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1 **Two-stage partial melting during the Variscan extensional tectonics**

2 **(Montagne Noire, France)**

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12

13 **ABSTRACT**

14 One of the striking features that characterise the late stages of the Variscan orogeny is the
15 development of gneiss and migmatite domes, as well as extensional Late Carboniferous and
16 Permian sedimentary basins. It remains a matter of debate whether the formation of domes
17 was related to the well documented late orogenic extension or to the contractional tectonics
18 that preceded. Migmatization and magmatism are expected to predate extension if the domes
19 are compression-related regional anticlines, but they must both precede and be
20 contemporaneous with extension if they are extensional core complexes.

21 In the Montagne Noire area (southern French Massif Central), where migmatization,
22 magmatism and the deformation framework are well documented, the age of the extensional
23 event was unequivocally constrained to 300-290 Ma. Therefore, dating migmatization in this
24 area is a key point for discriminating between the two hypotheses and understanding the Late
25 Palaeozoic evolution of this part of the Variscan belt. For this purpose, a migmatite and an
26 associated anatectic granite from the Montagne Noire dome were dated by LA-ICP-MS (U-

27 Th/Pb on zircon and monazite) and laser probe ^{40}Ar - ^{39}Ar (K-Ar on muscovite). Although
28 zircon did not record any Variscan age unequivocally related to compression (380-330Ma),
29 two age groups were identified from the monazite crystals. A first event, at ca. 319 Ma (U-
30 Th/Pb on monazite), is interpreted as a first stage of migmatization and as the emplacement
31 age of the granite, respectively. A second event at ca. 298-295 Ma, recorded by monazite (U-
32 Th/Pb) and by the muscovite ^{40}Ar - ^{39}Ar system in the migmatite and in the granite, could be
33 interpreted as a fluid-induced event, probably related to a second melting event identified
34 through the syn-extensional emplacement of the nearby Montalet leucogranite ca. 295 Ma
35 ago. The ages of these two events post-date the Variscan compression and agree with an
36 overall extensional context for the development of the Montagne Noire dome-shaped massif.
37 Comparison of these results with published chemical (EPMA) dating of monazite from the
38 same rocks demonstrates that the type of statistical treatment applied to EPMA data is crucial
39 in order to resolve different monazite age populations.

40

41 **Keywords:** monazite, LA-ICP-MS, U-Th-Pb dating, muscovite, ^{40}Ar - ^{39}Ar dating, Variscan,
42 Montagne Noire

43

44 **1. Introduction**

45 Until the late 1980s, wrench tectonics was considered to control the late Palaeozoic
46 tectonic evolution of the Variscan orogen (Arthaud and Matte, 1977). It was interpreted as
47 corresponding to an ultimate phase of N-S compression during the Late Carboniferous, and
48 marked the end of the Variscan continental collision. In such compressive context, the
49 commonly coal-bearing continental sedimentary basins that developed during the very late
50 Carboniferous (305 -295 Ma) were interpreted as pull-apart basins or as related to horsetail
51 splay faults at the termination of strike-slip systems faults (e.g. Arthaud and Matte, 1977, Blès

52 et al. 1989). The development of widespread continental sedimentary basins during the
53 Permian was attributed to a subsequent pervasive N-S extension that occurred throughout the
54 Variscan domain and was considered to result from a plate kinematics re-arrangement without
55 any causal relation with the previous Variscan continental collision (e.g. Arthaud and Matte,
56 1977, Blès et al. 1989).

57 More recently, the late Palaeozoic tectonic evolution has been compared to extensional
58 tectonics of both the Tibetan plateau and the North American Cordillera during the Cenozoic
59 (e.g. Ménard and Molnar 1988; Burg et al. 1994). E-W extension, nearly parallel to the belt
60 took place between 330-305 Ma during escape tectonics driven by still active N-S
61 compression forces. It was followed by a NE-SW to N-S extension between 300 Ma and 260
62 Ma, which started during the waning shortening, and implies a radical change in extension
63 direction induced by the modification of the boundary conditions and the collapse of the
64 entire chain after continental convergence (e.g. Burg et al. 1994). Both episodes of extension
65 are viewed as a consequence of the previous N-S shortening, extension being induced by the
66 collapse of the crust, considerably thickened during the continental collision, after thermal
67 relaxation. In this interpretation, and contrary to older “compressive” interpretations, the late
68 Carboniferous basins are extensional in origin as well as the Permian basins (Becq-Giraudon
69 and Van Den Driessche 1993).

70 In both interpretations, the pervasive high-temperature low-pressure (HT-LP)
71 metamorphism and magmatism that occurred throughout the Variscan chain during the late
72 Carboniferous resulted from crustal thickening. A striking feature of this period was the
73 development of gneiss and migmatite domes, such as those found in the Montagne Noire and
74 the Velay areas in the southern part of the French Massif Central. However, the two
75 interpretations disagree on the cause of their development. In the compressive scenario these
76 structures are interpreted as regional anticlines that developed in response to the N-S

77 shortening (Arthaud et al. 1966; Burg and Matte 1978; Matte et al., 1998), whereas they are
78 interpreted as extensional gneiss domes, similar to the Cenozoic metamorphic core complexes
79 of the Basin and Range province, in the extensional scenario (Van Den Driessche and Brun
80 1989, 1991; Echtler and Malavieille 1990; Brun and Van Den Driessche 1994). In the first
81 case migmatization and magmatism predate extension. The second interpretation requires
82 thermal relaxation and related rheological softening, and change in boundary conditions in
83 order for the crust to collapse. Consequently, migmatization both precedes and is
84 contemporaneous with the onset of extension, especially because extension can enhance
85 partial melting by adiabatic decompression. In the Montagne Noire gneiss dome, the age of
86 the extensional event was unequivocally constrained to ca. 295 Ma by dating a syntectonic
87 leucogranite emplaced within the northward-dipping normal fault that bounds the gneiss
88 dome to the north and controlled the development of Upper Carboniferous – Lower Permian
89 sedimentary basins (Poilvet et al., 2011).

90 The Montagne Noire gneiss dome is a typical case where geochronology can yield
91 critical constraints on tectonic models, and where the precision obtained on each individual
92 age is crucial. This becomes even more important in a region that underwent a complex
93 polyphased metamorphic/magmatic history possibly characterised by several phases of
94 mineral growth (involving datable minerals such as zircon, monazite and muscovite) in a
95 relatively short period of time. For the purpose of this study, two samples (a migmatite and an
96 associated granite) from the Montagne Noire dome were selected for geochronological
97 investigations (U-Th-Pb on monazite and zircon and K-Ar on muscovite), in order to
98 discriminate between the two contradictory tectonic interpretations.

99

100 **2. Geological setting**

101

102 The Montagne Noire gneiss-migmatite massif is located in the southern French Massif
103 Central (Fig. 1). It is composed of a high-grade gneissic core surrounded by mostly low-grade
104 metasediments. The gneissic core is composed of migmatites and augen orthogneisses, with
105 some fine-grained gneissic intercalations that have been interpreted as either metasediments
106 or mylonitic zones (Bogdanoff et al. 1984; Van Den Driessche and Brun 1992, and references
107 therein). Some of these intercalations contain HP/HT mafic and ultramafic metamorphic
108 rocks, suggesting possible major early tectonic contacts (Bogdanoff et al. 1984; Allabouvette
109 and Demange 1993; Demange et al. 1995). The migmatites resulted mostly from partial
110 melting of sediments, but also of felsic augen orthogneisses (e.g. Bogdanoff et al. 1984;
111 Demange, 1982). Weakly deformed to undeformed anatectic granites intrude both the
112 orthogneisses and the migmatites. The gneissic core is surrounded by weakly metamorphosed
113 or unmetamorphosed lower to middle Palaeozoic sediments that are intensely deformed by
114 southward verging folds and thrust faults (e.g. Arthaud 1970; Bogdanoff et al. 1984; Echtler
115 1990). Late Carboniferous to Early Permian detrital sediments unconformably overlie these
116 tectonic units to the South. In contrast, to the North, the EW-trending north-dipping normal
117 fault zone (Espinouse detachment) marks the tectonic contact between these sediments and
118 the core units, and controls the development of the Lodève-Graissessac and Saint-Affrique
119 basins (Fig. 1; Van Den Driessche and Brun 1989, 1992; Burg et al. 1994).

120 The foliation of the gneissic core developed within the lower crust during the thrusting event
121 responsible for the deformation of the lower to middle Palaeozoic sedimentary cover. Its
122 dome-shaped structure and tectonic evolution is a matter of debate since long. Three types of
123 models have been proposed ranging from a diapir (e.g. Schuilling 1960; Faure and Cottureau
124 1988) a double megafold (Arthaud 1970; Burg and Matte 1978; Bogdanoff et al. 1984) or a
125 core complex (Van den Driessche and Brun 1989, Echtler and Malavielle 1990). Many recent
126 models combine in a more or less complex way the processes responsible for these three

127 types of structures to explain the final structure of the Montagne Noire: diapirism coeval with
128 compression (Faure et al. 2010), compression and subsequent extension (e.g. Cassard et al.,
129 1993; Franke et al. 2011, Doublier et al. 2015, Rabin et al. 2015), compression during
130 extension (Rey et al. 2011), or compression, diapirism and extension (e.g. Soula et al. 2001,
131 Charles et al. 2009). The precise structure of the Montagne Noire dome-shaped massif is
132 beyond the scope of the present paper. We just note that structural and metamorphic analyses
133 have not allowed to reach a consensus, although these different models are built from mostly
134 similar (especially structural) data (e.g. Rey et al. 2011, Van Den Driessche and Pitra 2012).
135 We conclude that until now, discriminating data are lacking to arbitrate between these
136 models.

137 On the scale of the Variscan belt, the tectonic origin of the Montagne Noire massif is
138 emblematic of the two end-member interpretations discussed before (i.e. compressive or
139 extensive). Eventually, the two main questions are the timing of (1) the development of the
140 HT-LP metamorphism, including partial melting, and (2) the initiation of the extensional
141 tectonics, which predominates during Permian times.

142

143 Previous geochronological works on the protolith of the augen orthogneisses yielded
144 Ordovician U-Pb zircon ages (456 ± 3 for Pont-de-Larn, 450 ± 6 Ma for the Gorges d'Héric,
145 Roger et al. 2004, 2015; 455 ± 2 Ma for the Saint-Eutrope gneiss, Pitra et al. 2012).
146 According to Faure et al. (2010), migmatization took place between 333 and 326 Ma (EPMA
147 dating on monazite) while the emplacement of late anatectic granitoids took place between
148 325 and 316 Ma (including the Vialais granite at 320 ± 3 Ma and Montalet leugranite at ca. 330
149 Ma, Fig. 1). However, a recent study by Roger et al. (2015) documented an emplacement age
150 of ca 303 Ma (U-Th-Pb on monazite) for the Vialais granite, while the Montalet leucogranite
151 yielded monazite and zircon U-Th-Pb emplacement ages of ca 294 Ma (Poilvet et al. 2011).

152 Three monazite grains from the Gorges d'Héric orthogneiss yielded $^{206}\text{Pb}/^{238}\text{U}$ ID-TIMS dates
153 around 310 Ma interpreted as a metamorphic age (Roger et al. 2015). Franke et al. (2011)
154 reported a similar age of 313 Ma for monazite extracted from a foliated aplite dyke from the
155 Gorges d'Héric, while Maluski et al. (1991) reported a biotite K-Ar plateau age of 316 ± 4 Ma
156 for the Caroux massif. The undeformed garnet-bearing leucogranite of Ourtigas yielded a U-
157 Th-Pb age of ca 298 Ma (Roger et al. 2015). Finally, a monazite Th-Pb age of 294.4 ± 4 Ma
158 (Pitra et al. 2012) as well as ^{40}Ar - ^{39}Ar ages on muscovite and biotite of ca. 297 Ma (Maluski
159 et al. 1991) have been obtained for orthogneiss samples sheared along the Espinouse
160 detachment.

161

162 **3. Sampling and petrography**

163

164 Two samples were selected for this study (Fig. 1): 1) a cordierite-bearing granite located in
165 the central part of the dome (sample ES7), and a migmatite (sample ES8), spatially associated
166 with the cordierite-bearing granite. Both rocks were sampled at the same locations as their
167 equivalent dated by Faure et al. (2010). One of the main reasons for this sampling strategy is
168 linked to the fact that previous dating (EPMA on monazite) by Faure et al. (2010) on the
169 Montalet granite returned an age (327 ± 7 Ma) that is very different from the age (294 ± 1 Ma;
170 U-Th-Pb on monazite) obtained by Poilvet et al. (2011) on the same granite. This age
171 difference was also noticed by Roger et al. (2015) for the Vialais granite. Therefore, the age
172 discrepancies cast some doubts on the EPMA ages obtained by Faure et al. (2010) on the
173 Laouzas cordierite-bearing granite and the spatially associated migmatite. They have also
174 been chosen because of the potentially complex history that these rocks underwent between
175 340 and 290 Ma.

176

177 *3.1 Laouzas granite, sample ES7*

178

179 The Laouzas granite (Fig. 1) crops out in the west-central part of the axial zone of the
180 Montagne Noire dome. It was sampled near the Laouzas dam (43°38'7.35"N, 2°45'10.00"E).
181 The rock is an undeformed heterogeneous coarse-grained (1-5 mm in average, locally up to
182 3 cm) biotite-bearing granite containing numerous large clusters of cordierite (up to 5 cm),
183 biotite-rich schlieren, tourmaline nodules and dark, foliated mica-rich enclaves (Fig. 2a).
184 Although the schlieren and enclaves locally display a preferred orientation, no solid-state
185 deformation is observed at the grain-scale in the granite, with the exception of a weak
186 undulose extinction of quartz crystals.

187 The sample is dominated by plagioclase, K-feldspar and quartz, and contains
188 subordinate amounts of biotite, cordierite and muscovite (Fig. 2b). Dumortierite, tourmaline,
189 andalusite and sillimanite are present locally. Plagioclase forms euhedral to subhedral stubby
190 prismatic crystals, 1-3 mm long. Plagioclase cores are generally altered (saussuritised) and
191 surrounded by a clear rim (Fig. 2c). The rims are similar to feldspar that also fills fractures in
192 the plagioclase cores. Some plagioclase rims are intergrown with tiny crystals of quartz in a
193 granophyric, myrmekite-like texture, in particular at the contact with K-feldspar. K-feldspar
194 and quartz are anhedral, 1-5 mm in size. Cordierite forms anhedral crystals (up to 2 mm) that
195 are slightly pinitised or replaced by fine-grained muscovite around the rims (Fig. 2b). Biotite
196 crystals (0.1-3 mm) are subhedral and locally partly altered to chlorite in association with
197 needles of rutile (sagenite). Rare minute needles of sillimanite are locally present in large
198 quartz crystals. Although euhedral muscovite crystals (~1 mm) are locally present, muscovite
199 mostly forms large subhedral poikiloblasts (up to 2 mm) or develops tiny crystals at the
200 expense of K-feldspar, plagioclase or cordierite. Needles of dumortierite (pink to violet,
201 strongly pleochroic acicular crystals, ~0.5 mm) or tourmaline (pale green, ~0.3 mm) are

202 commonly associated with clear plagioclase overgrowths, anhedral pink andalusite (~0.5 mm)
203 and muscovite (Fig. 2c).

204 These observations suggest a two-stage evolution. The crystallisation of the relatively
205 coarse-grained granite (plagioclase cores, K-feldspar, quartz, biotite, cordierite, ± muscovite
206 ± sillimanite) was followed by a second event resulting in the crystallisation of the plagioclase
207 rims, dumortierite, tourmaline, andalusite and muscovite. The second stage was possibly
208 associated with the alteration of the plagioclase cores and biotite. It could be either magmatic
209 or, more probably, hydrothermal in origin. The hydrothermal origin is supported by the
210 textures and in particular the position of the boron-bearing minerals. Indeed, tourmaline and
211 dumortierite are known to be related to hydrothermal alteration (e.g. Taner and Martin, 1993),
212 but are liquidus rather than late-stage phases in leucogranitic magmatic systems (Benard et
213 al., 1985).

214

215 *3.2 La Salvetat migmatite, sample ES8*

216

217 The La Salvetat migmatite crops out in the central part of the axial zone of the Montagne
218 Noire gneiss dome, generally to the south of the Laouzas granite (Fig. 1). It was sampled ca.
219 2 km south of the Laouzas dam, close to the summit of a hill called Al Rec del Bosc
220 (43°37'1.65"N, 2°45'23.70"E). The rock is a banded stromatic migmatite (Fig. 2d) and is
221 locally garnet-bearing. The foliation is defined by a weak preferred orientation of biotite that
222 is parallel to alternating layers of leucosome, mesosome and biotite-dominated melanosome.
223 Leucosomes are relatively coarse-grained (0.5-3 mm), up to 1 cm thick, and are composed of
224 subhedral plagioclase, quartz and subordinate K-feldspar, and locally contain cordierite,
225 muscovite, biotite and tourmaline (Fig. 2e). Tourmaline commonly forms anhedral to
226 subhedral interstitial, optically zoned grains. Plagioclase and K-feldspar have a dusty

227 appearance and plagioclase is partly replaced by zoisite/clinozoisite and white mica (Fig. 2f).
228 Cordierite is subhedral and partly altered to pinitite. Biotite is locally partly replaced by
229 chlorite and contains lenses of minute prehnite (?) or clay minerals that are parallel to the
230 (001) cleavage (Fig. 2f), in particular in the leucosome and in the adjacent melanosome.
231 Euhedral muscovite is locally present in the leucosome. Subhedral muscovite, forming either
232 fine-grained clusters or larger poikilitic crystals, commonly develops at the expense of biotite,
233 cordierite and feldspars in the leucosomes.

234 These observations suggest at least two stages of evolution, where the migmatite
235 textures, attributable to partial melting, are partly overprinted by hydrothermal alteration. The
236 geographic proximity and the common petrographic character of the leucosomes and the
237 Laouzas granite suggest a genetic relation between the two. Therefore, the La Salvetat
238 migmatite is interpreted to be a likely source for the anatectic Laouzas granite.

239

240 **4. U-Th-Pb LA-ICP-MS and ^{40}Ar - ^{39}Ar dating**

241

242 *4.1 Analytical techniques*

243 4.1.1 NanoSIMS analytical protocol

244 The distribution of selected species was imaged in some monazite grains using the NanoSIMS
245 50 ion probe at the University of Rennes 1. Secondary ion images of ^{89}Y , ^{139}La , ^{140}Ce , ^{149}Sm ,
246 ^{206}Pb , ^{208}Pb , ^{232}Th and $^{238}\text{U}^{16}\text{O}$ were collected using the same primary O- beam of ~ 170 pA
247 over $90\ \mu\text{m} \times 90\ \mu\text{m}$ areas. The mass resolving power was set to ~ 3500 , sufficient to readily
248 resolve isobaric interferences such as $^{143,145}\text{NdPO}_2$ on $^{206,208}\text{Pb}$. A single plane of image data,
249 divided in $128\ \text{px} \times 128\ \text{pixels}$, was collected using a dwell time of 40 ms/pixel, representing
250 an acquisition time of ~ 11 min for each area. The raw image data were processed using the

251 L'image (Larry Nittler, Carnegie Institute of Washington, USA;
252 http://home.dtm.ciw.edu/users/nittler/limage/limage_manual.pdf) and ImageJ softwares.

253

254 4.1.2 U-Th-Pb dating technique

255 A classic mineral separation procedure has been applied to concentrate minerals suitable for
256 U-Th-Pb dating using the facilities available at Géosciences Rennes (see Poilvet et al., 2011).
257 Zircon and monazite grains were carefully handpicked under a binocular microscope and
258 embedded in epoxy mounts. The grains were then polished on a lap wheel with a 6 μm and 1
259 μm diamond suspension successively. Zircon grains were imaged by cathodoluminescence
260 (CL) using a Reliotron CL system equipped with a digital colour camera available in
261 Géosciences Rennes and monazite grains by backscattered electron imaging on a JEOL JSM
262 6400 as well as by NanoSIMS. In addition, monazite grains have also been identified in thin
263 sections in order to date them in context.

