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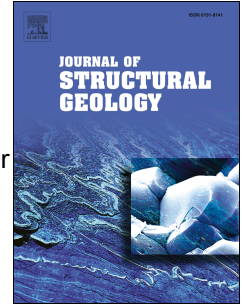
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# Journal Pre-proof

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1 **Deformation, crustal melting and magmatism in the crustal-scale East-Variscan Shear Zone**  
2 **(Aiguilles-Rouges and Mont-Blanc massifs, Western Alps).**

3

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20

21 **Key points:** Variscan Belt, Transpression, Structural analysis, Zircon and monazite LA-ICMPS  
22 U-Th-Pb dating, crustal-scale East Variscan Shear Zone

23

#### 24 **Abstract**

25 The Aiguilles-Rouges and Mont-Blanc massif represent a segment of a crustal-scale  
26 transpressional shear zone named the East Variscan Shear Zone (EVSZ) along which two  
27 plutonic pulses occurred during Early and Late Carboniferous times. The aim of this study is to  
28 constrain the relationships between the dynamics of the crustal-scale shear zone, the  
29 mechanisms of pluton emplacement at different structural levels within the crust and the  
30 magma sources. A detailed structural analysis of the whole massif highlights the crustal-scale  
31 anastomosed network of the EVSZ. Microstructural observations and LA-ICPMS U-Th-Pb zircon  
32 ages from large plutons constrain the beginning of the transpression at ca. 340 Ma. From 340  
33 to 305 Ma, the EVSZ broadened and formed a 25 km-wide dextral S-C-C' anastomosed shear  
34 zone network with dilation zones acting as preferential pathways for melt migration and  
35 pluton growths. Moreover, LA-ICPMS U-Th-Pb zircon ages from small magmatic bodies (i.e.  
36 pegmatite, aplite and microgranite) indicate an Ordovician-age inheritance component. Field  
37 evidences and zircon inheritance indicate that Late Carboniferous granitic melts are mainly  
38 derived from water-fluxed melting of Ordovician orthogneiss with the input of mantellic-  
39 source derived magmas. Over time, the growth of the dextral anastomosed network enhanced  
40 water transfer through the shear zones and water-fluxed melting to produce more anatectic  
41 melts.



42

43 **1. Introduction**

44 Continent-scale shear zones are pathways along which ductile and brittle deformation leads  
45 to segregation and transport of melts from deep to shallow crustal levels where syn-kinematic  
46 plutons might be emplaced (e.g. D'Lemos et al., 1992; Tikoff and Teyssier, 1994; Tommasi et  
47 al., 1994; Brown and Solar, 1998; Brown, 2013). Large crustal-scale shearing may last tens of  
48 millions of years (Oriolo et al., 2018; Carosi et al., 2022) but may also be the sum of localized  
49 and transient events (e.g. Fossen and Cavalcante, 2017). The duration and amount of melt  
50 production depends on main parameters such as the rock composition, melting reactions,  
51 mantle and crustal heat flux and the amount of water. Recently, water-fluxed crustal melting  
52 has been increasingly regarded as an important mechanism for initiation of voluminous  
53 melting (Weinberg and Hasalová, 2015) and for production of large batholiths (Collins et al.,  
54 2016) as an alternative to biotite or amphibole dehydration melting. This issue of the  
55 contribution of water-fluxed melting is disputed (Clemens and Stevens, 2015) and remains to  
56 be tackle.

57 The dynamics of granitic pluton emplacement depends on the source of melts and the  
58 geodynamic context (e.g. Jacob et al., 2022). The timing of pluton emplacement depends on  
59 their volume and progressive infilling rates, and large batholiths ( $>10 \text{ km}^3$ ) can grow at rates  
60 of about 1-10 Ma (Brown, 2013; de Saint Blanquat et al., 2011). Pluton emplacements in large-  
61 scale shear zones can induce local stress field and modify the regional strain partitioning (e.g.  
62 Brun and Pons, 1981; Neves et al., 1996). To fully understand the genesis and emplacement  
63 of granitic magmas along crustal-scale shear zones, timing, rates and interplay between

64 processes like shear deformation, melt production, melt and aqueous fluid transfer, pluton  
65 growth and emplacement must be further examined.

66 In the Western Alps, the Aiguilles-Rouges (AR) and Mont-Blanc (MB) massifs expose sections  
67 of middle and upper crust where migmatites and syn-kinematic Carboniferous granitic plutons  
68 are spatially and temporally correlated with the continental-scale East-Variscan Shear Zone  
69 (EVSZ; Guillot et al., 2009; Simonetti et al., 2020) (Fig. 1A). Previous geochronological studies  
70 have documented two distinct magmatic events at ca. 340-330 Ma and ca. 310-300 Ma (von  
71 Raumer and Bussy, 2004 and references therein). This twofold Carboniferous plutonism is  
72 typical for the Variscan basement of the External Crystalline Massifs (ECMs) of the Alps (Debon  
73 and Lemmet, 1999) and other parts of the Variscan belt (Corsica-Sardinia: Paquette et al.,  
74 2003; Rossi et al., 2009; Vosges: Tabaud et al., 2014, 2015). In the AR and MB massifs, the  
75 Early Carboniferous plutons are small (ca. 1-2 km<sup>2</sup>) and emplaced in the upper crust whereas  
76 the Late Carboniferous plutons are large, with an approximate area of ca. 20 to 200 km<sup>2</sup> (Bussy  
77 et al., 2000). These large plutons growth and crystallized in the migmatitic middle crust. The  
78 source of the granitic melts is thought coming from the deep part of the over thickened  
79 continental crust (Bussy, 1990; von Raumer and Bussy, 2004). Synchronous basic intrusions  
80 and peraluminous dykes (Bussy et al., 2000) suggest that the source is more complex. Also,  
81 the draining structures and melt-present deformation history can be better understood.

82 We present a multi-scale structural analysis performed to define the strain pattern of the EVSZ  
83 and the relationships with syn-kinematic granitic intrusions in the AR and MB massifs. Field  
84 work and LA-ICPMS U-Th-Pb zircon and monazite ages provide new insights about the nature  
85 of the protolith source, partial melting and emplacement age of magmatic bodies within the  
86 metamorphic basement. We propose a model for the production, ascent and emplacement

87 of granitic magmas within the EVSZ. It emphasizes the importance of water-fluxed crustal  
88 melting and the occurrence of kilometre-scale dilation zones controlling melt transfers from  
89 the anatectic source to the pluton sink.

90

## 91 **2. Geological setting**

92 The AR and MB massifs, located in the western Alpine external domain, are two narrow NE-  
93 SW trending Variscan massifs bounded by autochthonous and allochthonous Mesozoic  
94 sedimentary rocks (Fig. 1B). These two massifs, part of the ECMs, represent an exhumed  
95 portion of the Variscan crust deformed between ca. 340 and 300 Ma (e.g. von Raumer and  
96 Bussy, 2004; Vanardois et al., 2022) (Fig. 1). Structures in the AR massif suggests dextral  
97 transpression (von Raumer and Bussy, 2004) and the Emosson-Bérard Shear Zone (EBSZ) is  
98 interpreted as a branch of the EVSZ network (Simonetti et al., 2020). However, the meter to  
99 regional scale strain pattern of the whole AR and MB massifs has not been documented yet.  
100 Besides, the place of the EVSZ and ECMs within the Variscan belt reconstruction are debated  
101 (see Fig. 1A for instance) (e.g. Ballèvre et al., 2018; Simonetti et al., 2020; Martinez-Catalan et  
102 al., 2021; Faure and Ferrière, 2022).

103 The AR and MB massifs are composed of Proterozoic and Cambro-Ordovician amphibolitic  
104 facies gneissic basement and two greenschists facies or unmetamorphosed Carboniferous  
105 basins (Servoz and Salvan-Dorénaz synclines respectively) (Fig. 1B). The protolith of the  
106 gneissic basement consists of an upper Proterozoic to Cambrian sedimentary and  
107 volcanoclastic sequence intruded by Ordovician granite laccoliths (Bussy et al., 2011; Paquette  
108 et al., 1989; Fig. 1B). Two metamorphic events are distinguished. The first, related to collision

109 and crustal thickening, consists of a mid- to high-pressure metamorphism recorded as garnet-  
110 kyanite bearing assemblage in micaschists and paragneisses, and as omphacite-bearing  
111 eclogitic assemblage within tholeiitic metamafic lenses (von Raumer and Schwander, 1985;  
112 von Raumer and Bussy, 2004; Liégeois and Duchesne, 1981; Vanardois et al., 2022). High-  
113 pressure conditions have been estimated at 1.6-1.85 GPa and 680-750°C for the Lac Cornu  
114 eclogites (Vanardois et al., 2022), and 1.3-1.5 GPa and 650-750°C for the Val Bérard eclogites  
115 (Schulz and von Raumer, 1993, 2011) (see Fig. 1B for locations). Recently, LA-ICPMS U-Th-Pb  
116 analyses on zircon and rutile from a Lac Cornu eclogite specimen has dated the HP  
117 metamorphism at 340-330 Ma and the emplacement age of the protolith at ca. 460 Ma  
118 (Vanardois et al., 2022). The AR and MB massifs were subsequently metamorphosed at  
119 pressures between 0.2 and 0.6 GPa and temperatures at ~600-750°C (Dobmeier, 1996, 1998;  
120 Schulz and von Raumer, 1993, 2011; von Raumer et al., 1996; Chiaradia, 2003; Marshall et al.,  
121 1997; Genier et al., 2008).

122 The development of the main fabric in the AR massif is coeval with the HT-LP metamorphism.  
123 It consists of sub-vertical 330 to 030 striking foliations bearing a sub-horizontal mineral  
124 lineation. Dextral kinematic indicators are common (Bellière, 1958; von Raumer and Bussy,  
125 2004; Simonetti et al., 2020) within centimeter- to meter-sized mylonites, documented in the  
126 whole gneissic basement (von Raumer and Bussy, 2004). Moreover, a hectometer-sized  
127 mylonitic zone is described near the Lac Emosson (Joye, 1989; Genier et al., 2008; Simonetti  
128 et al., 2020). This shear zone recorded dextral transpression (von Raumer and Bussy, 2004;  
129 Joye, 1989; Simonetti et al., 2020). Bellière (1958) proposed a crustal-scale structural model  
130 but modern concepts like strain partitioning, heterogeneous or supra/subsolidus deformation  
131 fabrics are not considered or documented at the scale of the whole AR and MB massifs. Relics

132 of earlier planar fabrics are reported in several studies (Bellière, 1958; Joye, 1989; von  
133 Raumer, 1984; von Raumer and Bussy, 2004). In the Lac Cornu area (see Fig. 1B for location),  
134 Vanardois et al. (2022) interpreted an early sub-horizontal foliation as the result of horizontal  
135 flow of the partially molten crust.

136 Partial melting in the AR and MB massifs started during the HT-HP metamorphism, at near  
137 peak pressure conditions at  $\sim 1.3\text{-}1.85$  GPa at ca. 340-330 Ma (Vanardois et al., 2022). Ongoing  
138 partial melting occurred during decompression and subsequent HT-LP metamorphism (Genier  
139 et al., 2008). The metamorphic peak recorded in metapelitic rocks from the Emosson area (see  
140 Fig. 1B for location) and the crystallization age of the anatectic melts occurred at  $327 \pm 2$  Ma  
141 and  $320 \pm 1$  Ma, respectively (ID-TIMS U-Pb on monazite, Bussy et al., 2000). Cordierite-  
142 bearing migmatites in the Fully area (Krummenacher, 1959) (see Fig. 1B for location) yield ID-  
143 TIMS zircon ages at ca. 307 Ma (Bussy et al., 2000). In the MB massif, Bussy and von Raumer  
144 (1994) dated leucogranitic injections into dextral shear bands at  $317 \pm 2$  Ma (ID-TIMS U-Pb on  
145 monazite). It remains unclear if the gneissic basement underwent one protracted partial  
146 melting event lasting from ca. 330 to 307 Ma or two distinct episodes at ca. 330-315 Ma and  
147 ca. 307 Ma.

148 In the Servoz area (see Fig. 1B), a Visean sequence is composed of metagreywackes, phyllites  
149 and metavolcano-sedimentary rocks overlying fine-grained gneisses ("Pormenaz gneisses" in  
150 Fig. 1B) (Dobmeier et al., 1999). It is affected by the transcurrent shearing under greenschist  
151 to low amphibolite facies metamorphism (Dobmeier, 1996, 1998; Bellière and Streeel, 1980).  
152 The uppermost Variscan crust is composed of Late Carboniferous fluvial and volcanic rocks  
153 (Pilloud, 1991; Capuzzo and Wetzel, 2004) lying (1) in the upper part of the Servoz syncline  
154 and (2) in the Salvan-Dorenaz syncline that are unconformably deposited over the Variscan

155 metamorphic rocks (Dobmeier and von Raumer, 1995; Lox and Bellière, 1993) (Fig.1B). These  
156 rocks were metamorphized by the Alpine deformation at temperatures lower than 350 °C  
157 (Boutoux et al., 2016). Dobmeier and von Raumer (1995) considered that these rocks were  
158 not affected by Variscan deformation, whereas Lox and Bellière described Variscan open folds  
159 with subvertical axial planes oriented N020 but without more details about any tectonic  
160 significance.

161 The syn-kinematic Vallorcine granite emplaced along the EBSZ at  $306.5 \pm 1.5$  Ma during dextral  
162 transpression (ID-TIMS U-Pb on zircon and monazite; Bussy et al., 2000). Similar emplacement  
163 ages (ID-TIMS U-Pb on zircon) at  $307 +6/-5$  Ma,  $303 \pm 2$  Ma and  $304 \pm 3$  Ma are reported for  
164 the Montenvers and the Mont-Blanc granites (Bussy and von Raumer, 1993, 1994) (Fig. 1B).  
165 The Mont-Blanc and Montenvers granites are cross-cut by local subsolidus mylonites (Bussy,  
166 1990; Bussy et al., 2000). The Morcles microgranite is meter-sized dykes dated at  $303 \pm 3$  Ma,  
167  $304 \pm 1$  Ma and  $311 \pm 2$  Ma (LA-ICPMS U-Th-Pb on zircon) and are interpreted as a shallow  
168 extension of the Vallorcine granite (Bussien et al., 2017) (Fig.1B). Rhyolitic dykes of the MB  
169 massif and dacites in the Salvan-Dorenaz syncline have been dated at  $307 \pm 2$  Ma and  $308 \pm 3$   
170 Ma, respectively (ID-TIMS U-Pb on zircon; Capuzzo and Bussy, 2000) (Fig. 1B). The Visean rocks  
171 of the Servoz syncline are intruded by the peraluminous Montées-Pélissier monzogranite and  
172 the metaluminous Pormenaz monzonite, dated at  $331 \pm 2$  Ma and  $332 \pm 2$  Ma, respectively  
173 (ID-TIMS U-Pb on zircon; Bussy et al., 2000) (Fig. 1B). These two granites, represent a first  
174 magmatic pulse at ca. 330 Ma. Several authors propose that the Pormenaz and Montées-  
175 Pélissier plutons are syn-tectonic granites emplaced along vertical shear zones during bulk  
176 dextral shearing (Bussy et al., 2000; Dobmeier, 1996, 1998).

177 In the basement, Alpine tectonics and metamorphism are limited to the development of shear  
178 zones active under greenschist facies conditions (Rolland et al., 2003; Rossi et al., 2005). In the  
179 surrounding Mesozoic sedimentary cover, Alpine metamorphism did not exceed 350°C  
180 (Boutoux et al., 2016). Alpine tectonics is also responsible for the pinch of the NE-SW  
181 elongated Carboniferous Salvan-Dorenaz syncline (Fig. 1B) (Pilloud, 1991). Variscan tectono-  
182 metamorphic imprint is widespread in the AR and MB with higher-grade metamorphic  
183 conditions easily distinguishable from the lower-grade rocks in the Alpine localized shear  
184 zones (e.g. von Raumer and Bussy, 2004; Simonetti et al., 2020).

185

### 186 **3. Structural data**

#### 187 *3.1. D1 deformation*

188 D1 deformation is recorded in the gneissic basement by a sub-horizontal S1 foliation that dips  
189 gently to the NE with an L1 O20-trending mineral lineation plunging at about 15° (Fig. 2B).  
190 Although S1 fabric has been transposed by subsequent D2 deformation, it is locally preserved  
191 at the outcrop-scale and at the regional-scale in the Pormenaz and Arpille areas (Fig. 2 and 3).  
192 In domains where D2 deformation is pervasive, S1 foliation is transposed and folded into open  
193 to isoclinal upright folds (Fig. 3 and 4A to D) or remains recognizable only in the hinge zones  
194 of F2 folds. Few rootless isoclinal folds (F1) have been recognized in the preserved D1 domains  
195 where an older planar fabric, designated Sx, is only locally observed in the hinges of F1 folds.  
196 (Fig. 4D and F). In the preserved domains, kinematic indicators such as asymmetrical  
197 boudinage, mica-fish and S-C fabrics indicate top-to-the-E and NE kinematics (Fig. 4E to H).

