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## Carboniferous tectono-metamorphic evolution of the Variscan crust in the Belledonne-Pelvoux area.

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1 **Carboniferous-Permian tectono-metamorphic evolution of the Pelvoux massif (External**  
2 **Crystalline Massif, Western Alps), with discussion on flow kinematics of the Eastern-**  
3 **Variscan Shear Zone.**

4  
5 **Évolution tectono-métamorphique Carbonifère-Permien du massif du Pelvoux (Massif**  
6 **cristallin externe, Alpes occidentales), avec discussion sur la cinématique de fluage de la**  
7 **zone de cisaillement Est Varisque.**

8  
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21  
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24  
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26 Est varisque, migmatite, transpression.

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**Abstract**

35

36 Based on new structural, petrological and U-Th-Pb geochronological data, a reappraisal of the  
37 Variscan tectono-metamorphic history of the Pelvoux massif (External Crystalline Massif,  
38 French Alps) is proposed with the aim to understand the flow pattern and kinematics of the  
39 Variscan partially molten crust and the Eastern Variscan Shear Zone. The Pelvoux massif  
40 consists of high-grade metamorphic rocks of middle to lower crust, mostly migmatites, that  
41 record a prominent syn-metamorphic deformation event ( $D_2$ ) characterized by a pervasive NE-  
42 SW striking, steeply dipping,  $S_2$  foliation, and a network of anastomosed NS and NW-SE  
43 trending shear zones, the kinematics of which indicates a sinistral transpression. Relics of an  
44 early synmetamorphic event ( $D_1/M_1$ ) related to crustal thickening and top-to-the east nappe  
45 stacking are also reported. Both the  $D_1$  and  $D_2$  features are interpreted as reflecting a NW-SE  
46 shortening event, firstly marked by dominant nappe stacking, and secondly overprinted by a  
47 sinistral transpression that started at peak metamorphism with the onset of crustal partial  
48 melting at ca. 650°C during the late Viséan (ca 335-330 Ma). Ongoing sinistral  $D_2$  transpression  
49 in the partially molten middle-lower crust of the Pelvoux involved strain partitioning between  
50 C and C' shear zones and horizontal longitudinal flow in the range 330-300 Ma. Along the  
51 anatectic front, vertical shortening and top-to-the NW shearing ( $D_3$ ) is coeval with  $D_2$  and argue  
52 for south-eastward motion of the partially molten crust. The contemporaneity between NW-SE  
53 directed transpressional flow and vertical shortening is supported by our radiometric data of  $D_2$   
54 and  $D_3$  and attests for strain partitioning between the suprastructure and infrastructure during  
55 horizontal crustal flow under transpressive regime. The exhumation of deep-seated rocks during  
56 sinistral transpression followed a near isothermal (ca. 700 °C) evolution down to pressure of  
57 ca. 0.5 GPa in the period 325-306 Ma. The sinistral transpression recorded in the Pelvoux massif  
58 might corresponds to an antithetic shear zone coeval with the dextral East-Variscan Shear Zone,  
59 proposed for this part of the Variscan orogen.

60

61

**Résumé**

63

64 Sur la base de nouvelles données structurales, pétrologiques et géochronologiques U-Th-Pb,  
65 une réévaluation de l'histoire tectono-métamorphique varisque du massif du Pelvoux (Massif  
66 cristallin externe, Alpes françaises) est proposée dans le but de comprendre le style et la  
67 cinématique du fluage de la croûte varisque partiellement fondue et de la Zone de

68 Cisaillement Est Varisque. Le massif du Pelvoux est constitué de roches métamorphiques de  
69 haut grade, de la croûte moyenne à inférieure, principalement des migmatites, qui enregistrent  
70 un événement de déformation syn-métamorphique prédominant ( $D_2$ ) caractérisé par une  
71 orientation NE-SW, une foliation  $S_2$  à fort pendage et un réseau anastomosé de zones de  
72 cisaillement d'orientation NS et NW-SE dont la cinématique indique une transpression  
73 senestre. Des reliques d'un événement synmétamorphique précoce ( $D_1/M_1$ ) lié à  
74 l'épaississement de la croûte et à l'empilement des nappes à vergence Est sont retrouvées. Les  
75 caractéristiques de  $D_1$  et  $D_2$  sont interprétées comme reflétant un événement de  
76 raccourcissement NW – SE, d'abord marqué par l'empilement dominant des nappes, qui  
77 évolue ensuite en une transpression senestre, initiée au pic du métamorphisme avec le début  
78 de l'anatexie crustale dès 650°C, à la fin du Viséen (335-330 Ma). Dans la croûte  
79 partiellement fondue, la déformation transpressive senestre  $D_2$  se partitionne avec la  
80 formation de zones de cisaillement C et C' qui accommodent le fluage longitudinal entre 330  
81 et 300 Ma. Le long du front anatectique, un raccourcissement vertical accompagné d'un  
82 cisaillement vers le NW (déformation  $D_3$ ) sont contemporains de  $D_2$  et participent aussi à  
83 l'échappement vers le sud-est de la croûte partiellement fondue. La contemporanéité entre le  
84 fluage transpressif dirigé NW-SE ( $D_2$ ) et le raccourcissement vertical à cinématique NW ( $D_3$ )  
85 est étayée par nos données radiométriques. L'exhumation des roches profondes lors de la  
86 transpression senestre a suivi une évolution quasi isotherme (~ 700 ° C) jusqu'à une pression  
87 d'environ 0,5 GPa dans la période 325-306 Ma. La transpression senestre enregistrée dans le  
88 massif du Pelvoux pourrait correspondre à une zone de cisaillement antithétique  
89 contemporaine de la zone de cisaillement dextre Est-Varisque.

90

## 91 **1. Introduction**

92 Together with the Maures-Corsica-Sardinia massifs, the External Crystalline Massifs  
93 (ECMs), exposed in the Helvetic zone of the Western Alpine belt represent the Eastern Branch  
94 of the Variscan orogen (Fig. 1). In spite of several geodynamic interpretations (Corsini &  
95 Rolland, 2009; Faure et al., 2014; Faure and Ferrière, 2022; Fernandez et al., 2002; Guillot &  
96 Ménot, 2009; Oliot et al., 2015; Rossi et al., 2009; Von Raumer et al., 2013), the timing of the  
97 main tectono-metamorphic events in the ECMs, and the correlations between these massifs  
98 remain poorly constrained mainly because of a strong imprint by late-orogenic transpressional

99 tectonics during Carboniferous time and intense partial melting and plutonism in the mid-lower  
100 crust at that time. Widespread Carboniferous crustal partial melting in response to thermal  
101 relaxation (i.e. Alcock et al., 2015; Barbey et al., 2015; Villaros et al., 2018) triggered horizontal  
102 flow of the lower and middle crust (Vanderhaeghe et al., 2020, Cochelin et al., 2017) and strain  
103 partitioning along strike-slip shear zone and exhumation of migmatitic domes (Vanderhaeghe  
104 et al., 1999; Ledru et al., 2001). In the ECMs, the structural and kinematic feature associated  
105 with partial melting and magmatism are still elusive.

106 The Eastern Crystallin Massifs (ECMs) stand out as a complex portion of the European  
107 Variscan Belt that was built along a major crustal-scale wrenching corridor, named the East  
108 Variscan Shear Zone EVSZ (Fig. 1A; EVSZ; Carosi et al., 2012; Corsini & Rolland, 2009;  
109 Guillot & Ménot, 2009; Padovano et al., 2012, 2014; Rolland et al., 2009; Simonetti et al.,  
110 2018). The EVSZ is considered as the main structure that accommodated the shaping of the  
111 variscan eastern orocline (Fig. 1A; Ballèvre et al., 2018; Bellot, 2005; Matte, 2001). A series  
112 of multidisciplinary studies have provided many structural, petrological, and radiometrical data  
113 in that part of the East Variscan branch that was affected by the EVSZ (Guillot and Menot,  
114 2009), i.e. the Aiguilles-Rouges and Mont-Blanc massif (Von Raumer et al., 2013; Von Raumer  
115 and Bussy, 2004, Simonetti et al., 2020a), the Belledonne-Pelvoux massifs (Guillot and Menot,  
116 2009), the Argentera Massif (Simonetti et al., 2018, 2021), the Maures-Tanneron massif  
117 (Rolland et al., 2009, Schneider et al., 2014; Gerbault et al., 2018, Simonetti et al., 2020b), and  
118 Sardinia (Carosi et al., 2012) showing that the EVSZ was responsible for complex strain  
119 partitioning in time and space during Carboniferous. Simonetti et al. (2020a) proposed the first  
120 detailed picture of the EVSZ with the position, orientation and kinematics of the major branches  
121 constituting the regional-scale anastomosed system (Fig. 1B). Because not all ECMs are  
122 considered in the EVSZ system, the location, thickness and internal strain pattern of the EVSZ  
123 remains elusive as well as the variations of strain regimes and kinematics that are expected to  
124 exist at lithospheric scale.

125 In this contribution we focus on the Belledonne-Pelvoux area that is a large but still poorly  
126 understood portion of the ECMs, and absent from the reconstruction of the EVSZ anastomosed  
127 system (Fig. 1B). The Pelvoux massif displays a well exposed section of the late-Variscan low  
128 and middle crust mainly composed of migmatites and granites formed in response to a crustal  
129 melting event developed at the end of a HT low-to-medium pressure Carboniferous  
130 metamorphism (Pecher, 1970; Le Fort, 1973). There, a sinistral kinematics was documented  
131 (Strzeczynski et al., 2005) making it unique in the transpressive framework of the ECMs where

132 dextral shearing dominates (Carosi et al., 2012; Corsini & Rolland, 2009; Guillot & Ménot,  
133 2009; Padovano et al., 2012, 2014; Rolland et al., 2009; Simonetti et al., 2018, 2020a).

134 Presently, the Pelvoux massif lacks large-scale structural analysis combined with  
135 quantified tectono-metamorphic evolution using modern petrological methods. Simonetti et al.  
136 (2018; 2020a, 2020b) suggested that dextral transpression in the ECMs was initiated at ca. 320  
137 Ma with the exception of the Argentera massif where it could have started at ca. 330-340 Ma.  
138 In the Pelvoux massif, rare geochronological data document the protolith age of some  
139 orthogneiss, but the syn-metamorphic deformation is still undated. A study of the Pelvoux  
140 massif will help integrating the sinistral kinematics in the general framework of the dextral  
141 transpression model of the EVSZ (e.g. Simonetti et al., 2020a) and of the whole Variscan belt  
142 (e.g. Ballèvre et al., 2018; Edel et al., 2018).

143 In this article, we present (i) the detailed finite strain pattern at the transition from the upper  
144 crust and the former partially molten crust that crops out in the Pelvoux massif and (ii)  
145 microstructural, petrological and geochronological analyses on samples from the unmolten and  
146 molten crust. These results allow us to discuss (i) the P-T-D-t evolution recorded in some high-  
147 grade metamorphic rocks; (ii) the geometrical and temporal relationships between deformation,  
148 metamorphism, partial melting, and magma emplacement; (iii) the kinematics of ductile flow  
149 in the mid-crust. Our findings are compared to those recently obtained on the adjacent  
150 Belledonne massif by Fréville et al. (2018) and Jacob et al. (2021) and enable us to propose a  
151 tectono-metamorphic evolution model of the Pelvoux that may represent an antithetic branch  
152 of the EVSZ.

153

## 154 **Geological setting.**

155

### 156 *2.1. Overview of the Variscan Belt in the Alpine Crystalline massifs*

157 The Variscan belt formed in response to collision between Gondwana and Laurussia  
158 continents, and several Gondwana-derived microcontinents during the Late Devonian to Early  
159 Carboniferous (Fig. 1A), (Autran and Cogné, 1980; Paris and Robardet, 1990; Franke, 2000;  
160 Tait et al., 1997, 2000; Matte, 1991, 2001, 2007; Von Raumer et al., 2003; Faure et al., 2005;  
161 Stampfli et al., 2013). From Late Viséan to Early Permian, thermal relaxation and mafic to  
162 felsic plutonism enhanced a widespread partial melting of the thickened low-middle crust, that

163 modified gravity vs boundary stress balance and enhanced a complex intracontinental strain  
164 partitioning in a global transpressive regime (e.g. [Rabin et al., 2015](#); [Cochelin et al., 2017](#); [Henk  
165 et al., 2000](#)).

166 In its present geometry, the External Crystalline Massifs (ECMs) of the Alps form an  
167 arcuate, concave to the East, branch of the Variscan belt that includes, from North to South, the  
168 *Aar-Gothard*, *Aiguilles Rouges-Mont Blanc*, *Belledonne*, *Grandes Rousses*, *Pelvoux*, and  
169 *Argentera* massifs (Fig. 1B) (e.g. [Barfety et al., 2000](#); [Guillot and Ménot, 2009](#)). A first-order  
170 three-fold subdivision, previously proposed by [Bordet and Bordet \(1963\)](#), and [Guillot and  
171 Ménot \(2009\)](#) (Fig. 1B), defines the Western, Central and Eastern domains.

172 The Western domain consists of slightly metamorphosed micaschists and  
173 metagreywackes considered as a turbiditic series of Ordovician age ([Bordet and Bordet, 1963](#);  
174 [Fréville et al., 2018](#)). The central domain, including the SW part of the Aiguilles Rouges, the  
175 SW part of Belledonne massifs, and the western part of the Pelvoux massif or Cortical Pelvoux  
176 area ([Le Fort, 1973](#); Fig. 2) is made of a stack of several litho-tectonic units, namely from top  
177 to bottom: (i) the Cambro-Ordovician Chamrousse ophiolite ([Carme, 1965a](#); [Carme, 1965b](#);  
178 [Carme, 1970](#); [Bodinier et al., 1981](#); [Ménot, 1987](#); [Pin and Carme, 1987](#); [Ménot, 1988a](#); [Ménot,  
179 1988b](#)); (ii) an amphibolitic facies gneiss, micaschists and volcano-sedimentary rocks (VSU,  
180 *Riouperoux-Livet* and *Allemont* units) overlain by (iii) a weakly metamorphosed and  
181 deformed conglomerate, black schist, and acidic volcanic rocks, named the *Taillefer* unit  
182 ([Gibergy, 1968](#); [Ménot, 1988](#); [Fréville et al. 2018](#)).

183 The Eastern part of the ECMs consists of high-grade rocks of the mid-lower crust with  
184 migmatites enclosing several lenses of HP granulites and retrogressed eclogites that crop out in  
185 the *Argentera* massif, the Inner Pelvoux area, the NE Belledonne area, the major part of the  
186 *Aiguilles Rouges-Mont Blanc* massif, and the *Aar-Gothard* massif. (Fig. 1B, [Paquette et al.,  
187 1989](#); [Abrecht and Biino, 1991](#); [Lombardo et al., 1997](#); [Von Raumer and Bussy,  
188 2004](#); [Ferrando et al., 2008](#); [Compagnoni et al., 2010](#); [Rubatto et al., 2010](#); [Jacob et al., 2021](#)).

189 These three crustal domains are juxtaposed along the Synclinal-Median Fault (SMF) and the  
190 Rivier-Belle Etoile Fault (RBEF, Fig. 1B)

191

## 192 *2.2. Impact of the post-variscan reworking in the Belledonne-Pelvoux area*

193

194 The Jurassic rifting, coeval with the opening of the Liguro-Piemonte ocean, was  
195 responsible for the development of brittle normal faults associated with the local tilting of the  
196 Paleozoic basement. It was responsible for the individualization of several Liassic blocks. These

197 are the *La Mure* and *Le Taillefer* blocks within the Belledonne massif, and *Le Rochail*,  
198 *L'Emparis*, *La Meije*, and *Le Combeynot* blocks in the Pelvoux massif (Fig. 2) (Lemoine et al.,  
199 1986; Barféty et al., 1988; Lemoine, 1988). The Miocene Alpine deformation inverted the  
200 Jurassic normal faults and was responsible for the development of localized NW-SE trending  
201 shear zones with a top-to-the NW ductile shearing (Bellahsen et al., 2014; Bellanger et al., 2014,  
202 2015; Boutoux et al., 2014). The Alpine shortening in the Paleozoic basement was coeval with  
203 a weak metamorphic overprint in the prehnite-pumpellyite to greenschist facies. Outside these  
204 localized Alpine shear zones, the markers of the Pre-Alpine tectono-metamorphic events are  
205 particularly well-preserved in the Belledonne-Pelvoux area.

206

### 207 2.3. Summary of previous P-T-t data on the Pelvoux Massif

208

209 In the literature, the Pelvoux massif is described as two-fold, with the Cortical and the  
210 Inner Pelvoux domains, the boundary of which is mainly reworked by alpine faulting (Le Fort,  
211 1973). The Cortical Pelvoux, located in the western part, consists of an alternation of  
212 volcanoclastic rocks and micaschists with migmatitic gneisses at the base of these series (Fig.  
213 2). Barrovian metamorphism is attested by kyanite-staurolite bearing micaschists documented  
214 in the Cortical Pelvoux (Le Fort, 1973) but quantitative thermobarometric estimates are not  
215 available. In the adjacent SW Belledonne, a MP-HT barrovian metamorphism ( $M_1$ ) is  
216 documented with P-T conditions at ca. 0.5-0.6 GPa, 600 °C, recorded in staurolite-bearing  
217 micaschists and up to ca. 0.8 GPa, 680 °C for the migmatitic gneiss in lowest unit (Guillot and  
218 Ménot, 1999; Fernandez et al., 2002; Fréville et al., 2018). The  $M_1$  metamorphism is coeval  
219 with a  $D_1$  deformation characterized by the development of a westward dipping foliation  $S_1$  and  
220 E-W stretching  $L_1$  lineation interpreted as an eastward nappe stacking event (Fréville et al.,  
221 2018). At upper structural level in the Cortical Pelvoux, a series of micaschists and  
222 volcanoclastic rocks is overlain by black schists and conglomerates, similar to the *Taillefer* unit  
223 observed in SW Belledonne (Barfety et al., 2000; Guillot and Ménot, 2009) (Fig. 2).

224 The Inner Pelvoux is composed of i) migmatites that developed through partial melting  
225 of paragneiss, orthogneiss and amphibolite, and ii) several generations of granitoids (Pecher,  
226 1970; Le Fort, 1973). Some mafic lenses (e.g. *Peyre-Arguet*, Fig. 2) within migmatitic  
227 paragneiss record amphibolite facies P-T conditions of  $0.7 \pm 0.1$  GPa,  $650 \pm 50$  °C, and a low-  
228 pressure granulite facies of  $0.5 \pm 0.1$  GPa,  $800 \pm 50$  °C, followed by a retrogressive evolution  
229 in the greenschist facies conditions (Grandjean et al., 1996). Granulitic conditions have also



230 been inferred from the migmatitic gneiss (Pecher, 1970; Pecher and Vialon, 1970) but without  
231 any phase diagram quantification. Two episodes of partial melting are recognized with a first  
232 low-temperature, cordierite-free migmatite, and a high-temperature – low-pressure, cordierite-  
233 bearing migmatite (Bogdanoff et al., 1991). In the Inner Pelvoux, the foliation is mostly steeply  
234 dipping to vertical, but superimposed deformation has been invoked (Pecher, 1970; Le Fort,  
235 1973) and the relationships between partial melting and deformation are still unclear.

236 Two groups of granitoids are distinguished, namely two-mica granites and monzonitic  
237 granites (Barf  ty et al., 1982; Debon and Lemmet, 1999). Presently, only the two-mica Rochail  
238 and Combeynot granites, and the Turbat-Lauranoure monzonite have been dated with proposed  
239 emplacement age at  $343 \pm 11$  Ma,  $312 \pm 7$  Ma and  $302 \pm 2$  Ma, respectively (U-Pb on zircon;  
240 Canic, 1998; Guerrot and Debon, 2000). N-S to NW-SE striking, syn-magmatic sinistral C-S  
241 fabrics are described in granitic plutons (Strzeczynski et al., 2005) but the geometrical and  
242 kinematic relationships with their migmatitic host rocks are poorly understood.

243

### 244 3. Structural analysis

245

#### 246 3.1. Strain patterns in the metamorphic and migmatitic pile

247

248 At the scale of the entire Pelvoux massif, field observations show that the dominant  
249 macroscopic ductile structure is a steeply dipping foliation, ascribed here to the D<sub>2</sub> event (Fig.  
250 3 and 4). Due to its pervasive character, the D<sub>2</sub> event will be presented first.

251

##### 252 3.1.1 The D<sub>2</sub> submeridian sinistral shearing

253

254 The majority of this D<sub>2</sub> planar structure is represented by a gneissic (i.e. solid-state  
255 deformation), and a migmatitic foliation (i.e. suprasolidus deformation). It ranges from NW-SE  
256 to NE-SW with the occurrence of three main directional populations: ~N30°E, ~N140°E and  
257 ~N170°E (Figs. 3 and 4). The ~N30°E foliation is less represented than the two other directions  
258 and is referred to as S<sub>2</sub> in the following. S<sub>2</sub> is axial planar to upright folds F<sub>2</sub> that deforms an  
259 earlier weakly dipping S<sub>1</sub> foliation (see below). S<sub>2</sub> developed in response to an E-W to NW-SE  
260 bulk shortening (Figs. 5A and 5B). In the Inner Pelvoux, S<sub>2</sub> consists of a migmatitic layering  
261 that almost totally transposes S<sub>1</sub> that is only preserved within F<sub>2</sub> folds hinges (see next  
262 paragraph and Fig. 5C).