264 U-Th-Pb geochronology of zircon and monazite was conducted by *in situ* laser
265 ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Laboratoire
266 Magmas et Volcans in Clermont-Ferrand, France. Ablation spot diameters of 26 μm and 7 μm
267 with repetition rates of 3 Hz and 1 Hz were used for zircon and monazite, respectively. Data
268 were corrected for U-Pb and Th-Pb fractionation and for the mass bias by standard
269 bracketing with repeated measurements of the 91500 zircon (Wiedenbeck et al. 1995) or the
270 Moacyr monazite standards (Gasquet et al. 2010). Repeated analyses of GJ-1 zircon (607 ± 15
271 Ma, N=6; Jackson et al. 2004) or Manangoutry monazite (554 ± 23 Ma, N=6; Paquette and
272 Tiepolo 2007) standards treated as unknowns were used to control the reproducibility and
273 accuracy of the corrections. Data reduction was carried out with the GLITTER® software
274 package developed by the Macquarie Research Ltd. (Jackson et al. 2004). Concordia ages and
275 diagrams were generated using Isoplot/Ex (Ludwig 2001). All errors given in Table 1 and 2

276 are listed at one sigma, but where data are combined for regression analysis or to calculate
277 weighted means, the final results are provided with 95% confidence limits. Further
278 information on the instrumentation and the analytical technique is detailed in Hurai et al.
279 (2010).

280 For each grain analyzed (zircon and monazite) we also estimated the concentrations of
281 U, Th and Pb as follows. First, the drift factor was calculated using the parameter a and b of a
282 linear regression of the average ^{206}Pb counts per second (cps) for all the standards measured
283 during the course of the analyses as a function of their position during the acquisition.

$$284 \quad (1) \quad ^{206}\text{Pb}_{\text{cps}} = a \times N + b$$

285 with $^{206}\text{Pb}_{\text{cps}}$ = average measured values for the standard in cps corrected from the blank, a =
286 slope of the regression, b = ordinate at origin and N = analysis number.

287 The drift factor for each analysis (DF^N) is then calculated as follows:

$$288 \quad (2) \quad DF^N = \frac{b}{(a \times N + b)}$$

289 Then the Pb, Th and U concentrations are calculated using the known concentrations of these
290 elements in the standards following:

$$291 \quad (3) \quad C_{\text{sample}}^N_{\text{ppm}} = C_{\text{sample}}^N_{\text{meas}} \times DF^N \times \frac{C_{\text{std}}_{\text{real}}}{C_{\text{std}}_{\text{aver}}}$$

292 with N = analysis number, $C_{\text{sample}}^N_{\text{ppm}}$ = calculated concentration of the element in ppm,

293 $C_{\text{sample}}^N_{\text{meas}}$ = measured values of the element in cps, DF^N = drift factor calculated for this

294 analysis, $C_{\text{std}}_{\text{real}}$ = known concentration of the standard and $C_{\text{std}}_{\text{aver}}$ = drift-corrected average

295 value for all the standards measured during the course of the analyses.

296

297 *4.1.3 Ar-Ar dating technique*

298 Single grains of muscovite used for the experiments were handpicked under a binocular

299 microscope from 0.25–1.00 mm fractions of crushed rock samples. Care was taken to select

300 inclusion-free crystals of about 1 mm in size, in order to avoid large poikilitic crystals as well
301 as fine-grained clusters.

302 The samples were wrapped in Al foil to form small packets (11 × 11 mm) that were
303 stacked up to form a pile within which packets of fluence monitors were inserted every 10
304 samples. Irradiation was performed at the HFR Petten reactor (Petten, the Netherlands) in the
305 Cd-shielded Rodeo P3 facility and lasted 72h ($J/h \approx 2.54 \times 10^{-4} \text{ h}^{-1}$). The irradiation standard
306 was amphibole Hb3gr (Turner et al. 1971; Roddick 1983, Jourdan et al. 2006; Jourdan and
307 Renne 2007), with an age of $1081.0 \pm 1.2 \text{ Ma}$ (Renne et al. 2010, 2011).

308 Step-heating analyses of single grains were performed with a CO₂ laser probe coupled
309 to a Map215® mass spectrometer. The experimental procedure is described in Ruffet et al.
310 (1991) and Ruffet et al. (1995). The five argon isotopes and the background baselines were
311 measured in eleven cycles, in peak-jumping mode. Blanks were performed routinely each first
312 or third/fourth run, and subtracted from the subsequent sample gas fractions. All isotopic
313 measurements are corrected for K, Ca and Cl isotopic interferences, mass discrimination and
314 atmospheric argon contamination. Apparent age errors are plotted at the 1σ level and do not
315 include the errors on the $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ ratio and age of the monitor and decay constant. The
316 errors on the $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ ratio and age of the monitor and decay constant are included in the
317 final calculation of the (pseudo-)plateau age error margins or for apparent ages individually
318 cited. Details on the method and $^{40}\text{Ar}^*/^{39}\text{Ar}$ analytical data are given in the Supporting
319 Information.

320 It is commonly considered that a plateau is obtained when calculated $^{40}\text{Ar}^*/^{39}\text{Ar}_K$
321 ratios of at least three consecutive steps, containing a minimum of 70% of the ^{39}Ar released,
322 agree with the weighted mean calculated $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ ratio of the plateau segment. Pseudo-
323 plateau ages can be defined with less than 70% of the ^{39}Ar released. All ages are displayed at
324 the 1σ level. Analytical data, parameters used for calculations (isotopic ratios measured on K,

325 Ca and Cl pure salts; mass discrimination; atmospheric argon ratios; J parameter; decay
326 constants...) and reference sources are available in a complementary data repository.

327

328 4.2 U-Th-Pb LA-ICP-MS and ^{40}Ar - ^{39}Ar results

329 4.2.1 Sample ES7 – Laouzas granite

330 Zircon and monazite grains were both recovered from this sample. Most of the zircon grains
331 were pink in colour, euhedral, with very variable shapes from elongated to oval.

332 Cathodoluminescence imaging revealed a rather heterogeneous population with anything
333 from homogeneous low luminescent to heterogeneous (core + rim) grains (Fig. 3A). Thirty-
334 seven analyses out of twenty-six zircon grains were made (Table 1). The heterogeneity of the
335 grains is confirmed in a Tera-Wasserburg diagram (Fig. 4A) where data points plot in a
336 concordant to very discordant position with apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 1010 Ma
337 down to 370 Ma. Because of this heterogeneity, which is probably caused by a complex
338 mixing of heterogeneous inheritance, plus variable degree of common Pb content and Pb loss,
339 it is not possible to calculate any relevant ages. We therefore favoured plotting the data in a
340 relative probability plot diagram (Fig. 4E) where only the $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages for the
341 more than 90% concordant points were considered. One main peak can be defined at ca. 500
342 Ma, with minor peaks around 700 and 800 Ma.

343 Two types of monazite grains were found in this sample. Type 1 monazite comprises
344 euhedral dark brown grains with sharp concentric zoning (Fig. 5) and type 2 monazite
345 comprises euhedral to subhedral yellowish to orange grains characterised by complex patchy
346 zoning (Fig. 6), as revealed by backscattered electron (BSE) imaging. Elemental imaging
347 carried out using the NanoSIMS ion probe reveals that the concentric zoning for type 1
348 monazite (Fig. 5) is visible with all the elements imaged (Y, La, Ce, Sm, U, Th and Pb) with
349 cores that are LREE-rich and poor in Y, U, Th and Pb. More importantly, the distributions of

350 U and Th in this monazite type perfectly match each other. For type 2 monazite (Fig. 6), the
351 complex zoning noticed in BSE images is well mimicked by the distribution of Y, REE, U
352 and ^{206}Pb while the distribution of Th and ^{208}Pb is less disturbed.

353 These two types of monazite grains were therefore analyzed separately. In addition, 19
354 analyses (11 grains) were performed directly in a thin section. In total, 50 analyses were
355 carried out (Table 2). Plotted in a $^{206}\text{Pb}/^{238}\text{U}$ versus $^{208}\text{Pb}/^{232}\text{Th}$ concordia diagram (Fig. 4B),
356 the two types plot in two distinct groups. For the monazite grains dated in context in the thin
357 sections, there is no evident correlation between the mineral hosting the monazite grains and
358 their apparent ages. Therefore, the location of type 1 and type 2 monazite is not related to any
359 specific host mineral. Type 1 monazite (N = 26; grains with sharp concentric zoning) plots in
360 a concordant to slightly discordant position. A cluster of 14 concordant analyses (Fig. 4B)
361 yields a concordia age (Ludwig 1998) of 318.0 ± 1.4 Ma (MSWD=0.87). This concordia age
362 is equivalent within error to the average $^{206}\text{Pb}/^{238}\text{U}$ date of 318.8 ± 1.5 Ma (N = 26; MSWD =
363 0.95) obtained for the 26 analyses defining this first group. Interestingly, the $^{208}\text{Pb}/^{232}\text{Th}$
364 apparent ages for this group display a bimodal distribution (see Fig. 4G), with one peak at
365 331.5 ± 2 Ma and a second one at 319.1 ± 2.0 Ma.

366 Data obtained on type 2 monazite (grains with complex patchy zoning; N = 20)
367 exhibits a slight reverse discordance (Fig. 4B). The mean $^{206}\text{Pb}/^{238}\text{U}$ date obtained for these
368 twenty analyses is consistent with a value of 293.5 ± 1.7 Ma (MSWD = 0.78) while the
369 $^{208}\text{Pb}/^{232}\text{Th}$ apparent dates yield average dates of 285.2 ± 2.2 Ma (MSWD = 0.66; N = 8) for
370 the grains analysed in the epoxy puck and of 296.5 ± 2.8 Ma (MSWD = 0.42; N = 7) for the
371 grains dated in the thin section (Fig. 4G).

372 Muscovite single grain from sample ES7 yielded a flat ^{40}Ar - ^{39}Ar age spectrum (Fig.
373 4H) over most of $^{39}\text{Ar}_K$ degassing (ca. 95%), corresponding to a calculated plateau age of
374 298.2 ± 0.8 Ma (2σ level).

375

376 *4.2.2 Sample ES8 – La Salvetat migmatite*

377 Both monazite and zircon grains were extracted from this sample. Two types of zircon grains
378 were found. The first type is characterized by elongate pinkish grains (Fig. 3B), while the
379 second type is constituted by squat prismatic grains (Fig. 3C). Both types display complex
380 zoning with core and rims apparent for most (Fig. 3B and C). Thirty-two analyses were
381 performed on twenty-eight grains (Table 1). Plotted in a Tera-Wasserburg diagram (Fig. 4C),
382 they plot in a concordant to discordant position, with apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from
383 ca. 2650 down to 300 Ma. Once again, it is difficult to get any valuable geochronological
384 constraint with this set of data. Plotted in a relative probability plot (Fig. 4E), two main peaks
385 arise at ca. 610 Ma and 875 Ma, with minor peaks at 690, 1000, 1310 and 2450 Ma.

386 From a morphological point of view, all monazite crystals were yellow and euhedral to
387 subhedral. Forty-six analyses were performed (38 on separated grains and 8 directly in
388 context in thin sections). Plotted in a $^{206}\text{Pb}/^{238}\text{U}$ versus $^{208}\text{Pb}/^{232}\text{Th}$ concordia diagram (Fig.
389 4D), they all plot in a concordant to slightly discordant position. A first group of 14 analyses
390 defines a concordia ages of 318.5 ± 0.7 Ma (MSWD = 1.3; Fig. 4D). A second cluster of 15
391 analyses yields a concordia age of 298.8 ± 1.3 Ma (MSWD = 0.68; Fig. 4D). The remaining
392 17 analyses plot in a slightly reverse discordant position either between the two previous
393 calculated concordia dates or are apparently younger than 299 Ma (Fig. 4D). The two
394 analyses performed in monazite grains hosted by quartz yielded dates close to 290 Ma while
395 the monazite grains hosted by biotite plot in a scattered position.

396 When looking at the BSE imaging, the first group (ca. 318.5 Ma) is characterized by
397 fairly homogeneous monazite grains (Fig. 7), while monazite in the second group (ca. 299
398 Ma) is characterized by more patchy zoning (Fig. 8). The NanoSIMS imaging of the first
399 group confirms the rather homogeneous distribution of the imaged elements with the

400 exception of U and ^{206}Pb that appear to be poorer in the core of the grain (Fig. 7). For the
401 second group, the elemental distributions are not as simple. The REE distribution seems to be
402 homogeneous throughout the grain whereas the Y, U, Th and Pb distributions are patchier
403 (Fig. 8).

404 Similar to monazite in ES7, monazite data in ES8 are characterized by evident
405 differences between the $^{206}\text{Pb}/^{238}\text{U}$ and the $^{208}\text{Pb}/^{232}\text{Th}$ dates (Fig. 4F and G). The
406 $^{208}\text{Pb}/^{232}\text{Th}$ dates fall into 3 distinct populations (Fig. 4G) at 319.8 ± 1.8 Ma (MSWD = 1.3;
407 $N = 15$), 298.2 ± 1.5 Ma (MSWD = 0.89; $N = 19$) and 284.7 ± 2.1 Ma (MSWD = 0.98; $N =$
408 8), respectively. $^{206}\text{Pb}/^{238}\text{U}$ dates define two different peaks at 316.2 ± 1.9 Ma (MSWD =
409 0.68; $N = 15$) and 296.1 ± 1.3 Ma (MSWD = 2.8; $N=26$), respectively (Fig. 4F).

410 Muscovite single grain from sample ES8 yielded a flat ^{40}Ar - ^{39}Ar age spectrum (Fig.
411 4H) over most of ^{39}ArK degassing (ca. 98%) that correspond to a calculated plateau age of
412 298 ± 1 Ma (2σ level). This age is similar to the ES7 plateau age.

413

414

415 **5. Geological significance of the geochronological data**

416 *5.1 Zircon dating*

417 Zircon data from both the Laouzas granite and the La Salvetat migmatite show a considerable
418 spread (Fig. 4E) and cannot be used to either date the emplacement of the granite or the age of
419 migmatization. They rather demonstrate the existence of a complex polygenic history in the
420 region, with dates ranging from the late Archean to the Ordovician. They are consistent with
421 the data published by Faure et al. (2010), although more date populations were found in our
422 study. In the La Salvetat migmatite, the youngest point (grain 1.1d) that plots close to the
423 concordia gives a $^{207}\text{Pb}/^{206}\text{Pb}$ date of 337 ± 27 Ma (1 sigma). This grain might have grown

424 during the migmatization, but because of its large error, it does not help to constrain this event
425 precisely.

426 5.2 Monazite dating

427 5.2.1 The Laouzas granite

428 In the $^{206}\text{Pb}/^{238}\text{U}$ versus $^{208}\text{Pb}/^{232}\text{Th}$ concordia diagram (Fig. 4B), the monazite grains
429 from the Laouzas granite plot in two clusters although the geochronological information
430 brought, for each cluster, by the monazite grains $^{206}\text{Pb}/^{238}\text{U}$ and $^{208}\text{Pb}/^{232}\text{Th}$ respective dates is
431 different. Indeed, within each cluster, the $^{206}\text{Pb}/^{238}\text{U}$ dates are comparable, while they are
432 more scattered in the case of the $^{208}\text{Pb}/^{232}\text{Th}$ ones.

433 To first order, four dates can be defined for the Laouzas granite. The oldest date at ca.
434 330 Ma can be calculated using the older apparent $^{208}\text{Pb}/^{232}\text{Th}$ dates (Fig. 4G). The second
435 one around 319 Ma is given by a concordia age of 318.0 ± 1.4 Ma (Fig. 4B), the mean
436 $^{206}\text{Pb}/^{238}\text{U}$ date of 318.8 ± 1.5 Ma obtained for all the analyses from the older cluster (Fig. 4B)
437 and from one of the peaks defined by the $^{208}\text{Pb}/^{232}\text{Th}$ dates at 319.1 ± 2.0 Ma (Fig. 4G). The
438 third date of around 298-292 Ma is defined by one peak in the $^{208}\text{Pb}/^{232}\text{Th}$ dates distribution at
439 298.2 ± 1.5 Ma (Fig. 4G) and the mean $^{206}\text{Pb}/^{238}\text{U}$ date of 293.5 ± 1.7 Ma calculated for the
440 second group (Fig. 4B). This third date is in a good agreement with the ^{40}Ar - ^{39}Ar age of 298.2
441 ± 0.8 Ma (2σ level) obtained on muscovite from the same sample (Fig. 4H). Finally, the
442 youngest date around 285 Ma is defined by the youngest $^{208}\text{Pb}/^{232}\text{Th}$ dates (Fig. 4G).

443 It seems evident that the dates of ca. 319 Ma and ca. 298 Ma are representative of
444 specific events as they are common to both chronometers (U/Pb and Th/Pb) and because the
445 second one is also defined by ^{40}Ar - ^{39}Ar dating. Therefore, two scenarios can be suggested.
446 Either the date of ca. 319 Ma yields the emplacement age of the Laouzas granite and the date
447 of ca. 298 Ma is related to a post emplacement event, or the granite was emplaced ca. 298 Ma
448 ago, in which case the date of ca. 319 Ma should be regarded as “inherited”. Three

449 observations are helpful to discriminate between these two scenarios. (i) The backscattered
450 imaging shows that the ca. 319 Ma monazite population (Type 1) is characterized by a rather
451 simple concentric zoning, whereas the ca. 298 Ma old population (Type 2) systematically
452 displays a complex patchy zoning. Concentric zoning is consistent with a magmatic origin,
453 whereas patchy zoning suggests the involvement of a post-crystallization perturbing event,
454 such as fluid-related dissolution/recrystallization (Williams et al. 2011; Tartèse et al. 2011;
455 Didier et al. 2013). (ii) As noticed on the NanoSIMS imaging (Fig. 5 and 6), the elemental
456 distributions perfectly match for the Type 1 monazite while they differ for Type 2. (iii)
457 Finally, petrographic observations suggest an overprint of the primary magmatic assemblage
458 associated with a later circulation of hydrothermal fluids. In the light of these observations,
459 we propose that the Laouzas granite was emplaced ca. 319 Ma ago and was affected by a
460 post-emplacement, fluid-related event, ca. 298 Ma ago. In this case, the ^{40}Ar - ^{39}Ar age at 298.2
461 ± 0.8 Ma yielded by muscovite from the same sample would also characterize this late
462 hydrothermal event, since it has been shown that the K-Ar geochronometer in muscovite can
463 be highly sensitive to fluid circulations in granites in a similar context (Questembert
464 leucogranite, Armorican massif, France) by Tartèse et al. (2011).

465 The oldest date at ca. 330 Ma is only evidenced by the $^{208}\text{Pb}/^{232}\text{Th}$ dates. A similar
466 phenomenon has also been noticed by Tartèse et al. (2012) for monazite grains from a
467 mylonitized granite from the South Armorican Shear Zone, in which the $^{208}\text{Pb}/^{232}\text{Th}$ dates
468 (defining an average date of 313 ± 3 Ma) were systematically older than the U-Pb dates
469 (defining an average date of 299 ± 4 Ma). A recent study by Didier et al. (2013) has
470 demonstrated that F-rich fluids can be responsible for the disturbance of the Th/Pb ratios in
471 monazite and the incorporation of excess Pb, leading to a large spread of the $^{208}\text{Pb}/^{232}\text{Th}$
472 dates. Disturbed $^{208}\text{Pb}/^{232}\text{Th}$ and $^{206}\text{Pb}/^{238}\text{U}$ data were also obtained by Poitrasson et al. (2000)
473 and were attributed to variable inputs and/or depletions in U, Th and Pb in the monazite

474 crystals during hydrothermal alteration. As detailed earlier, the Laouzas anatectic granite
475 bears petrographic evidence of hydrothermal fluid circulation. We therefore believe that this
476 date of ca. 330 Ma is meaningless and is attributed to fluid perturbation of some of the
477 monazite grains leading to a fractionation of their Th/Pb ratios (cf. Didier et al. 2013).