198 In the Lac Cornu area (see Fig. 1 and 2 for locations), the D1 deformation is defined by an S1  
199 compositional layering in stromatitic orthogneiss migmatites (Fig. 4C), and within the core of  
200 boudins of retrogressed eclogite (Vanardois et al., 2022). In the Arpille massif (Fig. 1B), S1  
201 foliation is defined by the shape and preferential alignment of the leucosomes in anatectic  
202 metapelites and metagraywackes (Fig. 4A). In the Pormenaz area, the S1 and L1 fabrics are  
203 observed in the non-anatectic fine-grained Pormenaz gneiss (Fig. 4H).

### 204 3.2. D2 deformation

#### 205 3.2.1. D2 deformation at the outcrop scale

206 D2 main fabric in the migmatitic basement and in the greenschist facies rocks of the Servoz  
207 syncline is an S2 sub-vertical foliation striking 150-170 (Fig. 2C). In D1 preserved domains, S2  
208 is a weak crenulation cleavage that strikes  $\sim$  N160 (Fig. 4A to D). A decameter-wide strain  
209 gradient from the D1 preserved domains toward the S2 pervasive foliation is observed with  
210 the progressive tightening of F2 folds and the reorientation of the S1 sub-horizontal foliation  
211 into a sub-vertical position. Steeply-dipping and 160-striking axial planes of F2 folds are sub-  
212 parallel to S2 foliation. F2 fold axes plunge shallowly to steeply along the 160-striking axial  
213 planes. In pervasive D2 domains, we observed S-C-C' fabrics where vertical C2 shear bands  
214 striking 000-020 progressively reorient S2 foliations and become the main planar fabric,  
215 before being reoriented by the vertical C'2 shear bands striking 020-040 (Fig. 5A to C).

216 In the Lac Cornu migmatites, the S2 foliation is defined by mineralogical layering in the  
217 stromatic migmatite. Injections of melt in the C2 and C'2 shear bands (Fig. 5A) argue for  
218 suprasolidus conditions of shearing in this part of the massif. In the Lac Cornu metamafic  
219 lenses, the retrogression of the eclogite facies to amphibolitic facies is associated with D2



220 (Vanardois et al., 2022). In the Fully area (see Fig. 1 for location), cordierite-bearing migmatites  
221 show a gneissic layering and cordierite clots sub-parallel to the orientation of  $C'2$  shear bands.  
222 Migmatites are also affected by centimeter-sized ultramylonitic bands sub-parallel to  $C'2$   
223 fabric (Fig. 5D).  $S2$ ,  $C2$  and  $C'2$  planar fabrics are commonly associated with a shallowly N-  
224 plunging ( $30^\circ$ )  $L2$  mineral lineation (Fig. 2C). The  $D2$  deformation is conspicuously associated  
225 with dextral kinematics highlighted by shear criteria and the  $S-C-C'$  fabrics (Fig. 5).

### 226 3.2.2. $D2$ architecture at the regional scale

227 The compilation of all measurements of planar fabrics related to  $D2$  led to a well-defined  
228 three-fold subdivision: a first group labelled as  $S2$  (150-170), a second group labelled as  $C2$   
229 (000-020) and a third group labelled as  $C'2$  (020-040) (Fig. 2C). Where one of the three planar  
230 fabrics ( $S2$ ,  $C2$  or  $C'2$ ) is predominant at the outcrop scale, the corresponding orientation is  
231 considered to build the foliations trajectory map of figure 2. One may notice that  $S2$  foliation  
232 is predominant in the western and upper structural levels (Servoz-Pormenaz-Brevent areas)  
233 whereas the eastern AR massif shows mostly  $C2$  and  $C'2$  planar fabrics (Fig. 2). The  $S-C-C'$   
234 regional structure resemble the one observed at all scales from millimetre to decametre.  
235 Furthermore, pervasive  $C2$  and  $C'2$ -domains form three main kilometre-wide dextral shear  
236 zones: the Cornu Shear Zone (CSZ), the Montenvers (MSZ) and Emosson-Bérard shear zones  
237 (EBSZ). The orientation of these structures is in good agreement with a massif-scale  $S-C-C'$ -like  
238 structures.

### 239 3.3. $D3$ deformation

240  $D3$  structures are only observed in the south-western part of the AR massif, within the  
241 Pormenaz gneiss and the Viséan metasedimentary rocks (Fig. 2, 6 and 7).  $D3$  is recorded in

242 metre- to decametre-sized domains where D2 deformation is folded by open to tight F3 folds  
243 with a sub-horizontal S3 cleavage (Fig. 6, 7 and 8). S3 cleavage and F3 fold axial planes are sub-  
244 parallel, and are both gently E-dipping (Fig. 6B). F3 folds axes are gently SE-plunging. L3  
245 lineation has been only locally observed (Fig. 6B) and corresponds to an intersection lineation  
246 between S2 and S3 fabrics. Due to the lack of mineral or stretching L3 lineation, kinematics of  
247 D3 deformation remains unknown. D3 fabrics are defined by typical greenschist facies  
248 minerals such as chlorite (Fig. 8B). Few quartz-feldspar bearing leucocratic bodies interpreted  
249 as leucosomes are folded by the S3 fabric (Fig. 8C).

250

#### 251 **4. Description of dated samples**

252 Eleven samples of magmatic rocks have been sampled from different locations of the  
253 “plumbing” in the AR and MB massifs, corresponding to five large magmatic bodies: Couteray  
254 orthogneiss (AR37), Pormenaz granite (AR801), Montées-Pélissier granite (AR865), Vallorcine  
255 granite (AR73), Montenvers granite (MB43), Mont-Blanc granite (MB37); and four smaller  
256 bodies: Morcles microgranite (AR1028) and pegmatitic and aplitic dykes (AR833, AR1020,  
257 AR1006 and AR916). See Figs. 1, 3, and 7, and Table 1 for sample locations. Mineral  
258 assemblages are detailed in Table 1..

##### 259 *4.1. Large magmatic bodies*

260 The Couteray orthogneiss (AR37) is a N-S-trending elongate meta-igneous body located in the  
261 Val Bérard near the Vallorcine granite (Fig. 1B and 3A). It shows well-pronounced N-S D2  
262 deformation, corresponding to C2 and C'2 planes based on their orientations, clearly

263 indicative of dextral shearing (Fig. 9A). Local myrmeckite are observed in shear bands passing  
264 through large K-feldspar grains (Fig. 9A).

265 The Pormenaz granite (AR801) emplaced in the gneisses of the eastern limb of the Servoz  
266 syncline (Fig. 1B). Field observations in the western part of the pluton, where sample AR801  
267 was collected, indicate that the magmatic fabric is marked by the alignment and preferred  
268 orientation of euhedral K-feldspar megacrysts that define a S1 sub-horizontal planar fabric  
269 and a mineral lineation L1 O20-trending and plunging 10° (Fig. 9B), similar to D1 deformation  
270 observed in the surrounding gneisses (Fig. 6 and 7). The D1 deformation is pervasive along the  
271 pluton contacts and is not observed in its core (Fig. 7A). In the eastern part of the pluton, the  
272 S1 foliation is deformed and reoriented by O00- to O20-striking D2 vertical structures (Fig. 6  
273 and 7). In this area, K-feldspar megacrysts are deformed as well as the surrounding matrix (Fig.  
274 9C). K-feldspar grains are fractured and no myrmeckite was observed. The quartz grains show  
275 undulose extinction and recrystallization by bulging grain boundaries.

276 The sample AR865 comes from the core of the Montées-Pélissier pluton, which is a fine-  
277 grained monzogranite that intruded the Visean metasedimentary rocks in the Servoz syncline  
278 (Fig. 1 and 7B). In the whole pluton and in our sample, the magmatic assemblage is pervasively  
279 deformed by the D2 such that any magmatic fabric that may have existed is not preserved. In  
280 thin-section, feldspar crystals are oriented sub-parallel with the C2 shear bands and show  
281 common extensive microfractures filled by quartz (Fig. 9D).

282 The Vallorcine granite (AR37) is a NE-SW-trending elongate pluton located in the north-  
283 eastern part of the AR massif in the EBSZ (Fig. 1B and 3). This granite crosscuts the C'2 shear  
284 bands near the Lac Emosson (Fig. 9E). The sample commonly possesses a magmatic foliation  
285 defined by biotite and feldspar sub-parallel to the C'2 orientation (Joye, 1989; Bussy et al.,

286 2000). At the microscale, in sample AR73, feldspar is undeformed and quartz is nested with  
287 undulose extinction and shows grain boundary migration in quartz (Fig. 9E). Local millimeter  
288 shear bands are associated to subgrain rotation recrystallization in quartz.

289 The Monteners granite (MB43) intruded paragneiss and orthogneiss migmatites of the MB  
290 massif (Fig. 1B and 3A). The Monteners granite and its host rocks are strongly deformed  
291 within an anastomosed network of C2 and C'2 shear zones of the MSZ (Fig. 2, 3A and 9F). In  
292 sample MB43, fractures in feldspar are filled by quartz and recrystallized polygonal quartz (Fig.  
293 9G). Locally, the quartz polygons are deformed within C'2 shear bands.

294 The Mont-Blanc granite (MB37) is a kilometer-large NE-SW-trending elongate pluton and  
295 forms the main part of the MB massif (Fig. 1B and 3B). The pluton contacts are deformed in  
296 C2 and C'2 structures whereas its core is weakly deformed. The granite shows a magmatic  
297 foliation defined by the weak alignment of K-feldspar, biotite crystals and mafic enclaves  
298 striking 020-040 (Bussy, 1990), sub-parallel to the C'2 shear planes (Fig. 9H).

#### 299 *4.2. Smaller magmatic bodies*

300 Sample AR1028 comes from one of the dykes composing the Morcles microgranite, located in  
301 the northern part of the AR massif (Fig 1B and 3C). This microgranite has a main NE-SW-  
302 trending orientation and locally crosscuts C2 and C'2 shear zones. There is no apparent  
303 preferred mineral orientation. Quartz grains do not show undulose extinction and are locally  
304 nested (Fig. 9I). Calcite had partially replaced some feldspar grains and is present in cracks in  
305 feldspar (Fig. 9I).

306 Pegmatites are common in the orthogneiss of the Lac Cornu area (Fig. 1B and 7D). The sample  
307 AR833 is from one of these pegmatites, that has a diffuse contact with the orthogneiss

308 migmatite (Fig. 10A). The feldspars in the pegmatite are preferentially oriented parallel to the  
309 C2 shear bands in the surrounding rocks (Fig. 10A). K-feldspar grains are surrounded by  
310 myrmekite.

311 The sample AR1020 corresponds to a pegmatite that crosscuts the C2 planes of an amphibolite  
312 lens in the Lac Cornu orthogneiss (Fig. 10B). It does not have an apparent preferred mineral  
313 orientation. Quartz has weakly developed undulose extinction and recrystallization by grain  
314 boundary migration.

315 The Lacs Noirs pegmatite is a ten centimeter-large dyke in paragneiss. It is affected by the D2  
316 dextral wrenching and C2 shear bands are recognized (Fig. 1B and 10C). Quartz is strongly  
317 deformed and well-developed undulose extinction. Tourmaline is either undeformed and  
318 oriented parallel to the foliation or sub-parallel to the foliation, fractured and truncated. K-  
319 feldspar is replaced by muscovite in shear bands.

320 The sample AR916 comes from an aplite dyke that emplaced within a decametric C2 shear  
321 zone in metasedimentary rocks (Fig. 1B and 10D). The mineral assemblage does not have an  
322 apparent preferred mineral orientation. Some plagioclase and K-feldspar are partially  
323 replaced by white mica.

324

## 325 **5. U-Th-Pb dating of studied samples**

### 326 *5.1. analytic method*

327 Zircon and monazite U-Th-Pb age determinations of these samples were carried out using  
328 Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) at the Laboratoire

329 Magmas et Volcans, Clermont–Ferrand (France). Separated zircon and monazite grains were  
330 mounted in epoxy resin discs that were polished to reveal equatorial cross sections.  
331 Cathodoluminescence (CL) and Back-Scattered Electron (BSE) images were used to select  
332 points for analysis. The analyses involve the ablation of minerals with a Resonetics Resolution  
333 M-50 powered by an ultra-short pulse ATL Atlex Excimer laser system operating at a  
334 wavelength of 193 nm (detailed description in Müller et al., 2009). The detailed analytical  
335 procedures are described in Paquette and Tiepolo (2007), Hurai et al. (2010), and Paquette et  
336 al. (2014) and detailed in the Supplementary material (S1). Data reduction was carried out  
337 with the GLITTER<sup>®</sup> software package developed by Macquarie Research Ltd (Jackson et al.,  
338 2004). The analytical data are provided in the Supplementary Material 1 (SM1). Ages and  
339 diagrams were generated using the Isoplot/Ex v. 2.49 software package by Ludwig (2001). Only  
340 the concordant data and the discordant data fitting with the discordia line were taken into  
341 account in the age calculation. In the text and figures, all uncertainties in ages are given at  $\pm$   
342  $2\sigma$  level.

#### 343 5.2. Couteray orthogneiss (AR37)

344 Zircon grains from the Couteray orthogneiss are transparent and euhedral with a shape that  
345 varies from equant to elongate. CL images show either the presence of inherited  
346 cores surrounded by rims with concentric oscillatory zones, or uniform grains also with  
347 concentric oscillatory zones (Fig. 11A). Twenty-eight analyses were conducted on seventeen  
348 zircon crystals (Fig. 12A; Table S1). Analyses of inherited cores with concentric zones and Th/U  
349 ratios between 0.18 and 0.99 (Table S1) yield one concordant date at 691 Ma (#12) and a  
350 cluster of five data (#8, 10, 18, 20, 25) giving a concordia age of  $587 \pm 10$  Ma ( $MSWD_{(C+E)} =$   
351 1.16) (Fig. 12A). Nineteen analyses on cores and rims with concentric zones and Th/U ratios

352 ranging between 0.01 and 0.76 (Table S1) yield a concordia age at  $480 \pm 4$  Ma ( $MSWD_{(C+E)} =$   
353 0.61,  $n = 19$ ) (Fig. 12A).

### 354 5.3. Early Carboniferous (Visean) granites (ca. 340-330 Ma).

#### 355 5.3.1. The Pormenaz granite (AR801)

356 Most of the zircon grains analysed are euhedral, either prismatic with a shape ratio up to 2:1  
357 or stubbier with a shape ratio of 1:1 (Fig. 11B). They are pinkish, transparent to slightly opaque.  
358 CL images show strong evidence of concentric or oscillatory igneous growth zones as well as  
359 the presence of cores displaying either sector-like or patchy zone textures surrounded by  
360 zoned rims (Fig. 11B). Seventy-five analyses were performed on sixty-five zircon crystals (Table  
361 S1). In the Tera Wasserburg diagram, excepting from two cores (#10 and 35) concordant  
362 around 650 Ma, all data are scattered along the concordia curve between around 340 to 190  
363 Ma with thirty-two data yielding a concordia age of  $338 \pm 2$  Ma ( $MSWD_{(C+E)} = 1.4$ ) (Fig. 12B).  
364 These data are mainly obtained on zoned cores (24 cores and 8 rims). The analysed grains  
365 have a range of Pb (8.5-69 ppm), Th (most 55-281 ppm) and U (150-1526 ppm) contents and  
366 Th/U ratios (most 0.15-0.51) (Table S1). Other discordant data (dotted ellipses) mainly  
367 composed of rims (34 rims and 7 cores) are characterized by similar Pb, Th and U contents  
368 (17-75 ppm, 64-458 ppm and 351-2027 ppm) and Th/U ratios (most 0.14-0.66) (Table S1).  
369 These data are not taken into consideration for the age calculation because they are  
370 discordant. These discordances are probably due to radiogenic Pb losses and common Pb  
371 contaminations.