263 The two most developed D<sub>2</sub> planar fabrics are striking N170°E and N140°E with a high  
264 (>70°) dip angle (Fig. 3). Both sets show melt-present and solid-state deformation features (Fig.  
265 5D). When the three directional populations of planar fabrics, i.e. ~N30°E, ~N140°E and  
266 ~N170°E are observed on the same outcrops, the cross-cutting relationships clearly indicate  
267 that the ~N170°E planar surface is a shear plane that reworks the ~N30°E directed foliation,  
268 and that both ~N30°E and ~N170°E trending planar surfaces are reworked by the ~N140°E  
269 shear zone, as portrayed in Figure 7.

270 In the northern and eastern portions of the Emparis and La Meije Blocks, the N170°E  
271 trending and highly penetrative planar surface forms 100 meters to several kilometers wide  
272 shear zones (Figs. 3 and 4) along which a southward low-angle plunging L<sub>2</sub> stretching lineation  
273 is observed (Fig. 3B). A sinistral kinematics is deduced from the observation of sigmoidal  
274 minerals or aggregates and the deflection of S<sub>2</sub> (Figs. 3, 5E, 5F, 6A). In the southern part of the  
275 Pelvoux massif, similar meter to kilometers sized sinistral high-strain corridors strike mostly  
276 ~N140°E (Fig. 3). Where the NW-SE planar fabric becomes preponderant, the N-S surface is  
277 only preserved within centimeter to meter scale lenticular bodies (Fig. 7A). The mineral and/or  
278 stretching lineations are rarely observed; but when it is the case, they are sub-horizontal or  
279 moderately plunging (Fig. 3). In some places, within stromatic migmatite, the oblate shape of  
280 mafic restites suggests that flattening strain without the development of a preferred stretching  
281 direction was dominant (Fig. 6B). At the outcrop scale, some conjugate dextral and sinistral  
282 shear bands are also observed (Fig. 6C). Considering the geometric and kinematic features of  
283 the D<sub>2</sub> structures, it appears that the N170°E and N140°E planar surfaces might be considered  
284 as C<sub>2</sub> and C'<sub>2</sub> shear planes that developed synchronously with S<sub>2</sub> in a bulk sinistral strike-slip  
285 regime. This S<sub>2</sub>, C<sub>2</sub>, C'<sub>2</sub> anastomosing system is observed from kilometer to meter scale (Figs.  
286 3). The presence of leucosome within the S<sub>2</sub>, C<sub>2</sub> and C'<sub>2</sub> shear bands attests for the onset of D<sub>2</sub>  
287 in a partially molten rock, under supra-solidus conditions (Fig. 5). Diatexite commonly shows  
288 rafts and schollens with a high aspect-ratio parallel to the migmatitic foliation arranged either  
289 on the C<sub>2</sub> or C'<sub>2</sub> trends (Figs. 6D, 6E and 6F). In some places, cm-scale elongated cordierite  
290 aggregates are preferentially aligned along C<sub>2</sub> and C'<sub>2</sub> planes (Fig. 6F) indicating that low-  
291 pressure/high-temperature partial melting was coeval with the D<sub>2</sub> sinistral strike-slip. The D<sub>2</sub>  
292 planar surface is also reported within garnet-bearing amphibolites (Fig. 7B) that are interpreted  
293 as retrogressed HP granulites (Grandjean et al., 1996).

294

295 3.1.2 The relictual D<sub>1</sub> structure

296

297 The D<sub>2</sub> anastomosed system reworks a nearly horizontal or westward shallowly dipping  
298 early foliation, named S<sub>1</sub> (Figs. 3 and 4). Within the Inner Pelvoux, the relictual S<sub>1</sub> foliation  
299 corresponds to a gneissic layering and lithological alternations, the attitude of which marks  
300 large scale F<sub>2</sub> folds. This is exemplified by the attitude of the La Lavey amphibolite formation  
301 in the La Meije block where a low angle (20-40°) S<sub>1</sub> foliation is observed (Fig 3). In the Inner  
302 Pelvoux, the S<sub>1</sub> foliation only remains as isolated F<sub>2</sub> fold hinges (Figs. 5A and 5B). In the  
303 Cortical Pelvoux, a S<sub>1</sub> gneissic layering with a low-angle dip is also recognized. It is worth  
304 noting that L<sub>1</sub> lineation is very rare with no clear preferred direction. Generally, the  
305 superimposition of S<sub>2</sub> and S<sub>3</sub> over S<sub>1</sub> makes the latter difficult to depict in the outcrop. Relics  
306 of S<sub>1</sub> are best recognized at the cm-scale (thin section) (Fig. 8B).

307

### 308 3.1.3 Late horizontal shearing: D<sub>3</sub> structure

309 A flat-lying foliation (S<sub>3</sub>) superimposed on both the D<sub>1</sub> and D<sub>2</sub> fabrics is observed in the  
310 Inner Pelvoux, at m-cm scale, and attributed here to a D<sub>3</sub> deformation (Fig. 3, 4 and 8). The D<sub>2</sub>  
311 planar fabric elements (S<sub>2</sub>-C<sub>2</sub>-C'<sub>2</sub>) are involved in the formation of S<sub>3</sub> axial planar F<sub>3</sub> folds, and  
312 C<sub>3</sub> shear bands with top-to-the-NW kinematics (Figs. 8 and 9). The attitude of leucosome that  
313 parallels S<sub>3</sub> and the horizontal axial plane of F<sub>3</sub> folds argue for melt migration during D<sub>3</sub> (Figs.  
314 9A and B). The melt-bearing S<sub>3</sub> foliation cuts across S<sub>2</sub> the upper structural level of the *La*  
315 *Meije* block.

316 In the *Le Rochail* block, a similar D<sub>3</sub> strain pattern is observed with centimeter-scale F<sub>3</sub>  
317 folds, with sub-horizontal axial planes that rework the subvertical S<sub>2</sub> foliation. F<sub>3</sub> fold axes are  
318 weakly plunging toward the NW. In the Cortical Pelvoux, a kilometer-scale D<sub>3</sub> decreasing strain  
319 gradient can be observed from west to east. The S<sub>3</sub> becomes more penetrative and presents a  
320 mylonitic fabric in which a N150-160°E stretching lineation L<sub>3</sub> is observed (Figs. 3 and 8D).  
321 Along the L<sub>3</sub> stretching lineation, kinematic criteria (sigmoidal structures, pressure shadow, and  
322 shear bands) indicate a top-to-the northwest sense of shear whatever the observation scale (Figs.  
323 8 and 9). A-type folds with axes parallels to L<sub>3</sub> lineation can be also observed. Accordingly, a  
324 similar stretching direction is documented by Jacob (2022) and Jacob et al. (2022) in the La  
325 Meije Block with the observations of a syn-migmatitic flat-lying foliation documenting a N150-  
326 N180 directed horizontal flow that reworks early D<sub>1</sub> and D<sub>2</sub> fabrics.

327

### 328 3.2. Strain patterns in the felsic plutons

329

330 Within the granitic bodies of the Inner Pelvoux area (e.g. Turbat-Lauranoure, Etages, La  
331 Bélarde-Promontoire plutons), the  $S_1$ ,  $S_2$  and  $S_3$  were not identified but the two  $C_2$  ( $\sim N170^\circ E$ )  
332 and  $C'_2$  ( $N140^\circ E$ ) structures are recognized. The preferred orientation of feldspar, biotite and  
333 shape ratio of mafic enclaves define a  $\sim N160-170^\circ E$  striking subvertical magmatic foliation.  
334 When observed, the stretching lineation is sub-horizontal and trends NNW-SSE as previously  
335 described by Strzeczynski et al. (2005). In agreement with these authors, we also document the  
336 presence of  $N135-140^\circ E$  striking and vertical ductile shear bands. These shear-bands rise to C-  
337 S-like structures, which reflect a sinistral strike-slip shearing, as best exemplified in the  
338 Bélarde-Promontoire and Etages granites (Fig. 3). In agreement with Strzeczynski et al. (2005),  
339 we consider that the sinistral kinematics was coeval with pluton emplacement. These  $C_2$  and  
340  $C'_2$  planar surfaces that developed under supra-solidus magmatic conditions, appear in  
341 continuity with the  $D_2$  structures observed in the country rocks, indicating a syn- $D_2$   
342 emplacement of those plutons.

343 In the northern part of the Cortical Pelvoux, the Rochail granite shows a sub-horizontal  
344 magmatic foliation inferred from biotite arrangement (Barf  ty et al., 1988) and does not show  
345 subsolidus deformation. The  $D_2$  deformation was not observed in the pluton, and the  $S_3$  foliation  
346 wraps around the granite (Fig. 4A). This may indicate that the flat-lying magmatic foliation  
347 could be ascribed to  $S_1$  (see discussion below in section 5).

#### 348 4. Petro-chronological results

349 This section presents U-Th-Pb radiometric analyses of monazite and zircon grains from  
350 (1) mylonitic gneiss (samples *MCE379* and *MCE382b*), (2) Al-rich metapelites (samples  
351 *MCE339v*, *MCE338* and *MCE328*), (3) migmatites (samples *MCE314*, *MCE330*, *MCE140b*  
352 and *MCE313b*) and (4) metamafigs (sample *MCE304v2*) sampled in the Cortical and Inner  
353 Pelvoux (Fig. 2; Table 1). A petrological description is given for each sample (Fig. 10). Before  
354 isotopic analyses, cathodoluminescence (CL) and back-scattered electron (BSE) images were  
355 acquired for all zircon and monazite grains, respectively, using a scanning electron microscope  
356 (SEM) in order to check spot locations with respect to the internal microstructures, inclusions,  
357 fractures and physical defects. For monazite, U-Th-Pb analyses were performed by LA-ICP-  
358 MS directly in thin section at the University of Montpellier (samples *MCE338*, *MCE314* and  
359 *MCE382b*) and at BRGM (Bureau de Recherche G  ologique et Mini  re) (*MCE328*, *MCE339v*  
360 and *MCE379*) (Table S1). The analytical protocol for the University of Montpellier followed

361 the procedure described in Bruguier et al. (2017) and is presented in Table S2. Manangotry  
362 (Poitrasson et al., 2000) and Moacyr (Goncalves et al., 2016) monazites used as calibration and  
363 quality control reference materials yielded concordia ages of  $552 \pm 2$  Ma (MSWD=2.2, n=38)  
364 and  $507 \pm 2.5$  Ma (MSWD=0.02, n=14), respectively. The analytical protocol for the BRGM is  
365 presented in Table S3 and the Madmon and Namaqualand monazites used as quality control  
366 reference materials yielded concordia ages of  $514 \pm 7$  Ma (MSWD=1.4, n=10) and  $994 \pm 17$   
367 Ma (MSWD=1.3, n=10), respectively.

368 The zircon U-Pb analyses were performed at BRGM (Sample *MCE330*, *MCE 304v2*  
369 and *MCE313b*) and at GeOHeLiS analytical platform (University Rennes 1) (Sample  
370 *MCE140b*, Table S1, S4). Zircon grains were obtained by a conventional mineral separation.  
371 The selected grains (~100-200  $\mu\text{m}$  size) were mounted in epoxy resin and polished down to  
372 expose their near equatorial sections. The analytical protocol for the BRGM is presented in  
373 Table S3 and the Plešovice zircon (Sláma et al., 2008) used as quality control reference material  
374 yielded a concordia age of  $340 \pm 3$  Ma (MSWD=1.5, n=24). The analytical protocol for the  
375 GeOHeLiS analytical Platform is presented in Table S4 and the Plešovice zircon (Sláma et al.,  
376 2008) used as quality control reference material yielded a concordia age of  $337.6 \pm 2.0$  Ma  
377 (MSWD=0.23, n=15). See Manzotti et al. (2016) for more details on the analytical protocol.

378 Two Al-rich metapelitic samples (*MCE339v* and *MCE338*) were investigated for their  
379 metamorphic evolutions through petrology and phase diagram calculations. Electron  
380 microprobe analysis has been performed at the University of Orléans on a CAMECA SX-FIVE.  
381 The P-T metamorphic conditions were obtained through calculations of pseudosection  
382 diagrams using Perple\_X 6.9.1. software (Connolly and Pettrini, 2002; Connolly, 2005;  
383 hpver62 database from Holland and Powell, 2011). The considered system was MnO-Na<sub>2</sub>O-  
384 CaO-K<sub>2</sub>O-FeO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O (MnNCKFMASH). Solution models used in the  
385 calculations were garnet, biotite, white mica, staurolite, cordierite, chlorite, chloritoid and melt  
386 (White et al., 2014) as well as plagioclase (Fuhrman & Lindsley, 1988) and ilmenite (White et  
387 al., 2000). Whole rock major element compositions (Table 2) were obtained using a  
388 PANalytical AxiosmAX X-Ray Fluorescence (XRF) Spectrometer at Lausanne University,  
389 Lausanne, Switzerland. The P-T conditions of biotite, muscovite and plagioclase equilibrium  
390 were estimated using the third model quality factor Qcmp described in Duesterhoeft & Lanari  
391 (2020) in order to have a quantitative approach. This factor calculates the fitting between the  
392 mineral composition and the composition modelled and takes account of the relative analytical  
393 uncertainty of the extracted compositions. The comparison of mineral composition was  
394 restricted to MnO, MgO, FeO, SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> contents for biotite, of Na<sub>2</sub>O, K<sub>2</sub>O, CaO, Al<sub>2</sub>O<sub>3</sub>,

395 FeO, MgO and SiO<sub>2</sub> contents for muscovite, and of CaO, K<sub>2</sub>O, Na<sub>2</sub>O, SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> contents  
 396 for plagioclase.

397

#### 398 4.1. Gneissic mylonites (samples MCE379 and MCE382b)

399

400 The sample *MCE379* is a gneiss from the volcano-sedimentary unit of the northern part  
 401 of the Cortical Pelvoux where the main planar fabric is a composite S<sub>1-3</sub> foliation (Fig. 4A). It  
 402 is composed of Qtz + Kfs + Bt with rare garnet and muscovite occurrences and few late white  
 403 micas (Fig. 10A). It is structured by D<sub>1</sub> shear planes oriented N120°E/30NW, kinematic is not  
 404 clear because of D<sub>3</sub> superimposition. Quartz ribbons show undulose extinction and Grain  
 405 Boundary Migration recrystallization (GBM; [Stipp et al., 2002](#)). Monazite is located either in  
 406 the quartzo-feldspathic matrix (Fig. 10B) or as an undeformed inclusion in biotite marking the  
 407 S<sub>1</sub> foliation (Fig. 10C and D). Monazite grains do not show any zonation in BSE images (Fig.  
 408 S1) and have U, Pb and Th contents ranging between 1322-3462 ppm, 869-2110 ppm and  
 409 22326-72038 ppm, respectively, with Th/U ratios between 8.1 and 27.8 (Table S1). Twenty-  
 410 nine analyses were performed on 26 monazite grains within the matrix. Except two discordant  
 411 analyses, all analyses yield a concordant date at  $334.8 \pm 3.2$  Ma ( $n = 27$ ;  $MSWD_{(C+E)} = 1.3$ )  
 412 (Fig. 12A).

413 Sample *MCE382b* is a gneiss coming from the same area as sample *MCE379* (Fig. 2).  
 414 It is composed of Qtz + Kfs + Bt + Grt + late Ms (Fig. 10E). In this sample, D<sub>3</sub> strain is higher  
 415 than in sample *MCE379* and the D<sub>3</sub> mylonitic planar fabric is oriented N133°E;30NE with a L<sub>3</sub>  
 416 stretching lineation trending N120°E. C-S structures and sigmoidal quartz aggregates indicate  
 417 top-to-the-NW kinematics (Fig. 10E). Quartz crystals are stretched and form quartz-ribbons  
 418 with undulose extinction and GBM recrystallization.

419 Fourteen monazite grains from sample *MCE382b* have been analyzed *in situ*, they do  
 420 not show any zonation (Fig. S1) but display two habitus: monazite included in large biotite  
 421 marking the S<sub>3</sub> foliation (group 1; Fig. 10G and H) and monazite located inside the quartzo-  
 422 feldspathic matrix (group 2; Fig. 10F). Monazite grains from the quartzo-feldspathic matrix  
 423 (group 2) have U, Pb and Th contents between 740-1016 ppm, 1198-1796 ppm and 15803-  
 424 26505 ppm, respectively, and Th/U ratios of 19.4-36.9 (Table S1). Monazite inclusions within  
 425 large biotite marking the S<sub>3</sub> foliation (group 1) have higher U contents (1241-1997 ppm),  
 426 similar Pb and Th contents (1063-1478 ppm and 11914-21818), and lower Th/U ratios (6.1-  
 427 16.4). Two ages can be identified (Fig. 11B), the oldest one is calculated from 7 monazite grains  
 428 located in the matrix (group 2) that provide a concordant date at  $334.5 \pm 3.4$  Ma ( $MSWD_{(C+E)}$ )

429 = 0.88). The second one is obtained from 4 grains included within large biotite (group 1)  
430 yielding a concordant date at  $306.0 \pm 3.5$  Ma ( $\text{MSWD}_{(C+E)} = 0.39$ ).

431

#### 432 4.2. Al-rich metapelites (samples MCE339v, MCE338 and MCE328)

433

434 Sample MCE339v is a micaschist composed of Qtz + Grt + Ky + St + Bt + Ms + Pl (Fig.  
435 11A) sampled in the middle part of the Cortical Pelvoux (SW of Entraigues village, Fig. 2). It  
436 is structured by a pervasive D<sub>2</sub> shear zone oriented N0°E;70E with a horizontal stretching  
437 lineation trending N0. Staurolite and kyanite are relictual and are strongly affected by the D<sub>2</sub>  
438 shearing. An old foliation, probably S<sub>1</sub>, is preserved in kyanite and garnet (Fig. 11B). Micas  
439 and quartz layers form sinistral sigmoids wrapping around garnet porphyroblasts.

440 Garnet grains show a slight zonation (Fig. 13A) with a core composed of ca. 64% of  
441 almandine, 5% of pyrope, 18.5% of grossular and 12.5% of spessartine, and a rim composed of  
442 74% of almandine, 12% of pyrope, 13% of grossular and 1% of spessartine (Table 3). Mineral  
443 compositions were modified by diffusion processes, as suggested by the smooth compositional  
444 zoning (Fig. 13A). Plagioclase is an oligoclase with Ab<sub>76</sub>, and biotite presents a stable  
445 composition at X<sub>Fe</sub> 0.57 (Table 3). A phase equilibrium diagram was calculated for this sample  
446 with a H<sub>2</sub>O content at 1.33 % wt, which corresponds to the saturation of the sample at the  
447 solidus conditions as estimated from a T-X<sub>H<sub>2</sub>O</sub> diagram (Fig. 13B). The obtained phase diagram  
448 defines a large stability field corresponding to the mineral assemblage of sample MCE339v  
449 (Qtz + Grt + Ky + St + Bt + Ms + Pl) with temperature and pressure conditions below 600 °C  
450 and 0.7 GPa, respectively (Fig. 13C). The phase diagram fails to reproduce the garnet core  
451 composition, perhaps due to diffusion process and modification of the initial composition of  
452 the garnet core. The Q<sub>cmp</sub> factor of the plagioclase composition only slightly varies, and its  
453 maximal value is 99.8% of fitting with the reference composition (Fig. 13C). This highest Q<sub>cmp</sub>  
454 value (Duesterhoeft et Lanari, 2020) indicates P-T conditions inferior to 650 °C and 0.6 GPa  
455 and is well expressed in the stability field of the mineral assemblage (Fig. 13C). The Q<sub>cmp</sub>  
456 factor of the biotite reaches a value of 95% of fitting with the reference composition and  
457 indicates temperatures between 525 and 750 °C and pressure conditions between 0.4 and 0.7  
458 GPa and only expressed in the stability field of the mineral assemblage at around 550 °C and  
459 0.5 GPa (Fig. 13D). These results must be taken with caution due to potential diffusion  
460 processes that might have affected the mineral compositions and analytical uncertainties on the  
461 reference compositions.

462 Monazite grains from sample *MCE339v* do not show any zonation, however two  
463 populations are recognized: the first one (group 1) is composed of monazite grains not oriented  
464 within the  $S_2$  foliation and often included in quartz and sometimes in kyanite (Fig. 11B),  
465 displaying U, Pb and Th contents at 2985-6844 ppm, 1894-4304 ppm and 20221-45439 ppm,  
466 respectively, and medium Th/U ratios (5.1-7.6). The second population (group 2) is composed  
467 of monazite grains oriented parallel to the main  $S_2$  foliation in mica-rich layers (Fig. 11C), with  
468 higher U and Pb contents ranging at 7069-8247 ppm and 4006-4827 ppm, Th varying in the  
469 range 33668-50915 ppm. The Th/U ratios are in the range 4.8-6.7 (Table S1). Analyses  
470 performed on monazite grains from the first group yield a concordant date at  $346.6 \pm 4.8$  Ma ( $n$   
471  $= 7$ ;  $MSWD_{(C+E)} = 0.51$ ) (Fig. 11C), whereas analyses from the second group of monazite grains  
472 provide a concordant date at  $319.2 \pm 6.1$  Ma ( $n = 4$ ;  $MSWD_{(C+E)} = 0.78$ ).