478 The other date at ca. 285 Ma is also obtained with only the $^{208}\text{Pb}/^{232}\text{Th}$ dates. Once
479 again, either this date is related to a fluid-induced perturbation of the monazite Th-Pb isotope
480 system, and is, therefore, meaningless, or it reflects the age of a yet unknown event in the
481 region.

482 *5.2.2 La Salvetat migmatite*

483 Monazite from the La Salvetat migmatite also yields different $^{208}\text{Pb}/^{232}\text{Th}$ and
484 $^{206}\text{Pb}/^{238}\text{U}$ dates but here again two main dates can be proposed. A first one at ca. 319 Ma is
485 given by a concordia age of 318.5 ± 0.7 Ma (Fig. 4D), a mean $^{208}\text{Pb}/^{232}\text{Th}$ date of 319.8 ± 1.8
486 Ma (Fig. 4G) and a mean $^{206}\text{Pb}/^{238}\text{U}$ date of 316.2 ± 1.9 Ma (Fig. 4F). The second one, around
487 298 Ma, is given by a concordia age of 298.8 ± 1.3 Ma (Fig. 4D), a mean $^{208}\text{Pb}/^{232}\text{Th}$ date of
488 298.2 ± 1.5 Ma (Fig. 4G), a mean $^{206}\text{Pb}/^{238}\text{U}$ date of 296.1 ± 1.3 Ma (Fig. 4F) and a muscovite
489 $^{40}\text{Ar}-^{39}\text{Ar}$ plateau age of 298 ± 1 Ma (Fig. 4H).

490 Lastly, the youngest $^{208}\text{Pb}/^{232}\text{Th}$ dates define a mean date of 284.7 ± 2.1 Ma. Monazite
491 is known to be very resistant to diffusional reequilibration (e.g. Seydoux-Guillaume et al.
492 2002; Gardés et al. 2007), preserving the age of their crystallisation. On the other hand, they
493 recrystallize readily by dissolution/precipitation processes, when fluids or magmas are
494 involved (Williams et al. 2011; Tartèse et al. 2011; Didier et al. 2013). As a general rule, two
495 major “pulses” of monazite growth are predicted in metapelitic rocks: subsolidus growth in
496 the upper amphibolite facies and growth during the cooling of leucosomes (rather than partial
497 melting) following migmatization (e.g. Foster et al. 2000; Rubatto et al. 2001; Kelsey et al.
498 2008; Spear and Pyle 2010). Furthermore, it is now well established that monazite may

499 (re)crystallise due to fluid-rock interactions relatively late in the metamorphic history (e.g.
500 Bosse et al. 2009; Tartèse et al. 2011, 2012; Didier et al. 2013).

501 Consequently, the three dates of ca. 319, ca. 298 and ca. 284 Ma obtained for the
502 monazite grains from the La Salvetat migmatite, may represent the ages of: (1) crystallisation
503 during the prograde metamorphism in the upper amphibolite facies conditions; (2)
504 crystallisation of the leucosomes following partial melting and (3) recrystallisation due to late
505 fluid circulations, respectively. On the other hand, the close spatial and inferred genetic
506 association of the migmatites with the Laouzas granite suggests that monazite grains of the
507 same age should be found in both rock types. The crystallisation of the Laouzas granite is
508 inferred to have taken place at ca. 319 Ma (see earlier), suggesting that the date of 319 Ma in
509 the La Salvetat migmatite should be interpreted as the age of the crystallisation of the
510 leucosomes, rather than that of the prograde amphibolite-facies metamorphism. The second
511 date of ca. 298 Ma found in the migmatite is identical within error to the date of ca. 298 Ma
512 found in the Laouzas granite, but also to the emplacement age of 294 ± 3 Ma (U-Pb on zircon)
513 obtained for the syntectonic Montalet leucogranite (Poilvet et al. 2011), situated about 20 km
514 to the NW (Fig. 1). It is conceivable that a second phase of partial melting of the La Salvetat
515 migmatite was the source of this leucogranite but the poor outcrop conditions do not allow to
516 validate such hypothesis. Alternatively and more probably, partial melting of other deeper
517 formations formed the Montalet magmas, which percolated with associated fluids through the
518 crust, resulting in the recrystallization of some monazite grains in the migmatite-granite
519 dome, as suggested by the late fluid circulations inferred from the petrographic observations
520 of the La Salvetat migmatite. A detailed study of the geochemical affinities between the
521 migmatites and the various granites would be necessary to answer this question.

522 Finally, the 284 Ma date, identical within uncertainty to the date of ca. 285 Ma
523 obtained in the Laouzas granite is, as argued above, either an artefact due to fluid-enhanced

524 modification of some of the monazite crystals, or, an evidence of a younger, although
525 unidentified, event in the region. Similar Permian ages are known elsewhere in the European
526 Variscan belt. Mougeot et al. (1997) reported an U-Pb apatite age ca. 289 Ma for the Velay
527 granite. Cathelineau et al. (1990) obtained Permian ages on vein-type deposits from the
528 Mortagne district in the South Armorican Massif and the French Massif Central, with a major
529 stage of uranium mobilization between 290 and 260 Ma. In the Erzgebirge (Germany), the
530 emplacement of vein-type deposits is also Permian in age and postdates the emplacement of
531 the youngest Variscan granites by no less than 20-25 Ma (e.g. Velichkin and Vlasov, 2011
532 and references therein). More recently, Boutin et al. (2015) reported some Permian U-Pb ages
533 obtained on titanite associated with chlorite-talc mineralization in the Pyrenees. This non-
534 exhaustive list demonstrates that this date of ca. 285 Ma is not unique at the scale of the
535 Variscan belt as numerous ore deposits linked to fluid circulations are contemporaneous, and
536 could, therefore, be considered as meaningful for the Montagne Noire. Finally, the remaining
537 data that plot in a scattered position (Fig. 4D) could be attributed to an incomplete resetting of
538 their U-Th-Pb system during the subsequent fluid circulation events.

539 *5.3 Partial melting and regional correlations*

540 In summary, the Laouzas granite and the La Salvetat migmatite are spatially close and
541 petrographically similar. The Laouzas granite is therefore interpreted as a product of the
542 partial melting recorded in the La Salvetat migmatite. Monazite grains from both rocks
543 recorded a date of ca. 319 Ma, which is interpreted as the emplacement age of the Laouzas
544 granite, and hence also that of a first stage of migmatization (or rather the crystallisation of
545 the leucosomes resulting from this partial melting). The date of ca. 298 Ma is tentatively
546 attributed either to a second stage of migmatization, or more probably to a pervasive
547 percolation of magmas and associated fluids coming from a deeper source and resulting in the
548 syntectonic crystallisation of the more superficial Montalet leucogranite.

549 It is interesting to draw a parallel with the scenario described for the Velay gneiss
550 dome, located some 150 km ENE of the Montagne Noire. In this area, Montel et al. (1992)
551 described two successive stages of migmatization that have been dated at 314 ± 5 Ma and 301
552 ± 5 Ma (U-Pb ID-TIMS on monazite, Mougeot et al., 1997). Barbey et al. (2015) suggest
553 three melting events, estimated to have occurred at 325-315 Ma, ca. 305 Ma, and 305-
554 295 Ma. In addition, Roger et al. (2015) bracketed the high temperature deformation and
555 metamorphism both in the Gorges d'Héric and the Vialais granite between 310-300 Ma.

556

557 **6. Tectonic implications for the formation of the Montagne Noire dome**

558 Two major hypotheses are proposed at present to explain the origin of the Montagne Noire
559 dome. Both agree on the presence of compressional and extensional features, but disagree on
560 their timing and their relative importance. The first hypothesis considers that the domal
561 structure developed as a regional anticline during the collisional stage of the Variscan
562 orogeny (e.g. Arthaud et al. 1966; Burg and Matte 1978, Charles et al. 2009) and interpret the
563 extensional features as second-order and late with respect to the formation of the dome. For
564 the second hypothesis, dome-like exhumation of the lower continental crust beneath a major
565 crustal-scale extensional detachment is at the origin of the Montagne Noire dome (Van Den
566 Driessche and Brun 1989; Echtler and Malavieille 1990; Van Den Driessche and Brun 1992).
567 Beyond the structural record, this second hypothesis is supported and constrained in time by
568 the syntectonic emplacement of a leucogranite at ca. 295 Ma (Poilvet et al. 2011) and by
569 monazite and mica ages of ca. 295 Ma in sheared metasediments and orthogneisses (Maluski
570 et al. 1991; Pitra et al. 2012) along the detachment that is contemporaneous with and controls
571 the development of the Stephanian to Permian Graissessac and Lodève basins (Fig. 1; Van
572 Den Driessche and Brun 1989; Bruguier et al. 2003). In contrast, the advocates of the
573 compressional origin of the dome either associate the extensional structures exclusively with

574 the compressional phase (Brunel and Languet 1997), or relegate it to a secondary role in the
575 brittle domain (Matte et al. 1998; Charles et al. 2009). The principal argument was the age of
576 the late- to post-kinematic Vialais granite, supposedly dated at 327 ± 5 Ma (TIMS on zircon
577 and monazite fractions; Matte et al. 1998), emplaced in the central-eastern part of the dome
578 (Fig. 1), and the ca. 330 Ma dates obtained by electron probe micro-analysis (EPMA)
579 monazite dating from migmatites and anatectic granites summarised in Charles et al. (2009)
580 and Faure et al. (2010).

581 In the “compressional” interpretation, migmatization and magmatism predate
582 extension. In the “extensional” interpretation, which requires thermal relaxation and related
583 rheological softening in order for the crust to collapse, migmatization is also
584 contemporaneous with the onset of extension, especially because extension can enhance
585 partial melting by adiabatic decompression (e.g. Hollister 1993; Holtz and Johannes 1994;
586 Holtz et al. 2001; Thompson 2001). Clearly, the clue is to be sought in the absolute timing of
587 regional migmatization and related granite emplacement.

588 First, the Vialais granite and an associated post-kinematic leucogranite have been
589 recently re-dated at 303 ± 4 Ma and 298 ± 2 Ma, respectively (U-Pb monazite ICP-MS ages,
590 Roger et al. 2015). Second, our data support a genetic link between the migmatites and
591 granites in the “axial zone” of the Montagne Noire gneiss dome. Three age groups were
592 identified from the monazite U-Th/Pb data. A first event, at ca. 319 Ma, is recorded in both
593 the La Salvetat migmatite and the Laouzas granite, and is interpreted as the end of a first stage
594 of migmatization and as the emplacement age of the Laouzas granite, respectively. A second
595 event, at ca. 298 Ma, is recorded in the migmatite and in the Laouzas granite, and could be
596 interpreted as a fluid-induced event, probably related to a second melting event identified
597 through the emplacement of the Montalet and Vialais leucogranites. The third event, dated
598 around 285 Ma, although not clear, could be linked to Permian fluid circulations. The

599 presence of two stages of partial melting at ca. 320 Ma and ca. 300 Ma confirms (i) the
600 interpretation of the Late Carboniferous-Early Permian evolution of the Variscan belt
601 dominated by the extensional collapse, which predicts migmatization both preceding and
602 contemporaneous of the onset of extension, and (ii) the interpretation of the Montagne Noire
603 dome as an extensional gneiss dome.

604

605 **7. EPMA versus LA-ICP-MS dating**

606 In recent years, some studies comparing monazite ages obtained by the LA-ICP-MS and
607 EPMA techniques encountered discrepancies between both sets of ages (Paquette and Tiepolo
608 2007; Poilvet et al. 2011 and references therein). Other studies also pointed out that EPMA
609 dating should be acquired with caution as, for example, incorrect determination of
610 background intensities could result in artificially older ages (Jercinovic and Williams 2005;
611 Spear et al. 2009).

612 This study offers, therefore, the opportunity to compare the results obtained through
613 EPMA chemical dating and those obtained by LA-ICP-MS. Indeed, two aspects differ
614 between our data and those of Faure et al. (2010) – (i) a minimum of two generations of
615 monazite are distinguished in our data set whereas only one was identified in Faure et al
616 (2010), and (ii) there is a significant difference in the absolute ages obtained by both
617 approaches.

618 Although Faure et al. (2010) identified “three groups of composition according to the
619 Th/U ratio” (p. 660) for monazite grains from the La Salvetat migmatite, they interpreted
620 them in terms of only one chemical date of 327 ± 7 Ma, reflecting the crystallization age of
621 these monazite grains. This age is barely within error of the oldest age of 319.8 ± 1.8 Ma
622 found in this study, although the latter is more precise. However, one more age at 298 Ma was
623 obtained by LA-ICP-MS (with another possible event at ca. 285 Ma). In the case of the

624 monazite from the Laouzas granite, EPMA dating yielded only one date at 336 ± 6 Ma,
625 whereas at least two (potentially four) were obtained by LA-ICP-MS. In this case, Faure et al.
626 (2010) describe their monazite as patchy zoned, a feature encountered only in our younger
627 monazite population dated at ca. 298 Ma. The fact that they did not find two age populations
628 in their data set could be explained if they did not encounter the concentrically zoned
629 monazite in their samples.

630 These differences could also be linked to the statistical treatment applied to EPMA
631 dating. Indeed, each individual analysis bears fairly high error, but once they are all combined
632 to calculate a total U-Th-Pb date, the resulting error becomes relatively small ($\leq 2\%$). One
633 could therefore argue that this statistic treatment is not able to resolve different populations
634 that are relatively close in age.

635 In order to test this hypothesis, we took the U, Th and Pb contents calculated for three
636 of our samples (ES7 and ES8, this study Table 2; ES5 of Poilvet et al. 2011), and ran them
637 into the EPMA dating add-in developed by Pommier et al. (2002) following the data
638 treatment described in Cocherie et al. (1998) and Cocherie and Albarède (2001). In order to
639 test the viability of our approach, we first took the data from the Montalet granite in Poilvet et
640 al. (2011). The monazite grains in this sample yielded a single concordia age of 294 ± 1 Ma,
641 identical to the concordia age of 294 ± 3 Ma obtained on zircon. Plotted in a Th/Pb versus
642 U/Pb diagram (Fig. 9A), they define a similar U-Th-Pb age of 295 ± 10 Ma. This
643 demonstrates that when dating a simple (i.e. single age) population of monazite, the results
644 obtained by both the LA-ICP-MS and EPMA dating techniques are comparable. We then
645 tested this approach with two other samples from this study, which gave several age
646 populations. For sample ES7, the resulting Th/Pb versus U/Pb isochron diagram (Fig. 9B)
647 allows to calculate a single U-Th-Pb date of 297 ± 15 Ma (MSWD = 0.28) at the centroid of
648 the population. In this diagram, the regression line lies fairly close to the theoretical isochron,

649 therefore this age of ca. 297 Ma would have been considered as reliable and, therefore,
650 unique. Yet, we know that in fact at least two ages can be calculated using the LA-ICP-MS
651 data (ca. 319 Ma and ca. 298 Ma respectively). Although these two ages are ~ 20 Ma apart,
652 the Th/Pb versus U/Pb isochron diagram is not able to distinguish them. If we do the same
653 operation with monazite data from sample ES8, we also end up with a U-Th-Pb chemical age
654 of 291 ± 8 Ma (MSWD = 0.18) at the centroid of the population (Fig. 9C) although three ages
655 can be calculated in a conventional concordia diagram (ca. 319 Ma, 298 Ma and, maybe, 284
656 Ma). In this case we reached the limits of the technique as the theoretical isochron fits just
657 within the limits of the error envelope. This does not explain however why the EPMA ages
658 found by Faure et al. (2010) are significantly older than the ages found by LA-ICP-MS.

659 It is interesting to note that, with the same data set, but using the procedure described
660 in Montel et al. (1996) where, for each individual age, the 95% confidence interval is
661 estimated by a Monte Carlo procedure assuming U, Th and Pb content to obey a Gaussian
662 distribution, we end up with completely different results, as the age distributions for sample
663 ES7 yield three different date peaks at ca. 318 Ma, 302 Ma and 270 Ma (Fig. 10), which is in
664 a good agreement with the ages found in this study.

665

666 **7. Conclusion**

667 The presence of two stages of partial melting, at ca. 320 Ma and ca. 300 Ma, confirms (i) the
668 interpretation of the Late Carboniferous-Early Permian evolution of the Variscan belt
669 dominated by extensional collapse, which predicts migmatization both preceding, and
670 contemporaneous with, the onset of extension, and (ii) the interpretation of the Montagne
671 Noire dome as an extensional gneiss dome.

672 We also demonstrate that EPMA dating of monazite in this type of complex poly-
673 phased environment should be used with extreme caution. Indeed, as illustrated here, the Pb/U

674 and Th/U isochron statistical data treatment (Pommier et al. 2002) can sometimes fail to
675 resolve different age populations and can, therefore, produce erroneous results.

676

677

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684

685

686

687 **References**

688

689 Alabouvette B, Demange M (1993) Notice explicative, Carte géol. France (1/50 000), feuille
690 Saint-Pons (1013). Orléans, BRGM, 123 pp

691 Arthaud F (1970) Etude tectonique comparée de deux domaines hercyniens : les nappes de la
692 Montagne Noire (France) et l'anticlinorium de l'Iglesiente (Sardaigne), Thesis, University of
693 Montpellier, Publications USTELA Géol. Struct., 175 pp

694 Arthaud F, Mattauer M, Proust F (1966) La structure et la microtectonique des nappes
695 hercyniennes de la Montagne Noire. In: Etages tectoniques : Colloque de Neuchâtel, 18-19
696 avril 1966, Université de Neuchâtel, 231-243.

697 Arthaud F, Matte P (1977) Late Paleozoic strike slip faulting in southern Europe and northern
698 Africa: Result of a right-lateral shear zone between the Appalachians and the Urals.
699 Geological Society of America Bulletin 88:1305-1320.

700 Barbey P, Villaros A, Marignac C, Montel J-M (2015) Multiphase melting, magma
701 emplacement and P-T-time path in late-collisional context: the Velay example (Massif
702 Central, France). Bull. Soc. géol. Fr. 186(2-3):93-116

703 Becq-Giraudon JF, Van Den Driessche J (1993) Continuité de la sédimentation entre le
704 Stéphanien et l'Autunien dans le bassin de Graissessac-Lodève (sud du Massif Central) :
705 implications tectoniques. *Comptes Rendus de l'Académie des Sciences série 2*, 317:939-945.

706 Benard F, Moutou P, Pichavant M (1985) Phase Relations of Tourmaline Leucogranites and
707 the Significance of Tourmaline in Silicic Magmas. *Journal of Geology* 93:271-291.

708 Blès J-L, Bonijoly C, Castaing C, Gros Y (1989) Successive post-Variscan stress fields in the
709 French Massif Central and its borders (Western European plate): comparison with
710 geodynamica data. *Tectonophysics* 169: 79-111.

711 Bogdanoff S, Donnot F, Ellenberger F (1984) Note explicative, Carte géol. France (1/50 000),
712 feuille Bédarieux (988),. Orléans, BRGM, 105 pp

713 Bosse V, Boulvais P, Gautier P, Tiepolo M, Ruffet G, Devidal J-L, Cherneva Z, Gerdjikov I,
714 Paquette J-L (2009) Fluid-induced disturbance of the monazite Th-Pb chronometer: In situ
715 dating and element mapping in pegmatites from the Rhodope (Greece, Bulgaria). *Chemical*
716 *Geology* 261:286-302.