#### 372 5.3.2. The Montées-Pélissier granite (AR865)

373 Zircon crystals from sample AR865 are pinkish, transparent, euhedral and elongate but  
374 commonly broken. CL images show strong evidence of concentric or oscillatory igneous  
375 growth zones (Fig. 11C). Forty-three analyses are obtained on rims or cores of 43 crystals and  
376 present Th/U ratios ranging between 0.04 and 1.02 (most 0.16-0.67) with homogeneous Pb  
377 content (most 21-64 ppm) and variable U (most 555–1450 ppm) and Th (most 90–347 ppm)  
378 contents (Table S1). In the Tera Wasserburg, the data are scattered along the concordia curve  
379 between around 350 to 210 Ma (Fig. 12C). The eight oldest data (#2, 6, 7, 8, 12, 13, 22 and 34)  
380 form a cluster around 340-335 Ma that yields a concordia age of  $340 \pm 5$  Ma ( $MSWD_{(C+E)} = 2.2$ ).  
381 Other data (dotted ellipses), often discordant, show younger  $^{206}\text{Pb}/^{238}\text{U}$  dates (Table S1; Fig.  
382 12C). These data are not considered because they were probably affected by radiogenic Pb  
383 losses as well as common Pb contaminations.

384

#### 385 *5.4. Late Carboniferous granite (ca. 305 Ma)*

##### 386 *5.4.1. Vallorcine granite (AR73)*

387 The zircon crystals from the Vallorcine granite (AR73) are transparent, pinkish and euhedral.  
388 Zircon ranges in shape from equant to elongate. The latter are commonly fractured. CL images  
389 show complex internal textures such as the presence of apparently inherited cores and  
390 concentric oscillatory and patchy zones textures (Fig. 11D). Twenty-nine analyses were carried  
391 out on twenty-two zircon crystals (Fig. 12D). Two data from two cores (#4 and 25) are sub-  
392 concordant and yield an upper intercept at  $2071 \pm 75$  Ma in the concordia diagram. These  
393 zircon cores have similar Pb (64-67 ppm), Th (31-59 ppm) and U (181-184 ppm) contents with  
394 Th/U ratios of 0.17 and 0.32 (Table S1). Three data obtained on cores show Th/U ratios of ca.



395 0.3 and are sub-concordant around 650 Ma (#15 and 20) and 840 Ma (#2) (Table S1). The other  
396 twenty-four data are scattered along the concordia curve between ca. 840 to 220 Ma in two  
397 main distinct clusters: one very wide between 485 and 450 Ma (group 1) and the other more  
398 restricted between 310 to 300 Ma (group 2). Group 1 dates (#3, 5, 6, 10, 12, 18, 22) were  
399 determined from 5 cores and 2 rims. These seven analyses are characterized by variable Pb  
400 and Th contents ranging from 19 to 52 ppm and 11 to 183 ppm, respectively and by Th/U  
401 ratios from 0.04 to 0.54 (most 0.13-0.54) (Table S1). The linear regression on these seven data  
402 yields a lower intercept of  $468 \pm 13$  Ma (MSWD = 2). Amongst these data, six give a concordia  
403 age of  $469 \pm 12$  Ma (MSWD<sub>(C+E)</sub> = 2.6). Group 2 dates (#7, 8, 11, 16, 19, 21, 23, 26, 27, 29) are  
404 obtained from 2 cores and 8 rims. Pb and Th contents ranging from 12-72 ppm and 11-201  
405 ppm, respectively, and with Th/U ratios from 0.01 to 0.31 (most 0.1-0.31). These ten data yield  
406 a concordia age of  $306 \pm 5$  Ma (MSWD<sub>(C+E)</sub> = 1.8). Five data (white ellipses) between these two  
407 clusters may correspond to a mixed age. The two youngest data (dotted ellipses) may be the  
408 result of radiogenic Pb loss.

#### 409 5.4.2. Montenvers granite (MB43)

410 Zircon crystals from sample MB43 are pinkish and transparent. They are either equant with a  
411 shape ratio up to 2:1 or in the form of prismatic or elongate grains. CL images show concentric  
412 or oscillatory igneous growth zones as well as the presence of cores displaying either sector-  
413 like or patchy zones textures surrounded by zoned rims with locally a thinner and CL-dark  
414 over-rim (Fig. 11E). Forty-five analyses are obtained on rims or cores of 40 crystals and present  
415 Th/U ratios ranging between <0.01 and 1.30 (most 0.01-0.82) with variable Pb (3.3-404 ppm),  
416 U (most 98–5721 ppm) and Th (most 29–869 ppm) compositions (Table S1). In the Tera  
417 Wasserburg diagram, excepting datum #4 (not plotted) measured on the inherited core of the

418 zircon Z9 with a Th/U ratio of 1.30 and a discordant position around 1.8 Ga, all other data are  
419 scattered along the concordia curve between ~620 to 220 Ma in a cluster around 310-220 Ma  
420 and two others more restricted around 600 Ma and 450 Ma (Fig. 12E). The cores of zircons  
421 Z10 (#9) and Z19 (#19) have a Th/U ratio of 0.32 and 0.79 and give concordant data at  $615 \pm$   
422  $16$  Ma and  $592 \pm 16$  Ma, respectively. The cluster at 450 Ma consisting of the analyses obtained  
423 on three tips (#1, 35, 43; Th/U = 0.01-0.26) and two cores (#29, 37; Th/U = 0.15-0.38) yields a  
424 concordia age of  $447 \pm 10$  Ma ( $\text{MSWD}_{(C+E)} = 1.6$ ,  $n = 4$ ). Among the thirty-eight youngest data,  
425 nineteen data from 10 cores and 9 rims yield a concordia age of  $306 \pm 3$  Ma ( $\text{MSWD}_{(C+E)} = 1.6$ )  
426 (Fig. 12E). In the diagram, the dotted ellipses are obtained mainly on the metamict CL-dark  
427 rim and are characterized by very high U contents (1315-9763 ppm).

#### 428 5.4.3. Mont-Blanc granite (MB37)

429 The zircon crystals from the Mont Blanc granite (MB37) are transparent, pinkish and euhedral  
430 with an elongate shape with a shape ratio up to 3:1. CL images show oscillatory igneous  
431 growth zones as well as the presence of few cores displaying either sector-like zones  
432 surrounded by CL-dark zoned rims (Fig. 11F). Forty-three analyses were carried out from forty-  
433 two zircons (Fig. 12F; Table S1). Among them, two are (#15 and 34) composed by cores  
434 characterized by concentric zones and a Th/U ratio of 0.34, and are concordant at ca. 485 Ma  
435 and ca. 558 Ma. There are two more data (#1 and 10) obtained on a core and a rim with a  
436 Th/U around 0.3-0.4, that are concordant at ca. 335 Ma. Otherwise, thirty-five data plot as a  
437 cluster characterized by Th/U ratios ranging between 0.2 and 0.86 and yield a concordia age  
438 of  $305 \pm 2$  Ma ( $\text{MSWD}_{(C+E)} = 1.5$ ,  $n = 35$ ). Two discordant data (dotted ellipses) (#37 and 42)  
439 obtained on CL-dark rims show youngest  $^{206}\text{Pb}/^{238}\text{U}$  dates, which may be the result of  
440 radiogenic Pb loss as well as common Pb contamination.

441 5.5. *Smaller granitic bodies (e.g. microgranite, aplite and pegmatite dykes)*

442 5.5.1. *Morcles microgranite (AR1028)*

443 Zircon crystals from sample AR1028 are colourless to slightly pink and transparent. They are  
444 either prismatic with an shape ratio up to 3:1, or ovoid, but also sometimes as fragment-like.  
445 CL images show complex internal features such as the presence of cores and concentric  
446 oscillatory and patchy zones textures (Fig. 13A). Some crystals have metamict rims, which  
447 could not be analysed because they are too rich in common Pb. Monazite crystals were found  
448 in this sample. They are light yellow, transparent and euhedral. EBS images exhibit concentric  
449 oscillatory or patchy zones (Fig. 13A).

450 Twenty analyses on seventeen zircon crystals yield Th/U ratios ranging between 0.08 and 0.62  
451 (most 0.1-0.44) with variable Pb (3.9-118 ppm), U (40–2298 ppm) and Th (16–731 ppm)  
452 contents (Table S1). In the Tera Wasserburg diagram, excepting data 5 and 8, the concordant  
453 to sub-concordant data are scattered between ca. 800 and ca. 450 Ma (Fig. 14A). The linear  
454 regression on ten data (#1, 4, 6, 9, 10, 11, 14, 16, 17, 18) obtained on 5 cores and 5 rims yields  
455 a lower intercept of  $463 \pm 10$  Ma (MSWD = 2.9 Ma). Sixteen analyses were also performed on  
456 nine monazite crystals (Table S1). Excepting the analysis #11, data form a cluster with a  
457 concordia age of  $313 \pm 2$  Ma (MSWD<sub>(C+E)</sub> = 0.49, n = 15) (Fig. 14B). Spot #11, that has a  
458 discordant position around ca. 360 Ma may correspond to an analytical mixture.

459 5.5.2. *Lac Cornu pegmatites (AR833 and AR1020)*

460 Zircon crystals from sample AR833 are euhedral, colourless and transparent. Their shapes are  
461 either elongate or rounded. CL images highlight various cores surrounded by rims with  
462 concentric and oscillatory zones (Fig. 14B). Sixty-three analyses on forty-three zircon grains

463 are distributed into four clusters (Fig. 14C). Three data (#15, 20, 46) from cores with Th/U  
464 ratios between 0.16 and 0.23 yield a mean  $^{238}\text{U}/^{206}\text{Pb}$  date at  $724 \pm 28$  Ma (MSWD = 1.3). Four  
465 data (#2, 4, 22, 34) also from cores with similar Th/U ratios (0.19-0.28) return a concordia age  
466 at  $552 \pm 12$  Ma (MSWD<sub>(C+E)</sub> = 2.4). The main cluster is composed of fifty-one analyses from  
467 cores and rims with concentric and oscillatory zones and lower Th/U ratios (mostly 0.04-0.15)  
468 from ca. 465 Ma to 420 Ma. Among them, twenty-eight data yield a concordia age at  $462 \pm 3$   
469 Ma (MSWD<sub>(C+E)</sub> = 1.08). In addition, two sub-concordant data (#45, 48) from rims with  
470 oscillatory and concentric zones and low Th/U ratios (0.00-0.01) yield a mean  $^{238}\text{U}/^{206}\text{Pb}$  date  
471 at  $317 \pm 6$  Ma (MSWD = 1.04). One datum (#16) from a zircon core is concordant at 2.0 Ga  
472 (Table S1).

473 Zircon crystals from the pegmatite AR1020 are not common, often metamict and pinkish, or  
474 transparent to milky. Their shapes vary from elongate to rounded. CL images reveal complex  
475 textures such as the presence of cores surrounded by rims, concentric oscillatory and patchy  
476 zones textures (Fig. 14C). Nineteen analyses were performed on eleven grains (Table S1).  
477 Despite the various and complex zones of these zircon grains and their scattered Th/U ratios  
478 (0.05-1.03), all the data are between ca. 465 and 375 Ma and thirteen yield a concordia age at  
479  $456 \pm 4$  Ma (MSWD<sub>(C+E)</sub> = 0.5) (Fig. 14D). Other analyses might reflect Pb loss or common Pb  
480 contamination.

### 481 5.5.3. *Lacs Noirs pegmatite (AR1006)*

482 Zircon crystals from the pegmatite specimen are colourless and transparent fragments. CL  
483 images show that most of the grains have resorption structures affecting cores and rims with  
484 oscillatory and concentric zones (Fig. 13D). Thirty-three analyses were performed on thirty-  
485 two zircon grains (Fig. 14E). Twenty-two data with Th/U ratios ranging between 0.04 and 0.70

486 align and form a lower intercept at  $455 \pm 3$  Ma (MSWD = 0.48). Among them, seventeen data  
487 yield a concordia age at  $456 \pm 3$  Ma (MSWD<sub>(C+E)</sub> = 0.89). Other analyses, except one (#14), are  
488 concordant or sub-concordant and spread from 535 to 997 Ma.

#### 489 5.5.4. Chéserys aplite (AR916)

490 Zircon crystals from aplite are not common and are mainly transparent and colourless grains  
491 with elongate to ovoid shapes. CL images show mainly simple internal structures with  
492 concentric and oscillatory zones (Fig. 13E). A few grains show a core surrounded by a rim with  
493 oscillatory zones. Some grains also display a metamorphic rim. Thirty-three analyses on thirty-  
494 two zircon grains (Fig. 14F) yield a cluster between 460 and 420 Ma. Among them, eighteen  
495 analyses on cores and rims with Th/U ratios between 0.04 and 0.95 yield a concordia age at  
496  $458 \pm 3$  Ma (MSWD<sub>(C+E)</sub> = 1.3). One analysis (#22) on a core is sub-concordant at 839 Ma.  
497 Several discordant data show  $^{206}\text{Pb}/^{238}\text{U}$  dates younger than 400 Ma.

498

## 499 6. Discussion

### 500 6.1. Emplacement ages of granites and pegmatites

#### 501 6.1.1. Ordovician magmatism

502 Zircon grains from the Couteray orthogneiss (AR37) yield two concordia ages: one Ordovician  
503 at  $480 \pm 4$  Ma and the other Precambrian at  $587 \pm 10$  Ma (Fig. 12A). The first one was obtained  
504 on zircon cores and rims showing oscillatory and concentric zones (Fig. 11A) typical of  
505 magmatic origin (Linnemann et al., 2011; Tiepel et al., 2004); we therefore interpret it as the  
506 Ordovician emplacement age of the magmatic protolith of the Couteray orthogneiss. The

507 Precambrian age was obtained on zircon cores that are locally partially resorbed (Fig. 11A,  
508 Zr36). The Precambrian one was obtained on zircon cores that are locally partially resorbed  
509 (Fig. 11A, Zr36). The geological significance of this inherited precambrian age remains  
510 unknown.- The Ordovician age is slightly older than the magmatic protolith emplacement ages  
511 of other orthogneisses from the AR and MB massifs dated between 465 and 455 Ma (Bussy  
512 and von Raumer, 1994; Bussy et al., 2011) (Fig. 1B). However, this age remains consistent with  
513 the 480-450 Ma age range proposed for the Ordovician magmatic event that is well-  
514 documented throughout the Variscan belt (Melleton et al., 2010 and references therein;  
515 Lotout et al., 2017; Chelle-Michou et al., 2017).

#### 516 *6.1.2. Early Carboniferous plutonism (ca. 340-330 Ma)*

517 Most of the zircon grains analysed from the Pormenaz (AR801) and Montées-Pélissier (AR865)  
518 granites show magmatic growth zones with Th/U ratios from 0.1 to 1.0 typical of an igneous  
519 zircon origin (Tiepel et al., 2004; Linnemann et al., 2011) (Fig. 11B and C; Table S1). The zircon  
520 concordia ages of  $338 \pm 2$  Ma and  $340 \pm 5$  Ma obtained on these two plutons match within  
521 uncertainties and are interpreted as emplacement ages (Fig. 12B and C). These results agree  
522 with the ages at  $332 \pm 2$  Ma and  $331 \pm 2$  Ma documented by Bussy et al. (2000), and therefore  
523 confirm the occurrence of an Early Carboniferous (Visean) magmatism in the AR massif (Fig.  
524 1B). Moreover, these two samples yield discordant data, mainly obtained on zircon rims,  
525 which are probably affected by radiogenic Pb losses during the successive Variscan and Alpine  
526 tectono-metamorphic events.

#### 527 *6.1.3. Late Carboniferous plutonism*

528 The concordia ages of  $306 \pm 5$  Ma,  $306 \pm 3$  Ma and  $305 \pm 2$  Ma on the Vallorcine (AR73),  
529 Montenvers (MB43) and Mont-Blanc granites (MB37), respectively, are from zircon cores and  
530 rims showing concentric and oscillatory zones with Th/U ratios mostly higher than 0.1 typical  
531 of igneous zircons (Tiepel et al., 2004; Linnemann et al., 2011) (Fig. 11D-F and 12D-F; Table  
532 S1). These dates are interpreted as emplacement ages and are consistent with previous  
533 published ID-TIMS U-Pb ages on zircon and monazite at ca. 305 Ma for these same plutons  
534 (Bussy et al., 2000; Bussy and von Raumer, 1993, 1994) (Fig. 1).

535 In this study, most of the concordant data obtained on zircon from the felsic dykes (AR1028,  
536 AR833, AR1020, AR1006 and AR916) range from ca. 465 to 455 Ma (Fig. 14; cf section 5.2).  
537 Field-work shows that these felsic dykes emplaced contemporaneously with dextral shearing  
538 during Carboniferous times (Bussy and von Raumer, 1994; von Raumer and Bussy, 2004; Fig.  
539 10). Therefore, the Ordovician record reflects the presence of an inherited component  
540 associated with an Ordovician magmatic event at ca. 465-455 Ma.