473  
474 Sample *MCE338* is a metapelite sampled in the middle of the Cortical Pelvoux (Fig. 2).  
475 It is composed of Qtz + Pl + Ms + Bt + Grt + Sill with scarce tourmaline (Fig. 11D). The main  
476 planar fabric is a  $S_1$  foliation showing numerous variscan sigmoidal and C-S structures  
477 reoriented by the alpine tectonics. Garnet grains are boudinaged by  $D_1$  with boudin necks filled  
478 by biotite, quartz and sillimanite (Fig. 11D). Fibrolitic sillimanite is localized in  $D_1$  structures  
479 and in  $D_1$  sigmoid tails, suggesting a syn- $D_1$  crystallization. A phase equilibrium diagram was  
480 calculated for this sample. (Fig. 14).  $H_2O$  amount was defined at 1.47 %wt, which corresponds  
481 to the saturation of the sample at the solidus conditions of the mineral assemblage and was  
482 estimated from a T- $X_{H_2O}$  pseudosection (Fig. 14B). Garnet grains show a slight zonation (Fig.  
483 14A) with a core composed of ca. 71% of almandine, 12.5% of pyrope, 5.5 % of grossular and  
484 11% of spessartine, and a rim composed of 68.5% of almandine, 8.5% of pyrope, 4% of  
485 grossular and 19% of spessartine (Table 3). Plagioclase is homogeneous in composition with  
486  $Ab_{75}$ , and biotite presents a stable composition at  $X_{Fe}$  0.56 (Table 3). The resulting  
487 pseudosection (Fig. 12B and C) indicates a stability field with the mineral assemblage  
488 corresponding to the one observed in the sample (i.e. Pl + Grt + Ms + Bt + Sill + Qtz). Due to  
489 its low proportion and variability, grossular was not used to constrain the P-T conditions. The  
490 almandine, pyrope and spessartine isopleths of the garnet core cross-cut at  $565 \pm 30$  °C and  $0.46$   
491  $\pm 0.04$  GPa in the stability field of the observed mineral assemblage (Fig. 12B). Regarding the  
492 low volume of garnet in this sample (i.e. inferior to 3 vol%), we did not calculate a new  
493 pseudosection removing the garnet core bulk composition. Isopleths from the garnet rims cross-  
494 cuts at  $450 \pm 30$  °C and  $0.36 \pm 0.02$  GPa (Fig. 12B). The best  $Q_{cmp}$  values of the biotite and  
495 plagioclase do not perfectly fit with these P-T conditions, but their  $Q_{cmp}$  remains high at the



496 P-T conditions defined by the garnet core composition (Fig. 14D and F). The best Qcmp factor  
 497 of the muscovite might indicate a higher-pressure stage around 0.7-0.8 GPa before the P-T  
 498 conditions defined by the garnet core (Fig. 14E).

499 In the sample *MCE338*, monazite grains are included in quartz, in biotite and in  
 500 muscovite-biotite layers (Fig. 11E and F). They are mainly parallel with the  $S_1$  foliation (Fig.  
 501 11F) and sometimes show syn- $D_1$  kinematic criteria (Fig. 11E). They do not show zonation on  
 502 BSE images (Fig. S1). Twenty-eight analyses display U, Pb and Th contents ranging between  
 503 1486-5802 ppm, 786-3070 ppm and 7372-33214 ppm, respectively, with constant Th/U ratios  
 504 (4.2-6.1; Table SE1). By removing discordant data (ja8, ja11, ja15, ja20, ja24, ja27, ja28 and  
 505 ja29; Table SE1), as well as the younger and older analyses (ja13 and ja5 respectively; Table  
 506 SE1), the remaining data points provide a concordia date of  $333.2 \pm 1.6$  Ma ( $n = 18$ ;  $MSWD_{(C+E)}$   
 507  $= 0.83$ ) (Fig. 11D).

508  
 509 Sample *MCE328* is a micaschist from the southern part of the Cortical Pelvoux (Fig. 2).  
 510 It is composed of quartz, muscovite, biotite, staurolite and kyanite (Fig. 11G). The main planar  
 511 fabric of this sample is a composite  $S_{1-3}$  foliation oriented  $N160^\circ E; 25^\circ E$  with a subhorizontal  $L_3$   
 512 stretching lineation trending  $N160^\circ E$ . The quartz and mica sigmoidal aggregates indicate a  $D_1$   
 513 top-to-the-NW sense of shear, while  $D_3$  shear bands indicate top-to-the-SE kinematics (Fig.  
 514 11G). Kyanite and staurolite, often surrounded by a white mica-corona, are deformed by the  $D_3$   
 515 shear bands. Biotites are commonly chloritized. Monazite grains are mainly located in the  
 516 quartz-matrix or in biotite marking the  $S_1$  foliation and are typically oriented parallel to the  $S_1$   
 517 foliation (Fig. 11H). Some monazite grains also seem included in staurolite (Fig. 11I). They do  
 518 not show chemical zoning (Fig. S1). The analyzed grains display U, Pb and Th contents ranging  
 519 between 3761-8639 ppm, 2160-5277 ppm and 24475-45307 ppm, respectively, and constant  
 520 Th/U ratios (5.2-7.1 except one data at 4.0; Table S1). As the whole, 17 analyses were  
 521 performed, among them, 14 are concordant and yield a concordia date of  $330.7 \pm 3.1$  Ma  
 522 ( $MSWD_{(C+E)} = 1.4$ ) (Fig. 11E).

### 523 524 4.3. Migmatites (samples *MCE314*, *MCE330*, *MCE140b* and *MCE313b*)

525  
 526 The cordierite bearing migmatite *MCE314* has been sampled in the Inner Pelvoux  
 527 massif (Fig. 2). It is composed of quartz, K-feldspar, muscovite, chloritized biotite and pinitized  
 528 cordierite. This sample exhibits a highly dipping and  $N140^\circ E$  striking  $S_2$  foliation defined by  
 529 quartz aggregates and phyllosilicates. Subsidiary deformation is rare, and  $S_2$  foliation is mainly

530 a suprasolidus planar fabric. The alpine tectonics induced a low-grade retrogression as shown  
531 by chlorite around biotites, and sericite around K-feldspar. Unfortunately, because of alpine  
532 retrogression and strong pseudomorphosis of cordierite, pseudosection calculation was not  
533 possible. One may consider that cordierite-bearing migmatites are generally formed under low-  
534 pressure and high temperature conditions at ca. 0.4-0.6 GPa; 750-850 °C (Barbey et al., 1999;  
535 Kalt et al., 1999).

536 Monazite grains, located within the quartzo-feldspathic matrix, are not zoned and  
537 display heterogeneous U and Th contents (3437-10171 ppm and 5909-86534 ppm,  
538 respectively), relatively constant Pb content (1210-5516 ppm), and heterogeneous Th/U ratios  
539 (1.3-20.2) (Table S1). Despite this chemical heterogeneity, all analyses are concordant or sub-  
540 concordant (except jb7; Table S1), and yield a concordia date of  $307.5 \pm 1.9$  Ma ( $n = 18$ ;  
541  $MSWD_{(C+E)} = 1.4$ ) (Fig. 11F).

542  
543 The Roux migmatite (*MCE330*), located in the Cortical Pelvoux, is a migmatitic gneiss  
544 developed at the base of the VSU (Fig. 2 and 4B). It is composed of quartz + K-feldspar +  
545 plagioclase + Biotite + Muscovite and is the equivalent of the Allemont migmatites from the  
546 SW Belledonne area (Fréville et al., 2018). The *MCE330* migmatite shows a N110°E40 solid-  
547 state protomylonitic foliation that erased syn-melting fabrics (Fig. 9F). The preferred  
548 orientation of mica and quartz-feldspar aggregates defines S-C fabrics that we attribute to D<sub>3</sub>.  
549 The CL images of the analysed zircon grains show inherited cores with a typical magmatic  
550 concentric oscillatory zoning and metamorphic rims (Fig. S1). Zircon cores and rims have  
551 similar U and Pb contents ranging between 247-2605 ppm and 12-140 ppm, respectively (Table  
552 S1). Thirty analyses have been performed on 30 zircon grains (Fig. 13A). In the Tera-  
553 Wasserburg diagram, analyses mainly cluster into two groups. The first one, includes 13  
554 concordant analyses on zircon cores, indicate a late Neoproterozoic age of crystallization.  
555 Among them 9 analyses yield a concordant date at  $590.6 \pm 6.2$  Ma ( $MSWD_{(C+E)} = 0.95$ ). Two  
556 zircon cores show concordant and sub-concordant dates at ca. 1700 Ma and 1800 Ma (Fig.  
557 13A), and two single analyses yield concordant dates at ca. 405 and 380 Ma. The second cluster  
558 includes 12 analyses performed on zircon rims and yields a concordia date at  $330.5 \pm 3.1$  Ma  
559 ( $MSWD_{(C+E)} = 0.92$ ) (Fig. 13A).

560  
561 The Etages migmatite (*MCE140b*), located in the Inner Pelvoux, forms the country rock  
562 of the Etages granite (Fig. 2 and 4A). Composed of chloritized biotite, feldspars and quartz this  
563 rock shows a slight C<sub>2</sub> orientation, and it was also superimposed by a low-temperature alpine

564 deformation (Fig. 4A). Euhedral zircon crystals with elongated shapes present oscillatory  
 565 zonings in CL (Fig. S1). Twenty-eight zircon grains were analysed and they form two age  
 566 groups (Fig. 13B). The first one is composed of four analyses forming a concordant cluster with  
 567 low U, Pb and Th contents and Th/U ratios ranging from 0.08 to 0.5 (Table S1), that yields a  
 568 concordant date at  $317 \pm 3.6$  Ma ( $\text{MSWD}_{(C+E)} = 0.38$ ) (Fig. 13B). The second group is composed  
 569 of 22 analyses with higher U, Pb and Th contents than the first group, but with similar Th/U  
 570 ratios ranging from 0.06 to 0.5 (Table S1). Among this group, numerous analyses show lead  
 571 loss (Fig. 13B) but ten analyses define a concordant date at  $297.8 \pm 2.1$  Ma ( $\text{MSWD}_{(C+E)} = 0.66$ )  
 572 (Fig. 13B). In addition, one analysis shows a concordant date at ca. 460 Ma.

573  
 574 The Peyre-Arguet cordierite-bearing migmatite (*MCE313b*) displays a  $C_2'$  foliation  
 575 along which the cordierite grains are aligned. Zircon grains display patchy and oscillatory  
 576 zoning (Fig. S1). Nineteen grains have been analysed and they broadly scatter along the  
 577 Concordia between 650 and 280 Ma. The most abundant age population is defined by 12  
 578 analyses ranging from 481 to 419 Ma with low U (292-1043 ppm) and Pb (19-66 ppm) contents  
 579 (Table SE1). Among this group, 7 analyses yield a concordant date of  $451.4 \pm 5.2$  Ma  
 580 ( $\text{MSWD}_{(C+E)} = 0.66$ ) (Fig. 13C).

581  
 582 *4.4. Peyre-Arguet garnet amphibolite (sample MCE304v2)*

583  
 584 The Peyre-Arguet meta-mafic (*MCE304v2*) is a garnet-bearing amphibolite from the  
 585 Inner Pelvoux (Fig. 2) that consists of an amphibole, quartz, plagioclase and garnet assemblage  
 586 that recorded  $D_2$  deformation. Relics of clinopyroxene have been described by Barféty et al.  
 587 (1982) and Jacob et al. (2022). Rutile grains are included within garnet and are replaced by  
 588 ilmenite in the matrix. Garnet grains are surrounded by plagioclase-amphibole coronas. CL  
 589 images of zircon included in garnet cores show cores with concentric oscillatory zoning  
 590 surrounded by near homogeneous rims (Fig. S1). Zircon cores have high U (102-1349 ppm)  
 591 and Pb (6.8-89.6 ppm) contents compared to rims (U: 3-72 ppm; Pb: 0.1-3.3 ppm) (Table SE1).  
 592 Twenty-nine analyses have been performed on 29 zircon grains that define two clusters (Fig.  
 593 13D). The first one, composed of 12 concordant analyses from zircon cores, yields a concordant  
 594 date at  $471.3 \pm 5$  Ma ( $\text{MSWD}_{(C+E)} = 1.06$ ;  $n = 11$ ) (Fig. 13D). The second cluster is formed by  
 595 11 analyses performed on zircon rims that define a lower intercept at  $329.6 \pm 9.2$  Ma ( $\text{MSWD}$   
 596  $= 0.85$ ). Among them, 8 analyses yield a concordant date at  $326.9 \pm 9.1$  Ma ( $\text{MSWD} = 0.85$ )  
 597 (Fig. 13D). Several analyses show concordant dates at ca. 379, 385, 409 and 432 Ma, which

598 probably reflect a mixture between an old core (~ 470 Ma) and a younger rim (~ 327 Ma) and  
599 are probably therefore without geological meaning.

600

## 601 5. Discussion

### 602 5.1. Pre-Variscan history

603

604 Inherited dates at  $451.4 \pm 5.2$  Ma and  $460 \pm 10$  Ma were obtained from magmatic zircon grains  
605 of the Peyre-Arguet and Etages migmatites (samples *MCE313b* and *MCE140b*; Fig. 13; Table  
606 S1). This Ordovician record is interpreted as the emplacement age of felsic laccoliths, i.e. the  
607 protolith of orthogneisses. Numerous orthogneiss-derived from Ordovician protoliths are well  
608 documented in the entire Variscan belt (e.g. [Melleton et al., 2010](#); [Lardeaux et al. 2014](#)) as  
609 within the ECMs (e.g. [Schaltegger, 1993](#); [Sergeev and Steiger, 1993](#); [Bussy and von Raumer,](#)  
610 [1994](#); [Bussy et al., 2011](#); [Bussien Grosjean et al., 2017](#)). Even though a continental magmatic  
611 arc setting is sometimes suggested, presently, the preferred interpretation for the Ordovician  
612 magmatism is rather a rifting episode related to the opening of the Variscan oceans (e.g. [Von](#)  
613 [Raumer et al., 1999](#), [Von Raumer et al., 2013](#); [Vanderhaeghe et al., 2020](#)).

614 Similarly, the magmatic zircon cores from the Peyre-Arguet amphibolite (sample  
615 *MCE304v2*) display an inherited date of  $471.3 \pm 5$  Ma that likely represents the intrusion age  
616 of a mafic protolith during the Ordovician crustal thinning, in agreement with inheritance  
617 recorded in other metabasites from the ECMs ([Paquette et al., 1989](#); [Oberli et al., 1994](#); [Rubatto](#)  
618 [et al., 2001](#); [Bussy et al., 2011](#); [Jacob et al., 2021, 2022](#); [Vanardois et al., 2022](#)).

619 Older detrital and inherited zircon ages from pre-Neoproterozoic to Cambrian were also  
620 obtained (Fig. 13). Lack of Mesoproterozoic dates (>1500 Ma; Fig. 13A) point to a  
621 Gondwanian origin, i.e. the West African Craton (e. g. [Melleton et al., 2010](#); [Linnemann et](#)  
622 [al., 2014](#); [Gärtner et al., 2017](#)), and NE Africa-Arabia, Baltica and Amazonia ([Stephan et al.,](#)  
623 [2019](#)) as possible source regions. In the Cortical Pelvoux, the Roux migmatite (*MCE330*) did  
624 not record any Ordovician inheritance, but magmatic zircon cores rather indicate a  
625 Neoproterozoic magmatism at  $590.6 \pm 6.2$  Ma (Fig. 13A). The Roux migmatite did not originate  
626 from the partial melting of an Ordovician intrusive protolith but from that of a metasedimentary  
627 protolith probably related to Pan-African (750-600 Ma) or Cadomian (590-540 Ma) orogenesis  
628 ([Linneman et al., 2014](#)). Similar metasedimentary rocks in the SW Belledonne display inherited

629 zircons at ca. 590 Ma (Fréville et al., 2018). These Pan-African and Cadomian inherited zircon  
 630 ages are common in the South-Western Variscan belt (e.g. Roger et al., 2004; Melleton et al.  
 631 2010; Schnaperelle et al., 2020) with a possible source region linked to the north-eastern  
 632 Gondwana margin (Linnemann et al., 2014; Couzinié et al., 2014; Von Raumer et al.,  
 633 2015; Chelle-Michou et al., 2017).

634

### 635 5.2. Carboniferous crustal thickening ( $D_1$ deformation)

636

637 The mineral assemblage Qtz + Bt + Ms + Pl + Grt + Ky + St from sample *MCE339v*  
 638 defines a large stability field with P-T conditions lower than 0.75 GPa and 625 °C (Fig. 13C).  
 639 A set of old monazite grains, some being included in kyanite, yield a concordant date at 346.6  
 640  $\pm$  4.8 Ma that gives a time constraint for prograde metamorphism (Fig. 16b). In the sample  
 641 *MCE338*, the main assemblage Qtz + Ms + Bt + Pl + Grt + Sill (Fig. 11D) gives P-T conditions  
 642 between 550-700 °C and 0.35-0.80 GPa (Fig. 16a). The highest  $Q_{cmp}$  factors for muscovite  
 643 and biotite give a P-T refinement at ca. 0.6 GPa and 650 °C (Fig. 16a). Garnet grains are also a  
 644 part of the mineral assemblage and mark the same planar fabric than micas (Fig. 11D), but their  
 645 core compositions are best modelled at lower-grade conditions (0.45 GPa and 575 °C; Fig. 14c).  
 646 Garnet core shows a perfect homogeneous composition (Fig. 14A) that might be the result of  
 647 diffusion process, which could explain the lower grade metamorphic conditions defined by the  
 648 garnet core composition. Garnet rim composition yields P-T conditions at 0.35 GPa and 450 °C  
 649 (Fig. 14c). The mineral composition modelling highlights a retrograde P-T path from the peak  
 650 of metamorphism at ca. 0.6 GPa and 650 °C to the end of the retrograde path at 0.35 GPa and  
 651 450 °C (Fig. 16a). In the corresponding sample (*MCE338*), monazite grains are often localized  
 652 within biotite-muscovite layers (Fig. 11F) and yield a concordant date of 332.2  $\pm$  1.6 Ma (Fig.  
 653 12D), which is therefore interpreted as the age of the peak of  $M_1$  metamorphism. These two  
 654 samples present near similar P-T paths (Fig. 16c) with metamorphic conditions slightly higher  
 655 in the sample *MCE338*, which is consistent with its deeper position into the crust (see Fig. 4B).

656 In sample *MCE339v*, the relictual  $S_1$  foliation preserved in garnet and kyanite is dated  
 657 by monazite at 346.6  $\pm$  4.8 Ma. Similarly, the  $S_1$  foliation in the sample *MCE338* is defined by  
 658 the alignment of micas and by the orientation of monazite and is dated at 332.2  $\pm$  1.6 Ma.  
 659 Similar ages are obtained in samples *MCE379*, *MCE382b* and *MCE328* with a main  $S_1$  foliation  
 660 with syn-kinematic monazite grains (Fig. 10, 11 and 12). These results indicate that a  $D_1$   
 661 deformation was active at ca. 345-330 Ma (Fig. 16d).

662 A similar  $D_1/M_1$  event is documented in the SW Belledonne area with the well-  
 663 preserved low angle  $S_1$ , holding a E-W trending  $L_1$  stretching lineation, interpreted as due to an  
 664 eastward nappe stacking event responsible for crustal thickening coeval with the barrovian  
 665 metamorphism ( $M_1$ ) (Fernandez et al., 2002; Guillot et al., 2009; Guillot and Ménot, 2009;  
 666 Fréville et al., 2018). In SW Belledonne massif, the peak of  $M_1$  metamorphism is dated on  
 667 monazite (LA-ICP-MS) and zircon (SIMS) at around  $337 \pm 7$  Ma and  $338 \pm 5$  Ma respectively  
 668 (Fig. 16d; Fréville et al., 2018). The  $D_1/M_1$  barrovian evolution culminated with the partial  
 669 melting as observed at the bottom of the VSU in the Cortical Pelvoux and SW Belledonne  
 670 (Gidon et al., 1980; Barféty et al., 1988; Guillot et al., 2009; Fréville et al. 2018; this study) as  
 671 exemplified by the “Roux migmatite” that yields a similar concordant age at  $330 \pm 3$  Ma (Fig.  
 672 13A) obtained on metamorphic rims of zircons (sample *MCE330* in this study).

673 The deposition age of the SW Belledonne VSU is dated at  $352 \pm 1$  Ma from a  
 674 plagioclase-rich leucocratic sill (Fréville et al., 2018). Based on the lithological similarities of  
 675 these volcano-sedimentary rocks in SW Belledonne and Cortical Pelvoux, we propose that the  
 676 volcano-sedimentary rocks of the Cortical Pelvoux deposited during the late-Devonian early-  
 677 Carboniferous rifting and therefore predated the  $D_1$  crustal thickening.

678 Retrogressed eclogites and HP granulites are well documented in others ECMs (e.g.  
 679 Albrecht et al., 1991; Von Raumer and Bussy, 2004; Ferrando et al., 2008; Jouffray et al., 2020;  
 680 Jacob et al., 2021; Vanardois et al., 2022) and yield zircon and rutile ages at ca. 340-330 Ma  
 681 (Rubatto et al., 2010; Vanardois et al., 2022). Recently,  $M_1$  high-pressure peak condition  
 682 recorded within retrograded eclogites of the NE Belledonne and Inner Pelvoux was constrained  
 683 at ca. 340-330 Ma (Jacob et al., 2021, 2022). In the Inner Pelvoux, the Peyre-Arguet mafic HP  
 684 granulite (Barféty et al., 1982) recorded a metamorphic age at  $326.9 \pm 9.1$  Ma (Fig. 13D),  
 685 confirming that a  $D_1/M_1$  crustal thickening event at 350-330 Ma is recorded in both the Pelvoux  
 686 and Belledonne massifs (Fig. 16e). Consistently, the sub-horizontal magmatic foliation we  
 687 recognized in the Rochail granite and dated at  $343 \pm 11$  Ma age (Guerrot and Debon, 2000) is  
 688 interpreted as a  $S_1$  foliation that resulted from crustal thickening.