717 Boutin A, de Saint Blanquat M, Poujol M, Boulvais P, de Parseval P, Rouleau C, Robert JF
718 (2015). Succession of Permian and Mesozoic metasomatic events in the eastern Pyrenees with
719 emphasis on the Trimouns talc-chlorite deposit. *International Journal of Earth Sciences*,
720 doi:10.1007/s00531-015-1223-x.

721 Brun J-P, Van Den Driessche J (1994) Extensional gneiss domes and detachment fault
722 systems: structures and kinematics. *Bulletin de la Société Géologique de France* 165:519-530.

723 Bruguier O, Becq-Giraudon JF, Champenois M, Deloule E, Ludden J, Mangin D (2003)
724 Application of in situ zircon geochronology and accessory phase chemistry to constraining
725 basin development during post-collisional extension: a case study from the French Massif
726 Central. *Chemical Geology* 201:319-336.

727 Brunel M, Lansigu C (1997) Déformation et cinématique de mise en place du dôme de la
728 zone axiale de la Montagne Noire: signification des nodules à quartz-sillimanite (Massif
729 central français) [Deformation and kinematics of emplacement of the axial dome of the
730 Montagne Noire: implications of quartz-sillimanite nodule attitudes (French Massif Central)].
731 *Comptes Rendus de l'Académie des Sciences Paris - Series IIA - Earth and Planetary Sciences*
732 325:517-523.

733 Burg J-P, Matte PJ (1978) A Cross Section through the French Massif Central and the Scope
734 of its Variscan Geodynamic Evolution. *Zeitschrift der Deutschen Geologischen Gesellschaft*,
735 129:429-460.

736 Burg J-P, Van Den Driessche J, Brun J-P (1994) Syn- to post-thickening extension in the
737 Variscan Belt of Western Europe: Modes and structural consequences. *Géologie de la France*
738 3:33-51.

739 Cassard D, Feybesse J-L, Lescuyer J-L (1993) Variscan crustal thickening, extension and late
740 overstacking during the Naumrian-Westphalian in the western Montagne Noire.
741 *Tectonophysics* 222: 33-53

742 Cathelineau M, Boiron M-C, Holliger P, Poty B (1990). Metallogenesis of the French part of
743 the Variscan orogen. Part II: Time-space relationships between U, Au and Sn-W ore
744 deposition and geodynamic events — mineralogical and U-Pb data. *Tectonophysics* 177:59–
745 79.

746 Charles N, Faure M, Chen Y (2009) The Montagne Noire migmatitic dome emplacement
747 (French Massif Central): new insights from petrofabric and AMS studies. *Journal of*
748 *Structural Geology* 31:1423-1440.

749 Cocherie A, Legendre O, Peucat J-J, Kouamelan AN (1998) Geochronology of polygenetic
750 monazites constrained by in situ electron microprobe Th–U–total lead determination;
751 implications for lead behaviour in monazite. *Geochimica Cosmochimica Acta* 62:2475 –
752 2497.

753 Cocherie A, Albarède F (2001) An improved U–Th–Pb age calculation for electron
754 microprobe dating of monazite. *Geochimica et Cosmochimica Acta* 65:4509-4522.

755 Didier A, Bosse V, Boulvais P, Bouloton J, Paquette J-L, Montel J-M, Devidal J-L (2013)
756 Disturbance versus preservation of U-Th-Pb ages in monazite during fluid-rock interaction:
757 textural, chemical and isotopic in situ study in microgranites (Velay Dome, France).
758 *Contributions to Mineralogy and Petrology* 165:1051-1072

759 Demange M (1982) Etude géologique du massif de l'Agout, Montagne Noire, France, Thèse
760 d'Etat, University Paris 6, 1050 pp

761 Demange M, Guérangé-Lozes J, Guérangé B (1995) Notice explicative, Carte géol. France
762 (1/50 000), feuille Lacaune (987). Orléans, BRGM, 153 pp

763 Doublier M P, Potel S, Wemmer K (2015) The tectono-metamorphic evolution of the very
764 low-grade hangingwall constrains two-stage gneiss dome formation in the Montagne Noire
765 (Southern France). *Journal of metamorphic Geology* 33: 71-89

766 Echtler H (1990) Geometry and kinematics of recumbent folding and low-angle detachment
767 in the Pardailhan nappe (Montagne Noire, Southern French Massif Central). *Tectonophysics*
768 177: 109-123

769 Echtler H, Malavieille M (1990) Extensional tectonics, basement uplift and Stephano-Permian
770 collapse basin in a late Variscan metamorphic core complex (Montagne Noire, Southern
771 Massif Central). *Tectonophysics* 177: 125-138

772 Faure M, Cottureau N (1988) Données cinématiques sur la mise en place du dôme
773 migmatitique carbonifère moyen de la zone axiale de la Montagne noire (Massif central
774 français). *Comptes rendus de l'Académie des Sciences* 307: 1787-1794

775 Faure M, Cocherie A, Bé Mézème E, Charles N, Rossi P (2010) Middle Carboniferous crustal
776 melting in the Variscan Belt: New insights from U-Th-Pb_{tot} monazite and U-Pb zircon ages of
777 the Montagne Noire Axial Zone (southern French Massif Central). *Gondwana Research*
778 18:653-673.

779 Foster G, Kinny P, Vance D, Prince C, Harris N (2000) The significance of monazite U–Th–
780 Pb age data in metamorphic assemblages; a combined study of monazite and garnet
781 chronometry. *Earth and Planetary Science Letters* 181:327-340.

782 Franke W, Doublier MP, Klama K, Potel S, Wemmer K (2011) Hot metamorphic core
783 complex in a cold foreland. *International Journal of Earth Sciences* 100: 753-785

784 Gardés E, Montel J-M, Seydoux-Guillaume A-M, Wirth R (2007) Pb diffusion in monazite:
785 New constraints from the experimental study of $Pb^{2+} \leftrightarrow Ca^{2+}$ interdiffusion. *Geochimica et*
786 *Cosmochimica Acta* 71:4036-4043.

787 Gasquet D, Bertrand J-M, Paquette J-L, Lehmann J, Ratzov G, De Ascensão Guedes R,
788 Tiepolo M, Boullier AM, Scaillet S, Nomade S (2010) Miocene to Messinian deformation and
789 hydrothermalism in the Lauzière Massif (French Western Alps): New U–Th–Pb and Argon
790 ages. *Bulletin de la Société Géologique de France* 181:227–241.

791 Hollister LS (1993) The role of melt in the uplift and exhumation of orogenic belts. *Chem.*
792 *Geol.* 108:31-48

793 Holtz F, Johannes W (1994) Maximum and minimum water contents of granitic melts:
794 implications for chemical and physical properties of ascending magmas. *Lithos* 32:149-159

795 Holtz F, Johannes W, Tamic N, Behrens H (2001) Maximum and minimum water contents of
796 granitic melts generated in the crust: reevaluation and implications. *Lithos* 56:1-14

797 Hurai V, Paquette J-L, Huraiová M, Konečný P (2010) U-Th-Pb geochronology of zircon and
798 monazite from syenite and pincinite xenoliths in Pliocene alkali basalts of the intra-
799 Carpathian back-arc basin. *Journal of Volcanology and Geothermal Research* 198:275-287.

800 Jackson SE, Pearson NJ, Griffin WL, Belousova EA (2004) The application of laser ablation-
801 inductively coupled plasma-mass spectrometry to in situ U-Pb zircon geochronology.
802 *Chemical Geology* 211:47-69.

803 Jercinovic MJ, Williams ML (2005) Analytical perils (and progress) in electron microprobe
804 trace elements analysis applied to geochronology: Background, interferences and beam
805 irradiation effects. *American Mineralogist* 90:526-546.

806 Jourdan F, Renne PR (2007) Age calibration of the Fish Canyon sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ dating
807 standard using primary K-Ar standards. *Geochimica Cosmochimica Acta* 71:387-402.

808 Jourdan F, Verati C, Féraud G (2006) Intercalibration of the Hb3gr $^{40}\text{Ar}/^{39}\text{Ar}$ dating standard.
809 *Chemical Geology* 231:77-189.

810 Kelsey DE, Clark C, Hand M (2008) Thermobarometric modelling of zircon and monazite
811 growth in melt-bearing systems: examples using model metapelitic and metapsammitic
812 granulites. *Journal of Metamorphic Geology* 26:199-212.

813 Ludwig KR (1998) On the treatment of concordant uranium-lead ages. *Geochimica et*
814 *Cosmochimica Acta* 62:665-676.

815 Ludwig KR (2001) User's manual for Isoplot/Ex Version 2.49, a geochronological toolkit for
816 Microsoft Excel. Spec Publ., 1a. Berkeley Geochronological Center, Berkeley, USA.

817 Maluski H, Costa S, Echtler H (1991) Late Variscan tectonic evolution by thinning of earlier
818 thickened crust. An $^{40}\text{Ar}-^{39}\text{Ar}$ study of the Montagne Noire, southern Massif Central, France.
819 *Lithos* 26:287-304.

820 Matte P, Lancelot J, Mattauer (1998) The Montagne Noire Axial Zone is not an extensional
821 metamorphic core complex but a compressional post-nappe anticline with an anatectic core.
822 *Geodinamica Acta* 11: 3-22

823 Ménéard G, Molnar P (1988) Collapse of a Hercynian Tibetan Plateau into a late Paleozoic
824 European Basin and Range province. *Nature* 334:235-237.

825 Montel J-M, Marignac C, Barbey P, Pichavant M (1992) Thermobarometry and granite
826 genesis: the Hercynian low-P high-T Velay anatectic Dome (French Massif Central). *Journal*
827 *of Metamorphic Geology* 10:1-15.

828 Montel J, Foret S, Veschambre M, Nicollet C, Provost A (1996) Electron microprobe dating
829 of monazite. *Chemical Geology* 131:37-53.

830 Mougéot R, Respaut J-P, Ledru P, Marignac C (1997) U-Pb geochronology on accessory
831 minerals of the Velay anatectic Dome (French Massif Central). *European Journal of*
832 *Mineralogy* 9:141-156.

833 Paquette J-L, Tiepolo M (2007) High resolution (5 μm) U-Th-Pb isotopes dating of monazite
834 with excimer laser ablation (ELA)-ICPMS. *Chemical Geology* 240:222-237.

835 Pitra P, Ballèvre M, Ruffet G (2010) Inverted metamorphic field gradient towards a Variscan
836 suture zone (Champtoceaux Complex, Armorican Massif, France). *Journal of Metamorphic*
837 *Geology* 28:183-208.

838 Pitra P, Poujol M, Van Den Driessche J, Poilvet J-C, Paquette J-L (2012) Early Permian
839 extensional shearing of an Ordovician granite: The Saint-Eutrope, "C/S-like" orthogneiss
840 (Montagne Noire, French Massif Central). *Comptes Rendus Geoscience* 344:377-384.

841 Pochat S, Van Den Driessche J (2011) Filling sequence in Late Paleozoic continental basins;
842 A chimera of climate change. A new light shed given by the Graissessac-Lodève basin (SE
843 France). *Palaeogeography, Palaeoclimatology, Palaeoecology* 302:170-186.

844 Poilvet J-C, Poujol M, Pitra P, Van Den Driessche J, Paquette J-L (2011) The Montalet
845 granite, Montagne Noire, France: An early Permian syn-extensional pluton as evidenced by
846 new U-Th-Pb data on zircon and monazite. *Comptes Rendus Geoscience* 343:454-461.

847 Poitrasson F, Chenery S, Shepherd TJ (2000) Electron microprobe and LA-ICP-MS study of
848 monazite hydrothermal alteration: Implications for U-Th-Pb geochronology and nuclear
849 ceramics. *Geochimica and Cosmochimica Acta* 64:3283-3297.

850 Pommier A, Cocherie A, Legendre O (2002) EPMA Dating User's manual: Age calculation
851 from electron probe microanalyser measurements of U-Th-Pb. BRGM, 9 pp.

852 Rabin M, Trap P, Carry N., Fréville K., Centi-Tok B, Lobjoie C, Goncalves P, Marquer D
853 (2015) Strain partitioning along the anatectic front in the Variscan Montagne Noire massif
854 (southern French Massif Central). *Tectonics*:34 :doi:10.1002/2014TC003790.

855 Renne PR, Balco G, Ludwig RL, Mundil R, Min K (2011) Response to the comment by W.H.
856 Schwarz et al. on “Joint determination of $(40)\text{K}$ decay constants and $(40)\text{Ar}^*/(40)\text{K}$ for the Fish
857 Canyon sanidine standard, and improved accuracy for $(40)\text{Ar}/(39)\text{Ar}$ geochronology” by PR
858 Renne et al. (2010). *Geochimica et Cosmochimica Acta* 75:5097–5100.

859 Renne PR, Mundil R, Balco G, Min K, Ludwig RL (2010) Joint determination of ^{40}K decay
860 constants and $^{40}\text{Ar}^*/^{40}\text{K}$ for the Fish Canyon sanidine standard, and improved accuracy for
861 $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. *Geochimica et Cosmochimica Acta* 74:5349–5367.

862 Rey PF, Teyssier C, Whitney DL (2011) Viscous collision in channel explains double domes
863 in metamorphic core complexes. *Geology* 39: 387-390

864 Roddick JC (1983) High precision intercalibration of $^{40}\text{Ar}/^{39}\text{Ar}$ standards. *Geochimica et*
865 *Cosmochimica Acta* 47:887–898.

866 Roger F, Respaut J-P, Brunel M, Matte P, Paquette J-L (2004) U-Pb dating of Augen
867 orthogneisses from the Axial Zone of the Montagne Noire (Southern Massif Central): new
868 witness of Ordovician magmatism into the Variscan Belt. *Comptes Rendus Geoscience*
869 336:19-28.

870 Roger F, Teyssier C, Respaut J-P, Rey PF, Jolivet M, Whitney DL, Paquette J-L, Brunel M
871 (2015) Timing of formation and exhumation of the Montagne Noire double dome, French
872 Massif Central. *Tectonophysics* 640-641:53-69

873 Rubatto D, Williams IS, Buick IS (2001) Zircon and monazite response to prograde
874 metamorphism in the Reynolds Range, central Australia. *Contributions to Mineralogy and*
875 *Petrology* 140:458-468.

876 Ruffet G, Féraud G, Amouric M (1991) Comparison of $^{40}\text{Ar}/^{39}\text{Ar}$ conventional and laser dating
877 of biotites from the North Trégor Batholith. *Geochimica et Cosmochimica Acta* 55:1675–1688.

878 Ruffet G, Féraud G, Ballèvre M, Kiénast JR (1995) Plateau ages and excess argon on phengites:
879 a $^{40}\text{Ar}/^{39}\text{Ar}$ laser probe study of alpine micas (Sesia zone). *Chemical Geology* 121:327–343.

880 Seydoux-Guillaume A-M, Paquette J-L, Wiedenbeck M, Montel J-M, Heinrich W (2002)
881 Experimental resetting of the U-Th-Pb systems in monazite. *Chemical Geology* 191:165-181.

882 Soula JC, Debat P, Brusset S, Bessière G, Christophoul F, Déramond J (2001) Thrust-related,
883 diapiric, and extensional doming in a frontal orogenic wedge: exemple of the Montagne noire,
884 Southern French Hercynian Belts. *Journal of Structural Geology* 23: 1677-1699

885 Spear FS, Pyle JM (2010) Theoretical modeling of monazite growth in a low-Ca metapelite.
886 *Chemical Geology* 273:111-119.

887 Spear FS, Pyle JM, Cherniak D (2009) Limitations of chemical dating of monazite, *Chemical*
888 *Geology* 266:218-230.

889 Taner MF, Martin RF (1993) Significance of dumortierite in an aluminosilicate-rich alteration
890 zone, Louvicourt, Quebec. *Canadian Mineralogist* 31:137-146.

891 Tartèse R, Ruffet G, Poujol M, Boulvais P, Ireland TR (2011) Simultaneous resetting of the
892 muscovite K-Ar and monazite U-Pb geochronometers: a story of fluids. *Terra Nova* 23:390-
893 398.

894 Tartèse R, Boulvais P, Poujol M, Chevalier T, Paquette J-L, Ireland TR, Deloule E (2012)
895 Mylonites of the South Armorican Shear Zone: Insights for crustal-scale fluid flow and water-
896 rock interaction processes. *Journal of Geodynamics* 56-57:86–107.

897 Thompson AB (2001) Clockwise P-T paths for crustal melting and H₂O recycling in granite
898 source regions and migmatite terrains. *Lithos* 56:33-45

899 Turner G, Huneke JC, Podosek FA, Wasserburg GJ (1971) ⁴⁰Ar/³⁹Ar ages and cosmic ray
900 exposure age of Apollo 14 samples. *Earth and Planetary Science Letters* 12:19–35.

901 Van Den Driessche J, Brun J-P (1989) Un modèle cinématique de l'extension paléozoïque
902 supérieur dans le sud du Massif Central. *Comptes Rendus de l'Académie des Sciences série 2*
903 309:1607-1613.

904 Van Den Driessche J, Brun J-P (1992) Tectonic evolution of the Montagne Noire (French
905 Massif Central): a model of extensional dome. *Geodinamica Acta* 5:85-99.

906 Van Den Driessche J, Pitra P (2012) Viscous collision channel explains double dome in
907 metamorphic core complexes: Comment. *Geology* 40: e279

908 Velichkin VI, Vlasov BP (2011) Domal structures and hydrothermal uranium deposits of the
909 Erzgebirge, Saxony, Germany. *Geol. Ore Depos.* 53:74–83.

- 910 Wiedenbeck M, Allé P, Corfu F, Griffin WL, Meier M, Oberli F, von Quadt A, Roddick JC,
911 Spiegel W (1995) Three natural zircon standards for U–Th–Pb, Lu–Hf, trace element and
912 REE analyses. *Geostandard Newsletter* 19:1–23.
- 913 Williams ML, Jercinovic MJ, Harlov DE, Budzyn Hetherington CJ (2011) Resetting monazite
914 ages during fluid-related alteration. *Chemical Geology* 283:218-225.
- 915

916 **Table and Figure captions:**

917

918 Figure 1. Structural map of the southern French Massif Central (MC) showing the
919 relationships between the Montagne Noire gneiss dome, the Stephanian-Permian basins, and
920 the Variscan thrusts and nappes (modified after Brun and Van Den Driessche, 1994). 7, 8:
921 locations of the samples ES7 and ES8, respectively, Af: St. Affrique basin, G: Graissessac
922 basin, L: Laouzas granite, Lo: Lodève basin P: Col de Picotalen (location of the sample of the
923 Montalet syntectonic leucogranite, ES5, Poilvet et al. 2011), V: Vialais granite.
924 Inset shows the location of the study area within the European Variscan belt (modified from
925 Pitra et al. 2010). A - Alps, AM - Armorican Massif, BM - Bohemian Massif, MC - Massif
926 Central. B - Teplá-Barrandian, Mo - Moldanubian, ST - Saxothuringian, RH -
927 Rhenohercynian. L: Lyon; M: Montpellier; R: Rennes.

928

929 Figure 2. (a) Outcrop photograph of the Laouzas granite (ES7). Dark spots are clusters of
930 cordierite, the elongated object in the lower central part is a biotite-rich schliere. (b-c)
931 Microphotographs of the granite. Note the presence of subhedral, partly altered crystals of
932 plagioclase (pl) and K-feldspar (kfs), partly pinitised crystals of cordierite (cd), and late
933 crystals of dumortierite (dum), andalusite (and) and muscovite (mu), and the clear rim around
934 altered plagioclase core. (d) Outcrop photograph of the banded La Salvetat migmatite (ES8).
935 Rare garnet crystals are shown by arrows. (e-f) Microphotographs of the migmatite
936 leucosome. Interstitial brown-blue tourmaline is located between subhedral, partly altered
937 crystals of feldspars and anhedral quartz (e). Plagioclase crystals are partly replaced by
938 clinzoisite (tiny high-relief crystals), biotite contains prehnite (prh) and/or clay minerals
939 parallel to the (001) cleavage; late muscovite is also present (f).