541 Zircon and monazite U-Th-Pb dating of the Morcles microgranite (sample AR1028) yielded two  
542 distinct concordia ages, one at  $313 \pm 2$  Ma and the other at  $463 \pm 10$  Ma (Fig. 14A and B). The  
543 younger one was determined on euhedral monazite grains showing concentric growth zones,  
544 and is similar to the zircon LA-ICPMS U-Th-Pb age at ca. 312-309 Ma obtained for one of the  
545 magmatic pulses proposed for the Morcles microgranite dykes in Bussien et al. (2017).  
546 Therefore, we interpret the monazite concordia age at  $313 \pm 2$  Ma as the emplacement age of  
547 the AR1028 microgranite dyke and the zircon concordia age at  $463 \pm 10$  Ma as the age of an  
548 inherited Ordovician component, which was identified in Bussien et al. (2017) too.

549 Moreover, two zircon grains from the Lac Cornu pegmatite AR833 show two sub-concordant  
550 analyses at ca. 317 Ma (Fig. 14C). These analyses were obtained on zircon rims with oscillatory

551 and concentric zones and low Th/U ratios (0.00-0.01; Table S1), which is characteristic of  
552 magmatic zircon that may have originated from high-SiO<sub>2</sub> and/or peraluminous granitoids  
553 (Lopez-Sanchez et al., 2016). This mean at  $317 \pm 6$  Ma might represent the emplacement age  
554 of the pegmatite AR833 and would be consistent with the emplacement age of the Morcles  
555 microgranite at  $312 \pm 2$  Ma and the  $317 \pm 3$  Ma age proposed for the anatectic leucogranitic  
556 dykes of the Mont-Blanc massif (Bussy and von Raumer, 1994). However, given the small  
557 number of data ( $n = 2$ ), we cannot exclude that these two analyses are be the result of a  
558 mixture between an Ordovician component and a younger component either Late  
559 Carboniferous ( $\sim 305$  Ma), Permo-Triassic or even Tertiary in age.

560

## 561 *6.2. Zircon inheritance and source of Carboniferous magmas*

562 Most of magmatic bodies we studied (i.e., microgranitic, pegmatitic and aplitic dykes) show  
563 zircon grains that do not record their age of emplacement (Carboniferous). Our results from  
564 zircon crystals from the Morcles microgranitic dyke show a well-marked Ordovician  
565 inheritance at  $463 \pm 10$  Ma (Caledonian event) and minor Ediacaran contributions (Pan-African  
566 event) (Fig. 14A) as already suggested in Bussien et al. (2017). The zircon U-Th-Pb ages from  
567 the Lac Cornu (AR833 and AR1020) and Lacs Noirs (AR1006) pegmatites and the Chéserys  
568 aplite (AR920) also yielded similar Ordovician ages at  $462 \pm 3$  Ma,  $456 \pm 4$  Ma,  $455 \pm 3$  and  $458$   
569  $\pm 3$  Ma, respectively. This ca. 460-450 Ma inheritance was obtained on zircon grains  
570 characterized by concentric growth zones and high Th/U ratios typical of an igneous origin  
571 (Tiepel et al., 2004; Lineman et al., 2011) (Fig. 13; Table S1).



572 In granitic magmas, inherited zircon crystals originate from the melted sources (Bea et al.,  
573 2021). Thus, the important Ordovician inheritance recorded by the zircon crystals of the  
574 smaller magmatic bodies argues for a genetic link between these intrusions and the partially  
575 molten Ordovician orthogneisses. Such hypothesis of orthogneisses as being the main source  
576 for silicic melts is consistent with our field-observations of, for instance, pegmatite AR833 that  
577 formed in-situ within orthogneiss migmatite (Fig. 10A) or the pervasive leucocratic vein and  
578 dykes complex into the partially molten orthogneiss that surrounds the Mont Blanc granite  
579 (Vitel, 1965; Bussy and von Raumer, 1994). All the smaller magmatic bodies dated in this study  
580 may thus represent anatectic melt that originated from orthogneiss migmatite and that  
581 crystallized during ascent (Brown, 2013 and references therein) between ca. 320-310 Ma.

582 Growth of zircon in an anatectic melt is considered to result solely from the dissolution of pre-  
583 existing zircon grains and (re)precipitation of overgrowths or neograins directly from the melt  
584 (Watson, 1996; Yakymchuk and Brown, 2014; Bea et al., 2006; Kelsey et al., 2008; Mintrone  
585 et al., 2020). The solubility of zircon in silicate melts depends on melt temperature  
586 composition (Watson and Harrison, 1983; Boehnke et al., 2013). It also depends on heating  
587 and cooling rates (Bea et al., 2007), that are controlled by the shape and size of the magmatic  
588 body (de Saint-Blanquat et al., 2011). In the AR and MB massifs, the range of metamorphic  
589 peak temperatures estimated in the partially molten gneissic basement is about 650-750°C  
590 (Schulz and von Raumer, 1993, 2011; Chiaradia, 2003; Genier et al., 2008) and rises 750-800°C  
591 in the lower crust (Vanandois et al., 2022). In the middle crust, at temperatures between 650-  
592 700 °C, biotite and amphibole dehydration melting is limited (e.g. Wienberg and Hasalova,  
593 2015). The absence of peritectic minerals in migmatite leucosome, their low muscovite and  
594 sillimanite contents and the high leucosome fraction observed in the AR and MB migmatites

595 (von Raumer and Bussy, 2004) attest for melt production through water-present melting  
596 reactions (White et al., 2005; Sawyer, 2010), as previously proposed in Genier et al. (2008) for  
597 migmatite of the Ecosson area. Couzinié et al. (2021) highlighted water-fluxed melting of  
598 quartzo-feldspathic orthogneisses in the eastern French Massif Central. The conclusions of  
599 Couzinié et al. (2021) are that low melting temperature involve limited zircon solubility in the  
600 melt phase. In addition, zircon grains armoured as inclusions in non-reacting biotite prevents  
601 the crystallization of newly formed zircon from the anatectic melt (Bea, 1996; Yakymchuk and  
602 Brown, 2014). We propose that most of the pegmatite, aplite and microgranite in the AR and  
603 MB massifs, that are characterized by important Ordovician inheritance without  
604 Carboniferous zircon recrystallization, originated from water-fluxed melting of Ordovician  
605 orthogneisses. Although less pronounced, the Ordovician inheritance was also recorded in  
606 magmatic zircon cores in the Monteners (MB43), Vallorcine (AR73) and Mont-Blanc (MB37)  
607 granites (Fig. 12D-F). These late Carboniferous granites (~305 Ma) have peraluminous  
608 chemical compositions and a continental crust origin (von Raumer and Bussy, 2004). They are  
609 also spatially associated to the orthogneiss migmatite (Fig. 1B; Vitel, 1965). Similarly, we  
610 propose that the main melt production process at the origin of the Vallorcine, Monteners  
611 and Mont-Blanc granites is water-fluxed melting of Ordovician orthogneisses. The discrete  
612 presence of Ordovician inheritance in the Monteners, Vallorcine and Mont-Blanc granites  
613 can be attributed to the kinetics of heat transfer in felsic magmas that impacted zircon  
614 dissolution. Because of a greater volume, plutons have lower cooling rates than dykes (de  
615 Saint-Blanquat et al., 2011), and have higher temperature conditions that enhance the  
616 dissolution of zircon grains (Bea et al., 2007). Zircon grains of Early Carboniferous plutons  
617 (AR801, AR865) show almost no inheritance (Fig. 12B and C). This could also be the result of

618 an efficient zircon dissolution process due to the metaluminous composition of magmas (Bea  
619 et al., 2006) and/or higher temperature conditions (Kelsey et al., 2008).

620 The importance of Lower Paleozoic igneous rock contributions, particularly Ordovician  
621 intrusions, has been widely proposed for the sources of the Late Carboniferous Variscan  
622 granites in the French Central Massif (Downes and Duthou, 1988; Pin and Duthou, 1990;  
623 Turpin et al., 1990; Downes et al., 1997), in the Armorican massif (Ballouard et al., 2017, 2018)  
624 and in Iberia (Neiva et al., 2012; Villaseca et al., 2012; Rodriguez et al., 2022). The strong  
625 contribution of meta-igneous rocks as melt sources for Late Carboniferous magmatism  
626 suggests that an important part of the melt fraction produced during the Variscan orogeny  
627 was generated by water-fluxed melting reactions rather than water-absent dehydration  
628 melting. This interpretation is consistent with recent studies highlighting that water-fluxed  
629 partial melting reactions are common phenomena in orogenic crust and are often at the origin  
630 of crustal-derived magmas (i.e. peraluminous magmas) (e.g. Wienberg and Hasalova, 2015;  
631 Sawyer et al., 2011). The water supply may originate from different sources such as water  
632 coming from the dehydration of nearby metapelitic rocks (Sawyer, 2010; White et al., 2005;  
633 Weinberg and Hasalová, 2015) or from the lower crust (Braga and Massone, 2012).

634 Mafic enclaves are found in the Mont-Blanc pluton (Bussy, 1990) and several ca. 307 Ma old  
635 mafic intrusions have also been documented in the Fully area (Bussy et al., 2000) arguing for  
636 a contribution of a mantle source in the Late Carboniferous magmatism. Similarly, based on  
637 their geochemical signatures, von Raumer and Bussy (2004) suggested that the Montées-  
638 Pélissier and Pormenaz plutons probably originated from partial melting of the overthickened  
639 lower crust and interpreted enclaves of durbachites and lamprophyres as evidence of a mantle  
640 source. Early Carboniferous plutons also described in other ECMs (e.g. Schaltegger and Corfu,

641 1992; Debon et al., 1994, 1998; Guerrot and Debon, 2000; Rubatto et al., 2001) show similar  
642 geochemical compositions and are also interpreted as a mixing between crustal and mantle  
643 sources (Debon and Lemmet, 1999 and reference therein). Granite emplacement with a major  
644 mantle component and dated between 340-330 Ma is also known in other Variscan massifs  
645 (e.g., Vosges: Guillot et al., 2020; Tabaud et al., 2015; Corsica: Paquette et al., 2003; Li et al.,  
646 2014). These similarities suggest that a mantle thermal anomaly may have affected a large  
647 part of the Variscan belt and may have contributed into the bulk heat budget of the  
648 continental crust. The significance of the two successive thermal anomalies (i.e. Early and Late  
649 Carboniferous) associated with the two magmatic pulses in the AR and MB massifs and others  
650 ECMs remains elusive. Several orogenic-scale geodynamic events have been proposed, such  
651 as delamination of the lithospheric mantle (e.g. Laurent et al., 2017; Vanderhaeghe et al.,  
652 2020), mantle plume (Franke, 2014) or sub-lithospheric relamination and magmatic flow as  
653 recently invoked in the Bohemian massif (Maierova et al., 2018, 2021).

654

### 655 *6.3. Melt drainage during crustal-scale shear zone evolution*

656 Based on structural and geochronological data, we propose a temporal evolution of the  
657 tectono-magmatic system during Carboniferous transpression. This conceptual model  
658 emphasizes the role of anastomosed shear zone network growth and water-fluxed melting of  
659 orthogneisses (Fig. 15). In the AR and MB massifs, the Variscan magmatism started around  
660 340-330 Ma with the emplacement of the Pormenaz and Montées-Pélessier granites (Fig. 12B  
661 and C; Bussy et al., 2000). This magmatic pulse occurred in an overthickened crust as  
662 documented by the pressure conditions at ca. 1.75 GPa recorded in the eclogites and dated at  
663 340-330 Ma (Vanardois et al., 2022). These two Early Carboniferous granites were emplaced

664 at upper crustal levels. The root zone of plutons is not exposed and the feeder structures are  
665 unknown. Our observations argue for a subsolidus deformation with the development of S2  
666 and C2 structures. In addition, microstructures show fractured K-feldspar grains without  
667 myrmekite formation and bulging recrystallization in quartz (Fig. 9C and D), suggesting a  
668 subsolidus deformation (Passchier and Trouw, 2005). The magmatic foliation and lineation in  
669 the western side of the Pormenaz granite show sub-parallel orientation to the D1 deformation  
670 in the surrounding rocks and can be interpreted as syn-D1. Alternatively, the Montées-  
671 Pélissier granite displays microfractures in plagioclase healed by quartz (Fig. 9D), which is  
672 typical of submagmatic deformation (Bouchez et al., 1992; Pawley and Collins, 2002), and  
673 plagioclase porphyroblasts are oriented sub-parallel to the S2 and C2 structures. These  
674 features may indicate an emplacement through vertical shear zones during the D2  
675 transpression (Fig. 15A) and a subsolidus deformation during the ongoing D2 transpression.  
676 Therefore, we propose that the vertical dextral shear zones may have initiated at 340-330 Ma  
677 with limited upward transfer of fluids and melts from the lower crust to upper crustal levels  
678 (Fig. 15A). Similar ages for the beginning of the dextral transpression are documented in the  
679 Argentera massif (Simonetti et al., 2018, 2021). Vanardois et al. (2022) proposed that D1  
680 initiated after the peak of pressure at ca. 340-330 Ma and interpreted D1 as a record of  
681 longitudinal flow of the partially molten lower crust. Based on the similar ages of the  
682 Pormenaz and Montées-Pélissier granites interpreted as syn-D1 and syn-D2 plutons,  
683 respectively, our results suggest that the initiation of D2 transpression is coeval with this D1  
684 longitudinal flow. The similar stretching direction (330-040) recorded by L1 and L2 lineations  
685 are consistent with the concomitant D1 deformation longitudinal flow and the onset of D2  
686 transpression. Similar partitioning of the deformation between horizontal and vertical fabrics

687 during longitudinal flow has been described in the Variscan belt (e.g. Cochelin et al., 2021) and  
688 in others hot orogens (e.g. Gapais et al., 2005; Yin and Taylor, 2011; Xu et al., 2015).

689 Ongoing dextral transpression is responsible for the development of a regional-scale  
690 anastomosed shear zone network with a S-C-C'-like structure. Numerous felsic dykes and  
691 pegmatites located in the C2 shear zones show evidences of syn-kinematic emplacements as  
692 exemplified by diffuse contact with the C2 migmatite layers (Lac Cornu pegmatite; Fig. 10A)  
693 or typical S-C structures (Lacs Noirs pegmatite; Berthé et al., 1979) (Fig. 10C). These dykes are  
694 dated between 310-320 Ma (Fig. 14B and C), similar to the  $317 \pm 2$  Ma age of leucogranitic  
695 injections in dextral shear bands documented in the MB massif (Bussy and von Raumer, 1994).  
696 These ages are also consistent with the dextral shearing constrained at ca. 320 Ma in the EBSZ  
697 (Simonetti et al., 2020). We propose that the formation and broadening of these shear zones  
698 enhanced aqueous fluid drainage in the orthogneisses and, thus, increased the water-fluxed  
699 melting reaction (Fig. 15B). The anatectic melts were collected in the C2 shear zones and  
700 formed the syn-kinematics dykes (Fig. 10 and 15B).

701 The Vallorcine granite crosscuts C'2 shear bands (Fig. 9E). The granite also shows magmatic  
702 planar fabrics sub-parallel to the C'2 structures (Bussy et al., 2000) and a weakly developed  
703 subvertical foliation in surrounding granitic dykes (Simonetti et al., 2020). Therefore, the  
704 emplacement of this granite is syn-C'2. A similar magmatic fabric in the core of the Mont-Blanc  
705 granite also indicates a syn-C'2 emplacement. The Monteners granite has recorded quartz-  
706 polygonal recrystallization typical of high-temperature deformation (Passchier and Trouw,  
707 2005) and fracture in plagioclase healed by quartz indicating submagmatic deformation  
708 (Bouchez et al., 1992; Pawley and Collins, 2002) (Fig. 9G), whereas deformation of quartz in  
709 shear bands emphasizes lower-temperature deformation (Fig. 9G). Our structural and

710 microstructural analyses indicate that the emplacements of the Vallorcine, Montenvers and  
711 Mont-Blanc granites took place inside crustal dextral C'2 shear zones (Fig. 2 and 9E to H) and  
712 no compressive structures are observed in their country rocks. Therefore, we interpret the  
713 C'2-dominant domains (i.e. the EBSZ and MSZ) as large-scale dilation shear structures that  
714 enhanced the emplacement of large volumes of melts within the continental crust at ca. 305  
715 Ma (Fig. 15C). The C'2 shear zones represent the last structures of the dextral transpressional  
716 system. This interpretation is also consistent with the occurrence of cordierite-bearing  
717 migmatites in the Fully area showing cordierite clots parallel to C'2 plans (Fig. 5D) indicating a  
718 syn-C'2 partial melting dated at ca. 307 Ma (Bussy et al., 2000). We speculate that local D3  
719 deformation observed in the upper structural levels in the Servoz syncline may represent a  
720 limited vertical thinning due to these dilation structures or to the upward movements and  
721 emplacements of plutons. This deformation phase is not shown in figure 15.

