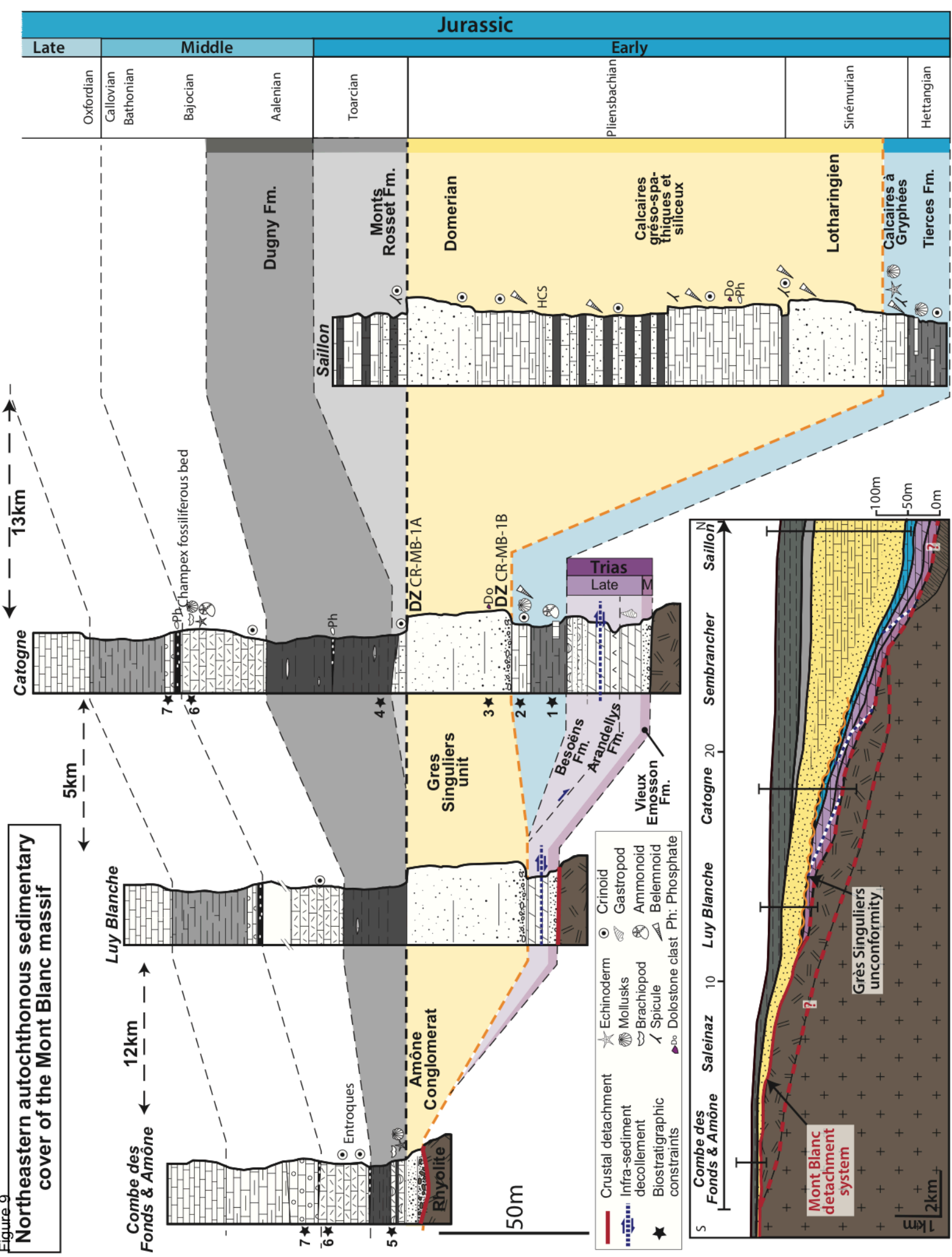




Figure 10