940

941 Figure 3: Cathodoluminescence images of some of the zircon grains dated in this study: A:
942 Laouzas granite; B and C: La Salvetat migmatite. The white circle represents the spot analysis
943 and the number corresponds to the $^{207}\text{Pb}/^{206}\text{Pb}$ age obtained. Zr number corresponds to the
944 grain number in Table 1.

945

946 Figure 4: Summary of the geochronological results. In all diagram, N refers to the number of
947 analyses. Grey ellipses correspond to the data used to calculate the concordia ages. A and C:
948 Tera-Wasserburg $^{207}\text{Pb}/^{206}\text{Pb}$ versus $^{238}\text{U}/^{206}\text{Pb}$ concordia diagram for the zircon grains
949 analyzed in the Laouzas granite (A) and the La Salvetat migmatite (C). B and D: $^{206}\text{Pb}/^{238}\text{U}$

950 versus $^{208}\text{Pb}/^{232}\text{Th}$ diagram for the monazite analyzed in the Laouzas granite (B) and the La
951 Salvetat migmatite (D). E: Relative probability plot of $^{207}\text{Pb}/^{206}\text{Pb}$ dates for all the more than
952 90% concordant zircon grains obtained in this study. F: Relative probability plots for all the
953 monazite $^{206}\text{Pb}/^{238}\text{U}$ dates obtained in this study. G: Relative probability plots for all the
954 monazite $^{208}\text{Pb}/^{232}\text{Th}$ dates obtained in this study. H: ^{40}Ar - ^{39}Ar spectra of muscovite from
955 samples ES5, ES7 and ES8. The error bars for each temperature steps are at the 1σ level. The
956 errors in the J-values are not included. Plateau age error is at the 2σ level.

957

958 Figure 5: Top picture: Backscattered electron image of the Type 1 monazite from sample ES7
959 (i.e. ca. 318 Ma). White circle represents the spot analysis and has a diameter of 7 microns.
960 Date refers to the $^{208}\text{Pb}/^{232}\text{Th}$ individual date. M number refers to the grain number in Table 2.
961 White square corresponds to the location of the NanoSIMS elemental images (8 bottom
962 pictures).

963

964 Figure 6: Top picture: Backscattered electron image of the Type 2 monazite from sample ES7
965 (i.e. ca. 294 Ma). White circle represents the spot analysis and has a diameter of 7 microns.
966 Date refers to the $^{208}\text{Pb}/^{232}\text{Th}$ individual date. M number refers to the grain number in Table 2.
967 White square corresponds to the location of the NanoSIMS elemental images (8 bottom
968 pictures).

969

970 Figure 7: Top picture: Backscattered electron image of the first group of monazite grains (i.e.
971 ca. 319 Ma) from sample ES8. White circle represents the spot analysis and has a diameter of
972 7 microns. Date refers to the $^{208}\text{Pb}/^{232}\text{Th}$ date. M number refers to the grain number in Table
973 2. White square corresponds to the location of the NanoSIMS elemental images (8 bottom
974 pictures).

975

976 Figure 8: Top picture: Backscattered electron image of the second group of monazite grains
977 (i.e. ca. 298 Ma) from sample ES8. White circle represents the spot analysis and has a
978 diameter of 7 microns. Date refers to the $^{208}\text{Pb}/^{232}\text{Th}$ date. M number refers to the grain
979 number in Table 2. White square corresponds to the location of the NanoSIMS elemental
980 images (8 bottom pictures).

981

982 Figure 9: Th/Pb versus U/Pb plots using data for the monazite grains from the Montalet
983 granite (A; from Poilvet et al. 2011), the Laouzas granite (B) and the La Salvetat migmatite

984 (C). For all the diagrams, ages obtained by LA-ICP-MS (this study) are given for comparison.
985 n refers to the number of analyses plotted in the diagrams. For more explanation on these
986 plots see Cocherie and Albarède (2001).

987

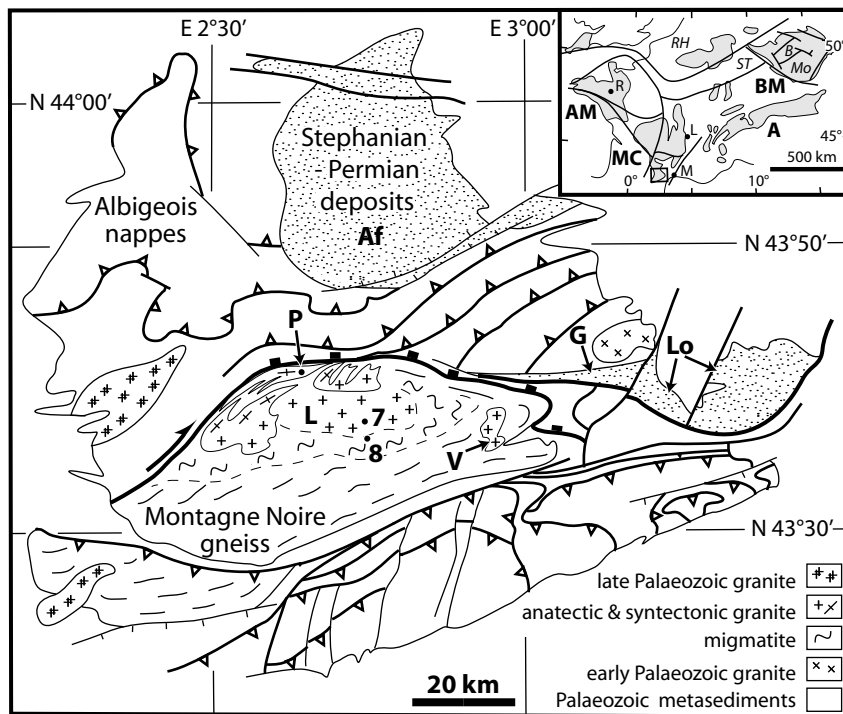
988 Figure 10: Weighted-histogram representation of the data acquired in this study for sample
989 ES7 following the statistical 1D data treatment of Montel et al (1996) for EPMA dating. For
990 more explanation on this plot see Montel et al. (1996).

991

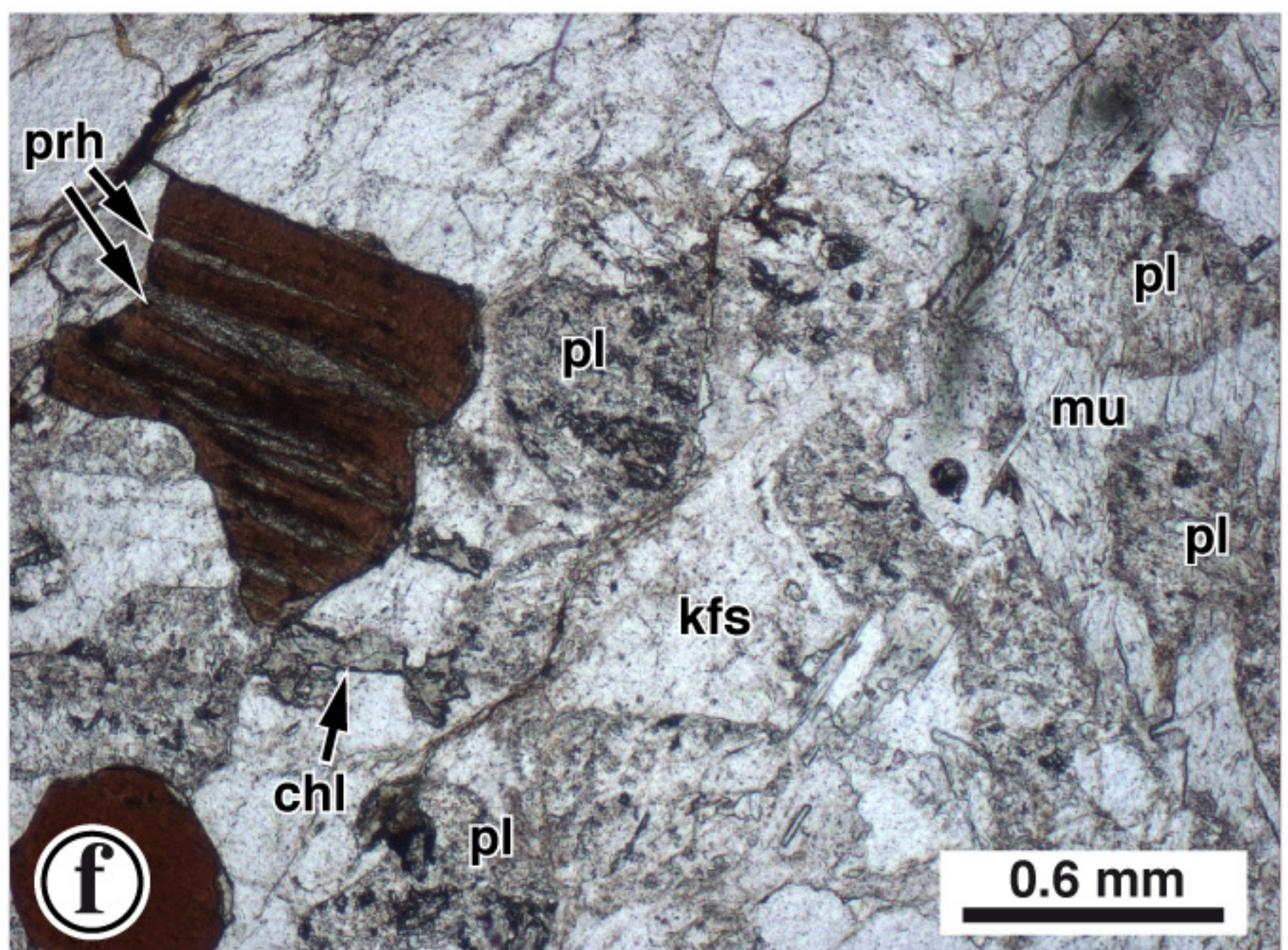
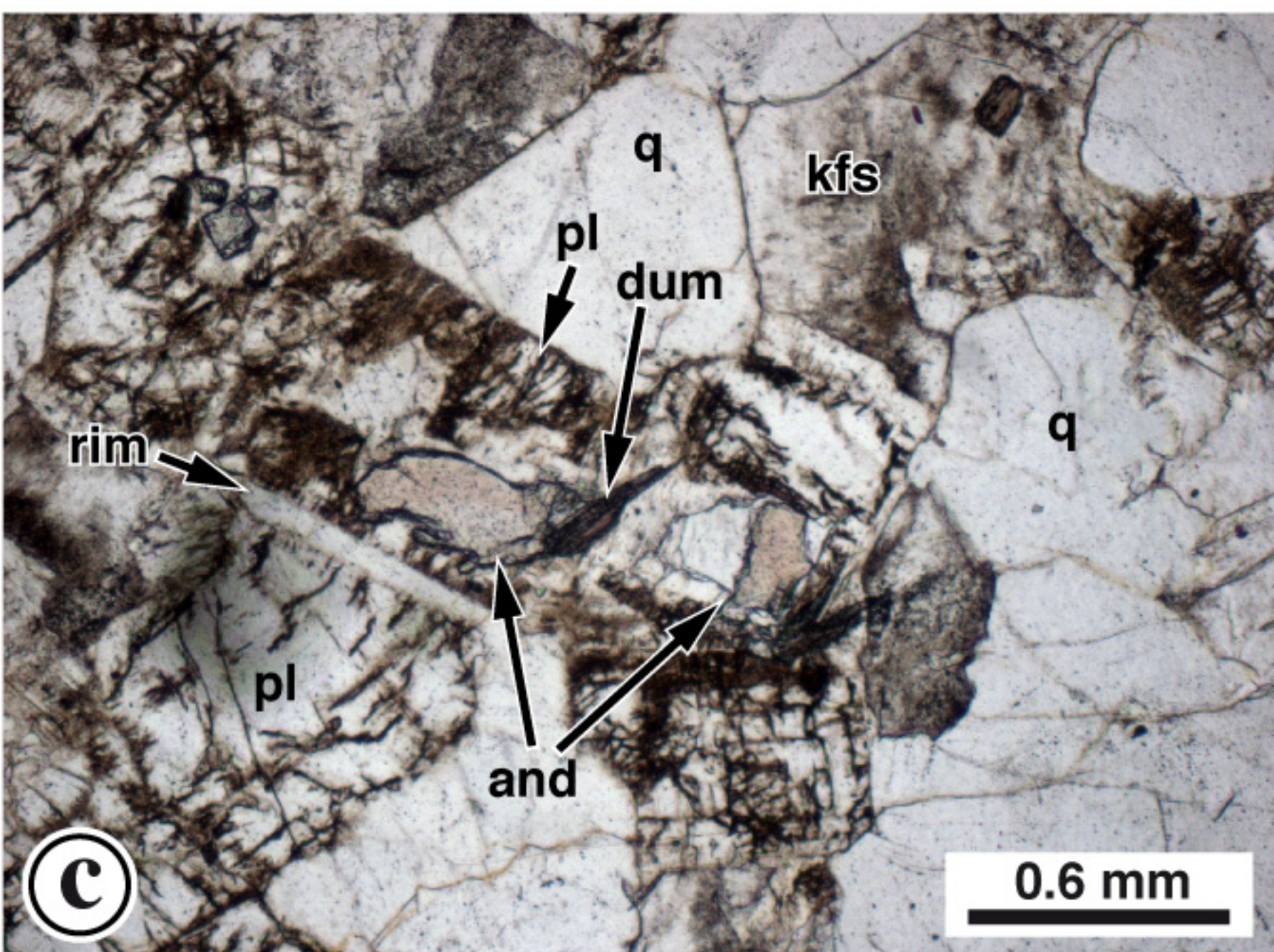
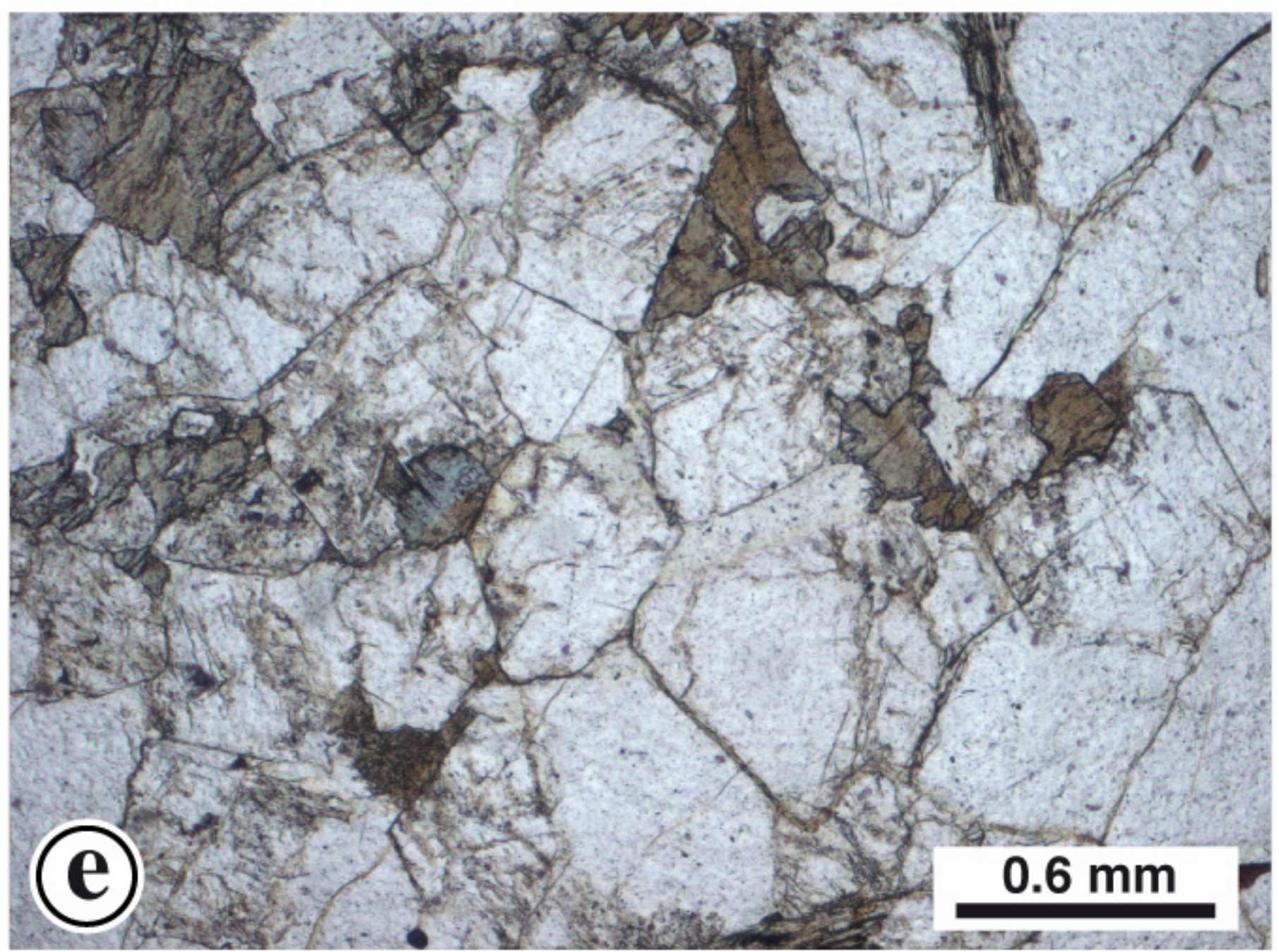
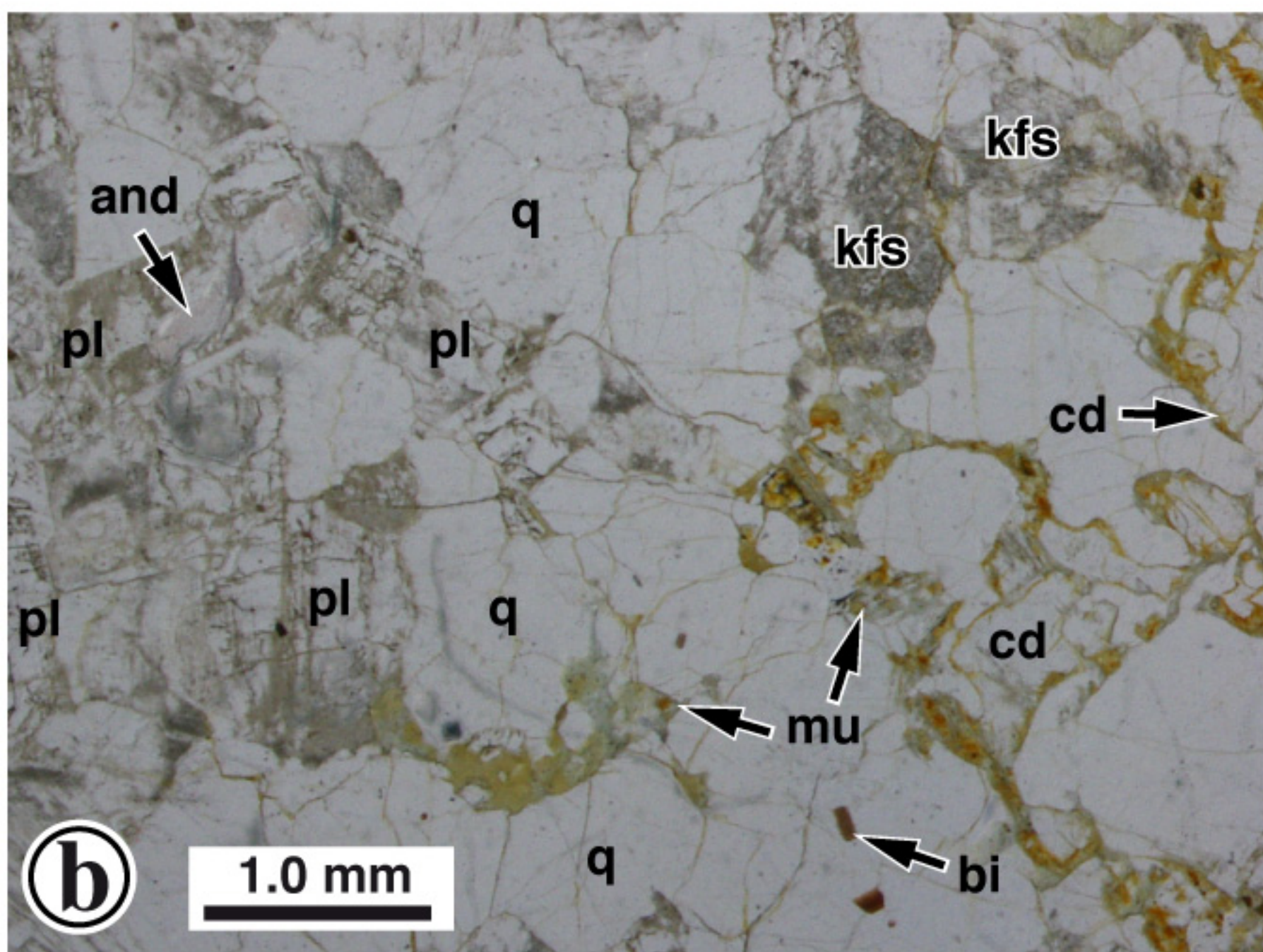
992 Table 1: U-Th-Pb LA-ICP-MS data for the zircon grains from sample ES7 and ES8. Errors
993 are reported at 1 sigma.