722 These structural and geochronological results document a progressive growth of an  
723 anastomosed shear zone network at the scale of the AR and MB massifs during the same large-  
724 scale transpressional deformation. The formation of this anastomosed network started with  
725 the progressive nucleation of the S2 foliation and C2-dominant shear zones at ca. 340-330 Ma.  
726 The development and broadening of the anastomosed shear zone network occurred between  
727 ca. 330-310 Ma. The formation of two large-scale dilation C'2 zones occurred at the end of  
728 the transpression at ca. 305 Ma.

729

## 730 **7. Conclusion**

731 Our bulk structural analysis on the Variscan crust at the scale of the Aiguilles-Rouges and  
732 Mont-Blanc massifs highlights a crustal scale S-C-C' anastomosed network formed during  
733 dextral transpression along the EVSZ closely associated to plutons ascent and emplacement.  
734 Zircon and monazite LA-ICPMS U-Th-Pb dating of syn-tectonic dykes and large plutons  
735 constrain this bulk continental dextral deformation between ca. 340 and 305 Ma. During this  
736 time span, the transcurrent EVSZ network broadened and formed a regional-scale  
737 anastomosed system enhancing vertical flow and where C'-type shear zones acted as dilation  
738 structures that guided the ascent and the preferential growth of plutons. Zircon inheritance  
739 indicates that Late Carboniferous granitic melts are mainly derived from water-fluxed melting  
740 of Ordovician orthogneiss with the input of mantle-source derived magmas. Over time, the  
741 growth of the dextral anastomosed network enhanced water transfer through the shear zones  
742 and water-fluxed melting to produce more anatexitic melts.

743

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752



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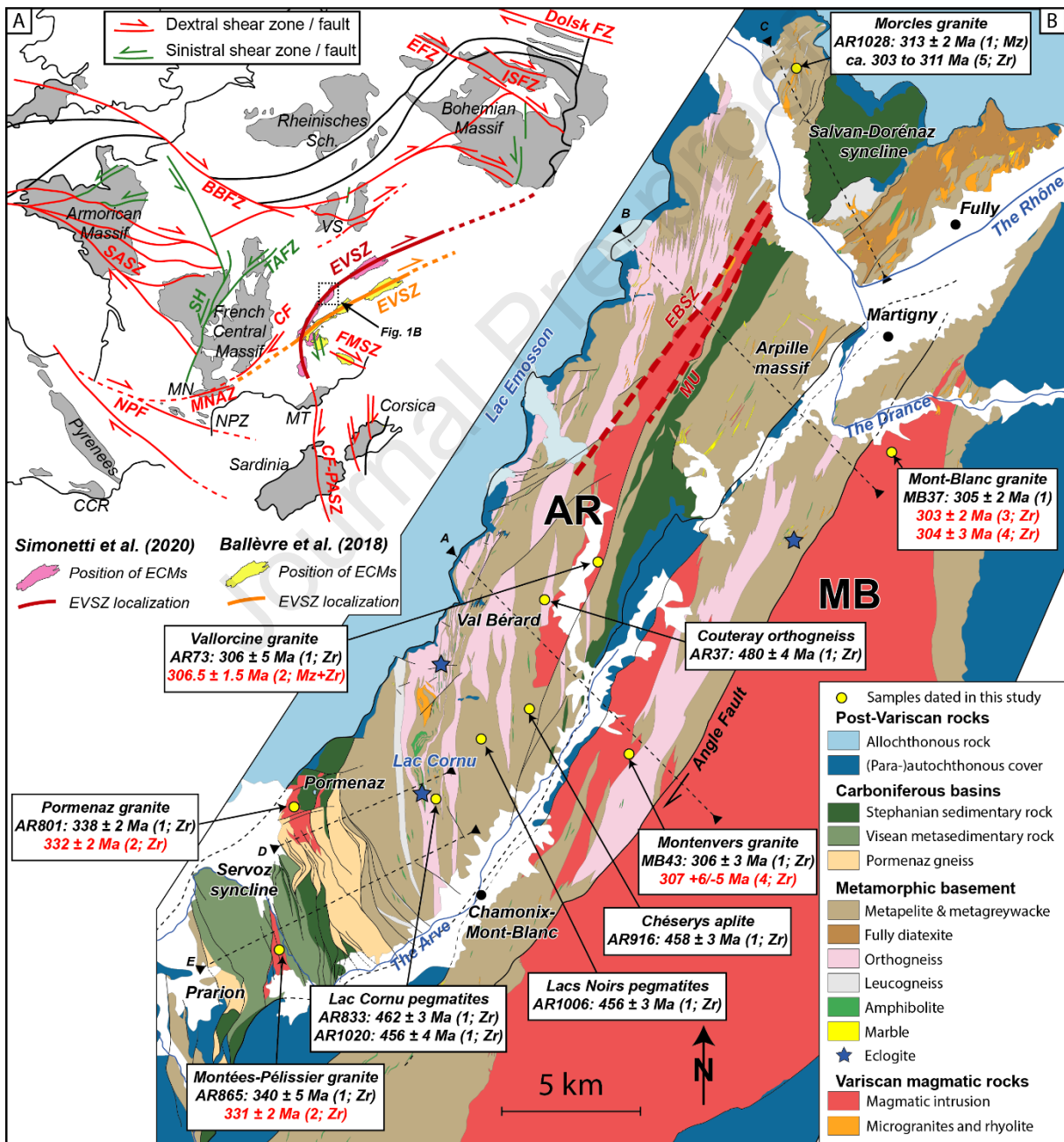


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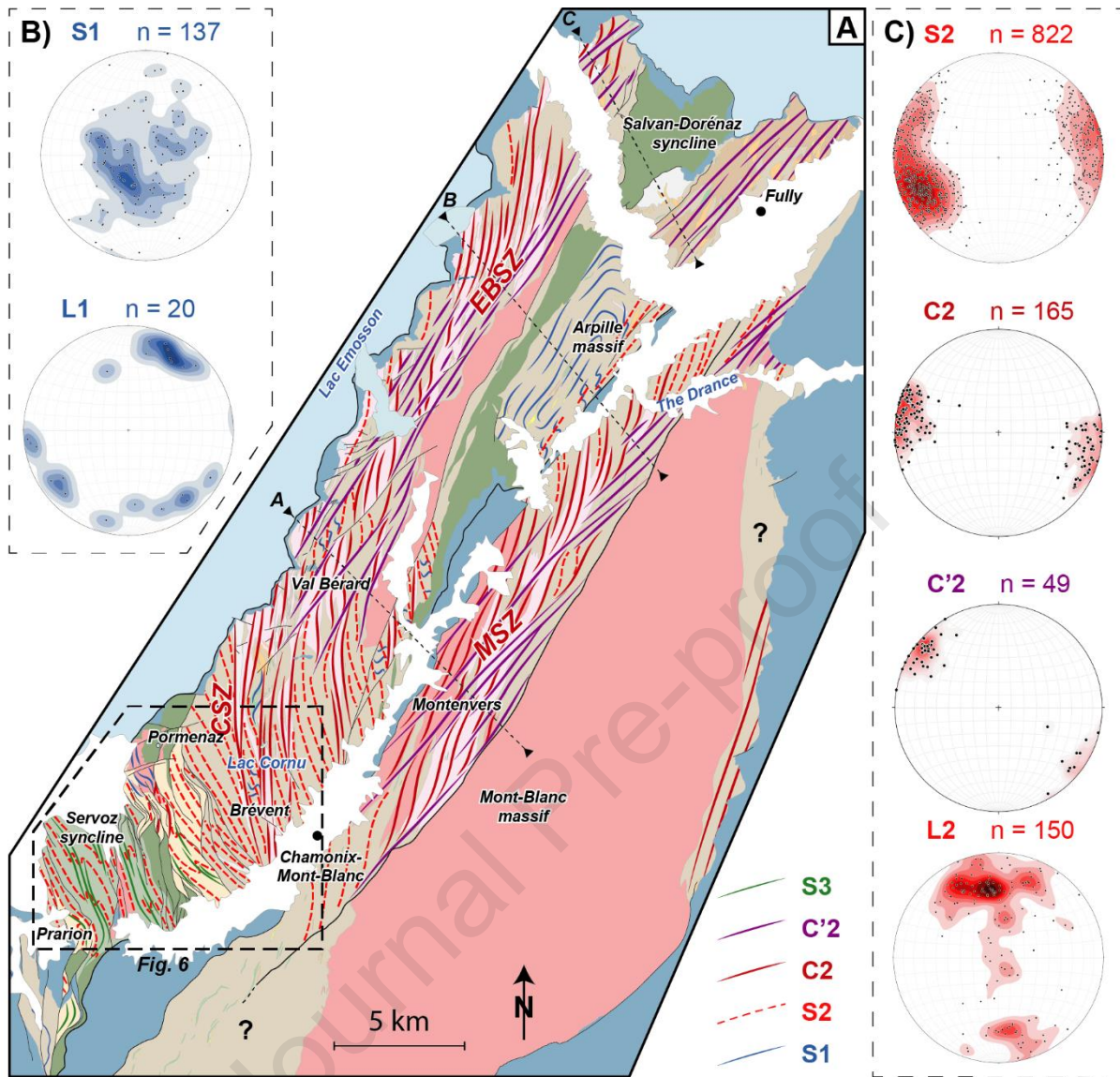
1115 **Figure captions**



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1117 **Fig. 1:** (A) Paleogeographic reconstitution of the European Variscan Belt at the end of the  
1118 Variscan orogeny modified from Franke et al. (2017). Sardinia and Corsica have the same  
1119 position as the one used in Simonetti et al. (2020). Models of the EVSZ are after Simonetti et  
1120 al. (2020) and Ballèvre et al. (2018). The position of ECMs is after Bellahsen et al. (2014) in the  
1121 Ballèvre et al. (2018) model. *BBFZ*: Bristol Bray Fault Zone; *CCR*: Catalan Coastal Ranges; *CF*:  
1122 Cévennes Fault; *EFZ*: Elbe Fault Zone; *EVSZ*: East Variscan Shear Zone; *FMSZ*: Ferrière-Mollière  
1123 Shear Zone; *CF-PASZ*: Cavalaire Fault - Posada-Asinara Shear Zone; *ISFZ*: Intra-Sudetic Fault  
1124 Zone; *MN*: Montagne Noire; *MNAZ*: Montagne Noire Axial Zone; *NPF*: North Pyrenean Fault;  
1125 *NPZ*: North Pyrenean Zone; *SASZ*: South Armorican Shear Zone; *SH*: Sillon Houiller fault; *TAFZ*:  
1126 Taure-Aigueperse Fault Zone; *VS*: Vosges-Schwarzwald. (B) Geological map of the Aiguilles-  
1127 Rouges (AR) and the Mont-Blanc (MB) Massifs with geochronological results and sample  
1128 locations. *EBSZ*: Emosson-Bérard shear zone; *MU*: Miéville ultramylonite. Synthesis of  
1129 Variscan ages obtained by ID-TIMS (red) and LA-ICPMS (black) U-Th-Pb method on zircon (Zr)  
1130 and monazite (Mz) after (1) this study, (2) Bussy et al. (2000), (3) Bussy and von Raumer (1993),  
1131 (4) Bussy and von Raumer (1994), (5) Bussien et al. (2017). Structure sections A, B, C, D and E  
1132 are to those in Figures 3 and 7.

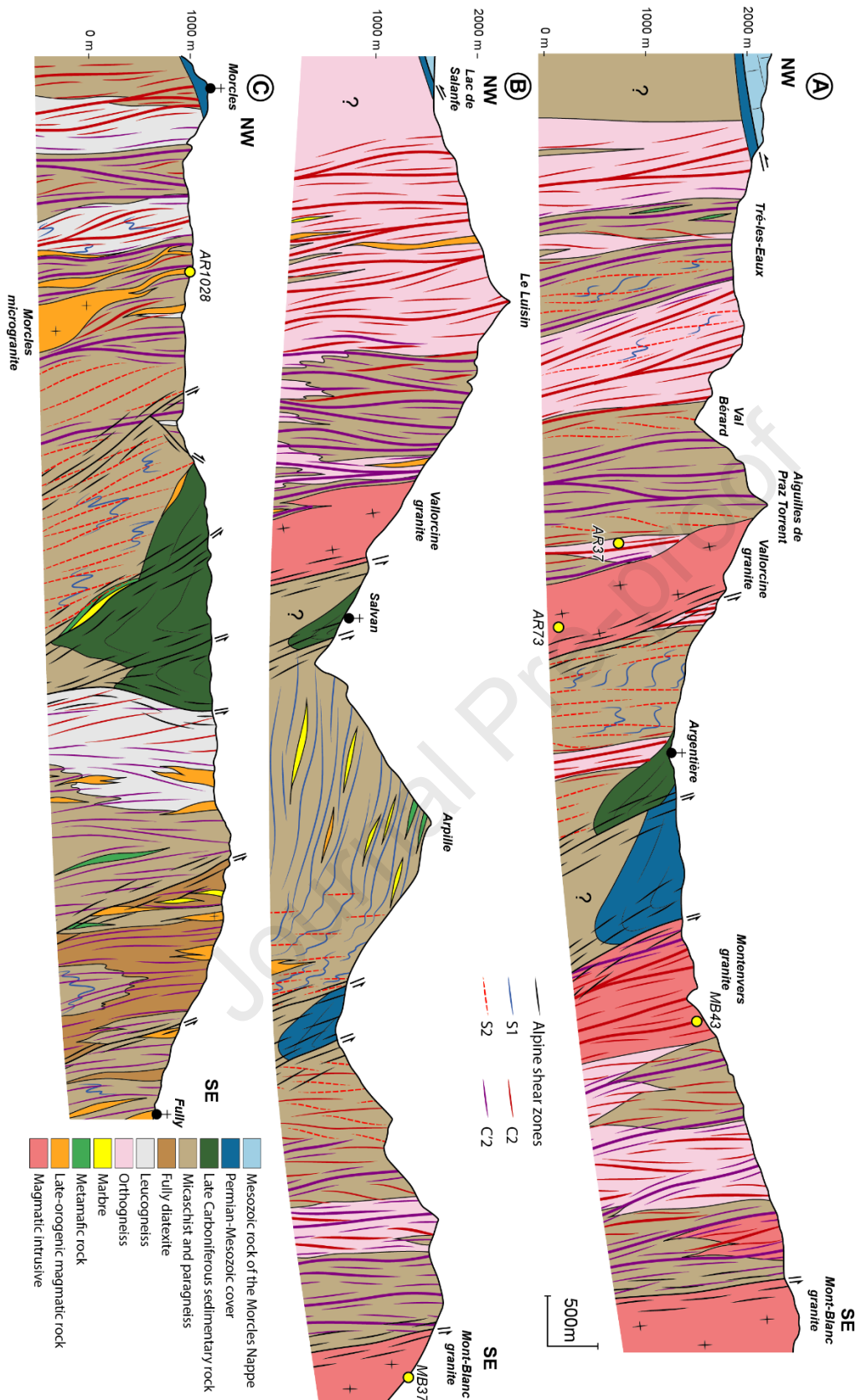
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1135 **Fig. 2:** (A) Synthetic map showing the simplified foliation trajectories of D1, D2 and D3  
 1136 deformation. Lithological legend is the same as in Figure 1B. The area corresponding to Figure  
 1137 6 is indicated. CSZ: Cornu Shear Zone; EBSZ: Emosson-Bérard Shear Zone; MSZ: Montenvers  
 1138 Shear Zone. (B and C) Stereograms of poles to planar fabrics and mineral lineation for D1 and  
 1139 D2 deformation are Wulff lower-hemisphere projections.