689

### 690 *5.3. Sinistral transpression and longitudinal flow ( $D_2$ and $D_3$ deformations)*

691

692 In the Cortical Pelvoux, the  $D_2$  tectono-metamorphic event corresponds to a NW-SE  
 693 shortening responsible for folding of the  $S_1$  and formation of the  $N30^\circ E$  striking  $S_2$  foliation,  
 694 also documented in the SW Belledonne (Fréville et al., 2018), in the course of  $D_1$  contraction.  
 695 In sample *MCE339v*, from the central part of the Cortical Pelvoux, the  $S_2$  foliation is defined

696 by the preferential alignment of biotite for which the highest  $Q_{\text{cmp}}$  factor indicates temperature  
697 conditions above 525 °C and allows us to refine the P-T condition of biotite-bearing  $S_2$  foliation  
698 at around 0.5 GPa and 550 °C near the kyanite-sillimanite transition (Fig. 13D). Monazite grains  
699 included in the biotite-layers (Fig. 11C) yield an age at  $319.2 \pm 6.1$  Ma (Fig. 11C) providing a  
700 time constraint for  $D_2$  transpression (Fig. 16b).

701 In the Inner Pelvoux,  $D_2$  structures are ubiquitous with the development of penetrative  
702 and steeply dipping planar surfaces, such as the  $S_2$  foliation, and  $C_2$ - $C'_2$  sinistral shear zones,  
703 and weakly plunging lineations formed under sinistral strike-slip regime (Fig. 17A). The syn-  
704  $D_2$  cordierite-bearing migmatite *MCE314* shows U-Th-Pb data obtained on monazite grains that  
705 form a cluster with an intercept at  $307.5 \pm 1.9$  Ma (Fig. 11F). It suggests that the partially molten  
706 crust was under high temperature and low-pressure conditions at ca. 308 Ma (Fig. 16c), giving  
707 another time constraint for the  $D_2$  deformation. In the Etages migmatite (*MCE140b*), four zircon  
708 grains yield a concordant date at  $317 \pm 4$  Ma (Fig. 13B) that we also relate to the  $D_2$   
709 transpression. The Etages migmatite *MCE140b* also gives a concordant date at  $297.8 \pm 2.1$  Ma,  
710 like the age of the Etages and the Bérarde-Promontoire syn- $D_2$  plutons (this study; [Strzeczynski](#)  
711 [et al., 2005](#)) dated at ca. 303-299 Ma ([Fréville, 2016](#)). Hence, we propose that the timing of the  
712  $D_2$  transpression ranged from at least ca. 320 Ma to 298 Ma (Fig. 16d), but it might have started  
713 as early as 330 Ma (Fig. 16e). In the SW and NE Belledonne massif, the onset of the  $D_2$   
714 transpression with the development of  $S_2$  occurred after the peak of pressure at 330 Ma ([Fréville](#)  
715 [et al., 2018](#); [Jacob et al., 2021](#)), a period that corresponds to the onset of partial melting in the  
716 lower crust. In both Pelvoux and Belledonne massifs, the transpression is more pervasive in the  
717 anatectic crust ([Fréville et al., 2018](#); this study). Melt-enhanced strength drop may have  
718 impacted stress distribution and initiated transpressional strain in the deep crust with the  
719 preferential appearance of the steeply dipping  $S_2$  cleavage in the partially molten middle-lower  
720 crust, while NW-SE contraction was accommodated by upright to SE-verging  $D_2$  folding in the  
721 upper-middle crust (Fig. 17).

722 Near the anatectic front, we have recognized a  $S_3$  sub-horizontal planar fabric affecting  
723 the former  $S_1$  and  $S_2$  foliations (Fig. 8, 9 and 17). In sample *MCE382b* located in the Cortical  
724 Pelvoux, 4 monazite grains included in undeformed biotite marking the  $S_3$  foliation (Fig. 10G  
725 and H) yield a concordant date at  $306 \pm 3.5$  Ma (Fig. 11B). The record of the  $D_3$  deformation  
726 in monazite is probably dependent on  $D_3$  strain localization. Thus, we propose that the ca. 306  
727 Ma age is a reliable one for the  $D_3$  deformation in the Cortical Pelvoux (Fig. 16d). Our results  
728 suggest that during the Late Carboniferous, the  $D_2$  and  $D_3$  deformations were partly  
729 synchronous (Fig. 16d) and therefore attest for strain partitioning during a same tectonic event

730 responsible for longitudinal flow of the middle-lower crust. We interpret the top-to-the NW  
731 shearing along  $S_3$  as a local accommodation of a southeastward horizontal flow of the partially  
732 molten lower crust during sinistral transpression. Recently, Jacob (2022) and Jacob et al. (2022)  
733 also show that in the central Inner Pelvoux (La Lavey area) the  $S_1$  foliation is reworked by a  
734 syn-migmatitic flat-lying foliation showing evidence for a NW-SE, i.e. N150-N180 directed  
735 horizontal flow. These authors argue that the horizontal flow was coeval with a sinistral  
736 shearing along a N140-N170 directed high-strain corridor ( $D_2$ ) characterized by a vertical  
737 shortening of the  $D_2$  planar fabrics by the syn-magmatic flat-lying foliation. This is consistent  
738 with our own field observations of the  $S_3$  foliation, made in the same La Meije block, a few  
739 kilometers to the SE (Fig. 3). The contemporaneity between NW-SE directed transpressional  
740 flow and vertical shortening in that part of the la Meije block is supported by our radiometric  
741 data of  $D_2$  and  $D_3$  and attests for strain partitioning between the suprastructure and infrastructure  
742 during horizontal crustal flow under transpressive regime as commonly described in the  
743 Variscan belt (Aguilar et al., 2014; Cochelin et al., 2017, 2021; Rabin et al., 2015; Trap et al.,  
744 2017).

745

#### 746 *5.4. Kinematic flow at the scale of the EVSZ*

747

748 At large scale, the shape and strike of the EVSZ and how it connects to other major shear  
749 zones of the Variscan belt framework is not straightforward (e.g. Ballèvre et al., 2018; Chardon  
750 et al., 2020; Simonetti et al., 2020a). In most of previous studies, the authors proposed that the  
751 EVSZ runs from the Aar-Gothard, Aiguilles-Rouges-Mont-Blanc, Belledonne massifs, and to  
752 the Argentera, Maures-Tanneron and Corsica-Sardinia massifs with a main trend that changes  
753 from NE-SW to N-S respectively (Fig. 1; e.g. Guillot et al., 2009; Padovano et al., 2012;  
754 Duchesne et al., 2013; Simonetti et al., 2020a) that consider a post-Variscan counterclockwise  
755 rotation of the Argentera massif of about  $90^\circ$  that is not recorded within the Permian  
756 sedimentary cover (Bogdanoff and Schott, 1977; Sonnette et al., 2014). The major rotational  
757 movements described in the internal Alps are accommodated by transcurrent faults that did not  
758 affect the ECMs (Collombet et al., 2002). Any rotation of the Argentera massif may have  
759 occurred prior to the deposition of Permian sedimentary rocks deposits and at these times the  
760 rotation in the southeastern part of the Variscan belt is clockwise (Edel et al., 2014, 2015).  
761 Following the work of Edel et al. (2014, 2018) that consider the rotation of the Maures-  
762 Tanneron - Corsica -Sardinia block, we propose an alternative geometry for the EVSZ with the  
763 individualization of several branches forming the anastomosed network (Fig. 18).



764 The large-scale transpression is a strain feature the whole ECMs have in common, with  
765 a general dextral kinematics (Von Raumer et al., 1999; Von Raumer and Bussy, 2004; Simonetti  
766 et al., 2018, 2020a; Jacob et al., 2021) except in the Pelvoux massif where it is sinistral (this  
767 study, Strzeczynski et al., 2005; Jacob et al., 2022). Our results argue that the sinistral shearing  
768 in the Pelvoux massif was active between at least ca. 320 and 300 Ma. Similar ages have been  
769 reported for the dextral transpressional shearing in the Aiguilles-Rouges - Mont-Blanc massifs  
770 (Simonetti et al., 2020a; Vanardois, 2021), in the Argentera massif (Sanchez et al., 2011;  
771 Simonetti et al., 2018, 2021), in the Maures-Tanneron massifs (Rolland et al., 2009; Corsini  
772 and Rolland, 2009), in Sardinia and Corsica (Giacomini et al., 2008; Carosi et al., 2012). Since  
773 dextral and sinistral shearing were synchronous, we propose that at the scale of the ECMs, the  
774 sinistral shearing in the Pelvoux massif corresponds to an antithetic domain within the dextral  
775 dominated shear zone network (Fig. 18). During the Late Carboniferous times, the average  
776 antithetic C' shear zone strikes N140-150E in the Pelvoux massif while dextral shear zones  
777 trends ca. N30E in the Aiguilles-Rouges-Mont-Blanc massif and Belledonne massif (e.g.  
778 Simonetti et al., 2020, Jacob et al., 2021). Vanardois (2021) argue that N30E directed dextral  
779 deformation in the Aiguilles-Rouges Massif (Fig. 18) corresponds to 1-2 km wide synthetic C'  
780 shear zones in a regional-scale (> 10km) N-S directed shear zone system. The strain pattern of  
781 the Aiguilles-Rouges massif is made of a S-C-C' dextral framework with NW-SE-directed S  
782 planes, N-S directed C planes and N30E directed C' planes (Fig. 18; Vanardois 2021). In that  
783 scheme, the average obtuse angle between synthetic C' and antithetic C' shear direction might  
784 be around  $105 \pm 10^\circ$  (Fig. 18) that is consistent with geometry and flow kinematics of a typical  
785 ductile shear zone (Fossen et al., 2012; Gillam et al., 2013) even if anticlockwise back-rotation  
786 between NE-SW dextral corridors is considered.

787

## 788 **Conclusions**

789

790 Our field work, structural, thermobarometric, and geochronological results argue that the  
791 Belledonne and Pelvoux massifs share the same Carboniferous tectono-metamorphic  
792 evolution. The Belledonne-Pelvoux area experienced a D<sub>1</sub> event related to crustal thickening  
793 during the Eastward nappe stacking event in response to E-W to NW-SE contraction. The  
794 D<sub>1</sub>/M<sub>1</sub> episode ended with the onset of crustal partial melting at ca. 650°C during Late Viséan  
795 time. Ongoing NW-SE bulk shortening is responsible for sinistral D<sub>2</sub> shearing in the partially  
796 molten middle-lower crust (i.e. Inner Pelvoux) with the strain partitioning between C and C'  
797 shear zones and horizontal longitudinal flow in the range 330-300 Ma. Field and radiometric

798 data argue for contemporaneity between D<sub>2</sub> and D<sub>3</sub> and attest for vertical strain partitioning  
 799 between the suprastructure and infrastructure during horizontal crustal flow and strike-slip  
 800 shearing, as commonly described in the Variscan belt. Within the orogen scale dextral East-  
 801 Variscan Shear Zone, the sinistral transpression recorded in the Pelvoux massif corresponds to  
 802 an antithetic strain domain. The data presented in this paper on the East Variscan Shear Zone  
 803 exposed in the Belledone-Pelvoux massifs, should be compared to other late-Variscan shear  
 804 zones in order to check for kinematic compatibility and to reconstruct plate-scale kinematics  
 805 during late carboniferous time.

806

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815

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817

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- 1140



1141 **Figure Captions:**

1142

1143 Figure 1. A: Location of the External Crystalline Massif (ECMs) within the Variscan  
 1144 framework, modified after Franke et al. (2017). B: State-of-the art concept showing the possible  
 1145 shear zone pattern along the ECMs and Corsica-Sardigna, in relation with the dextral EVSZ  
 1146 (modified from Simonetti et al. 2020). The studied area, i.e. the Belledonne-Pelvoux massif, is  
 1147 not yet considered in this scheme.

1148

1149 Figure 2. A: Simplified Geological map of the ECMs. Dashed square shows the extent of Figure  
 1150 2B. B: Geological map of the Pelvoux Massif with sample location. Dashed area shows the  
 1151 location of Figure 3.

1152

1153 Figure 3. A: Structural map of the Pelvoux massif showing the heterogeneous Variscan strain  
 1154 pattern. Lower-hemisphere Wulf stereographic plots of poles of foliations and strikes  
 1155 of lineation.

1156

1157 Figure 4. A: NW-SE cross-section through the northern part of the Pelvoux massif. B: E-W  
 1158 cross-section through the western part of the Pelvoux massif. C: W-E cross-section through the  
 1159 central part of the Pelvoux Massif.

1160

1161 Figure 5. Field pictures of  $D_2$  folding and shearing. A and B:  $F_2$  folding of migmatitic  $S_1$  and  
 1162 development of  $N30^\circ E$  trending  $S_2$  foliation as axial surface or transposition layering. C and D:  
 1163 Folding and shearing along the  $C_2$  and  $C'_2$  trend (NS and NW-SE). The folded and sheared  
 1164 foliation is a  $S_1$ ,  $S_2$  or  $C_2$  planar surface. In photograph 5C, the gneissic protolith was folded  
 1165 when the anatectic melt was present, and the melt also migrated along  $D_2$  shear zone that  
 1166 parallels the axial plane. In 5D, shearing parallel to the axial plane resulted in solid-state  
 1167 recrystallization. E: Diatexite with a high proportion of leucocratic neosome with metamafic  
 1168 layers showing  $D_2$  folding and sinistral shearing along a  $N120^\circ E$  trending  $C'_2$  syn-melt shear  
 1169 zone. F: Schollen diatexite with meter scale metamafic enclaves stretched along N-S direction  
 1170 ( $C_2$ ) and shearing by a NW-SE trending  $C'_2$  infilled by melt. Location of outcrop photographs  
 1171 is given in Figure 2.

1172

1173 Figure 6: Field pictures of  $D_2$  deformation synchronous with partial melting. A: Sigmoidal  
 1174 quartz-rich resistor within  $D_2$  metatexite indicating sinistral shearing along  $C_2$  directed

1175 migmatitic foliation. B: Oblate metamafic enclave observed in the XY-section within a  
 1176 stromatic diatexite. C: Conjugate melt-bearing dextral and sinistral shear bands within  
 1177 heterogeneous diatexite. Main foliation is subvertical and trends ca. N170°E. D: Schollen  
 1178 diatexite migmatite developed from a hornblende-bearing volcano-sedimentary protolith. E:  
 1179 Close-up on Figure 6D showing the dioritic to tonalitic composition of the leucocratic material  
 1180 containing various proportions of hornblende, some pyroxenes are also observed. The pen  
 1181 points to a garnet + hornblende rich schlieren. F: Metatexite migmatite showing two sets of late  
 1182 cordierite-bearing leucosome, one set parallels the main foliation trends (~N15°E, i.e. C<sub>2</sub>) and  
 1183 the other one is oblique to the foliation, and oriented ~N135°E (C'<sub>2</sub>).

1184  
 1185 Figure 7: A: Schematic drawing showing the three main trends of the D<sub>2</sub> planar surface arranged  
 1186 in a sinistral S<sub>2</sub>-C<sub>2</sub>-C'<sub>2</sub> like anastomosed transpressional system. This representative outcrop  
 1187 comes from the Bans valley, southeastern Inner Pelvoux. Picture 7B shows the steeply dipping  
 1188 S<sub>2</sub> cleavage observed within the Peyre-Arguet mafic granulite, retrogressed into amphibolite.  
 1189 Very thin seams of leucosome are located parallel to the compositional layering, and S<sub>2</sub> or C<sub>2</sub>  
 1190 foliation. Picture 7C shows a strongly layered stromatic migmatite that has been reworked by  
 1191 solid-state deformation during sinistral shearing along a C'<sub>2</sub> plane.

1192  
 1193 Figure 8. Outcrop photographs and micro-photographs of the D<sub>3</sub> deformation. A: Folding and  
 1194 transposition of the subvertical S<sub>2</sub> foliation by the flat laying S<sub>3</sub> foliation in the northern part of  
 1195 the *Le Rochail* block. B: Folding and transposition of the relictual S<sub>1</sub> foliation by the flat laying  
 1196 S<sub>3</sub> foliation in the northern part of the *Le Rochail* block. C: S<sub>3</sub>-C<sub>3</sub> structures showing top-to-  
 1197 the-NW kinematics from sample *MCE382b*. D: Zoom of the photo E with top-to-the-NW  
 1198 kinematic indicators and schematic block diagram of the outcrop.

1199  
 1200 Figure 9. Field pictures of D<sub>3</sub> deformation. A and B. Low-angle S<sub>3</sub> reworking a steep S<sub>2</sub>  
 1201 foliation. Both foliations are melt-bearing and a pegmatitic leucosome parallels C<sub>3</sub> shear bands.  
 1202 The outcrop is located near the Gioberney mountain refuge. C. Melt-bearing flat-lying D<sub>3</sub> shear  
 1203 zone cross-cutting the steep S<sub>2</sub> foliation. Outcrop photographs A, B C and D are located around  
 1204 the Gioberney mountain refuge, in the La Meige Block. D. Vertical shortening of S<sub>2</sub> and  
 1205 development of axial planar S<sub>3</sub>. E. Mylonitic S<sub>3</sub> with top-to-the NW shearing at the base of the  
 1206 Cortical Pelvoux, near Villard-Notre-Dame village. F. Moderately dipping migmatitic gneiss  
 1207 (*MCE 330*) showing a solid-state protomylonitic foliation S<sub>3</sub> developed during D<sub>3</sub> shearing and  
 1208 cooling.

1209  
 1210 Figure 10. Thin-sections photographs and BSE images showing structural and petrological  
 1211 relationships of samples *MCE379* and *MCE382b*. A: Thin-section photograph of sample  
 1212 *MCE379* structured by D<sub>1</sub> planar fabric. B: BSE image of a monazite included in K-feldspar. C  
 1213 and D: BSE images of monazite grains in mica marking the S<sub>1</sub> foliation. E: Thin-section  
 1214 photograph of sample *MCE382* structured by D<sub>1</sub> planar fabric and D<sub>3</sub> shear bands. F: BSE  
 1215 image of a monazite included in K-feldspar. G and H: BSE images of monazite grains in biotite  
 1216 marking the S<sub>3</sub> foliation. Mineral abbreviations from Kretz (1983).

1217  
 1218 Figure 11. Thin-sections photographs and BSE images showing structural and petrological  
 1219 relationships of samples *MCE339v*, *MCE338* and *MCE328*. A: Thin-section photograph of  
 1220 sample *MCE339v* structured by D<sub>2</sub> planar fabric. B: BSE image of a monazite oriented parallel  
 1221 with the ancient S<sub>1</sub> foliation preserved in kyanite (white dotted line). C: BSE image of monazite  
 1222 grains in mica marking the S<sub>2</sub> foliation. D: Thin-section photograph of sample *MCE338*  
 1223 structured by D<sub>1</sub> planar fabric showing elongated garnet grains parallel to the S<sub>1</sub> foliation. E:  
 1224 BSE image of a monazite included in quartz showing a sigmoidal shape. F: BSE image of a  
 1225 monazite in micas marking the S<sub>2</sub> foliation. G: Thin-section photograph of sample *MCE328*  
 1226 structured by D<sub>1</sub> planar fabric and D<sub>3</sub> shear bands. H: BSE image of a monazite elongated  
 1227 parallel to the S<sub>1</sub> foliation included in quartz. I: BSE image of a monazite staurolite and quartz.  
 1228

1229 Figure 12. Monazite U-Pb concordia diagrams obtained by LA-ICPMS. A: *MCE379*; B:  
 1230 *MCE382b*; C: *MCE339v*; D: *MCE338*; E: *MCE328*; F: *MCE314*. Error ellipses and  
 1231 uncertainties in ages are  $\pm 2\sigma$ . Dotted ellipses are not considered for the age calculation.

1232  
 1233 Figure 13. Thermobarometric modelling of metapelitic sample *MCE339v* located in the Cortical  
 1234 Pelvoux. A: Chemical profile of a garnet. B: T-XH<sub>2</sub>O diagram calculated with a pressure of 0.7  
 1235 GPa, the mineral assemblage of the sample indicates a H<sub>2</sub>O content of 1.33 %wt. C:  
 1236 Pseudosection calculated in the MnNCKFMASH system. D: Modelling of the Q<sub>cmp</sub> factor of  
 1237 the mineral composition of biotite based on MgO, FeO, MnO, Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> contents (Table  
 1238 S2). Bi, Biotite; Mu, muscovite; Crd, Cordierite; Kfs, K-feldspar; Pl, Plagioclase; Gt, Garnet;  
 1239 and, Andalousite; ky, Kyanite; sill, Sillimanite; Opx, Orthopyroxene; q, Quartz; melt, silicate  
 1240 liquid.

1241

1242 Figure 14. Thermobarometric modelling of metapelitic sample *MCE338* located in the Cortical  
 1243 Pelvoux. A: Chemical profile of a garnet. B: T-XH<sub>2</sub>O diagram calculated with a pressure of 0.5  
 1244 GPa, the mineral assemblage of the sample indicates a H<sub>2</sub>O content of 1.47 %wt. C:  
 1245 Pseudosection calculated in the MnNCKFMASH system. Modelling of the Qcmp factor of the  
 1246 mineral composition of (D) biotite based on MgO, FeO, MnO, Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> contents, (E)  
 1247 muscovite based on Na<sub>2</sub>O, K<sub>2</sub>O, CaO, Al<sub>2</sub>O<sub>3</sub>, FeO, MgO and SiO<sub>2</sub> contents, and (F) plagioclase  
 1248 based on K<sub>2</sub>O, Na<sub>2</sub>O, CaO, Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> contents (Table S2). Bi, Biotite; Mu, muscovite; Crd,  
 1249 Cordierite; Kfs, K-feldspar; Pl, Plagioclase; Gt, Garnet; and, Andalousite; ky, Kyanite; sill,  
 1250 Sillimanite; Opx, Orthopyroxene; q, Quartz; melt, silicate liquid.