994

995 Table 2: U-Th-Pb LA-ICP-MS data for the monazite grains from sample ES7 and ES8. Errors
996 are reported at 1 sigma.



Poujol et al.: Fig. 1



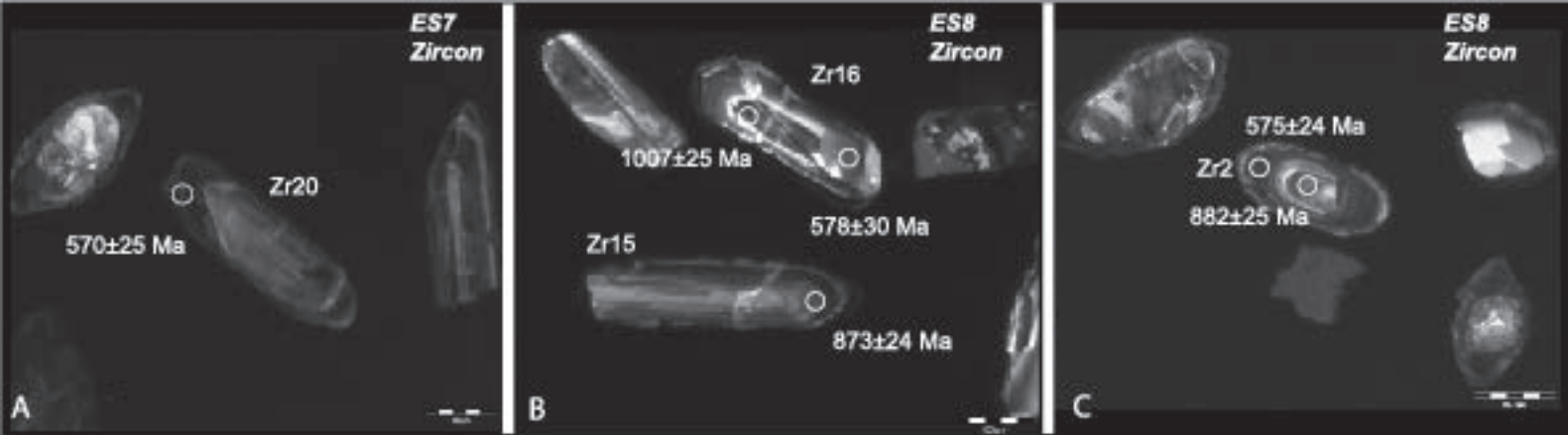
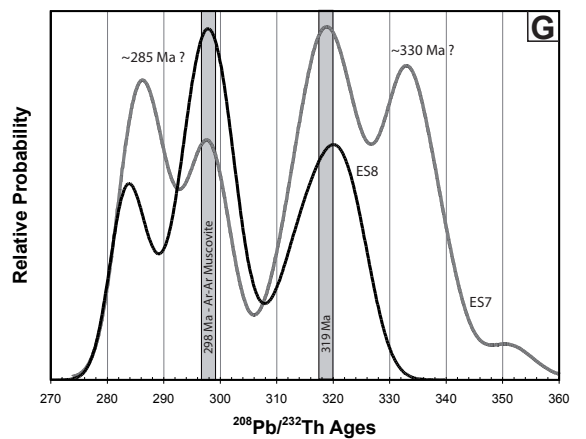
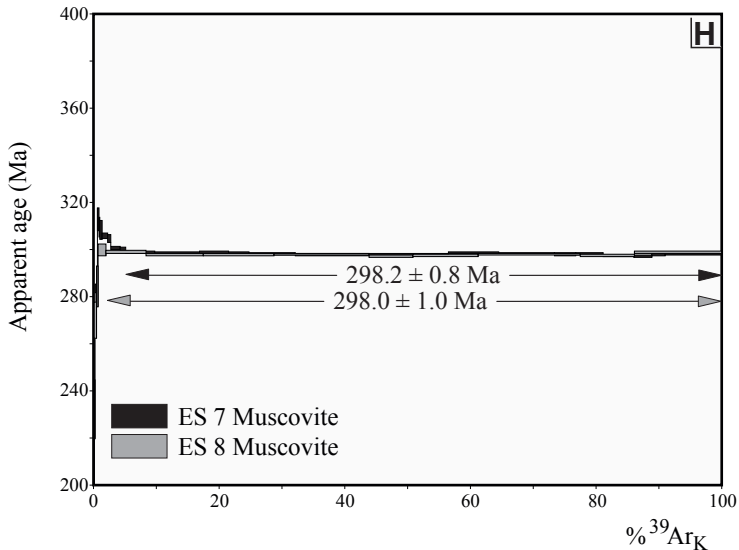
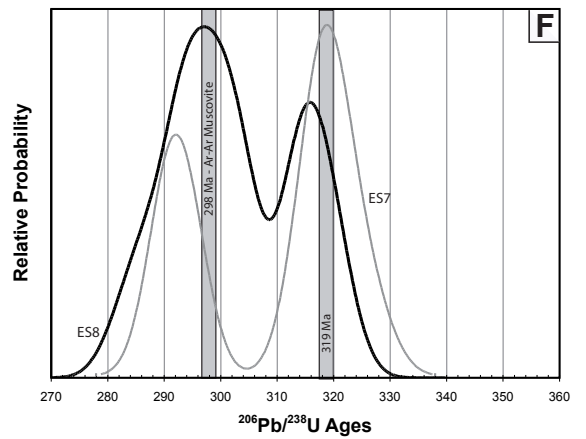
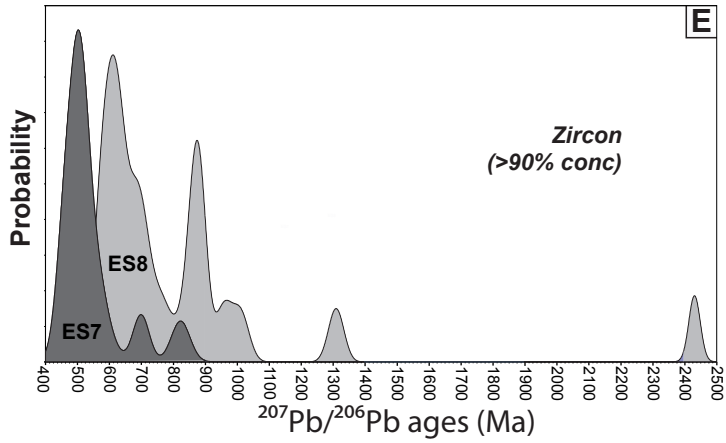
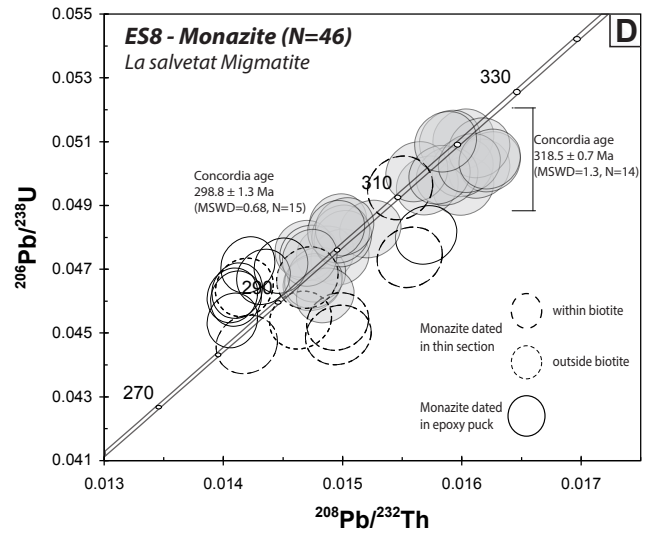
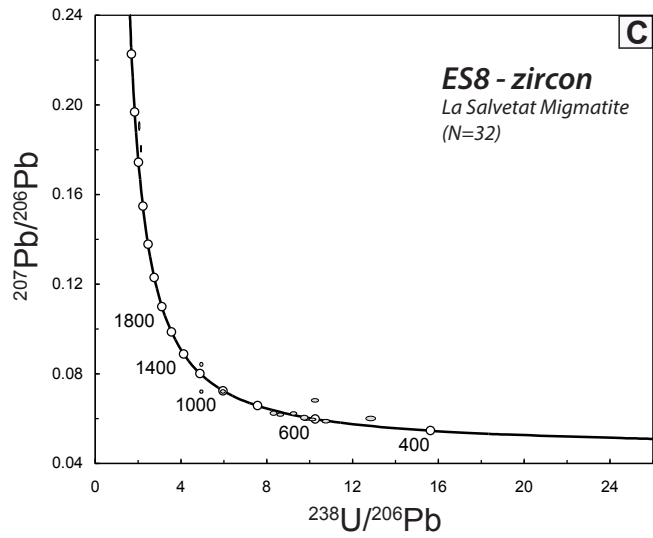
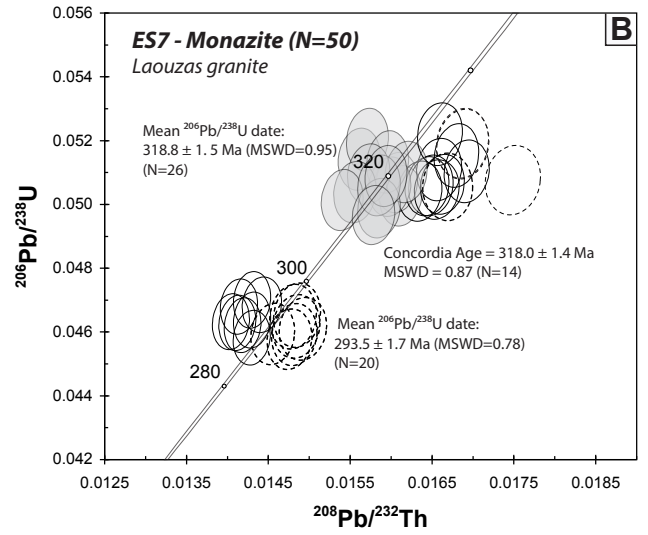
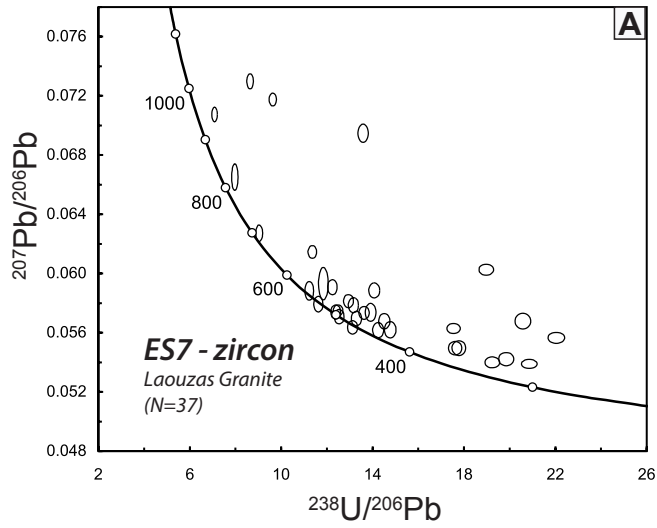
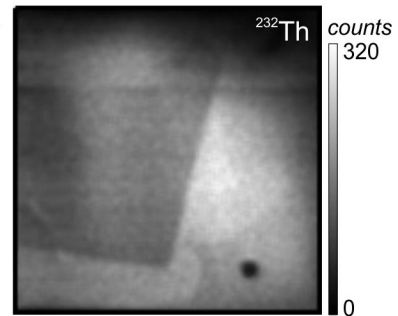
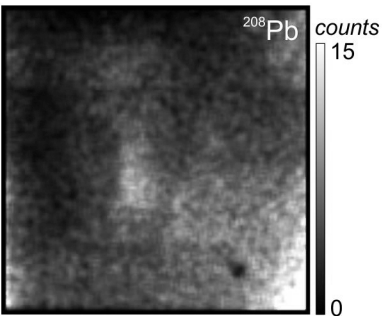
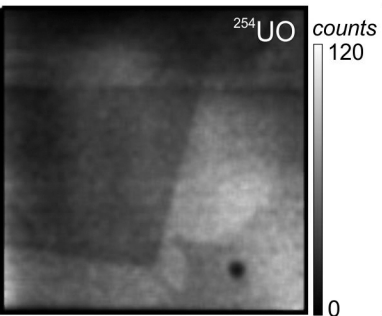
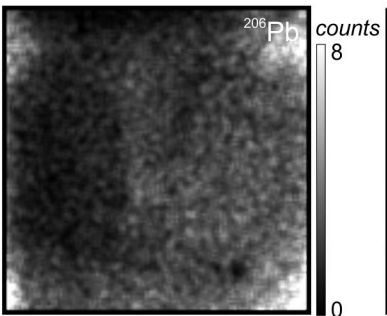
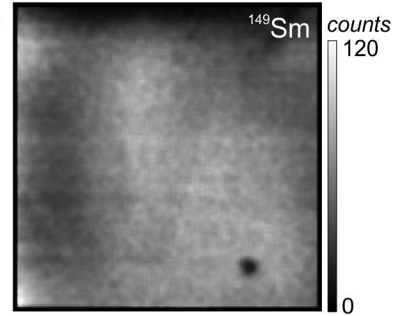
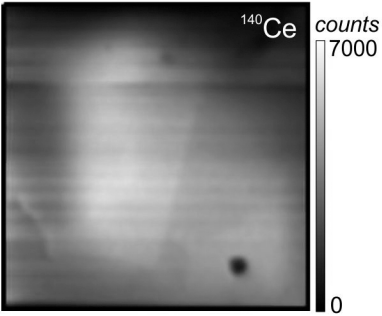
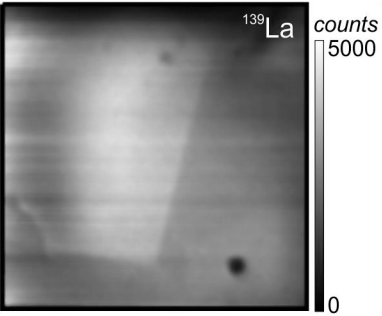
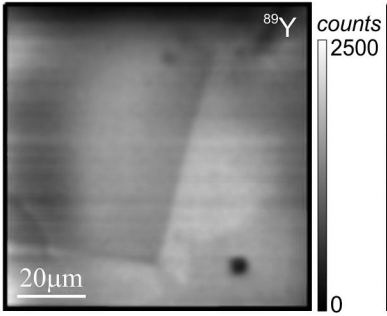
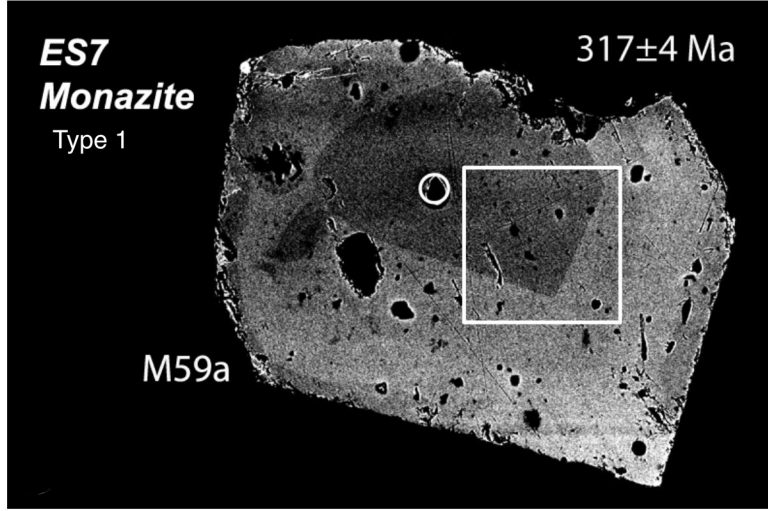
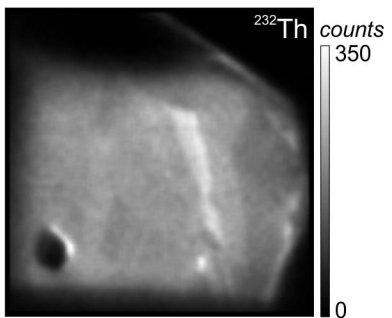
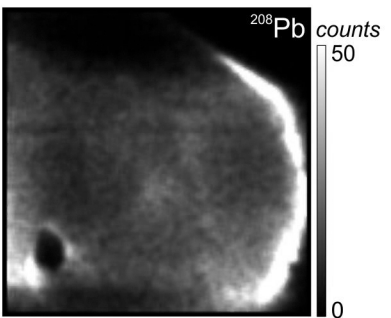
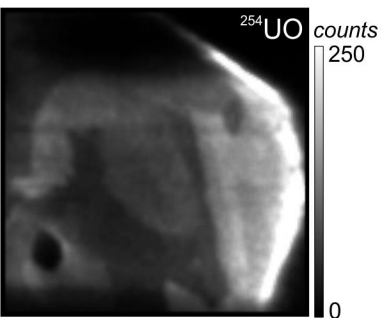
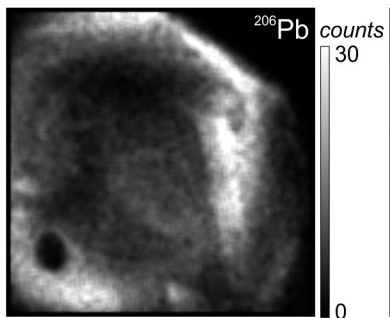
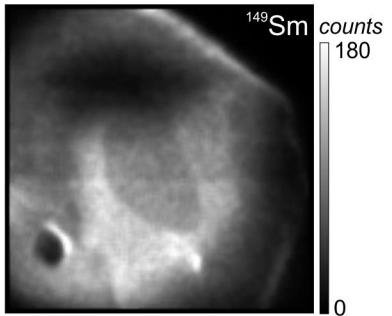
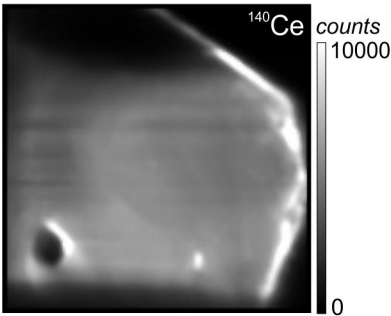
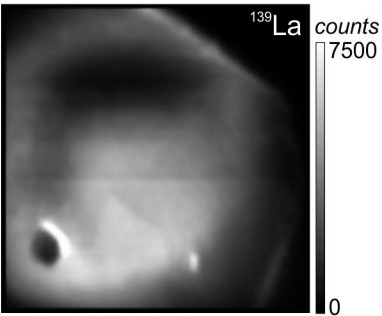
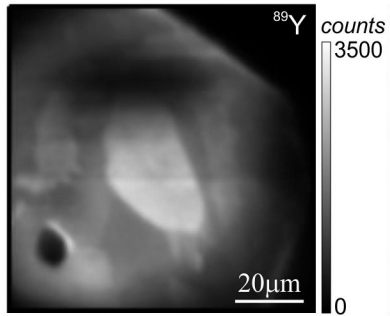
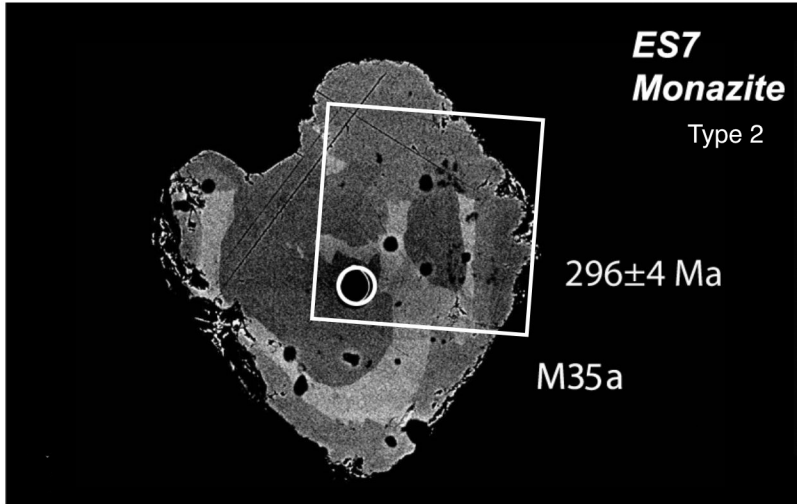
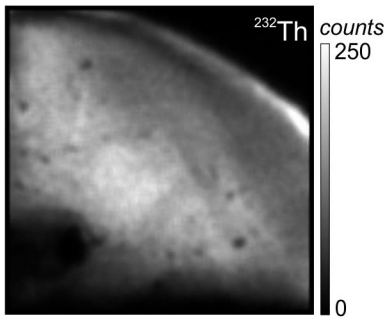
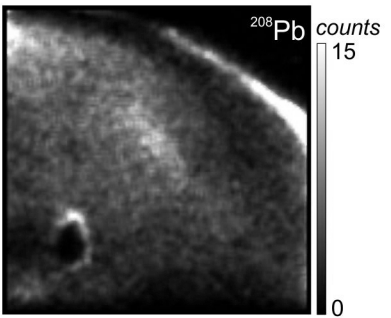
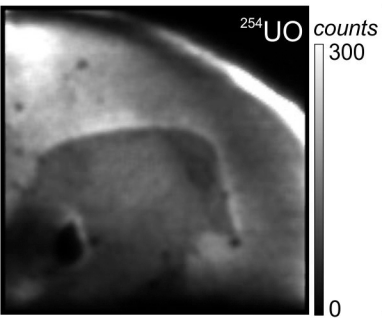
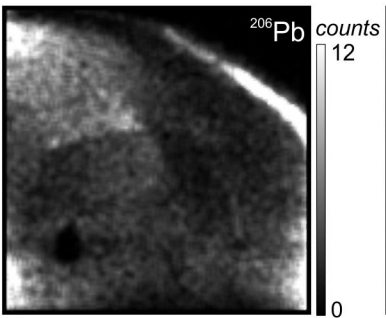
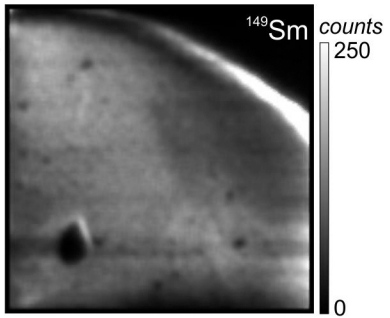
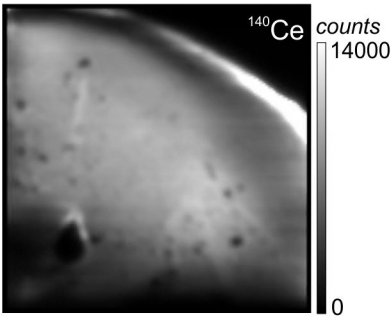
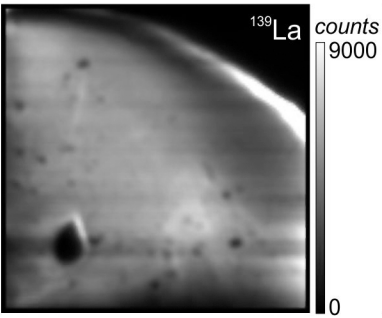
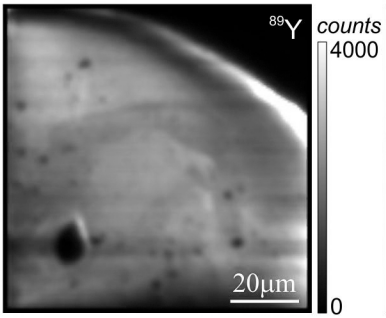
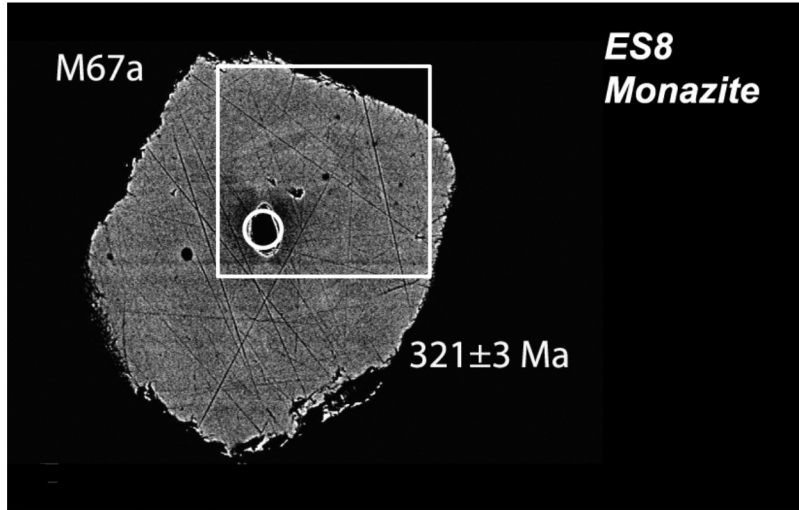