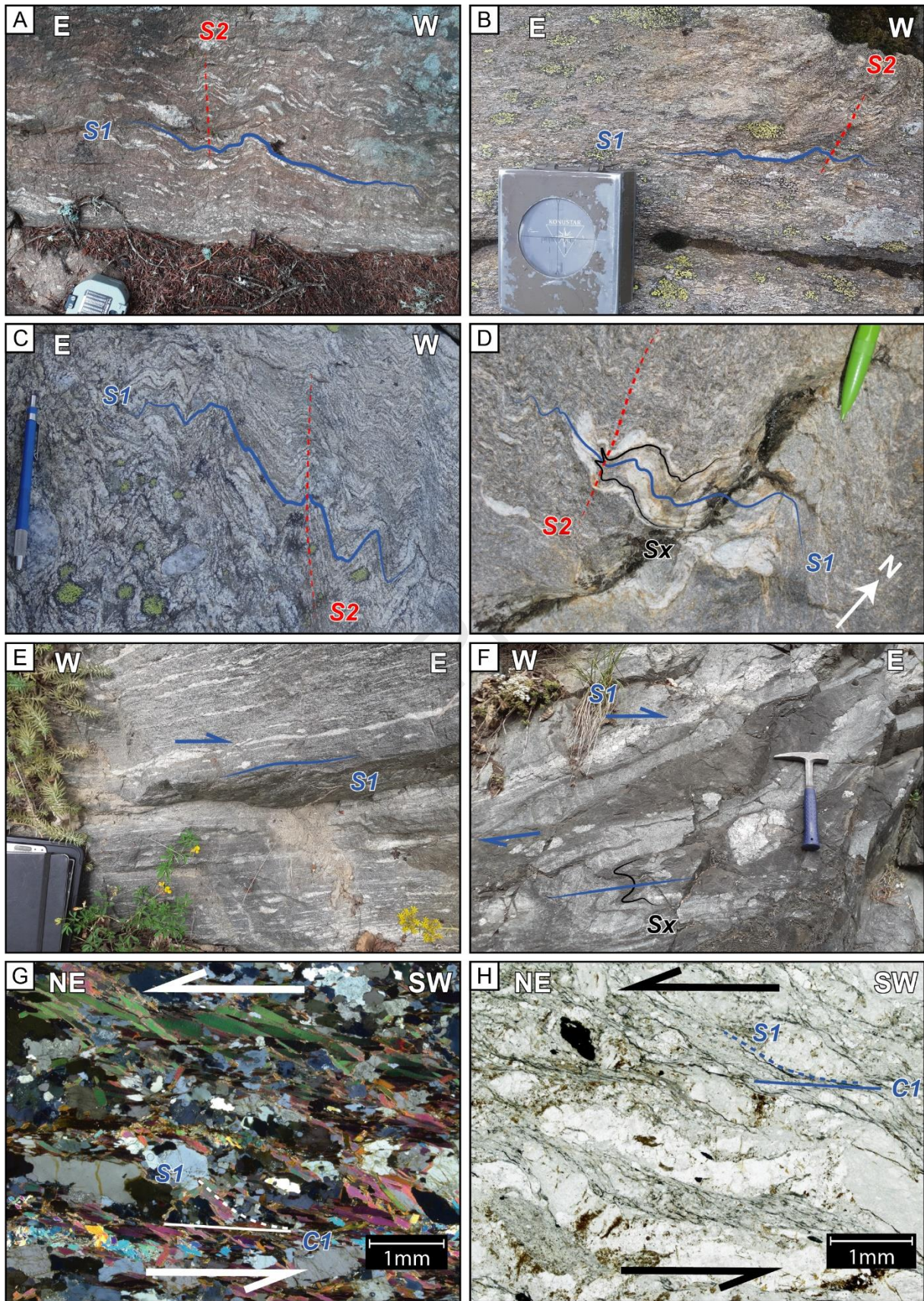




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1141 **Fig. 3:** E-W Structure sections through the Aiguilles-Rouges and the Mont-Blanc Massifs (see  
 1142 location of sections on Figures 1 and 2). Same structures symbols as in Figure 2.

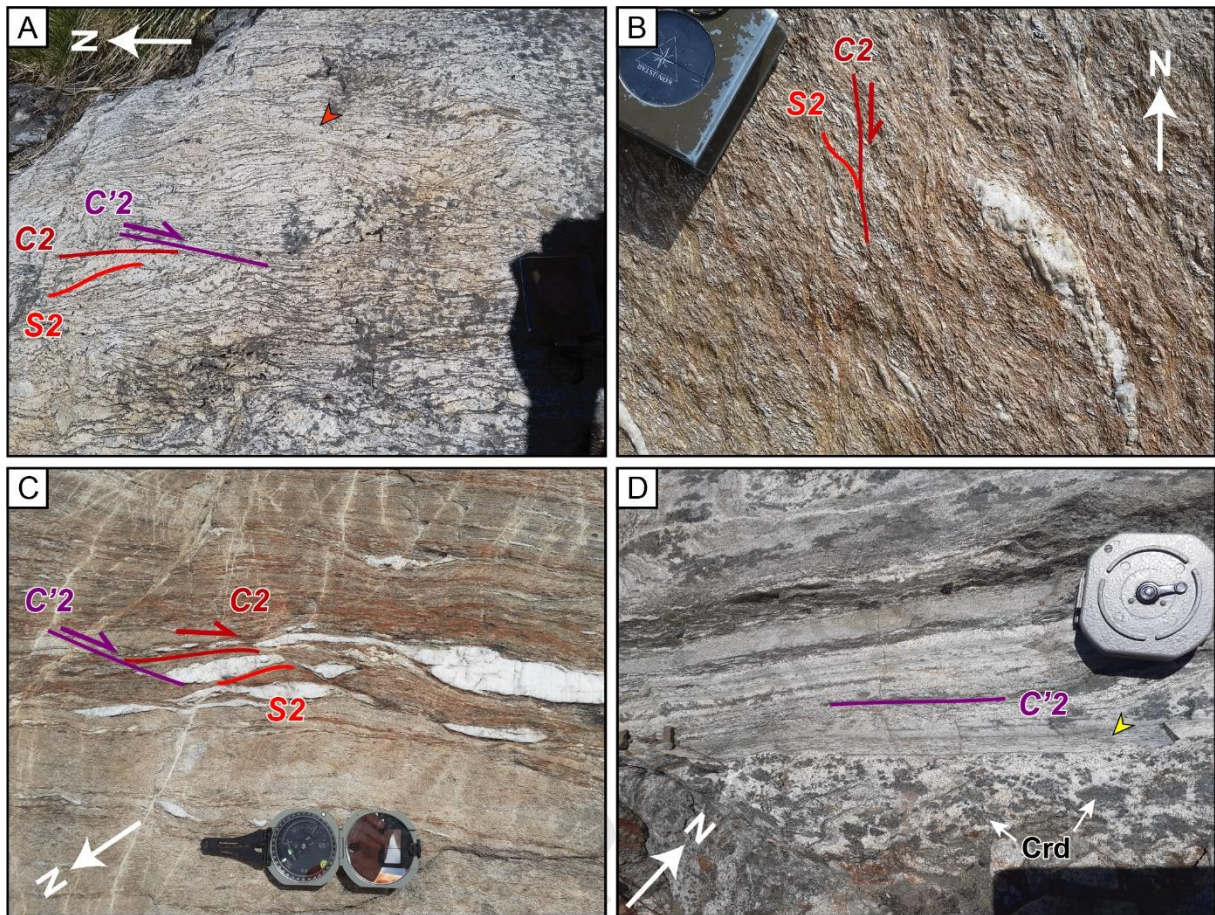






1144 **Fig. 4:** D1 deformation and D1/D2 relationships. S1 foliation and weak S2 schistosity in the  
1145 Arpille massif (A; N46.110779; E7.039935), near the Brévent location (B; N45.941226;  
1146 E6.842971) and in the Lac Cornu area (C; N45.956048; E6.853897). (D) D1/D2 fold  
1147 interference: an F1 fold deforming an Sx foliation, the S1 foliation is subsequently deformed  
1148 by F2 folds with an associated S2 schistosity, Val Bérard area (N46.004630; E6.872713). (E and  
1149 F) Top-to-the-NE kinematics indicated by asymmetric boudinage/structures in Prarion  
1150 metabasites (N45.865415; E6.734047). (G) Top-to-the-NE kinematics indicated by sheared  
1151 biotite mica-fish, Arpille massif (N46.110362; E7.040006). (H) Top-to-the-NE C-S structures in  
1152 a low-grade Pormenaz gneiss (N45.941793; E6.782782).

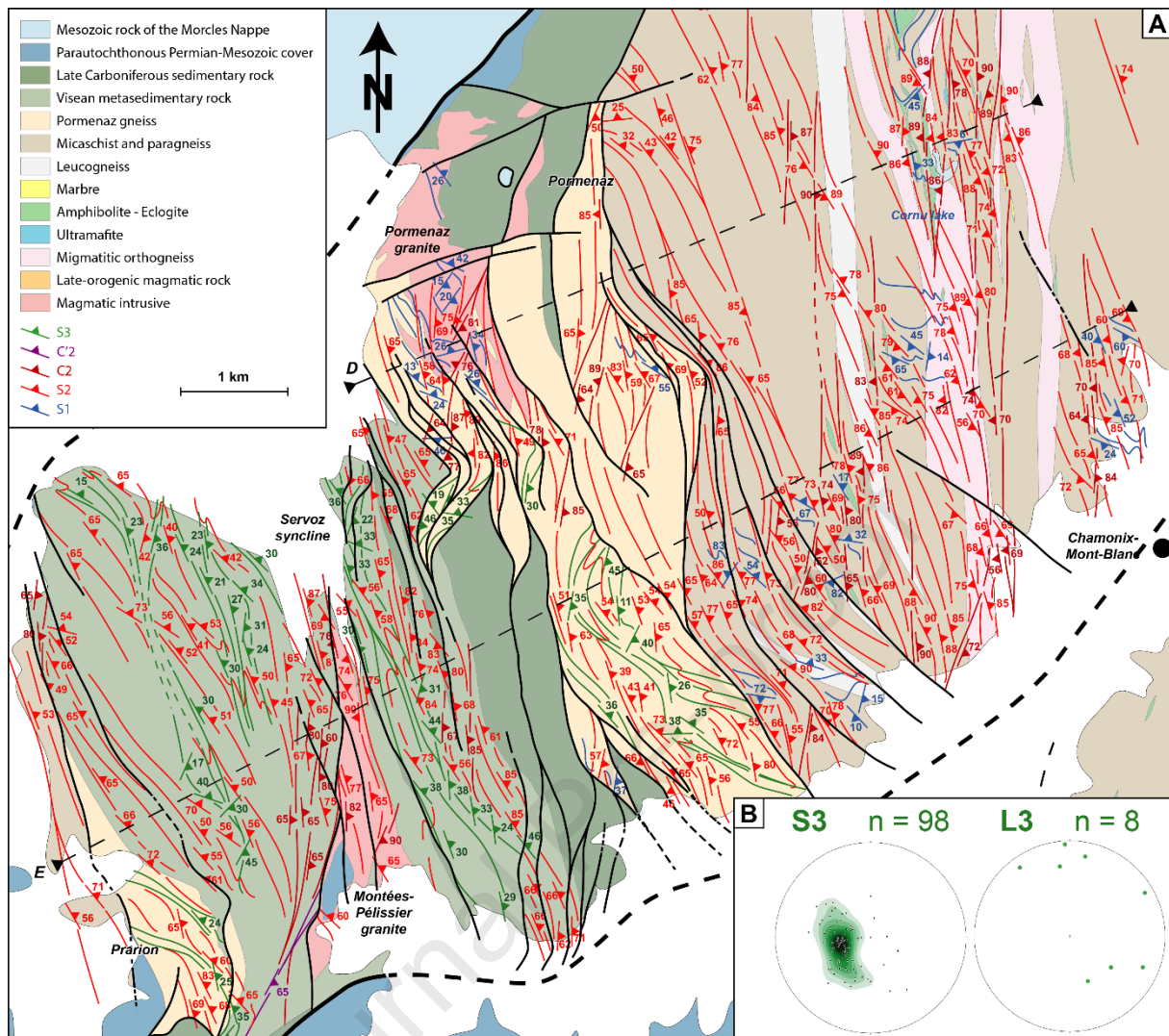
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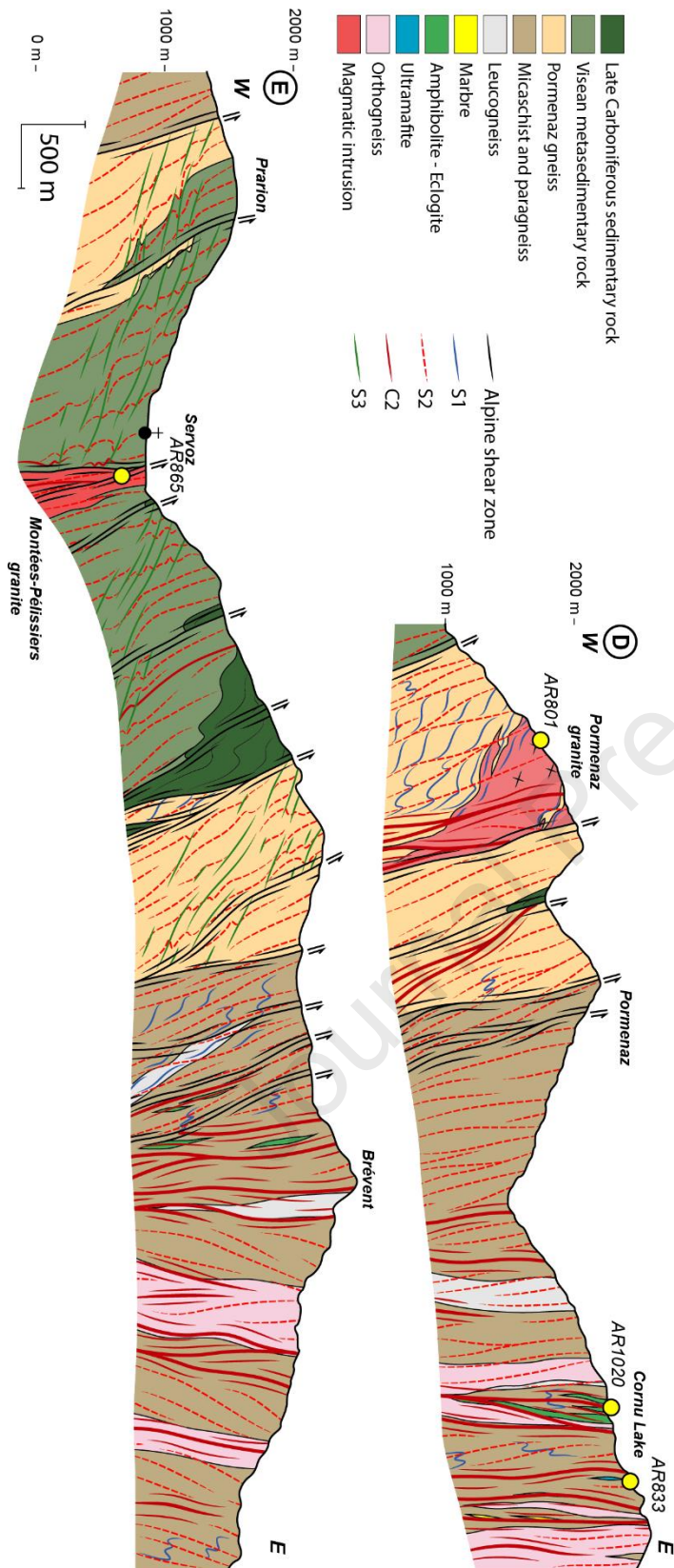
1155 **Fig. 5:** D2 deformation. S2-C2-C'2 structures in the Lac Cornu area (A) (N46.066231;  
 1156 E6.916211) and near Chamonix-Mont-Blanc (B) (N45.927587; E6.825600). Red arrow indicates  
 1157 melt injection in a C'2 shear band. (C) S2-C2-C'2 structures in the Lac Emosson area  
 1158 (N46.067197; E6.923349). (D) Cordierite-bearing migmatite with cordierite clots (Crd)  
 1159 oriented parallel with C'2 planes and centimeter-sized ultramylonitic C'2 shear bands (yellow  
 1160 arrow) (N46.123427; E7.078374).





1161

1162 **Fig. 6:** (A) Detailed map of the D1-D2-D3 foliations and their trajectories in the southwestern  
 1163 part of the Aiguilles-Rouges Massif. (B) Stereograms of poles of planar fabrics and lineations  
 1164 of D3 deformation are Wulff lower-hemisphere projections. Location of structure sections D  
 1165 and E is indicated.