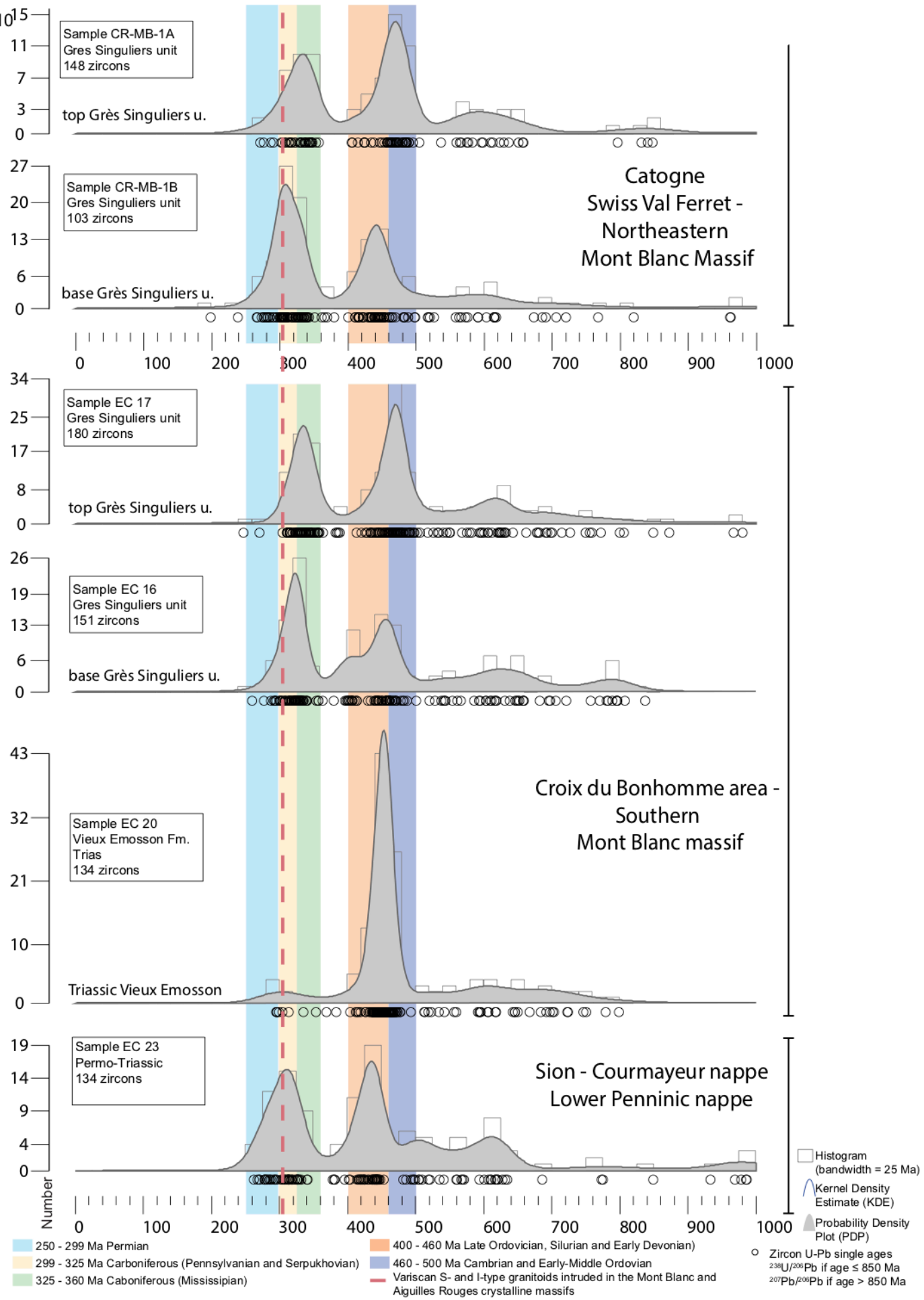
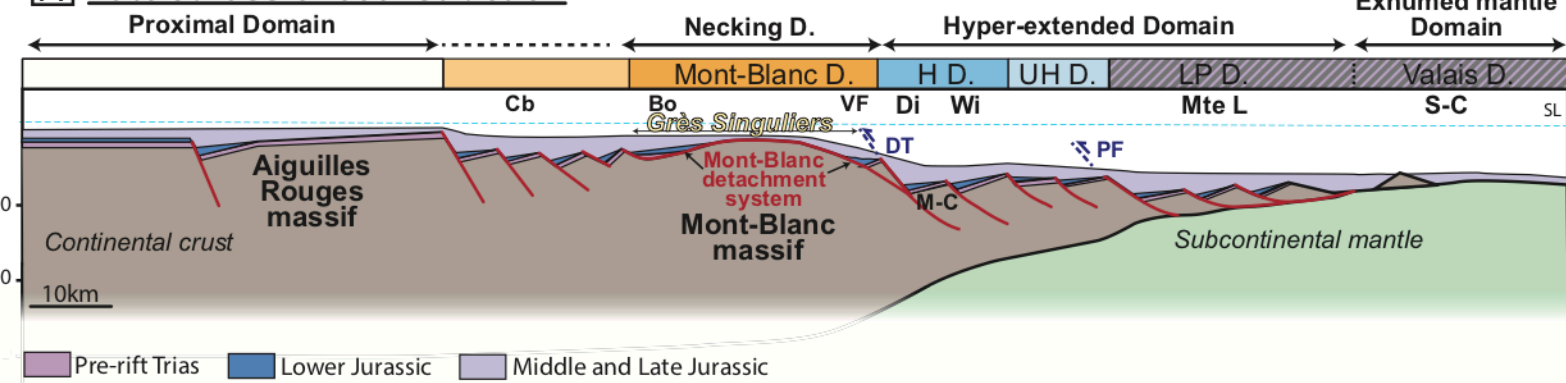