1251  
 1252 Figure 15. Zircon U-Pb Tera Wasserburg diagrams obtained by LA-ICPMS. A: *MCE330*; B:  
 1253 *MCE140b*; C: *MCE313b*; D: *MCE304v2*. Error ellipses and uncertainties in ages are  $\pm 2\sigma$ .  
 1254 Dotted ellipses are not considered for the age calculation.

1255  
 1256 Figure 16. Geochronological and tectono-metamorphic interpretations for the Pelvoux massif.  
 1257 (a) P-T-t path of sample *MCE338* inferred from the mineral assemblage and mineral  
 1258 compositions and from textural features of monazite. (b) P-T-t path of sample *MCE339v*  
 1259 inferred from the mineral assemblage and biotite composition and from textural features of  
 1260 monazite. (c) P-T-t conditions from the Pelvoux massif. P-T-t paths of the Cortical Pelvoux are  
 1261 from this study. P-T data from metabasites of the Inner Pelvoux are from Jacob et al. (2022)  
 1262 and Grandjean et al. (1996). P-T conditions of Crd-migmatites are theoretical and age  
 1263 corresponds to monazite age of sample *MCE314* from this study. (d) Geochronological results  
 1264 constraining the ages of D<sub>1</sub>, D<sub>2</sub> and D<sub>3</sub> from this study, (Fréville et al., 2018; Fréville, 2016).  
 1265 (e) Inferred tectono-metamorphic evolutions of the Cortical and Inner Pelvoux.

1266  
 1267 Figure 17. Sketch showing the strain partitioning in the Belledonne-Pelvoux orogenic crust  
 1268 suffering bulk NW-SE directed contraction (black arrows). The upper unmolten crustal level  
 1269 recorded folding, while the partially molten lower domain recorded lateral flow and sinistral  
 1270 transpression.

1271 Figure 18. Sketch map of the anastomosed network of dextral shear zones of the EVSZ with  
 1272 local conjugate sinistral shear zones in the Pelvoux massif. Ante-alpine positions of the ECMs  
 1273 (black arrow) are from Bellahsen et al. (2014), except the Argentera massif. Positions of the  
 1274 Maures-Tanneron, Corsica and Sardinia massifs are from Edel et al. (2014, 2018). Blue arrow  
 1275 represents the present orientation in reference to the north. AG: Aar-Gothard; Arg: Argentera;

1276 AR-MB: Aiguilles-Rouges - Mont-Blanc; Bell: Belledonne; BSZ: Barrabisa Shear Zone;  
1277 EBSZ: Emosson-Bérarde Shear Zone; FMSZ: Ferrière-Mollière Shear Zone; GF: Grimaud  
1278 Fault; MF: La Moure Fault; PAL: Posada-Asinara Shear Zone; Pelv: Pelvoux; PVSZ: Porto  
1279 Vecchio Shear Zone.

1280

1281 Table 1. Summary of geographic location, rock types, and U-Pb geochronological results for  
1282 samples analyzed in this study.

1283

1284 Table 2. Bulk-chemical composition in weight percent oxides for samples *MCE339v* and  
1285 *MCE338*.

1286

1287 Table 3. Representative chemical compositions of minerals used for themobarometric  
1288 calculation.

1289

1290 Table 4. Summary of tectonic and metamorphic events recorded in the Belledonne-Pelvoux  
1291 area.

1292

1293 Supplementary material:

1294

1295 Figure S1. Zircon cathodoluminescence and monazite back-scattered electrons images from  
1296 studied samples.

1297

1298 Table S1. U-Pb analyses for dated samples.

1299

1300 Table S2. Operating conditions for the LA-ICP-MS equipment for Montpellier.

1301

1302 Table S3. Operating conditions for the LA-ICP-MS equipment for BRGM.

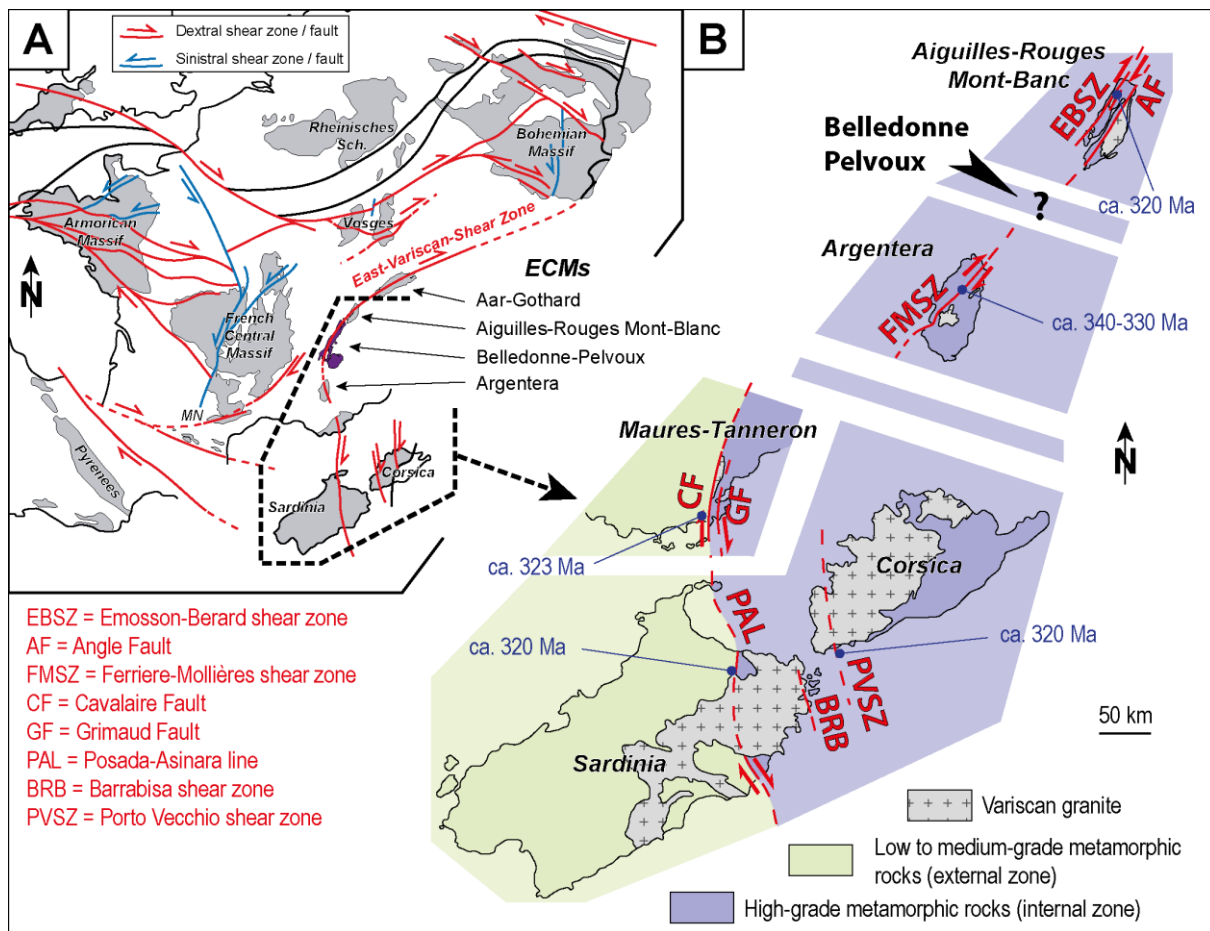
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1304 Table S4. Operating conditions for the LA-ICP-MS equipment for Rennes.

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1306

1307 Figure 1



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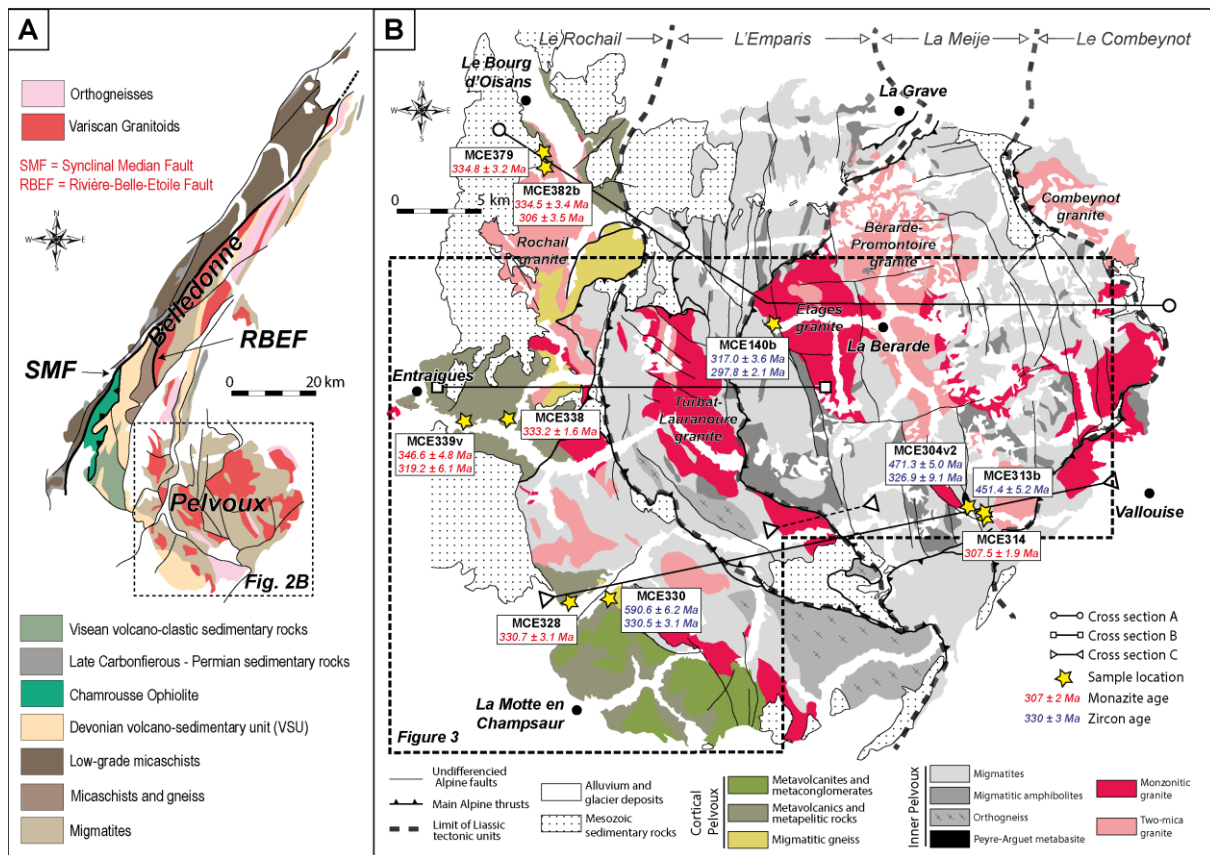
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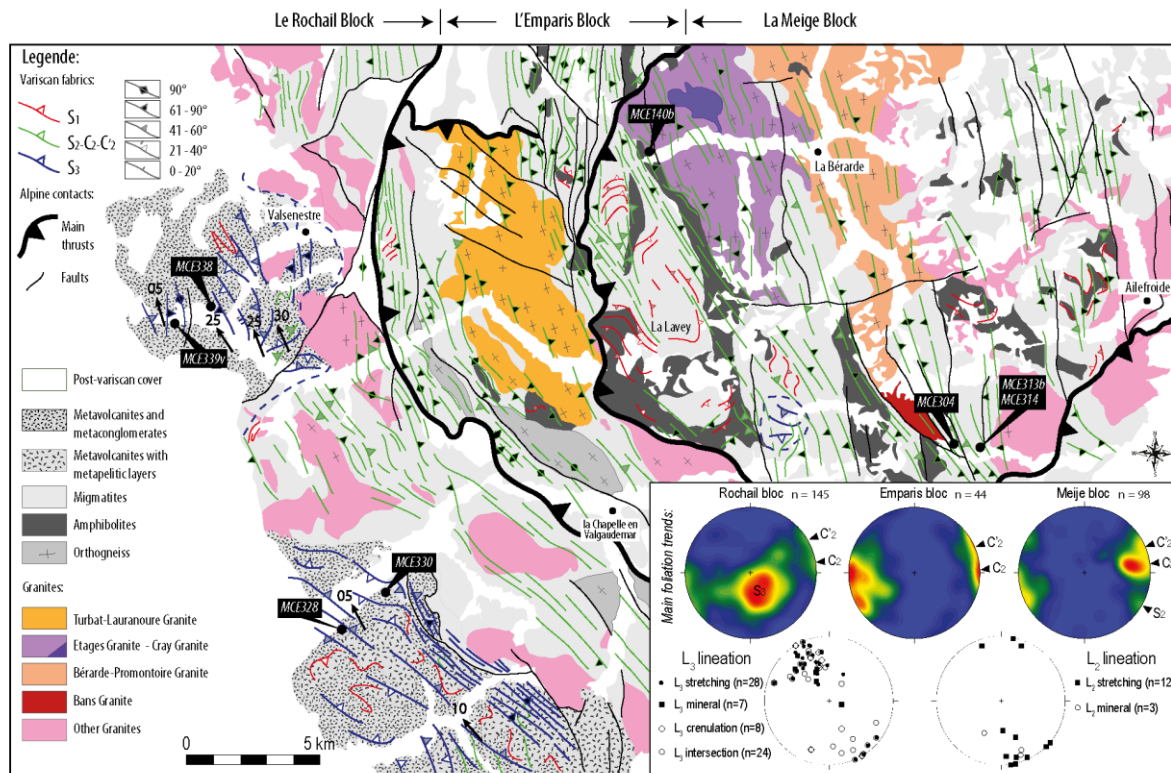
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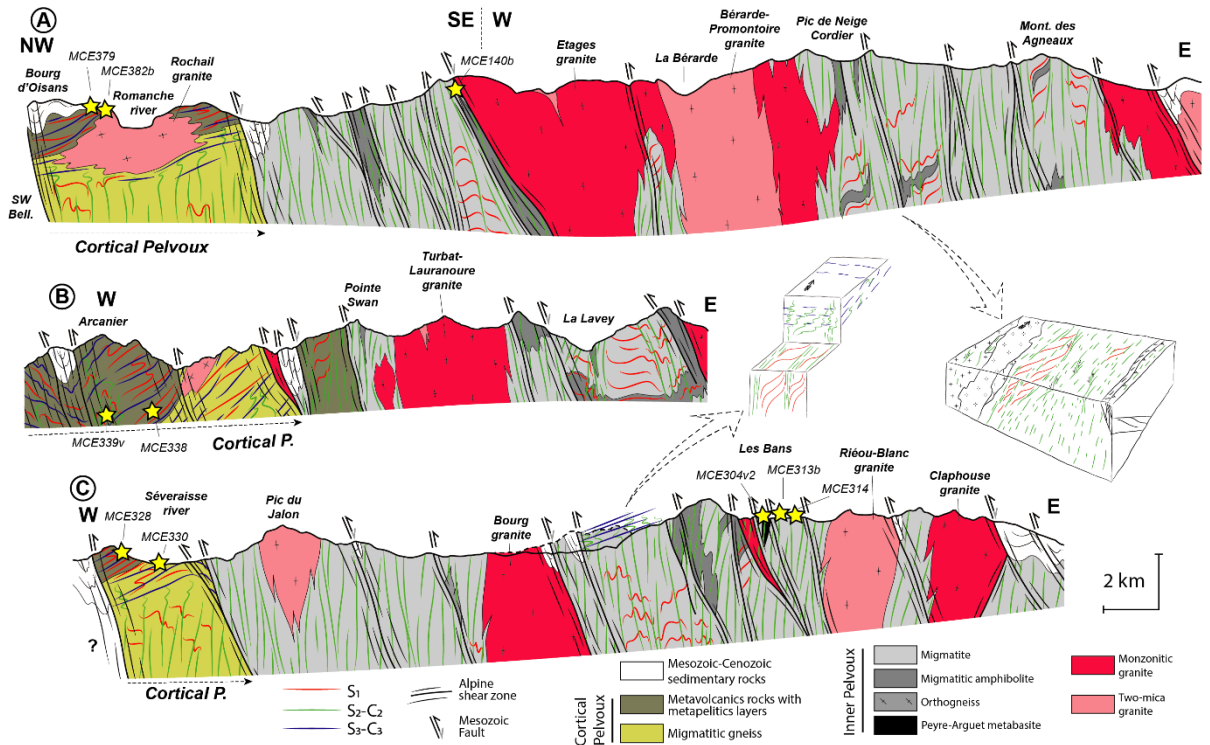
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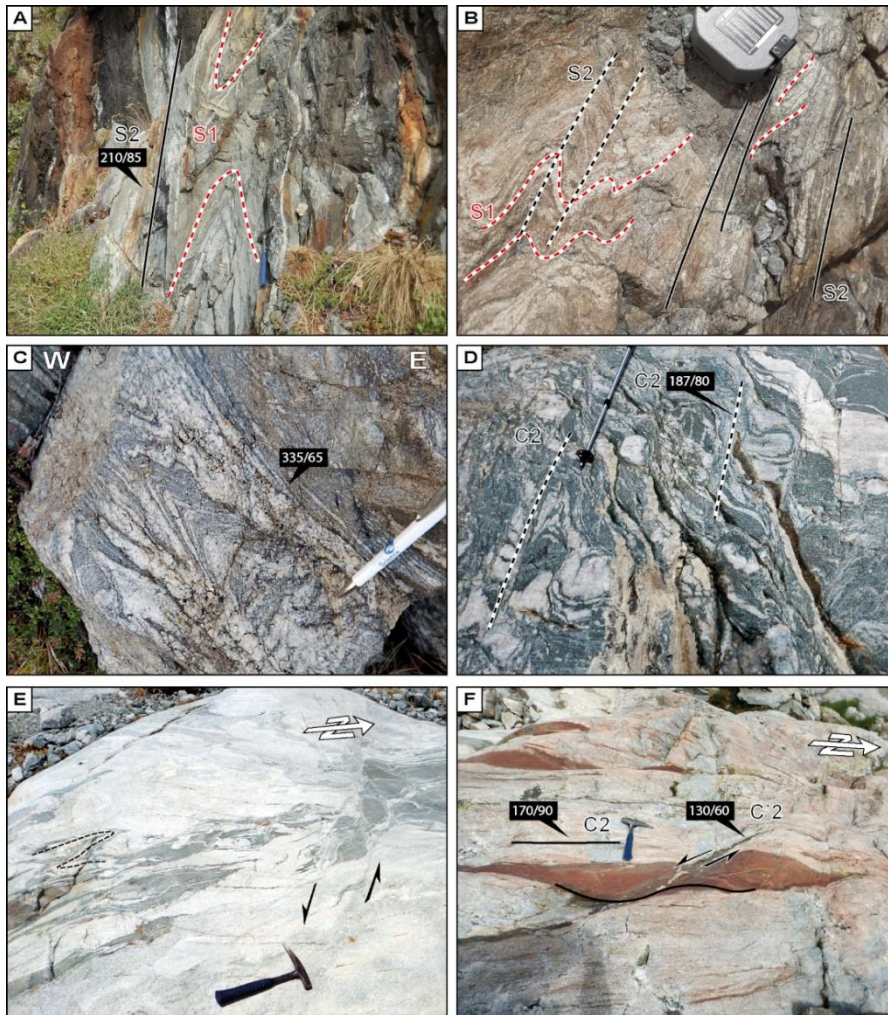
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1329 Figure 5

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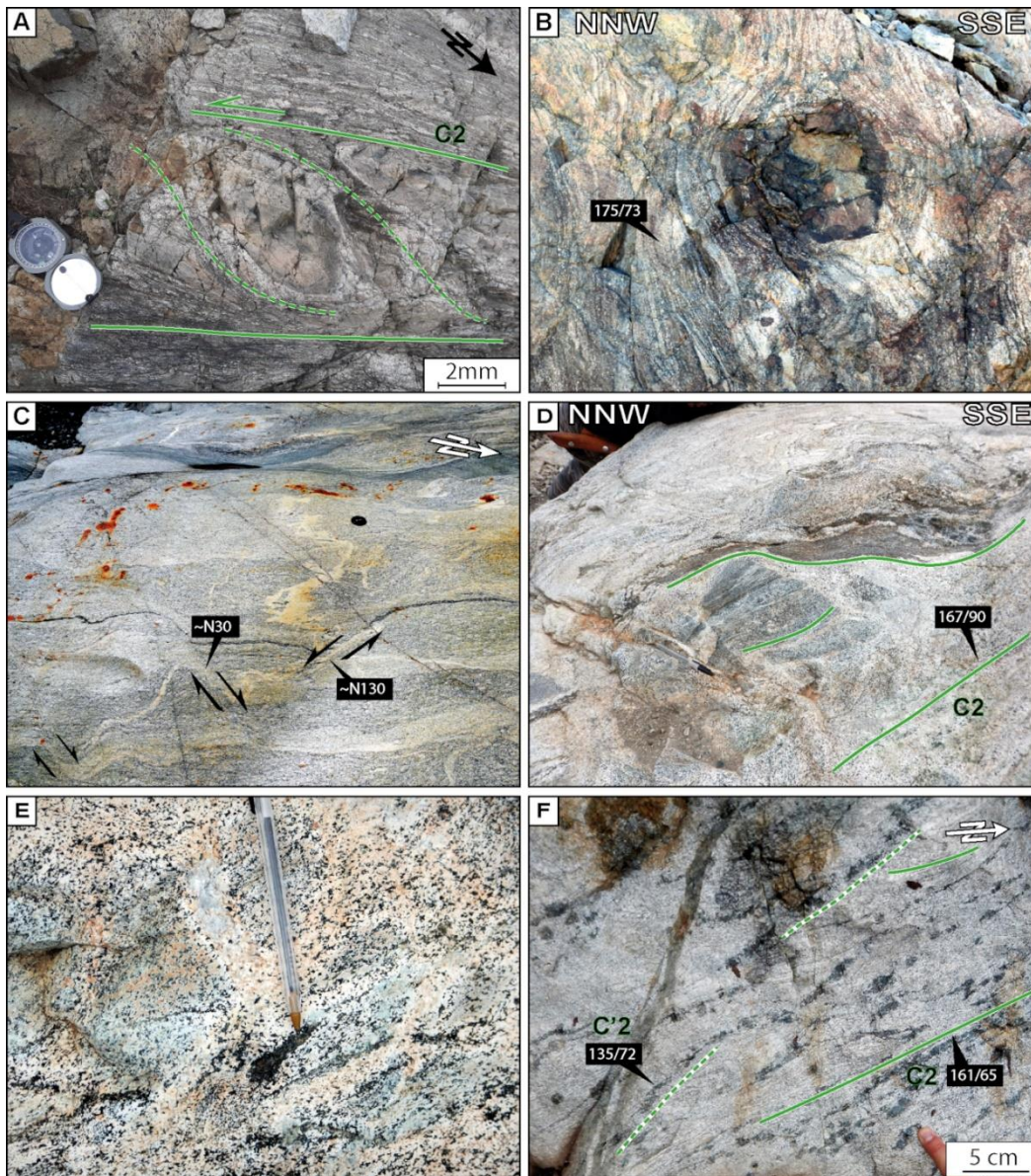