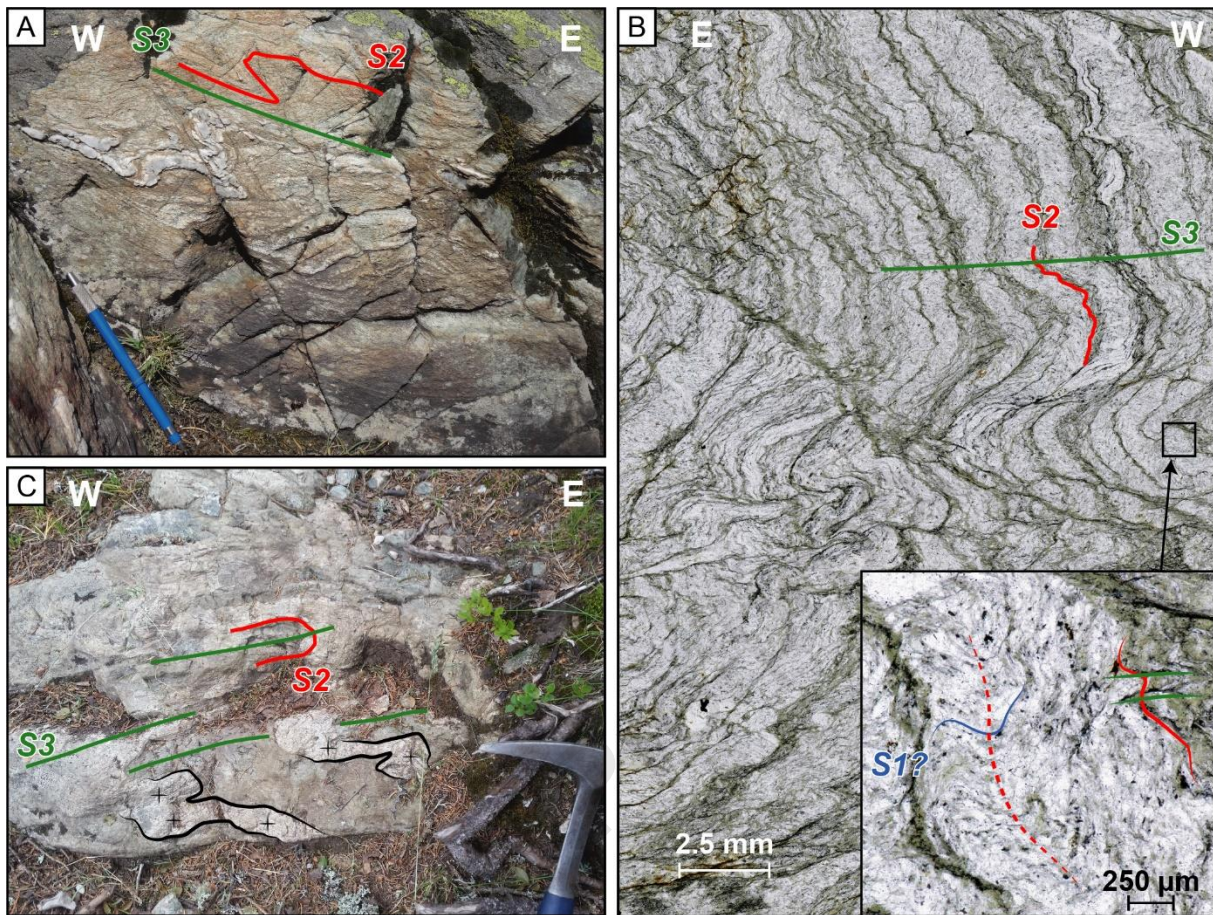
1166

1167 **Fig. 7:** E-W structure sections at the southwestern extremity of the Aiguilles-Rouges Massif.

1168 (D) In the Pormenaz area and (E) through the Servoz syncline. Location on Figure 6.



1169



1170

1171 **Fig. 8:** D3 deformation. (A) F3 folds from the western limb of the Servoz syncline, Prarion area  
 1172 (N45.894366; E6.750432). (B) Photomicrograph in plane-polarized light showing the  
 1173 relationships between S1-S2-S3 planar fabrics in Visean metasedimentary rocks (N45.906481;  
 1174 E6.778808). (C) Weakly deformed trondhjemitic melts (highlighted in black) affected by F3  
 1175 folds (N45.887808; E6.753523).



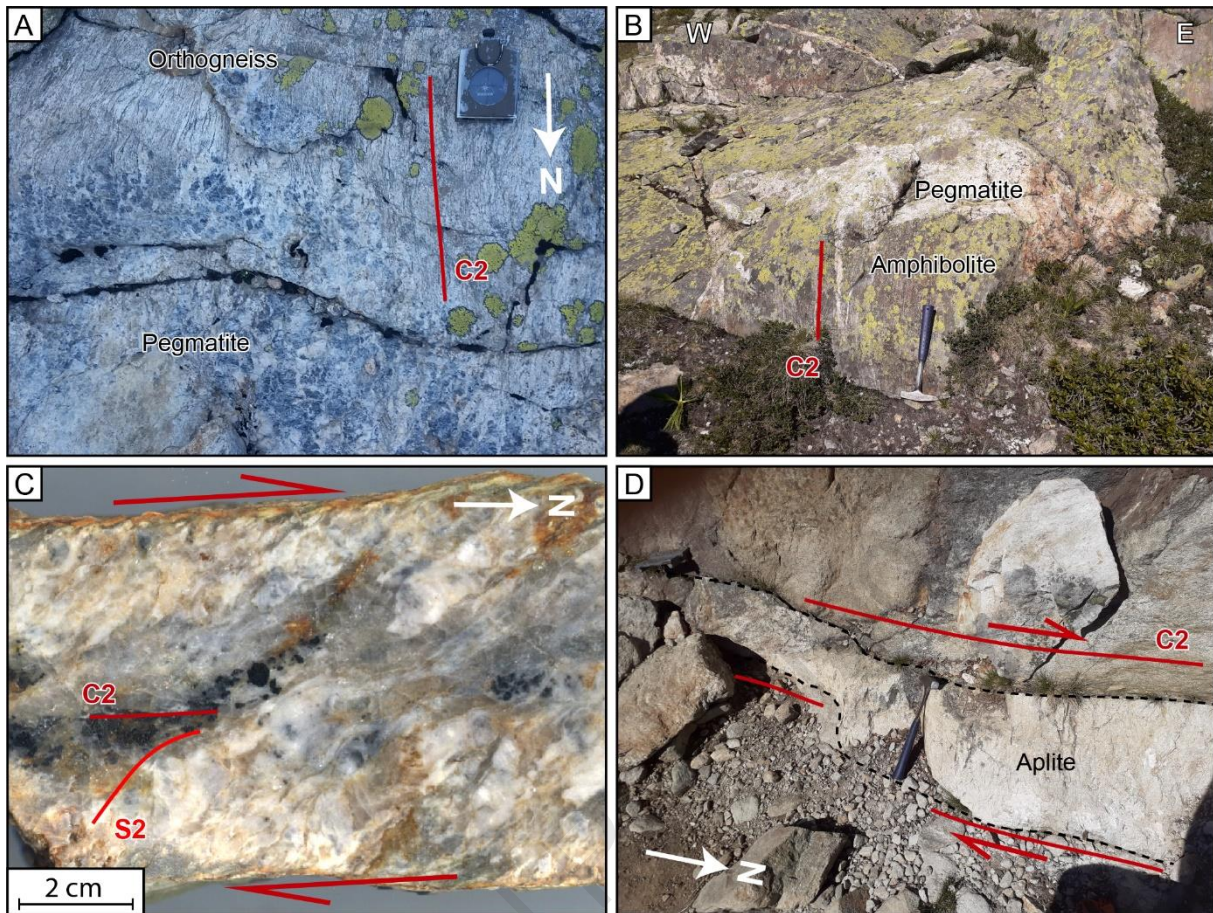


1176

1177 **Fig. 9:** Deformation features in the magmatic rocks of the AR and the MB Massifs. Sample  
 1178 locations are shown in Fig.1B. (A) Couteray orthogneiss with C2-C'2 shear bands highlighted  
 1179 and local preserved leucosomes are visible (orange arrow). (B) L1 mineral lineation indicated



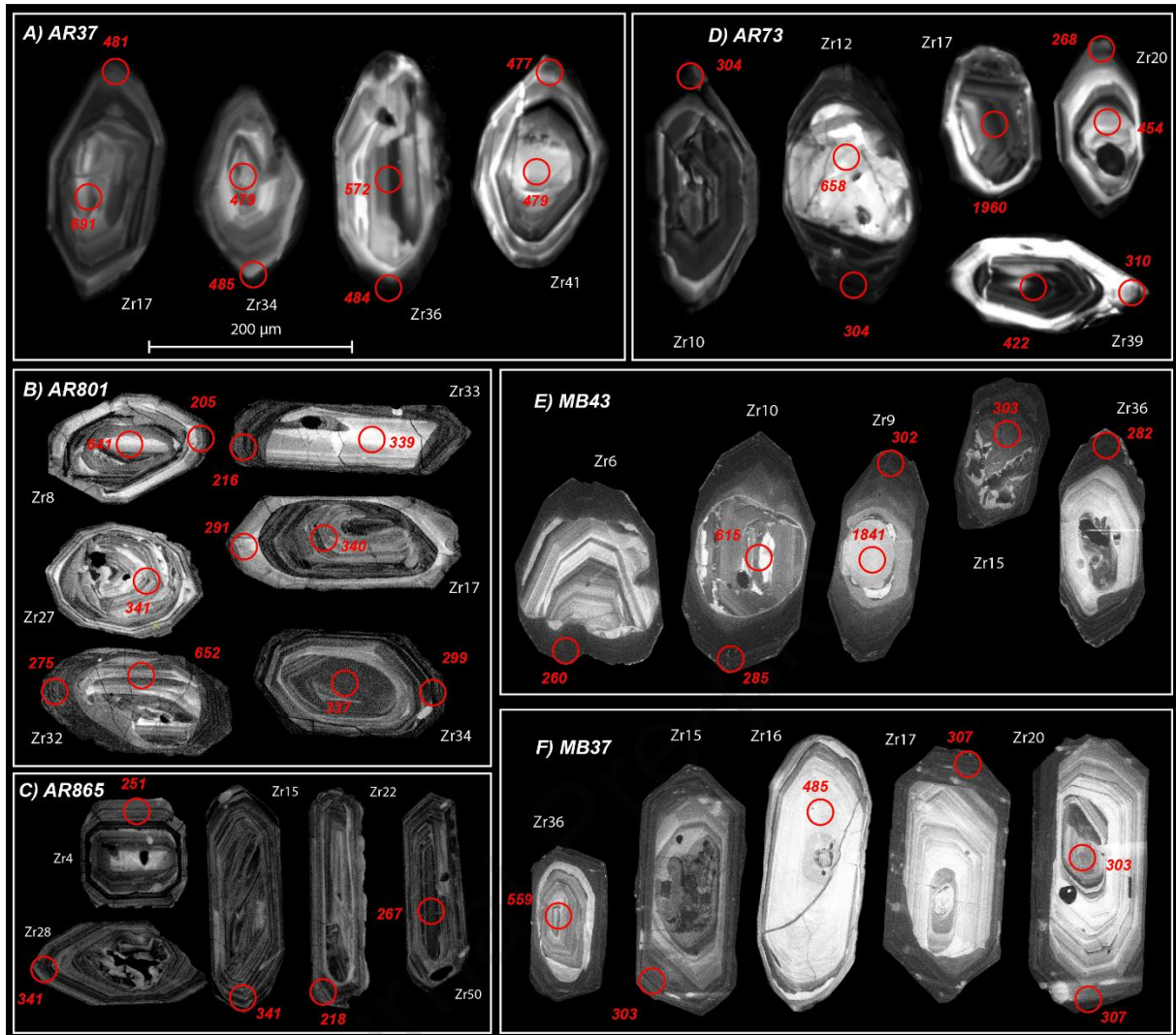
1180 by euhedral K-feldspar from the western part of the Pormenaz granite (AR801). (C) Pormenaz  
1181 granite deformed in D2 in the eastern part of the pluton. (D) Photomicrograph in cross-  
1182 polarized light of the Montées-Pélessier granite (AR865) with feldspar oriented parallel with  
1183 the C2 planes. Orange arrows indicate microfractures in feldspar infilled by quartz  
1184 emphasizing the presence of melt during deformation. (E) Vallorcine granite (AR73) cross-  
1185 cutting the C'2 planar fabrics of the EBSZ and cross-polarized light microphotograph showing  
1186 grain boundary migration recrystallization in quartz aggregates. (F) Montenvers granite  
1187 deformed during D2. (G) Photomicrograph in cross-polarized light of the Montenvers granite  
1188 (MB43). Orange and yellow arrows indicate microfractures in feldspar infilled by quartz and  
1189 polygonal quartz suggesting high temperature deformation. Blue arrows indicate polygonal  
1190 quartz deformed at lower temperature. (H) Mont-Blanc granite (MB37) with a magmatic  
1191 foliation inferred by the alignment of K-feldspar sub-parallel to C'2. (I) Photomicrograph in  
1192 cross-polarized light of the Morcles microgranite (AR1028) without preferred mineral  
1193 orientation.



1194

1195 **Fig. 10:** Pegmatitic and aplitic samples. (A) Pegmatite AR833 from the Lac Cornu area  
 1196 embedded in a orthogneiss migmatite with diffusive contacts. (B) Pegmatite AR1020  
 1197 crosscutting the C2 planes of an amphibolite boudin in the Lac Cornu area. (C) Section of the  
 1198 Lacs Noirs pegmatite (AR1006) showing C-S structures. (D) Chéserys aplite (AR916) emplaced  
 1199 in a C2 shear zone.

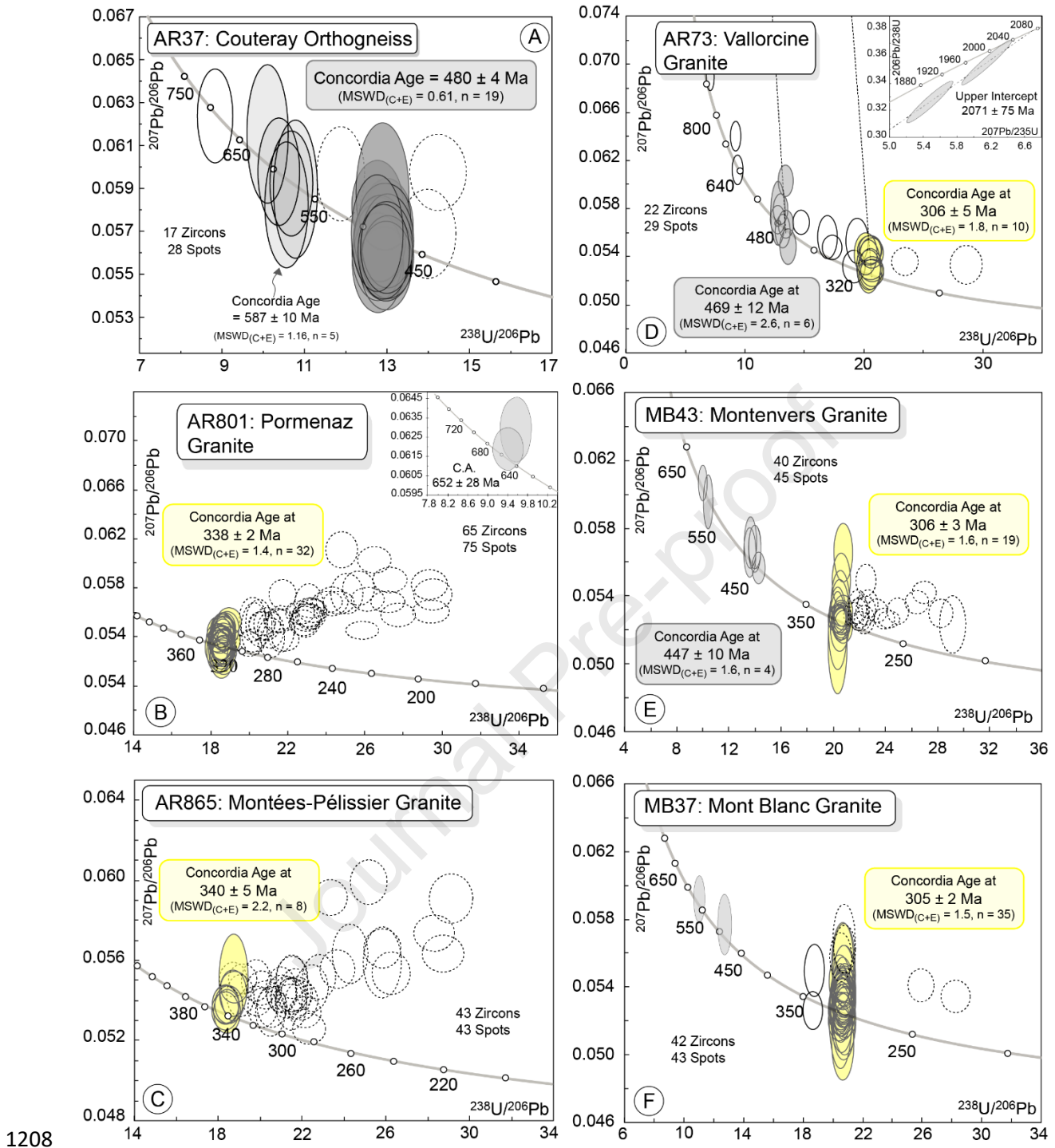
1200



1201

1202 **Fig. 11:** Cathodoluminescence images of zircon grains from: (A) the Couteray orthogneiss; (B)  
 1203 the Pormenaz granite (sample AR 801); (C) the Montées Pélissier granite (AR865); (D) the  
 1204 Vallorcine granite (AR73); (E) the Montenvers granite (MB43); (F) the Mont Blanc granite  
 1205 (MB37). Red circles indicate the analytical spot locations with the  $^{206}\text{Pb}/^{238}\text{U}$  age without  
 1206 errors associated. Zr number corresponds to the zircon grain numbers reported in Table S1.  
 1207 The bar scale indicated in A is used for all pictures (B to F).