Figure 3: Poujol et al.









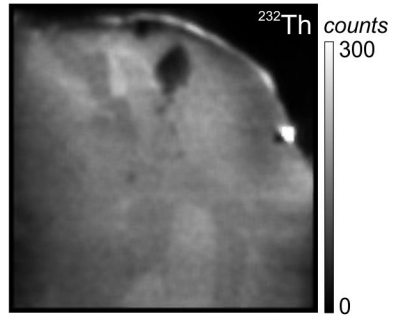
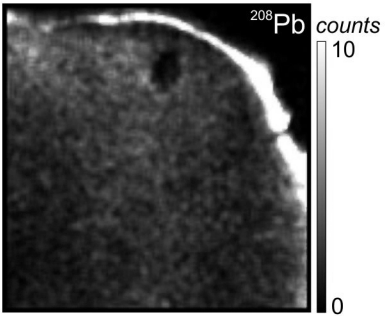
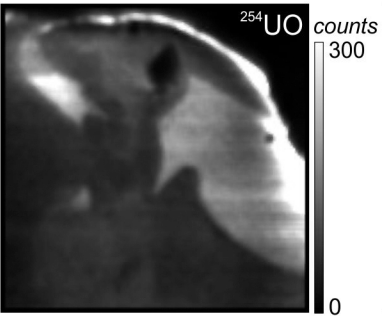
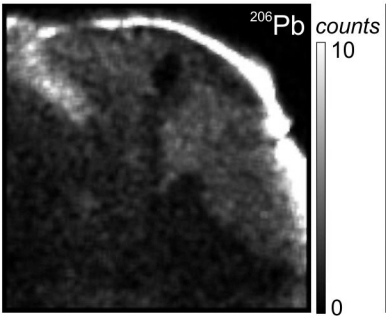
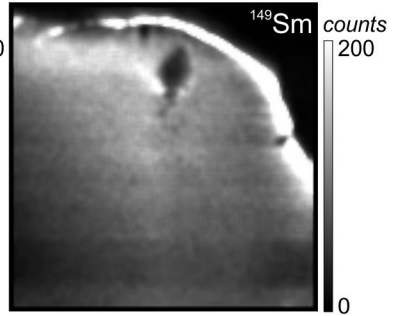
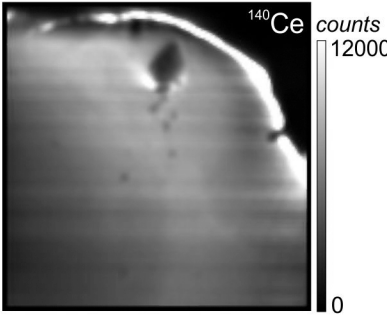
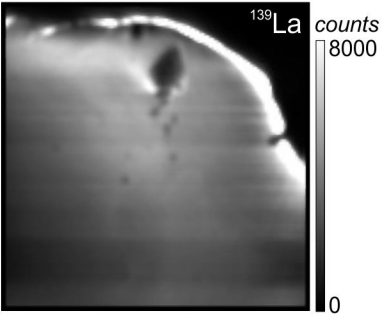
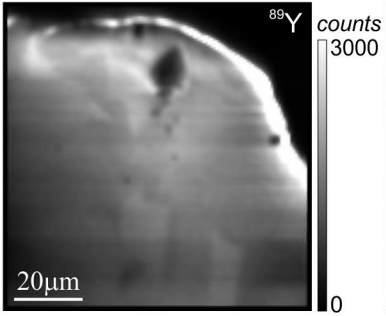
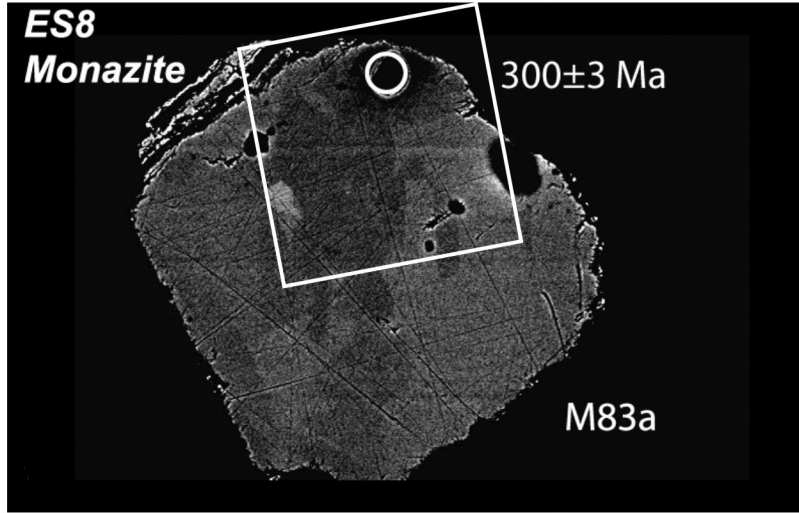


Figure 9: Poujol et al.

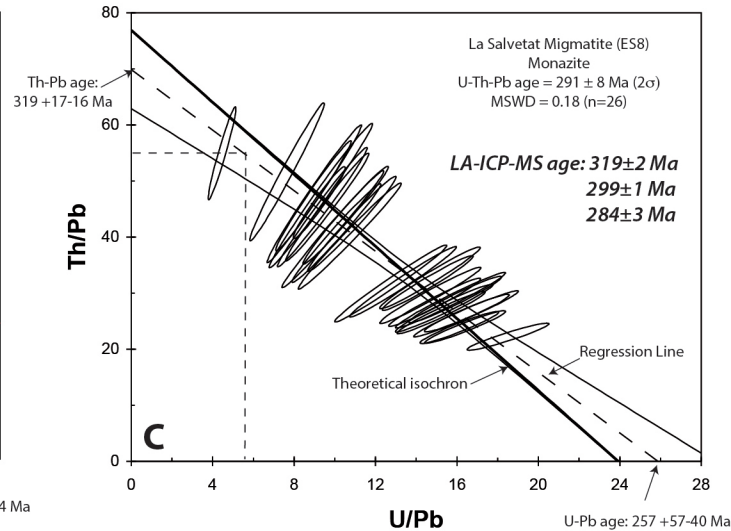
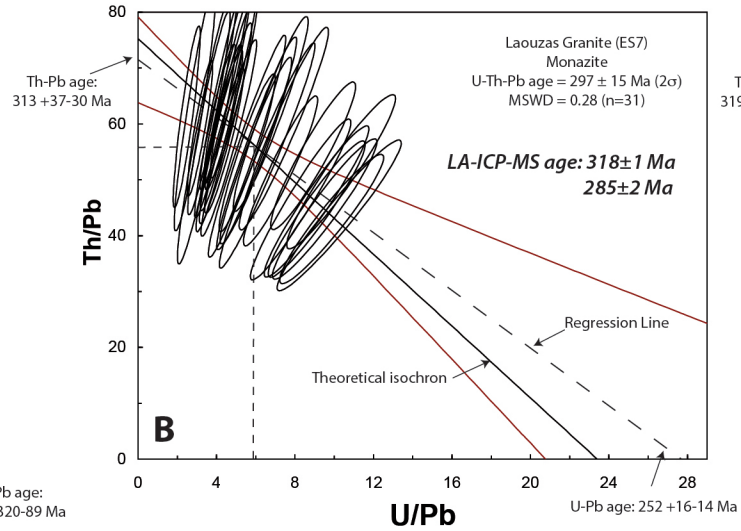
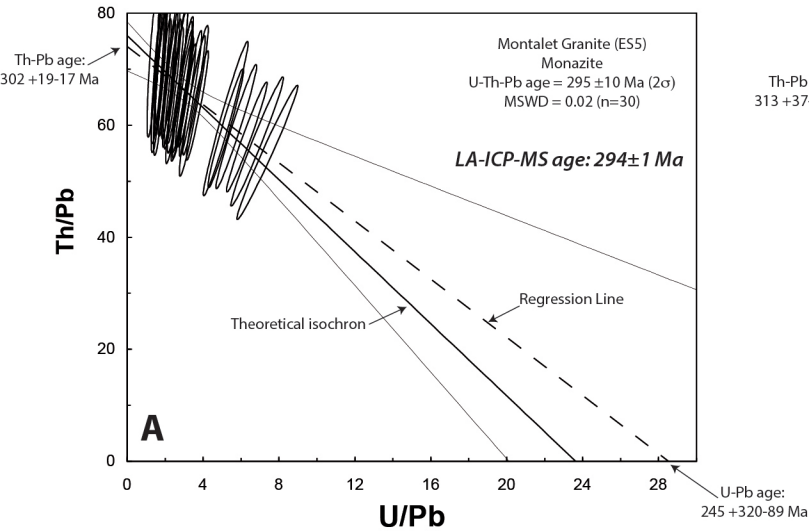
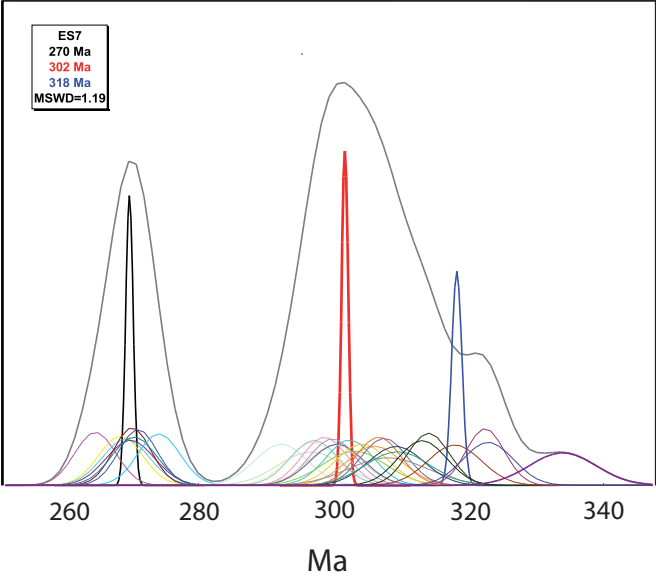


Figure 10: Poujol et al.