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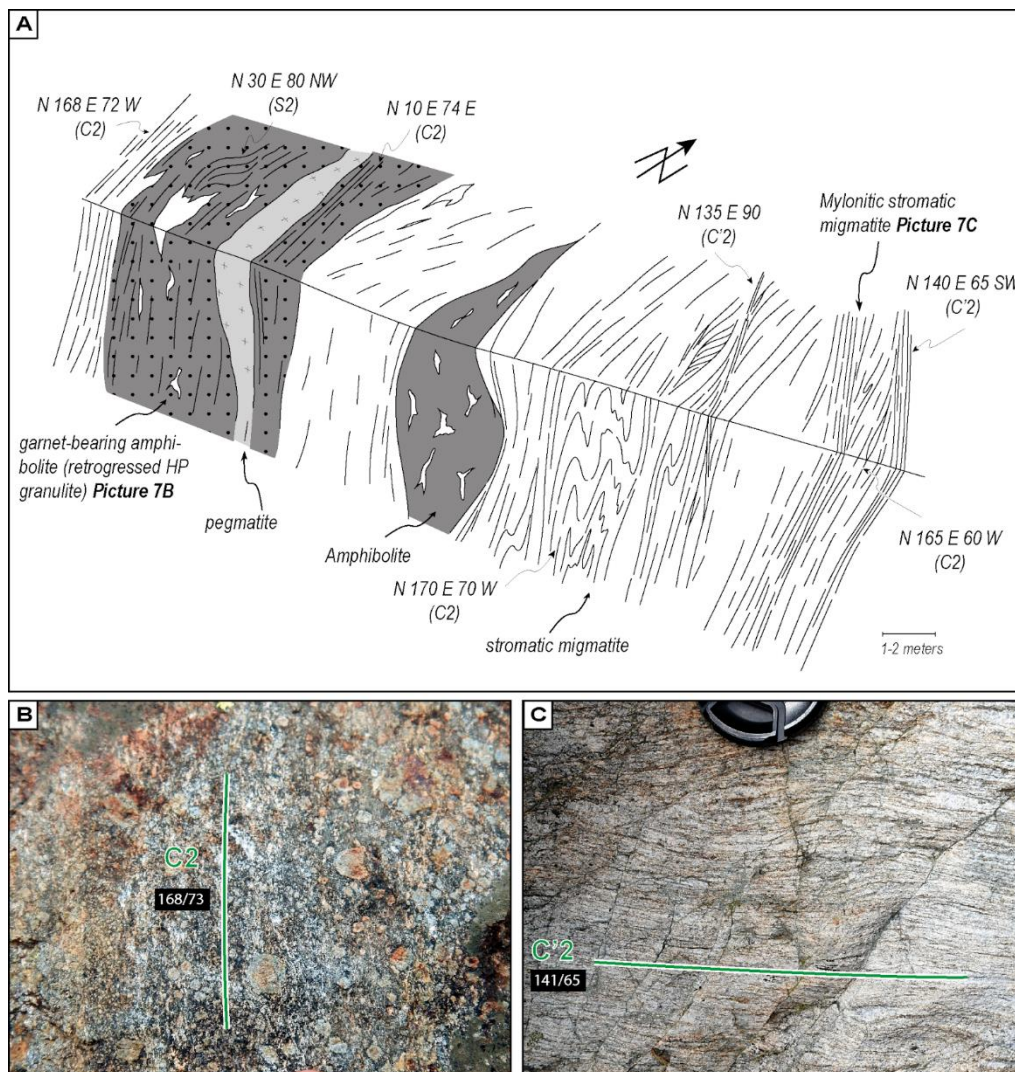
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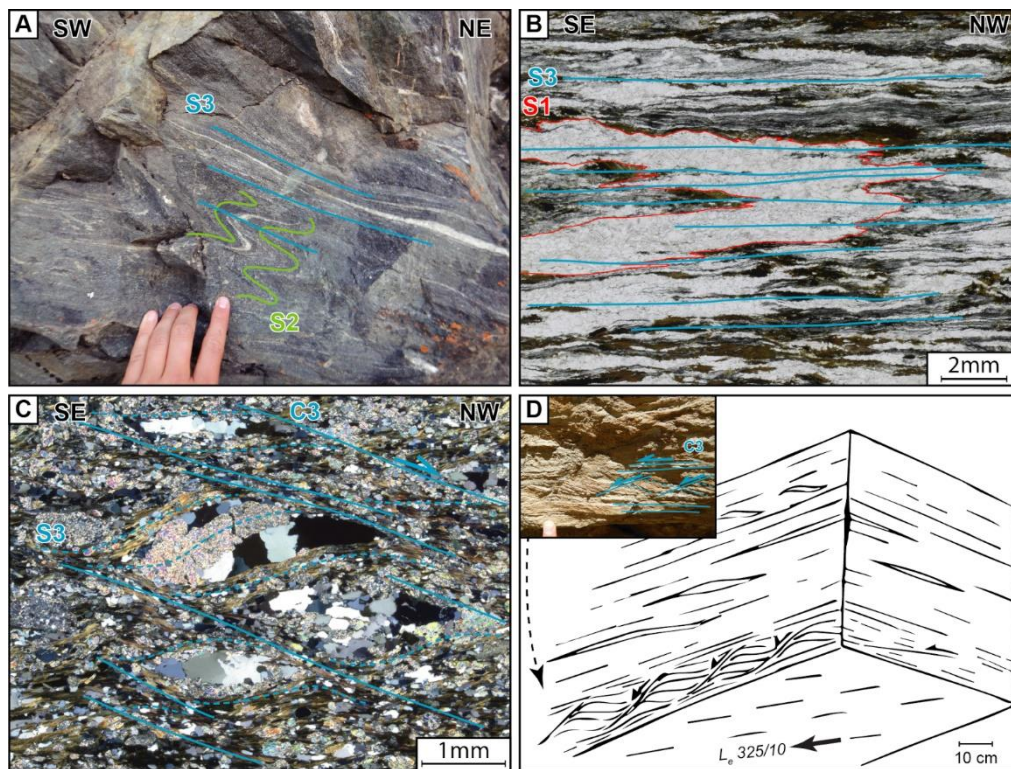
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1343 Figure 8

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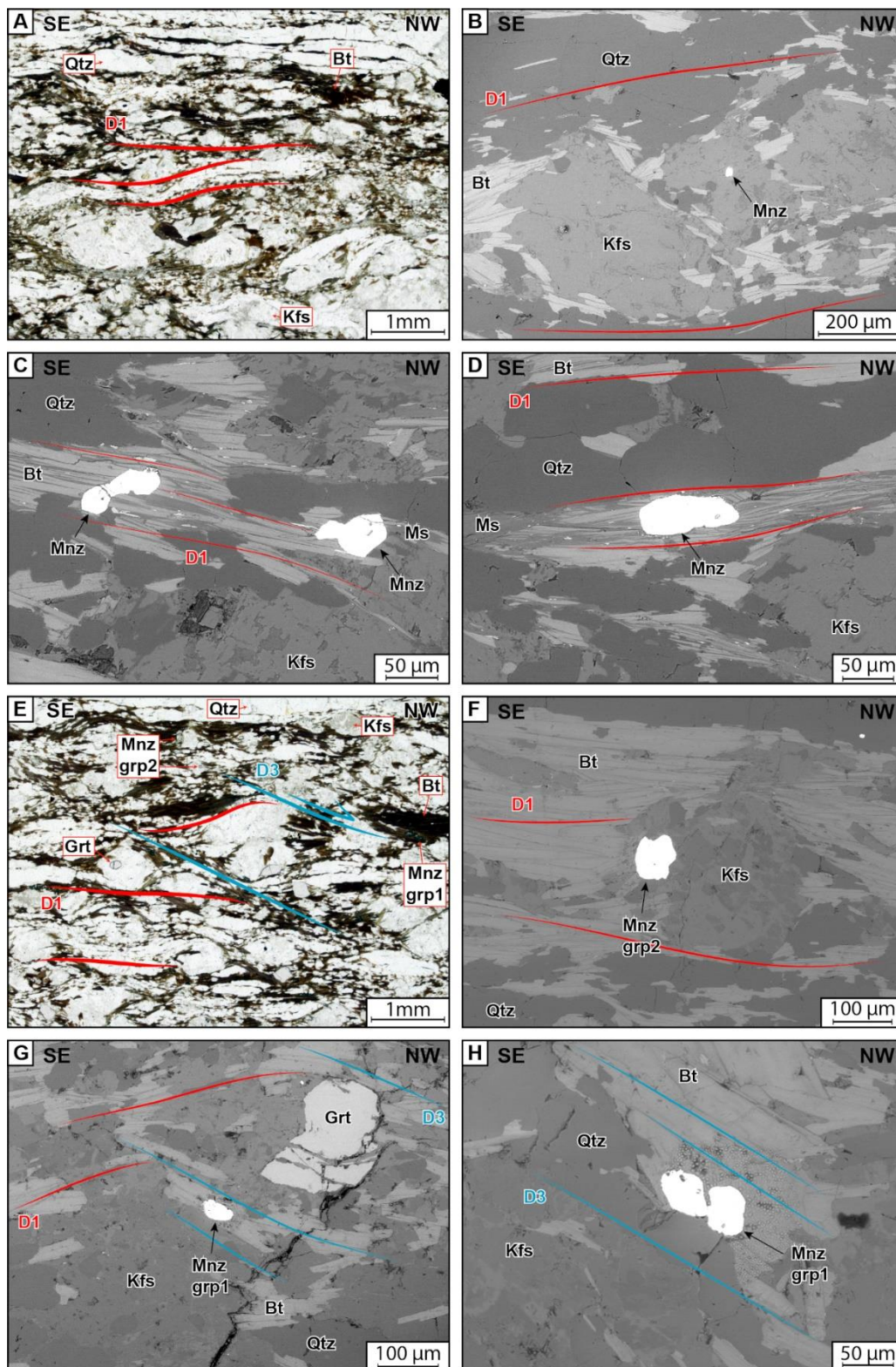
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1354 Figure 10

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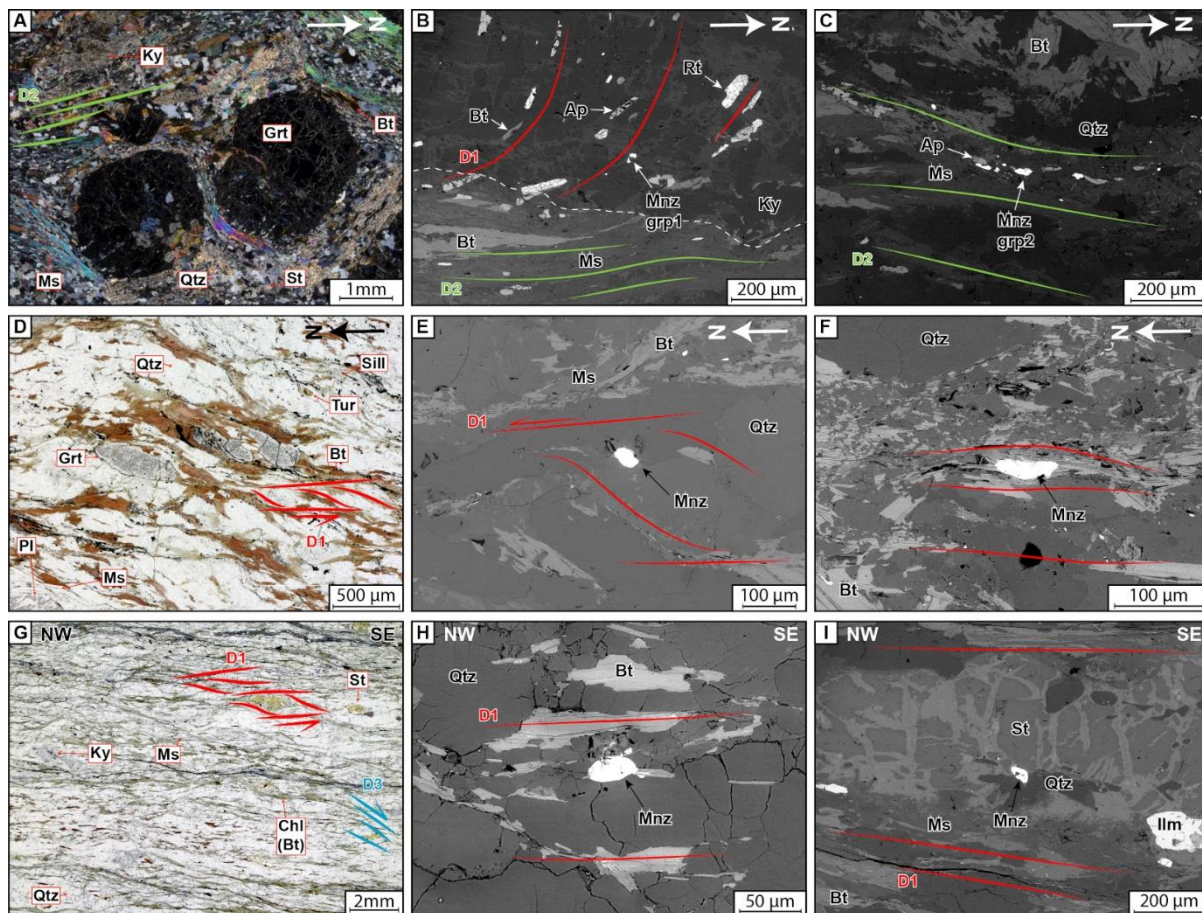
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1359 Figure 11

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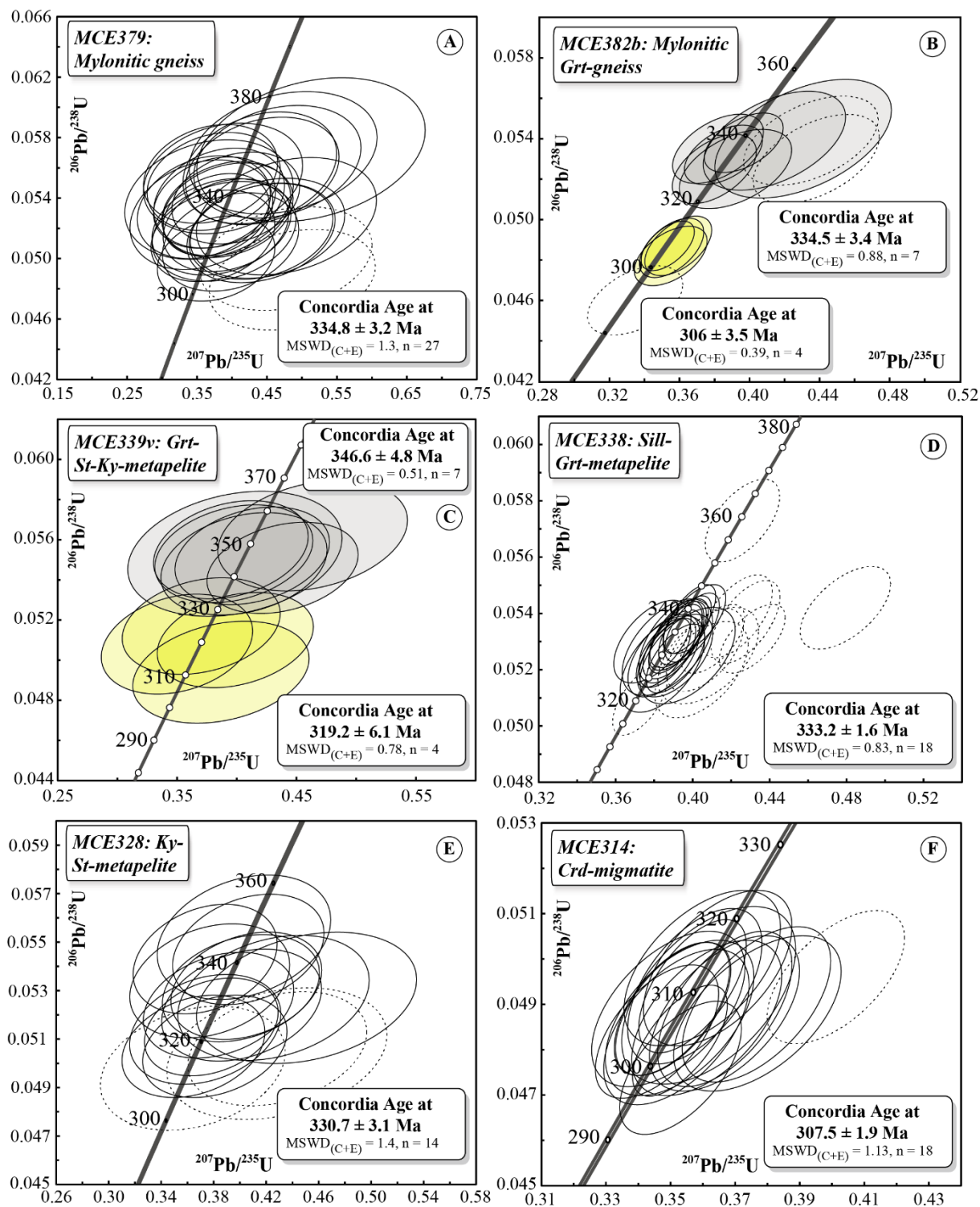
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1365 Figure 12

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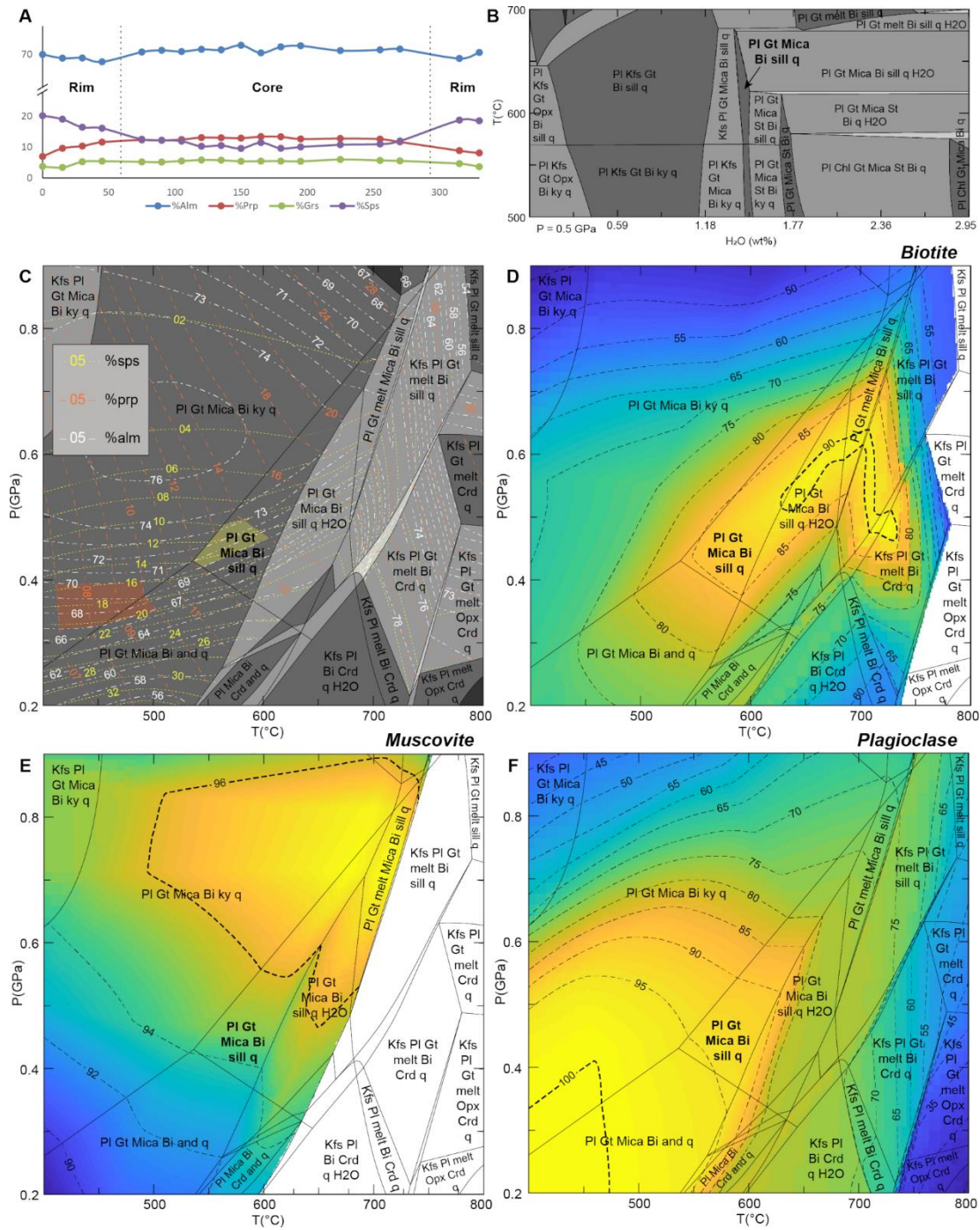
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1374 Figure 14