1209 **Fig. 12:** Zircon U-Pb Tera Wasserburg diagrams obtained by LA-ICPMS from (A) the Couteray  
 1210 orthogneiss, (B) the Pormenaz granite (AR801), (C) the Montées Pélissier granite (AR865), (D)  
 1211 the Vallorcine granite (AR73), (E) the Montenvers granite (MB43), (F) the Mont Blanc granite  
 1212 (MB37). Error ellipses and uncertainties in ages are  $\pm 2\sigma$  level. The discordance of dotted

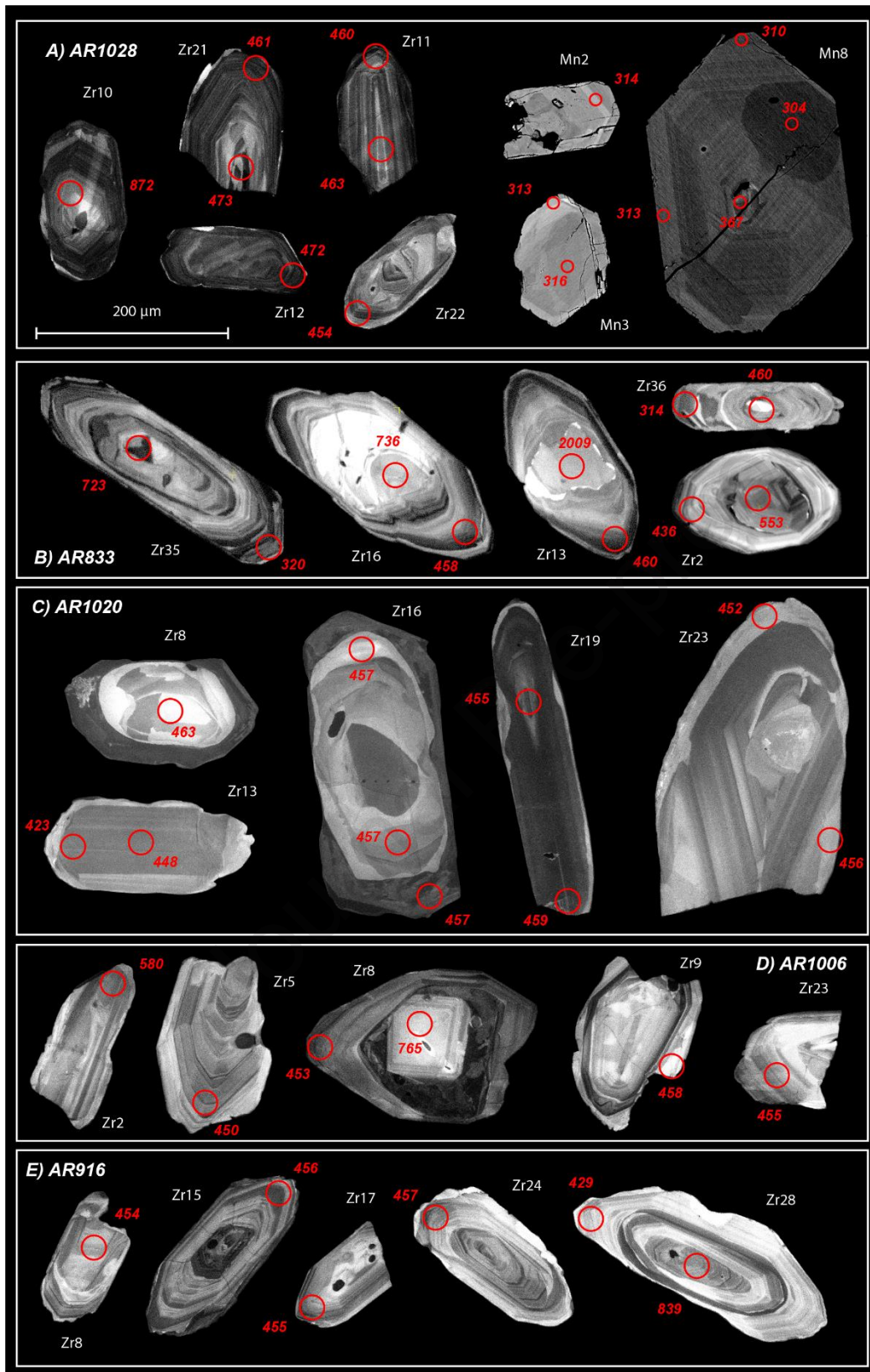


1213 ellipses is due to radiogenic Pb losses and common Pb contaminations. Dotted and white

1214 ellipses are not considered for the age calculation.

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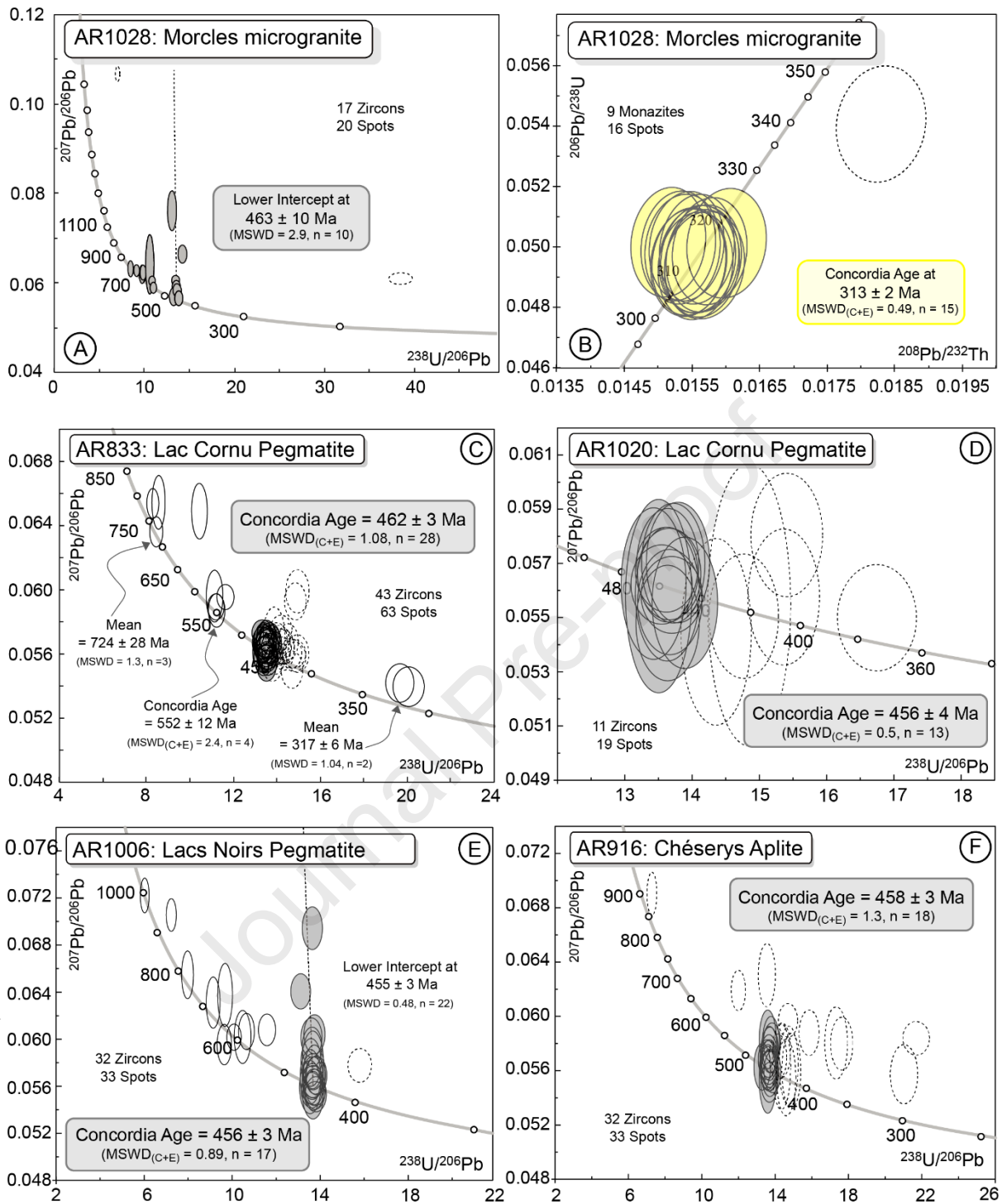


1216

1217 **Fig. 13:** Cathodoluminescence and back-scattered electron images of zircon (Zr) and monazite  
 1218 (Mn) grains from: (A) the Morcles microgranite (AR1028); (B) a Lac Cornu pegmatite (AR833);

1219 (C) a Lac Cornu pegmatite (AR1020); (D) the Lacs Noirs pegmatite (AR1006); (E) the Chéserys  
1220 aplite (AR916). Red circles indicate the analytical spot locations with the  $^{206}\text{Pb}/^{238}\text{U}$  or  
1221  $^{208}\text{Pb}/^{232}\text{Th}$  ages measured without the error associated for the zircon and the monazite grains  
1222 analysed, respectively. Zr (or Mn) number corresponds to the zircon (or monazite) grain  
1223 numbers reported in Table S1. The bar scale indicated in A is used for all pictures (B to E).

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1224

1225 **Fig. 14:** Zircon U-Pb Tera Wasserburg diagrams (A, C, E, F, D) and monazite U-Th-Pb concordia  
 1226 diagram (B) obtained by LA-ICPMS: (A and B) on the Morcles microgranite (AR1028), (C and D)  
 1227 on the Lac Cornu pegmatites (AR833 and AR1020), (E) on the Lacs Noirs pegmatite (AR1006),  
 1228 (F) on the Chéserys aplite (AR916) Error ellipses and uncertainties in ages are  $\pm 2\sigma$  level. The

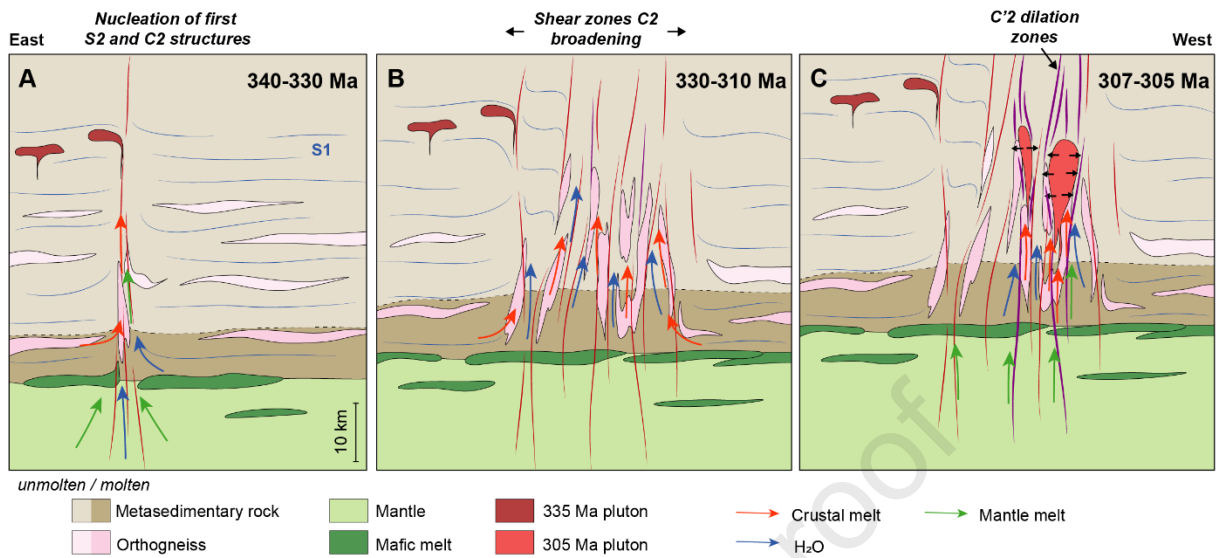
1229 discordance of dotted ellipses is due to radiogenic Pb losses and common Pb contaminations.

1230 Dotted and white ellipses are not considered for the age calculation (see text for detail).

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1233

1234 **Fig. 15:** Tectono-magmatic evolution of the AR and MB massifs. (A) Initiation of the dextral  
 1235 shearing after the nappe stacking. The fluids, anatectic lower crustal melts and mantle mafic  
 1236 melts are drained upward and form small plutons in the upper crust. (B) Broadening of the  
 1237 C2 shear zones drains more fluids that increase the partial melting of meta-igneous rocks  
 1238 forming the numerous aplitic and pegmatitic dykes. (C) C'2 shear zones, acting as dilation  
 1239 zones, collect anatectic melts and the small mantle supply to form large plutons.

1240

1241 **Table 1:** Sample descriptions and locations

Sample	Rock type	GPS location	Mineral assemblage	Mineral dated	U-Th-Pb age
AR37	Courtenay orthogneiss	N46.019559 E06.907883	Qtz + Kfs + Pl + Ms + Bt	Zircon	587 ± 10 Ma 480 ± 4 Ma
AR801	Pormenaz granite	N45.949951 E06.789104	Qtz + Kfs + Pl + Bt(Chl)	Zircon	338 ± 2 Ma
AR865	Montées-Pélessier granite	N45.917067 E06.77147	Qtz + Kfs + Pl ± Ms ± Bt(Chl)	Zircon	340 ± 5 Ma
AR73	Vallorcine granite	N46.032901 E06.936665	Qtz + Kfs + Pl + Bt	Zircon	306 ± 5 Ma
MB43	Montenvers granite	N45.96768 E06.949665	Qtz + Kfs + Pl + Ms + Bt ± Grt	Zircon	306 ± 3 Ma
MB37	Mont-Blanc granite	N46.063859 E07.08007	Qtz + Kfs + Pl + Bt	Zircon	305 ± 2 Ma
AR1028	Morcles microgranite	N46.193943 E07.043689	Qtz + Kfs + Pl ± Ms ± Bt(Chl)	Zircon Monazite	463 ± 10 Ma 313 ± 2 Ma
AR833	Lac Cornu Pegmatite	N45.956094 E06.853814	Qtz + Kfs + Pl ± Ms	Zircon	462 ± 3 Ma 317 ± 6 Ma
AR1020	Lac Cornu Pegmatite	N45.958210 E06.846594	Qtz + Kfs + Pl	Zircon	456 ± 4 Ma
AR1006	Lac Noirs Pegmatite	N45.966231 E06.871656	Qtz + Kfs + Tur + Ms	Zircon	456 ± 3 Ma
AR916	Chéserys Pegmatite	N45.982963 E06.908710	Qtz + Kfs + Pl + Ms ± Tur ± Grt	Zircon	458 ± 3 Ma



## Highlights

- The strain pattern of a portion of the crustal East-Variscan Shear Zone is given.
- The main shear direction is not NE-SW but N-S directed.
- The S-C-C'- like strain pattern controls the transfer and emplacement of magmas.
- Late-orogenic magmas come from H<sub>2</sub>O-saturated melting of meta-igneous protoliths.

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Jonas Vanardois: Conceptualization, Investigation, Writing - Original Draft, Project administration, Funding acquisition

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**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jonas Vanardois reports financial support was provided by Bureau for Geological and Mining Research.

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