grain (zircon)	[Pb] (ppm)	[U] (ppm)	Th/U	²⁰⁷ Pb/		²⁰⁶ Pb/		²⁰⁷ Pb/		Rho	Ages				Conc. (%)
				²³⁵ U	± 1 σ	²³⁸ U	± 1 σ	²⁰⁶ Pb	± 1 σ		²⁰⁷ Pb/ ²³⁵ U	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²⁰⁶ Pb	± 1 σ	
ES 7 Laouzas Granite															
1.2c	31	509	0.19	0.705	0.009	0.0736	0.0008	0.0695	0.0008	0.88	542	458	913	25	50
2.1c	39	376	0.43	1.166	0.014	0.1158	0.0013	0.0730	0.0008	0.92	785	707	1014	23	70
2.2c	104	2810	0.01	0.356	0.004	0.0480	0.0005	0.0539	0.0006	0.95	310	302	367	25	82
3c	110	2469	0.03	0.443	0.005	0.0570	0.0006	0.0563	0.0006	0.94	372	358	463	24	77
4.1c	102	988	0.85	1.028	0.012	0.1039	0.0011	0.0718	0.0008	0.94	718	637	979	22	65
4.2c	99	2374	0.02	0.438	0.005	0.0527	0.0006	0.0603	0.0007	0.94	369	331	613	24	54
6.1c	10	90	0.50	1.151	0.017	0.1255	0.0014	0.0665	0.0009	0.78	778	762	823	29	93
6.2c	15	212	0.17	0.723	0.010	0.0891	0.0010	0.0588	0.0008	0.84	552	550	561	27	98
7.2c	73	1834	0.02	0.387	0.005	0.0520	0.0006	0.0540	0.0006	0.92	332	327	371	25	88
8.1c	62	501	0.44	1.378	0.016	0.1413	0.0016	0.0708	0.0008	0.92	880	852	950	23	90
8.2c	29	317	0.20	0.958	0.012	0.1107	0.0012	0.0627	0.0008	0.88	682	677	699	25	97
10c	61	834	0.22	0.746	0.009	0.0880	0.0010	0.0615	0.0007	0.92	566	544	655	24	83
11.1c	7	87	0.78	0.691	0.012	0.0845	0.0010	0.0593	0.0010	0.69	533	523	579	36	90
11.2c	98	1572	0.05	0.635	0.008	0.0801	0.0009	0.0575	0.0006	0.93	499	497	511	24	97
12.1c	19	325	0.19	0.569	0.008	0.0719	0.0008	0.0574	0.0007	0.85	457	448	506	28	89
12.2c	157	4467	0.11	0.348	0.004	0.0454	0.0005	0.0557	0.0006	0.93	303	286	439	24	65
13c	46	1043	0.03	0.430	0.005	0.0568	0.0006	0.0550	0.0006	0.90	364	356	411	26	87
14.2c	87	2249	0.02	0.377	0.005	0.0504	0.0006	0.0542	0.0006	0.90	325	317	380	26	83
15c	67	1133	0.07	0.607	0.008	0.0760	0.0009	0.0579	0.0007	0.89	481	472	525	26	90
16.2c	86	1453	0.04	0.592	0.007	0.0762	0.0009	0.0564	0.0007	0.90	472	474	466	26	102
17c	106	1769	0.05	0.620	0.008	0.0773	0.0009	0.0582	0.0007	0.91	490	480	535	26	90
18c	75	1739	0.02	0.427	0.005	0.0563	0.0006	0.0550	0.0007	0.88	361	353	411	27	86
19c	117	2052	0.07	0.580	0.007	0.0734	0.0008	0.0573	0.0007	0.91	465	457	504	25	91
20c	72	1135	0.05	0.666	0.008	0.0817	0.0009	0.0591	0.0007	0.89	518	506	570	25	89
22c	74	1972	0.03	0.381	0.005	0.0486	0.0005	0.0568	0.0007	0.87	328	306	483	27	63
23c	99	1573	0.07	0.639	0.008	0.0808	0.0009	0.0574	0.0007	0.90	502	501	507	26	99
24c	102	1656	0.05	0.628	0.008	0.0798	0.0009	0.0571	0.0007	0.90	495	495	495	26	100
25c	112	2013	0.05	0.577	0.007	0.0711	0.0008	0.0589	0.0007	0.89	463	443	562	26	79
26c	94	1728	0.04	0.544	0.007	0.0702	0.0008	0.0562	0.0007	0.88	441	438	459	27	95
27c	133	2301	0.04	0.591	0.007	0.0753	0.0009	0.0570	0.0007	0.89	472	468	490	27	96
28c	114	1701	0.08	0.687	0.009	0.0861	0.0010	0.0579	0.0007	0.88	531	532	527	27	101
29c	96	1801	0.06	0.540	0.007	0.0689	0.0008	0.0568	0.0007	0.88	438	430	482	27	89
30c	95	1818	0.06	0.525	0.007	0.0677	0.0008	0.0562	0.0007	0.87	428	422	460	28	92
ES 8 La Salvetat Migmatite															
1.1d	33	892	0.01	0.351	0.004	0.0478	0.0005	0.0532	0.0006	0.88	305	301	337	27	89
1.2d	18	156	2.20	0.766	0.011	0.0932	0.0011	0.0596	0.0008	0.79	578	575	590	30	97
2.1d	27	184	0.80	1.447	0.018	0.1533	0.0017	0.0685	0.0008	0.88	909	919	882	25	104
2.2d	82	828	1.03	0.812	0.010	0.0995	0.0011	0.0592	0.0007	0.93	604	611	575	24	106
3d	44	497	0.33	0.867	0.011	0.1047	0.0012	0.0601	0.0007	0.91	634	642	607	25	106
4d	25	631	0.01	0.389	0.006	0.0504	0.0006	0.0560	0.0009	0.69	334	317	451	36	70
5d	52	353	0.93	1.480	0.019	0.1512	0.0017	0.0710	0.0009	0.88	922	908	957	25	95
6d	26	341	0.29	0.753	0.010	0.0886	0.0010	0.0616	0.0008	0.86	570	547	661	27	83
7d	67	635	1.41	0.839	0.011	0.0983	0.0011	0.0619	0.0008	0.86	619	605	670	27	90
8d	61	644	0.72	0.817	0.010	0.1014	0.0011	0.0585	0.0007	0.90	607	623	547	26	114
9d	25	194	0.99	1.141	0.016	0.1276	0.0014	0.0648	0.0009	0.83	773	774	768	28	101
10d	55	429	0.36	1.413	0.017	0.1496	0.0017	0.0685	0.0008	0.91	894	899	884	24	102
11d	10	81	0.52	1.306	0.020	0.1414	0.0016	0.0670	0.0010	0.74	848	853	838	32	102
12d	116	764	0.11	2.616	0.032	0.1827	0.0020	0.1039	0.0012	0.91	1305	1082	1694	21	64
13d	201	2497	0.17	0.830	0.010	0.0990	0.0011	0.0608	0.0007	0.93	614	608	633	24	96
14d	71	605	0.12	1.370	0.018	0.1463	0.0016	0.0679	0.0008	0.88	876	880	866	25	102
15d	89	752	0.16	1.366	0.017	0.1454	0.0016	0.0681	0.0008	0.89	875	875	873	24	100
16.1d	29	413	0.09	0.713	0.010	0.0872	0.0010	0.0593	0.0008	0.78	547	539	578	30	93
16.2d	43	172	2.04	2.044	0.027	0.2038	0.0023	0.0728	0.0009	0.86	1130	1195	1007	25	119
17d	40	255	0.73	1.693	0.023	0.1685	0.0019	0.0729	0.0010	0.83	1006	1004	1010	26	99
18d	59	627	0.18	1.002	0.013	0.1162	0.0013	0.0625	0.0008	0.87	705	709	692	26	102
19d	36	516	0.53	0.653	0.010	0.0779	0.0009	0.0608	0.0009	0.74	511	484	632	33	77
20d	94	1132	0.29	0.824	0.011	0.0990	0.0011	0.0604	0.0007	0.87	611	608	619	26	98
21d	53	597	0.50	0.852	0.011	0.1020	0.0012	0.0606	0.0008	0.87	626	626	627	27	100
22d	295	653	0.48	11.792	0.149	0.4746	0.0053	0.1802	0.0022	0.89	2588	2504	2655	20	94
23.1d	10	98	0.26	1.049	0.016	0.1205	0.0014	0.0631	0.0010	0.75	728	734	713	32	103
23.2d	19	215	0.22	0.942	0.014	0.1084	0.0012	0.0630	0.0009	0.78	674	663	709	30	94
24d	93	1001	0.69	0.927	0.012	0.0977	0.0011	0.0688	0.0009	0.84	666	601	894	26	67
25d	31	352	0.69	0.764	0.011	0.0930	0.0011	0.0596	0.0008	0.81	576	573	588	29	98
26d	113	653	0.28	2.378	0.031	0.2036	0.0023	0.0847	0.0011	0.86	1236	1195	1309	24	91
27d	176	360	0.63	13.005	0.171	0.4959	0.0056	0.1902	0.0024	0.86	2680	2596	2744	20	95
28d	13	138	0.53	0.867	0.014	0.1026	0.0012	0.0613	0.0010	0.73	634	630	649	33	97

grain	[Pb]	[U]	[Th]	Th/U	206 Pb/	±	207 Pb/	±	208 Pb/	±	Ages			
	(ppm)	(ppm)	(ppm)		238 U	(1σ)	235 U	(1σ)	232 Th	(1σ)	206 Pb/ 238 U	207 Pb/ 235 U	208 Pb/ 232 Th	± (1σ)
ES7 Laouzas Granite														
33a	1405	14522	72329	5	0.0459	0.0006	0.3167	0.0045	0.0143	0.0002	289	279	287	3
34a	1331	8983	82279	9	0.0463	0.0006	0.3171	0.0046	0.0142	0.0002	292	280	284	3
35a	1561	13906	84806	6	0.0469	0.0006	0.3241	0.0046	0.0144	0.0002	296	285	289	3
36a	1255	5650	86272	15	0.0464	0.0006	0.3174	0.0050	0.0140	0.0002	292	280	282	3
37a	1526	7457	102172	14	0.0469	0.0006	0.3195	0.0048	0.0141	0.0002	295	282	284	3
38a	1422	6446	95482	15	0.0471	0.0006	0.3250	0.0050	0.0143	0.0002	296	286	287	3
39a	1223	9071	72384	8	0.0464	0.0006	0.3141	0.0046	0.0143	0.0002	293	277	287	3
40a	1316	6291	88790	14	0.0464	0.0006	0.3234	0.0050	0.0141	0.0002	292	285	283	3
41a	1869	5871	110726	19	0.0510	0.0006	0.3636	0.0064	0.0169	0.0002	321	315	339	4
42a	1664	7306	95010	13	0.0511	0.0006	0.3540	0.0056	0.0166	0.0002	321	308	332	4
43a	1427	5587	83966	15	0.0506	0.0006	0.3511	0.0057	0.0165	0.0002	318	306	330	4
44a	1505	6351	89387	14	0.0503	0.0006	0.3457	0.0056	0.0161	0.0002	316	302	323	3
45a	1421	3511	87118	25	0.0515	0.0007	0.3737	0.0068	0.0168	0.0002	324	322	337	4
46a	1467	8153	80517	10	0.0504	0.0006	0.3488	0.0053	0.0163	0.0002	317	304	328	4
47a	1385	12594	62010	5	0.0505	0.0006	0.3437	0.0050	0.0166	0.0002	317	300	332	4
48a	1402	13808	60267	4	0.0506	0.0006	0.3464	0.0050	0.0164	0.0002	318	302	330	4
50a	1343	12757	60159	5	0.0507	0.0006	0.3468	0.0051	0.0161	0.0002	319	302	322	3
51a	1254	5577	75446	14	0.0514	0.0006	0.3570	0.0058	0.0156	0.0002	323	310	313	3
52a	1210	10014	56262	6	0.0506	0.0006	0.3483	0.0051	0.0166	0.0002	319	304	333	4
53a	1279	11628	59034	5	0.0506	0.0006	0.3470	0.0051	0.0160	0.0002	318	302	320	3
54a	1275	4595	79000	17	0.0520	0.0006	0.3656	0.0063	0.0157	0.0002	327	316	315	3
55a	864	3086	52825	17	0.0513	0.0006	0.3551	0.0065	0.0160	0.0002	323	309	320	3
56a	1224	5645	70387	12	0.0510	0.0006	0.3458	0.0053	0.0162	0.0002	321	302	324	3
57a	1238	7421	68419	9	0.0510	0.0006	0.3418	0.0054	0.0157	0.0002	320	299	315	3
58a	1312	5427	74832	14	0.0522	0.0006	0.3527	0.0056	0.0166	0.0002	328	307	333	4
59a	1003	6587	54512	8	0.0504	0.0006	0.3473	0.0057	0.0156	0.0002	317	303	312	3
60a	1107	6681	62592	9	0.0502	0.0006	0.3376	0.0057	0.0154	0.0002	316	295	309	3
61a	1453	10545	74983	7	0.0499	0.0006	0.3476	0.0053	0.0158	0.0002	314	303	318	3
62a	1050	5823	58804	10	0.0506	0.0006	0.3544	0.0057	0.0158	0.0002	318	308	318	3
63a	1061	3078	66792	22	0.0509	0.0006	0.3549	0.0065	0.0159	0.0002	320	308	319	3
64a	1212	12417	52947	4	0.0497	0.0006	0.3419	0.0050	0.0158	0.0002	313	299	316	3
Mz1.1 (fsp)	346	3072	14349	5	0.0506	0.0007	0.5039	0.0078	0.0167	0.0002	318	414	335	4
Mz1.2 (fsp)	1015	7710	50744	7	0.0473	0.0006	0.3374	0.0048	0.0154	0.0002	298	295	309	4
Mz2.1 (crd)	1072	8419	51320	6	0.0489	0.0007	0.3815	0.0055	0.0157	0.0002	308	328	315	4
Mz2.2 (crd)	1218	7907	57072	7	0.0519	0.0007	0.3798	0.0054	0.0169	0.0002	326	327	338	4
Mz3.1 (qtz)	1372	10036	73905	7	0.0458	0.0006	0.3173	0.0045	0.0148	0.0002	289	280	296	4
Mz3.2 (qtz)	1444	10503	79124	8	0.0460	0.0006	0.3171	0.0045	0.0145	0.0002	290	280	292	4
Mz4.1 (fsp)	1373	1157	55048	48	0.0460	0.0006	0.3170	0.0046	0.0148	0.0002	290	280	297	4
Mz4.2 (fsp)	1423	1206	56888	47	0.0462	0.0006	0.3264	0.0049	0.0149	0.0002	291	287	299	4
Mz5 (qtz)	880	732	35685	49	0.0576	0.0008	0.4697	0.0089	0.0195	0.0003	361	391	390	5
Mz6 (qtz)	1247	1045	50170	48	0.0508	0.0007	0.3525	0.0053	0.0175	0.0002	319	307	350	4
Mz7 (qtz)	1396	10994	73918	7	0.0474	0.0007	0.3261	0.0050	0.0157	0.0002	298	287	314	4
Mz8 (qtz)	713	5795	37073	6	0.0462	0.0007	0.3156	0.0049	0.0148	0.0002	291	279	298	4
Mz9.1 (fsp)	667	7610	33851	4	0.0478	0.0007	0.3389	0.0054	0.0152	0.0002	301	296	305	4
Mz9.2 (fsp)	136	1285	4509	4	0.0565	0.0008	0.3988	0.0065	0.0198	0.0003	354	341	396	5
Mz10.1 (qtz)	1305	6046	81834	14	0.0465	0.0007	0.4293	0.0069	0.0148	0.0002	293	363	297	4
Mz10.2 (qtz)	1318	8843	61053	7	0.0469	0.0007	0.3484	0.0057	0.0151	0.0002	295	304	303	4
Mz10.3 (qtz)	1344	10119	76298	8	0.0491	0.0007	0.3752	0.0062	0.0153	0.0002	309	324	306	4
Mz11.1 (qtz-j)	1121	8693	56704	7	0.0466	0.0007	0.3239	0.0054	0.0148	0.0002	294	285	298	4
Mz11.2(qtz-j)	1359	1165	55336	48	0.0474	0.0007	0.3382	0.0056	0.0152	0.0002	298	296	304	4

grain	[Pb]	[U]	[Th]	Th/U	206 Pb/	±	207 Pb/	±	208 Pb/	±	Ages			
	(ppm)	(ppm)	(ppm)		238 U	(1σ)	235 U	(1σ)	232 Th	(1σ)	206 Pb/	207 Pb/	208 Pb/	±
											238 U	235 U	232 Th	(1σ)
ES8 La Salvetat Migmatite														
65a	1230	5483	67669	12	0.0518	0.0006	0.3603	0.0058	0.0163	0.0002	326	312	327	3
66a	1189	18268	32530	2	0.0496	0.0006	0.3407	0.0050	0.0160	0.0002	312	298	321	3
67a	853	8595	34736	4	0.0511	0.0006	0.3507	0.0054	0.0160	0.0002	321	305	321	3
68a	942	12580	30216	2	0.0502	0.0006	0.3479	0.0052	0.0161	0.0002	316	303	324	3
69a	730	7226	30260	4	0.0510	0.0006	0.3552	0.0055	0.0159	0.0002	321	309	319	3
70a	1097	16108	32500	2	0.0496	0.0006	0.3411	0.0051	0.0157	0.0002	312	298	315	3
71a	854	10883	27100	2	0.0522	0.0006	0.3715	0.0056	0.0164	0.0002	328	321	328	3
72a	1543	25307	37012	1	0.0502	0.0006	0.3449	0.0050	0.0160	0.0002	316	301	321	3
73a	1307	19895	34723	2	0.0504	0.0006	0.3497	0.0052	0.0162	0.0002	317	305	325	3
74a	1229	18313	34893	2	0.0499	0.0006	0.3445	0.0051	0.0159	0.0002	314	301	318	3
75a	1571	25306	37535	1	0.0508	0.0006	0.3528	0.0052	0.0161	0.0002	319	307	324	3
76a	781	8381	31410	4	0.0501	0.0006	0.3488	0.0055	0.0156	0.0002	315	304	313	3
77a					0.0500	0.0006	0.3426	0.0052	0.0158	0.0002	314	299	317	3
78.1a					0.0503	0.0006	0.3496	0.0052	0.0161	0.0002	317	304	322	3
78.2a					0.0505	0.0006	0.3483	0.0052	0.0162	0.0002	317	303	325	3
78.3a					0.0510	0.0006	0.3529	0.0055	0.0159	0.0002	321	307	318	3
79a					0.0485	0.0006	0.3352	0.0053	0.0150	0.0002	305	294	300	3
80.1a					0.0475	0.0006	0.3316	0.0052	0.0147	0.0002	299	291	295	3
80.2a					0.0475	0.0006	0.3375	0.0053	0.0149	0.0002	299	295	298	3
81.1a					0.0474	0.0006	0.3294	0.0050	0.0150	0.0002	299	289	300	3
81.2a					0.0467	0.0006	0.3245	0.0049	0.0148	0.0002	294	285	296	3
82a					0.0466	0.0006	0.3221	0.0049	0.0147	0.0002	294	284	296	3
83a					0.0477	0.0006	0.3292	0.0052	0.0147	0.0002	300	289	294	3
84a					0.0469	0.0006	0.3236	0.0049	0.0148	0.0002	295	285	297	3
2b	713	6409	34056	5	0.0483	0.0006	0.3501	0.0062	0.0152	0.0002	304	305	306	3
3.1b	929	9780	40809	4	0.0480	0.0006	0.3415	0.0059	0.0150	0.0002	302	298	301	3
3.2b	772	5903	39878	7	0.0481	0.0006	0.3461	0.0063	0.0150	0.0002	303	302	301	3
3.3b	890	7957	42165	5	0.0484	0.0006	0.3458	0.0061	0.0150	0.0002	305	302	301	3
4b	869	8361	39428	5	0.0483	0.0006	0.3421	0.0062	0.0149	0.0002	304	299	300	3
5.2b	924	10015	39179	4	0.0474	0.0006	0.3393	0.0062	0.0147	0.0002	299	297	295	3
6b	676	6290	32046	5	0.0472	0.0006	0.3230	0.0063	0.0142	0.0002	297	284	285	3
7b	1186	19504	31251	2	0.0472	0.0006	0.3296	0.0062	0.0145	0.0002	297	289	291	3
8.1b	1213	17656	38626	2	0.0468	0.0006	0.3330	0.0064	0.0143	0.0002	295	292	288	3
8.2b	1300	20670	37530	2	0.0462	0.0006	0.3263	0.0063	0.0141	0.0001	291	287	283	3
9b	1738	32151	38690	1	0.0455	0.0006	0.3196	0.0063	0.0141	0.0001	287	282	282	3
10b	1074	16844	30899	2	0.0464	0.0006	0.3196	0.0065	0.0141	0.0001	292	282	283	3
11b	1481	24419	39221	2	0.0461	0.0006	0.3241	0.0066	0.0141	0.0001	291	285	283	3
12b	784	7353	35558	5	0.0474	0.0006	0.3314	0.0073	0.0140	0.0001	299	291	280	3
Mz12 (qtz)	731	9662	27745	3	0.0465	0.0006	0.3554	0.0054	0.0142	0.0002	293	309	285	3
Mz13 (qtz)	973	11793	39613	3	0.0455	0.0006	0.3248	0.0047	0.0146	0.0002	287	286	294	3
Mz15 (bt)	137	1909	5184	3	0.0447	0.0006	0.3430	0.0067	0.0142	0.0002	282	300	285	3
Mz17 (bt)	838	11024	30254	3	0.0454	0.0006	0.3177	0.0048	0.0149	0.0002	286	280	300	3
Mz20 (bt)	735	8040	29039	4	0.0474	0.0006	0.3310	0.0053	0.0156	0.0002	299	290	312	4
Mz21.1 (bt)	1007	12699	36732	3	0.0495	0.0006	0.3700	0.0059	0.0155	0.0002	311	319	311	4
Mz21.2 (bt)	1138	12832	44059	3	0.0450	0.0006	0.3459	0.0067	0.0150	0.0002	284	302	300	4
Mz23 (bt)	463	4871	15302	3	0.0468	0.0006	0.4067	0.0071	0.0147	0.0002	295	346	295	3

No data due to a « bug »
with Glitter.