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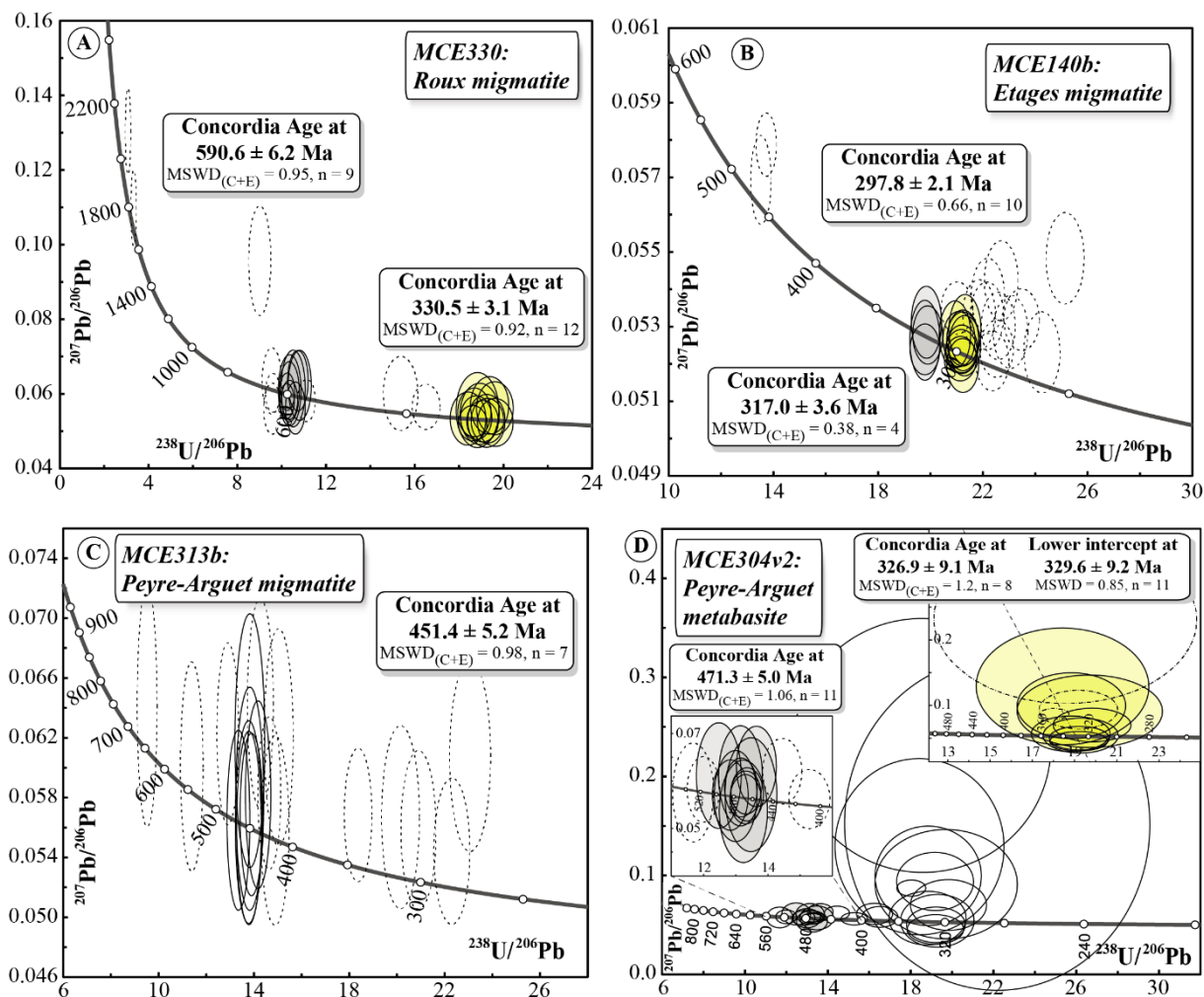
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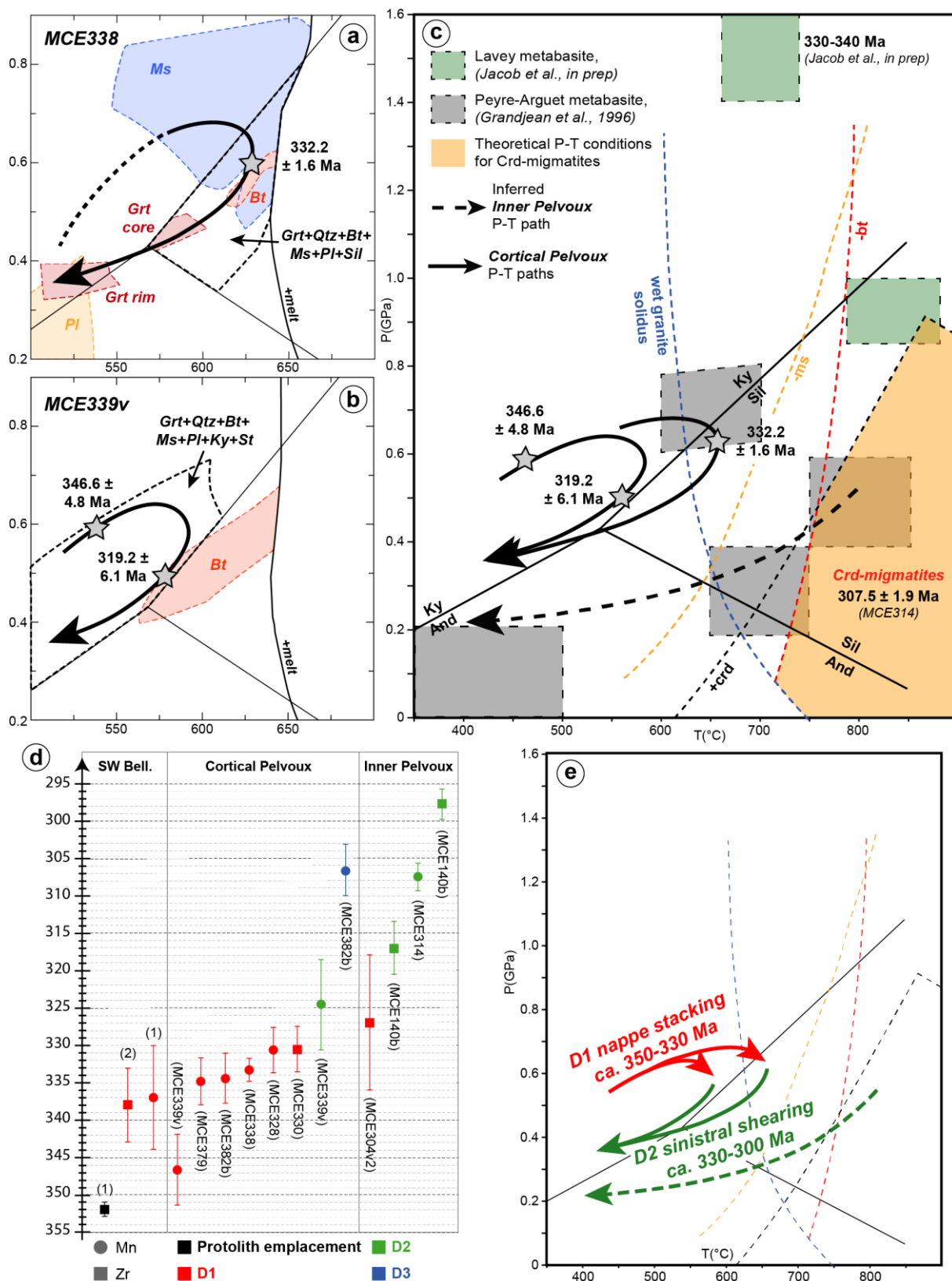
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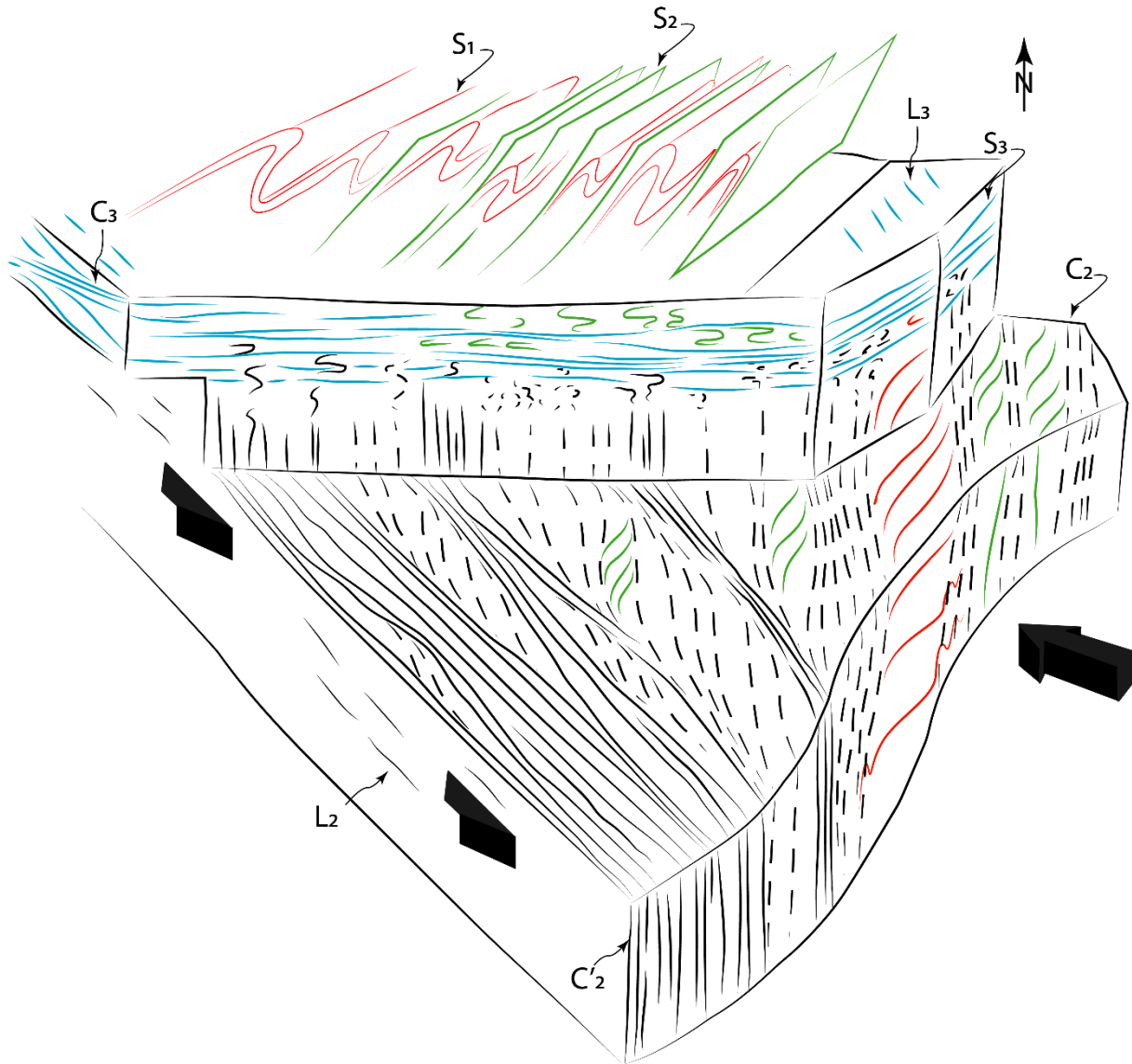
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1392 Figure 17

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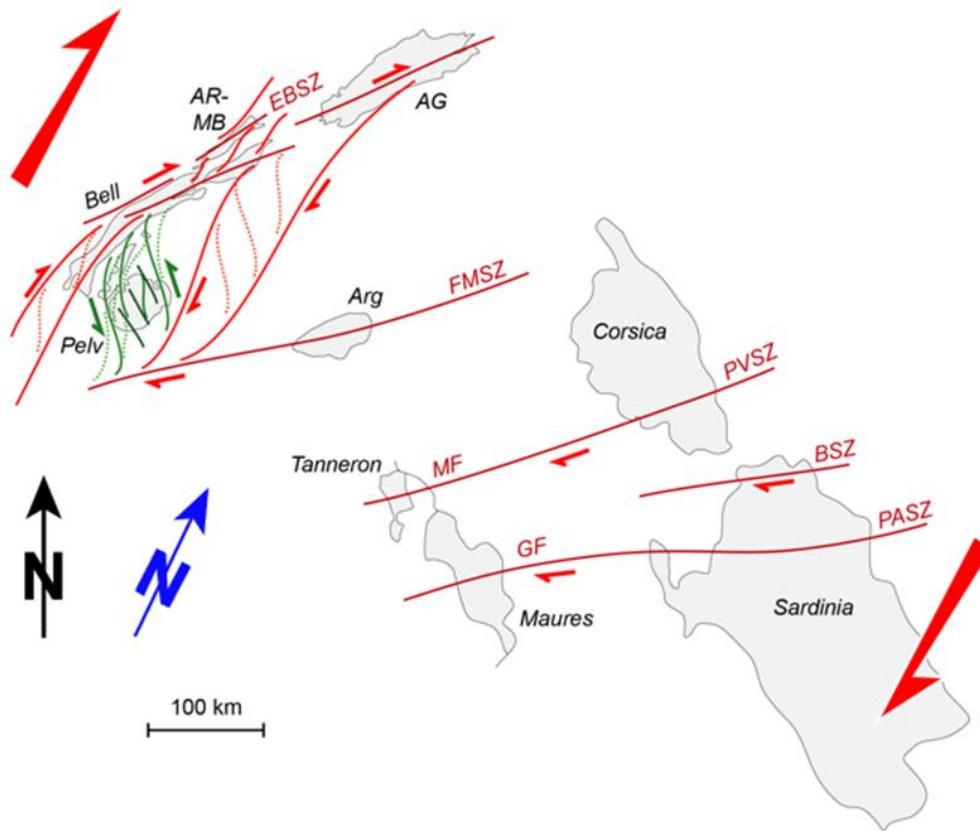
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1403 Table 1

1404

Sample	Rock type	GPS location	Mineral dated	U-Th-Pb age ( $\pm 2\sigma$ )
<b>Cortical Pelvoux</b>				
MCE379	Mylonitic gneiss	N45°1'23.49" E06°2'33.70"	Monazite	334.8 $\pm$ 3.2 Ma
MCE382b	Mylonitic Grt-gneiss	N45°1'2.61" E06°2'50.99"	Monazite	334.5 $\pm$ 3.4 Ma
				306.0 $\pm$ 3.5 Ma
MCE339v	Grt-St-Ky-metapelite	N44°52'52.00" E05°59'17.34"	Monazite	346.6 $\pm$ 4.8 Ma
				319.2 $\pm$ 6.1 Ma
MCE338	Sill-Grt-metapelite	N44°52'58.84" E06°0'49.10"	Monazite	333.2 $\pm$ 1.6 Ma
MCE328	Ky-St-metapelite	N44°47'12.12" E06°4'1.62"	Monazite	330.7 $\pm$ 3.1 Ma
MCE330	Roux migmatite	N44°47'29.86" E06°5'18.09"	Zircon	330.5 $\pm$ 3.1 Ma
				590.6 $\pm$ 6.2 Ma
<b>Inner Pelvoux</b>				
MCE314	Peyre-Arguet Crd-migmatite	N44°50'6.69" E06°22'2.42"	Monazite	307.5 $\pm$ 1.9 Ma
MCE313b	Peyre-Arguet migmatite	N44°56'4.37" E06°12'55.58"	Zircon	451.4 $\pm$ 5.2 Ma
MCE140b	Etages migmatite	N44°56'4.37" E06°12'55.58"	Zircon	297.8 $\pm$ 2.1 Ma
				317.0 $\pm$ 3.6 Ma
MCE304v2	Peyre-Arguet metabasite	N44°50'15.34" E06°21'22.25"	Zircon	326.9 $\pm$ 9.1 Ma
				471.3 $\pm$ 5.0 Ma

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1407 Table 2

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<i>oxyde (wt%)</i>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	MnO	P <sub>2</sub> O <sub>5</sub>	Cr <sub>2</sub> O <sub>3</sub>	NiO	LOI	total
<i>MCE339v</i>	67,30	16,00	5,95	2,26	1,01	2,09	3,18	0,75	0,07	0,16	0,01	0,00	2,15	100,93
<i>MCE338</i>	59,70	19,00	7,32	3,26	1,09	2,07	3,82	0,93	0,11	0,12	0,02	0,00	2,95	100,39

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1412 Table 3

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	Garnet				Biotite		Muscovite	Plagioclase
	MCE339v		MCE338		MCE339v	MCE338	MCE338	MCE338
	Core	Rim	Core	Rim				
<i>Oxydes (wt%)</i>								
SiO <sub>2</sub>	36,39	36,71	36,38	36,54	34,19	35,05	46,27	61,19
Al <sub>2</sub> O <sub>3</sub>	20,34	20,44	20,48	20,16	19,23	18,45	36,41	23,14
TiO <sub>2</sub>	0,19	0,05	0,03	0,01	1,66	1,47	0,34	
FeO	29,56	33,90	31,96	30,09	20,16	20,48	1,33	
MgO	1,27	2,31	3,14	2,02	8,63	9,10	0,69	
MnO	4,57	0,86	4,78	8,13	0,05	0,05	0,02	
CaO	6,62	5,14	1,93	1,31	0,00	0,02	0,03	4,83
Na <sub>2</sub> O					0,11	0,18	1,31	8,61
K <sub>2</sub> O					8,51	8,99	9,62	0,11
<i>Total</i>	<i>98,94</i>	<i>99,41</i>	<i>98,70</i>	<i>98,26</i>	<i>92,54</i>	<i>93,79</i>	<i>96,02</i>	<i>97,88</i>
<i>Mol cations</i>								
Si	2,97	2,97	2,97	3,02	2,68	2,72	3,05	2,79
Al	1,96	1,96	1,98	1,96	1,78	1,69	2,83	1,24
Ti	0,01	0,00	0,00	0,00		0,09	0,02	
Fe <sup>2+</sup>	2,02	2,30	2,14	2,05	1,32	1,33	0,07	
Fe <sup>3+</sup>	0,00	0,00	0,05	0,03				
Mg	0,16	0,28	0,38	0,25	1,01	1,05	0,07	
Mn	0,32	0,06	0,33	0,61	0,00	0,00	0,00	
Ca	0,58	0,45	0,57	0,11	0,00	0,00	0,00	0,24
Na					0,02	0,03	0,17	0,62
K					0,85	0,89	0,81	0,01
X <sub>Fe</sub>					0,57	0,56		
<i>End members</i>								
An								71,89
Orth								27,34
Prp	5,13	9,21	12,66	8,35				0,77
Alm	65,26	74,09	70,77	68,69				
Grs	18,87	14,49	5,51	3,85				
Sps	10,45	1,96	10,97	19,07				