Figure 11  
**A** Late Jurassic reconstruction



**B** Necking System Tract - Pliensbachian

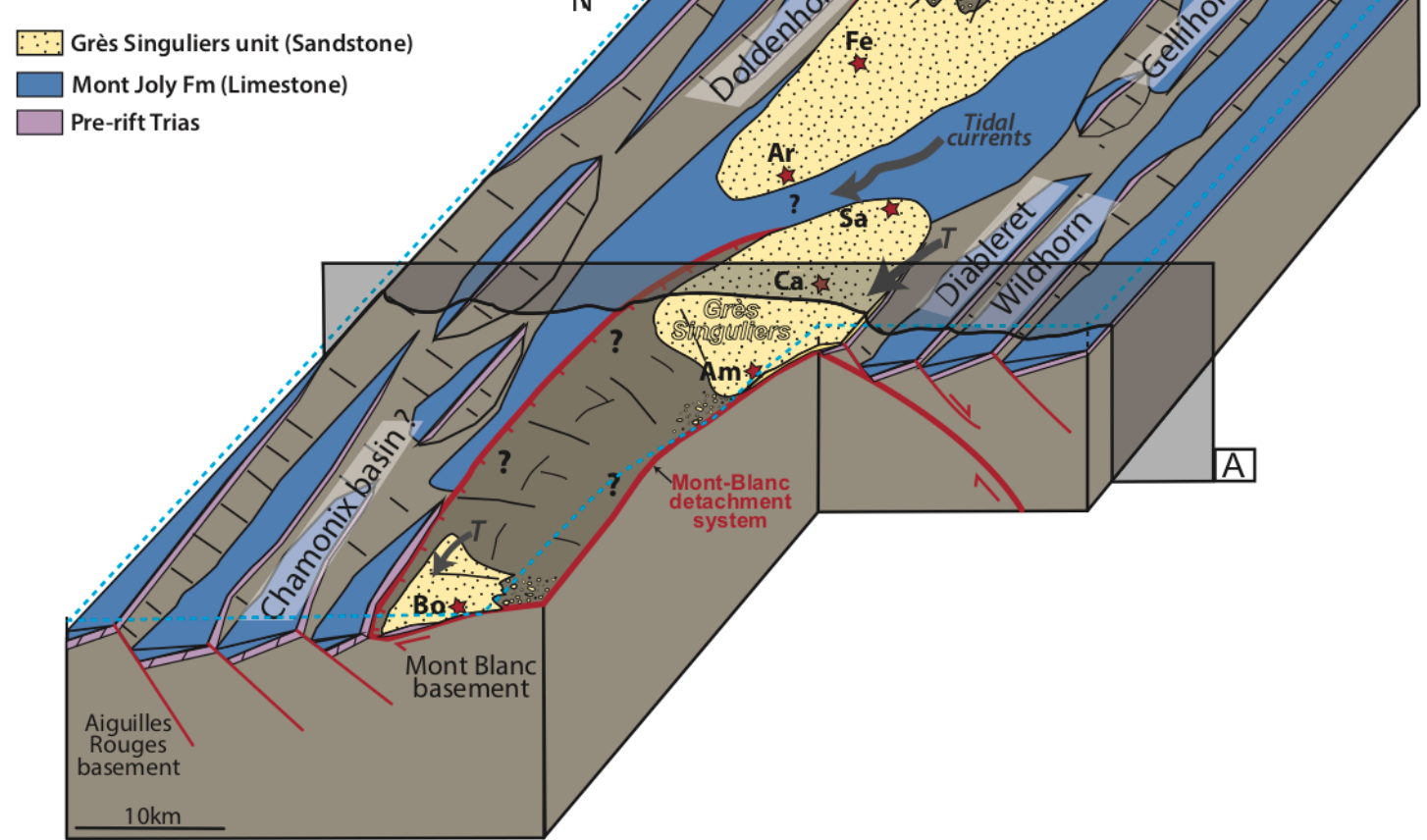


Figure 12