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1416 Figure 4

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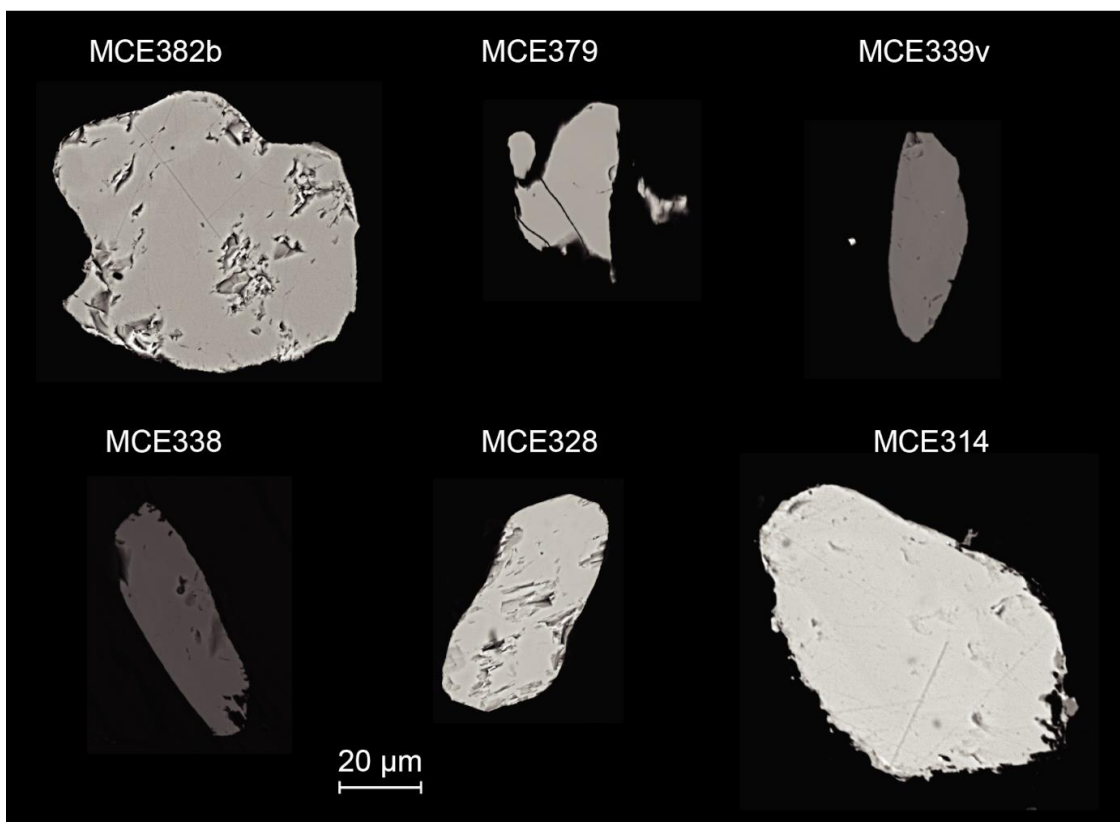
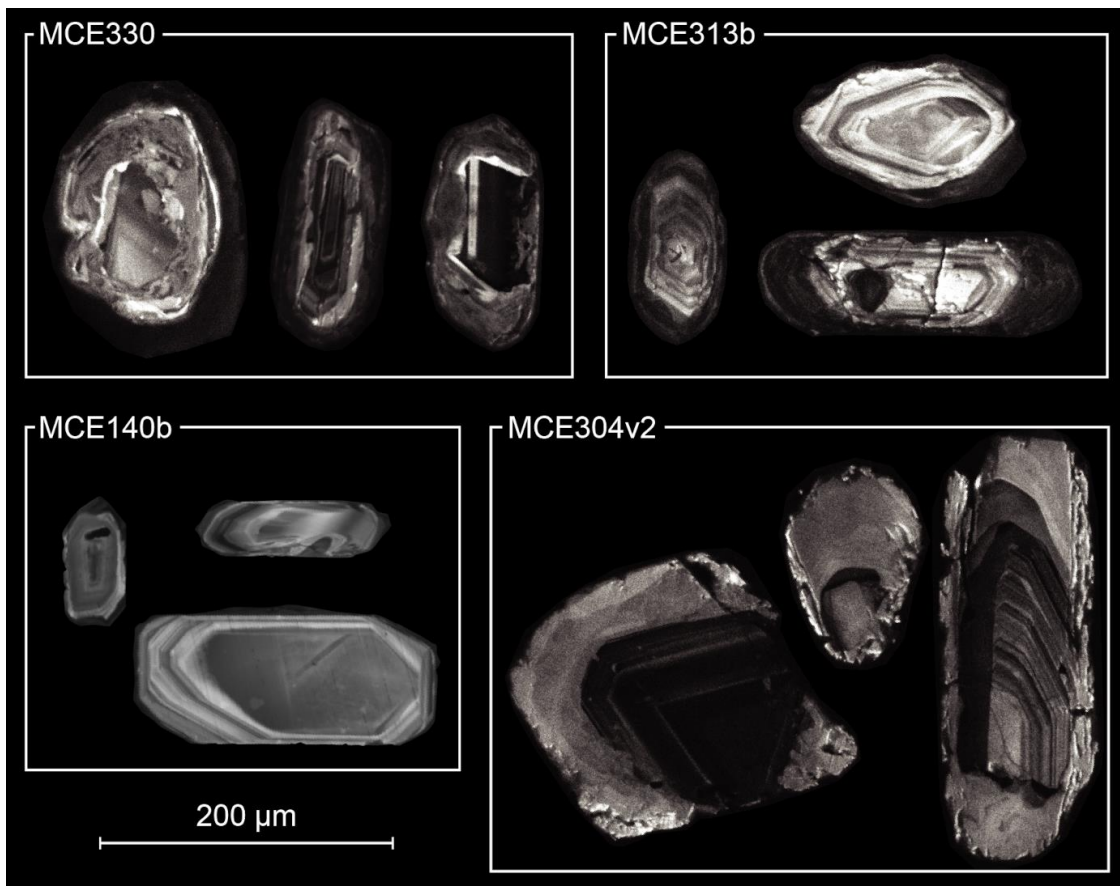
Event		Belledonne SW	Cortical Pelvoux	Inner Pelvoux
<b>D3</b>	Structure		Low angle S3 +/- mylonitic Horizontal axis F3 fold and a-Type F3 fold Top to NE shearing	Low angle S3 +/- mylonitic Horizontal axis F3 fold
	P-T		Retrograde amphibolite facies 0.45-0.35 GPa-450- 50 °C	High-T migmatite Cordierite bearing migmatite
	Age		ca. 306-298 Ma	ca. 306-298 Ma ?
<b>D2</b>	Structure	High angle S2 N030E Upright fold NE-SW axis NE-SW L2	High angle S2 N030E High angle C2 N-S High angle C'2 N150E Folded S2, Horizontal axis	High angle S2 N030E Upright fold NE-SW axis High angle C2 N-S High angle C'2 N150E NS to NE-SW L2
	P-T	Sill +melt	Low-T migmatite	Low-T migmatite
	Age	ca. 330-310 Ma <i>Freville et al. 2018</i>	ca. 330-298 Ma	ca. 330-298 Ma
<b>D1</b>	Structure	Low angle S1 Recumbent fold to the east E-W L1	Mark the lithological limits low angle S1-3	Mostly erased Relictual S1 in F2 fold hinge
	P-T	Amphibolite facies Grt-Bt +melt 0.6-0.8 GPa-600-630°C	Amphibolite facies ? +melt	No evidence
	Age	339 +/- 5 Ma	ca. 350-330 Ma	ca. 340-330 Ma ? (HP stage, <i>Jacob et al., in review</i> )

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1420 Figure S1

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1423

1424 Table S1

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	U (ppm)	Pb (ppm)	<i>Isotopic Ratios</i>				
			207Pb/206Pb	±1σ	207Pb/235U	±1σ	206Pb/238U
<b>MCE330 (Roux migmatite)</b>							
mce330-1	1093	101	0,0602	0,0024	0,8661	0,0329	0,104
mce330-2	1258	58	0,0528	0,0027	0,3776	0,0185	0,053
mce330-3	1614	140	0,0580	0,0021	0,7825	0,0276	0,097
mce330-4	951	45	0,0536	0,0026	0,3939	0,0186	0,053
mce330-5	868	74	0,0584	0,0024	0,7774	0,0306	0,096
mce330-6	331	31	0,0560	0,0030	0,8072	0,0426	0,104
mce330-7	139	40	0,1303	0,0053	5,8510	0,2323	0,323
mce330-8	1142	99	0,0606	0,0023	0,8151	0,0296	0,097
mce330-9	2004	95	0,0521	0,0021	0,3862	0,0154	0,053
mce330-10	1007	80	0,0582	0,0025	0,7221	0,0307	0,089
mce330-11	247	12	0,0556	0,0044	0,4076	0,0313	0,053
mce330-12	1055	49	0,0527	0,0025	0,3811	0,0174	0,052
mce330-13	506	42	0,0635	0,0036	0,8163	0,0449	0,093
mce330-14	923	49	0,0565	0,0027	0,4721	0,0219	0,060
mce330-15	649	173	0,1098	0,0046	4,5500	0,1852	0,300
mce330-16	150	15	0,0957	0,0066	1,4641	0,0977	0,111
mce330-17	765	36	0,0550	0,0029	0,4060	0,0208	0,053
mce330-18	1226	55	0,0523	0,0028	0,3675	0,0195	0,050
mce330-19	621	52	0,0562	0,0031	0,7296	0,0391	0,094
mce330-20	1561	70	0,0562	0,0031	0,3948	0,0215	0,053
mce330-21	321	26	0,0623	0,0041	0,7939	0,0514	0,092
mce330-22	624	53	0,0606	0,0036	0,8077	0,0462	0,096
mce330-23	1178	54	0,0528	0,0031	0,3783	0,0218	0,052
mce330-24	1237	59	0,0534	0,0031	0,3998	0,0229	0,054
mce330-25	651	30	0,0547	0,0036	0,3979	0,0256	0,052
mce330-26	2605	119	0,0569	0,0034	0,4050	0,0236	0,053
mce330-27	787	73	0,0635	0,0039	0,9153	0,0551	0,104
mce330-28	338	29	0,0610	0,0042	0,8110	0,0545	0,096
mce330-29	323	27	0,0615	0,0045	0,8054	0,0577	0,095
mce330-30	396	23	0,0601	0,0044	0,5393	0,0381	0,065
<b>MCE304v2 (Peyre-Arguet metabasite)</b>							
mce304V2-1	301	20,2	0,0586	0,0028	0,6144	0,0283	0,076
mce304V2-2	32	1,4	0,0702	0,0111	0,4882	0,0751	0,050
mce304V2-3	545	36,2	0,0562	0,0023	0,5822	0,0237	0,079
mce304V2-4	164	11	0,0536	0,0047	0,5586	0,0477	0,079
mce304V2-5	153	8,2	0,0581	0,0046	0,4854	0,0372	0,060
mce304V2-6	27	1,3	0,0569	0,0115	0,4170	0,0826	0,053

mce304V2-7	1349	89,6	0,0576	0,0021	0,5964	0,0210	0,079
mce304V2-8	27	1,3	0,0939	0,0130	0,6750	0,0904	0,052
mce304V2-9	199	13,6	0,0568	0,0042	0,6032	0,0435	0,077
mce304V2-10	104	7	0,0611	0,0046	0,6409	0,0473	0,076
mce304V2-11	189	12,3	0,0631	0,0038	0,6378	0,0369	0,073
mce304V2-12	8	0,3	0,0911	0,0243	0,6372	0,1644	0,050
mce304V2-13	166	11,5	0,0570	0,0033	0,6131	0,0344	0,078
mce304V2-14	12	0,6	0,0996	0,0219	0,7286	0,1553	0,053
mce304V2-15	81	6,1	0,0576	0,0046	0,6802	0,0527	0,083
mce304V2-16	43	2	0,0502	0,0076	0,3599	0,0536	0,052
mce304V2-17	72	3,3	0,0455	0,0063	0,3269	0,0446	0,052
mce304V2-18	801	53,3	0,0572	0,0025	0,5908	0,0254	0,074
mce304V2-19	483	35,8	0,0582	0,0031	0,6695	0,0344	0,083
mce304V2-20	5	0,2	0,1517	0,0743	0,9431	0,4450	0,043
mce304V2-21	1852	91,5	0,0872	0,0037	0,6665	0,0275	0,055
mce304V2-22	6	0,3	0,1290	0,0398	0,9654	0,2859	0,054
mce304V2-23	114	6,3	0,0612	0,0047	0,5190	0,0387	0,063
mce304V2-24	142	10,2	0,0612	0,0049	0,6761	0,0526	0,080
mce304V2-25	29	1,3	0,0542	0,0112	0,3874	0,0790	0,053
mce304V2-26	677	41,8	0,0621	0,0031	0,5925	0,0289	0,065
mce304V2-27	3	0,1	0,2312	0,0686	1,7179	0,4555	0,053
mce304V2-28	102	6,8	0,0571	0,0052	0,5848	0,0522	0,074
mce304V2-29	1480	86,5	0,0562	0,0028	0,5072	0,0245	0,065
<b>MCE140b (Etage migmatite)</b>							
5010616	25	469	0,0527	0,0051	0,3668	0,0053	0,050
6010616	21	404	0,0531	0,0046	0,3690	0,0052	0,050
7010616	189	4205	0,0523	0,0044	0,3407	0,0043	0,047
8010616	84	1723	0,0524	0,0045	0,3651	0,0047	0,050
9010616	195	4292	0,0524	0,0044	0,3408	0,0043	0,047
10010616	71	1548	0,0528	0,0044	0,3658	0,0049	0,050
11010616	129	2730	0,0522	0,0046	0,3401	0,0043	0,047
12010616	54	1196	0,0525	0,0046	0,3397	0,0045	0,046
16010616	106	2329	0,0527	0,0044	0,3420	0,0044	0,047
17010616	69	1541	0,0526	0,0046	0,3417	0,0046	0,047
18010616	109	2361	0,0535	0,0040	0,3510	0,0045	0,047
19010616	80	1727	0,0524	0,0046	0,3208	0,0042	0,046
20010616	90	1971	0,0520	0,0049	0,3374	0,0044	0,047
21010616	71	938	0,0579	0,0029	0,5814	0,0076	0,072
22010616	95	2083	0,0527	0,0045	0,3443	0,0045	0,047
23010616	64	1460	0,0521	0,0049	0,3212	0,0043	0,046
27010616	20	279	0,0569	0,0035	0,5804	0,0084	0,073
28010616	90	2143	0,0532	0,0043	0,3123	0,0042	0,046
29010616	55	1165	0,0528	0,0046	0,3477	0,0047	0,047
30010616	55	1174	0,0529	0,0046	0,3423	0,0047	0,046
31010616	78	1818	0,0530	0,0045	0,3236	0,0044	0,046



32010616	43	1112	0,0548	0,0041	0,3007	0,0045	0,03
33010616	89	2001	0,0533	0,0044	0,3363	0,0046	0,04
34010616	129	2961	0,0533	0,0044	0,3316	0,0045	0,04
38010616	53	1308	0,0523	0,0053	0,2974	0,0043	0,04
39010616	216	5260	0,0529	0,0047	0,3161	0,0044	0,04
40010616	78	1772	0,0538	0,0043	0,3344	0,0047	0,04
41010616	87	1954	0,0542	0,0042	0,3294	0,0047	0,04

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**MCE313b (Peyre Arguet migmatite)**


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mce313b-1	1645	79	0,0568	0,0020	0,4266	0,0147	0,05
mce313b-2	353	23	0,0565	0,0027	0,5834	0,0268	0,07
mce313b-4	411	26	0,0560	0,0029	0,5597	0,0278	0,07
mce313b-5	1043	66	0,0569	0,0024	0,5642	0,0234	0,07
mce313b-7	631	38	0,0583	0,0023	0,5489	0,0210	0,06
mce313b-9	466	32	0,0623	0,0027	0,6653	0,0283	0,07
mce313b-12	472	29	0,0643	0,0031	0,6211	0,0294	0,07
mce313b-15	2404	96	0,0544	0,0022	0,3364	0,0132	0,04
mce313b-17	327	21	0,0582	0,0028	0,5660	0,0264	0,07
mce313b-18	2335	90	0,0608	0,0029	0,3633	0,0165	0,04
mce313b-19	2106	90	0,0558	0,0024	0,3684	0,0153	0,04
mce313b-21	499	30	0,0620	0,0033	0,5689	0,0289	0,06
mce313b-22	436	28	0,0579	0,0033	0,5778	0,0320	0,07
mce313b-23	815	49	0,0558	0,0028	0,5169	0,0254	0,06
mce313b-24	566	37	0,0564	0,0030	0,5639	0,0293	0,07
mce313b-26	292	19	0,0618	0,0038	0,6162	0,0364	0,07
mce313b-28	1608	71	0,0567	0,0028	0,3880	0,0182	0,04
mce313b-29	286	27	0,0641	0,0036	0,9290	0,0508	0,10
mce313b-30	753	59	0,0601	0,0031	0,7272	0,0368	0,08

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1429 Table S2

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1431 **Table S2: Operating conditions for the LA-ICP-MS equipment**

<b>Laboratory &amp; Sample Preparation</b>	
Laboratory name	Géosciences Montpellier, UMR CNRS 5243, Montpellier, France
Sample type/mineral	Monazite
Sample preparation	Polished thin-section
Imaging	Hirox SH3000, BSE detector BRGM
<b>Laser ablation system</b>	
Make, Model & type	LambdaPhysiks, Compex 102, Excimer
Ablation cell	Geolas
Laser wavelength	193 nm
Pulse width	15 ns
Fluence	10 J/cm <sup>2</sup>
Repetition rate	2 Hz
Spot size	26 µm
Sampling mode / pattern	Single spot
Carrier gas	100% He mixed with Ar before entering the plasma
Background collection	15 seconds
Ablation duration	45 seconds
Wash-out delay	/
Cell carrier gas flow (He)	0.3 l/min
<b>ICP-MS Instrument</b>	
Make, Model & type	Element XR, SF-ICP-MS
Sample introduction	Via conventional tubing
RF power	1350W
Sampler, skimmer cones	Ni
Extraction lenses	/
Make-up gas flow (Ar)	0.6 l/min
Detection system	Electron multiplier
Data acquisition protocol	Time-resolved analysis
Scanning mode	Peak hopping, three points per peak
Detector mode	Pulse counting, except for <sup>208</sup> Pb and <sup>232</sup> Th (analog mode), dead time correction applied.
Masses measured	<sup>204</sup> (Hg + Pb), <sup>206</sup> Pb, <sup>207</sup> Pb, <sup>208</sup> Pb, <sup>232</sup> Th, <sup>238</sup> U
Integration time per peak	10.24 ms for all masses, except <sup>208</sup> Pb and <sup>232</sup> Th (5.12 ms) and <sup>207</sup> Pb (40.96 ms)
Sensitivity / Efficiency	3000 cps/ppm Pb (26µm, 4Hz)
<b>Data Processing</b>	
Gas blank	15 seconds on-peak
Calibration strategy	Manangotry monazite standard used as primary reference material.
Reference Material info	Manangotry (Poitrasson et al., 2000)
Data processing package used	GLITTER ® (van Achterbergh et al., 2001)
Quality control / Validation	/

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1435 Table S3

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<b>Laboratory &amp; Sample Preparation</b>	
Laboratory name	Bureau de Recherche Géologique et Minière (BRGM), Orléans, France
Sample type/mineral	Zircon
Sample preparation	Polished thin-section
Imaging	Hirox SH3000, BSE detector BRGM
<b>Laser ablation system</b>	
Make, Model & type	CETAC Excite 193, Excimer
Ablation cell	HelEx II
Laser wavelength	193 nm
Pulse width	15 ns
Fluence	6 J/cm <sup>2</sup>
Repetition rate	3 Hz
Spot size	15 µm
Sampling mode / pattern	Single spot
Carrier gas	100% He mixed with Ar with 'Squid system' before entering the plasma
Background collection	20 seconds
Ablation duration	40 seconds
Wash-out delay	/
Cell carrier gas flow (He)	0.45 l/min
<b>ICP-MS Instrument</b>	
Make, Model & type	Thermo-scientific, X-serie II, Q-ICP-MS
Sample introduction	Via conventional tubing
RF power	1400W
Sampler, skimmer cones	Ni
Extraction lenses	/
Make-up gas flow (Ar)	1 l/min
Detection system	Electron multiplier
Data acquisition protocol	Time-resolved analysis
Masses measured	<sup>204</sup> (Hg + Pb), <sup>206</sup> Pb, <sup>207</sup> Pb, <sup>208</sup> Pb, <sup>232</sup> Th, <sup>238</sup> U
Integration time	50 ms for all masses
<b>Data Processing</b>	
Calibration strategy	Trebilcock monazite standard used as primary reference material.
Reference Material info	Trebilcock (272 ± 2 Ma, Tomascak et al. 1996)
Data processing package used	GLITTER ® (van Achterbergh et al., 2001)
Quality control / Validation	Madmon Monazite standard used has quality control (515 Ma, Schulz et al., 2007.)

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1441 Table S4

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1443 **Table S4: Operating conditions for the LA-ICP-MS equipment**

<b>Laboratory &amp; Sample Preparation</b>	
Laboratory name	GeOHeLiS Analytical Platform, OSUR, Univ Rennes 1, France
Sample type/mineral	Detrital zircon
Sample preparation	Epoxy mount
Imaging	MIRA3 TESCAN, Tescan CL detector (semi-parabolic mirror and light guide), BRGM
<b>Laser ablation system</b>	
Make, Model & type	ESI NWR193UC, Excimer
Ablation cell	ESI NWR TwoVol2
Laser wavelength	193 nm
Pulse width	< 5 ns
Fluence	8 J/cm <sup>2</sup>
Repetition rate	4 Hz
Spot size	25 µm
Sampling mode / pattern	Single spot
Carrier gas	100% He, Ar make-up gas and N <sub>2</sub> (3 ml/min) combined using in-house smoothing device
Background collection	20 seconds
Ablation duration	60 seconds
Wash-out delay	15 seconds
Cell carrier gas flow (He)	0.75 l/min
<b>ICP-MS Instrument</b>	
Make, Model & type	Agilent 7700x, Q-ICP-MS
Sample introduction	Via conventional tubing
RF power	1350W
Sampler, skimmer cones	Ni
Extraction lenses	X type
Make-up gas flow (Ar)	0.85 l/min
Detection system	Single collector secondary electron multiplier
Data acquisition protocol	Time-resolved analysis
Scanning mode	Peak hopping, one point per peak
Detector mode	Pulse counting, dead time correction applied, and analog mode when signal intensity > ~ 10 <sup>6</sup> cps
Masses measured	<sup>204</sup> (Hg + Pb), <sup>206</sup> Pb, <sup>207</sup> Pb, <sup>208</sup> Pb, <sup>232</sup> Th, <sup>238</sup> U
Integration time per peak	10-30 ms
Sensitivity / Efficiency	22000 cps/ppm Pb (50µm, 10Hz)
<b>Data Processing</b>	
Gas blank	20 seconds on-peak
Calibration strategy	GJ1 zircon standard used as primary reference material, Plešovice used as secondary reference material (quality control)
Reference Material info	GJ1 (Jackson et al., 2004) Plešovice (Slama et al., 2008)
Data processing package used	GLITTER ® (van Achterbergh et al., 2001)
Quality control / Validation	Plešovice: concordia age = 336.3 ± 3.3 Ma (N=6; MSWD=0.54)

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