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## LA-ICP-MS U/Pb zircon timescale constraints of the Pleistocene latest magmatic activity in the Sancy stratovolcano (French Massif Central)

Jean-Louis Paquette, Etienne Médard, Justine Francomme, Patrick Bachèlery,  
Jean-Marc Hénot

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1 **LA-ICP-MS U/Pb zircon timescale constraints of the Pleistocene latest**  
2 **magmatic activity in the Sancy stratovolcano (French Massif Central).**

3  
4 Jean-Louis Paquette<sup>a\*</sup>, Etienne Médard<sup>a</sup>, Justine Francomme<sup>a</sup>, Patrick Bachèlery<sup>a</sup>  
5 and Jean-Marc Hénot<sup>a</sup>  
6

7 <sup>a</sup> Université Clermont-Auvergne, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, F-  
8 63000 Clermont-Ferrand, France.

9 \* Corresponding author.

10 *E-mail address:* [j.l.paquette@opgc.univ-bpclermont.fr](mailto:j.l.paquette@opgc.univ-bpclermont.fr)

11  
12 Abstract

13 It has been demonstrated for several years that the U-Pb zircon system can provide  
14 useful dating information for understanding the time-evolution of the volcanic systems. In  
15 addition, in situ techniques were successfully used for determining the formation age of  
16 young Pliocene and Pleistocene volcanic rocks and to record the spatial and temporal  
17 distribution and the lifetime evolution of the magma chambers, generally in the case of large  
18 volcanic domains.

19 Here we show that it is possible to obtain a precision at the percent level on zircon  
20 from a short-size and late volcanic event from the Sancy stratovolcano (French Massif  
21 Central). LA-ICP-MS dating of Pleistocene magmatic zircons allow to distinguish the  
22 timescale of these late magmatic events within the complex volcanic activity of this large  
23 stratovolcano. A syenite xenolith enclosed into a trachyte pumice flow were dated at  $277.6 \pm$   
24  $3.2$  ka and  $260.1 \pm 3.6$  ka, respectively, whereas an earlier trachyandesite dome was emplaced  
25 at  $284.4 \pm 4.2$  ka. These different ages allow to propose a minimum evolution time of about

26 24 ± 8 kyrs for a differentiated magma chamber, which corresponds to a short lifetime  
27 associated with low magma volumes. The duration of this discrete volcanic event should be  
28 compared to the hundreds of thousands of years reported for the large volcanic systems.  
29 Interestingly, the zircon crystals from the pumices were embedded into a thin layer of glass of  
30 trachytic composition, demonstrating that these zircons crystallized into the melt only a short  
31 time before eruption.

32

33 Keywords: U-Pb zircon geochronology; LA-ICP-MS dating; Sancy Massif; French Massif  
34 Central; Pleistocene volcanism; ignimbrites.

35

36 1 - Introduction

37

38 Analytical improvements along more than four decades makes U-Pb zircon dating by  
39 CA-ID-TIMS a very high precision geochronological technique illustrated by analytical  
40 uncertainties better than 0.05 % of the age (Schmitz and Kuiper, 2013; Schoene et al., 2013;  
41 Schaltegger et al., 2015). The numerous analysed single zircons allowed to decipher the  
42 evolution of magma chambers and plutons construction in many intrusive complexes (e.g.  
43 Matzel et al., 2006; Miller et al., 2007; Michel et al., 2008; Schaltegger et al., 2009; Leuthold  
44 et al., 2012; Schoene et al., 2012; Wotzlaw et al., 2012; Barboni et al., 2013; Zeh et al., 2015).  
45 Such small age uncertainties cannot be achieved by in situ techniques because matrix  
46 matching standardization cannot challenge isotope dilution in terms of analytical precision.  
47 Consequently, the best levels obtained by high spatial resolution analyses by SIMS or LA-  
48 ICP-MS remains close to 1-2% of the age (Nemchin et al., 2013). Nevertheless, such a  
49 precision can be maintained up to very young mineral ages, lower than 1 Ma, by increasing  
50 the radiogenic Pb vs. common Pb ratio to preserve concordant analytical points. When zircon

51 crystals containing common Pb-enriched inclusions are discarded, then common Pb mostly  
52 corresponds to the blank level of the analytical system, itself composed of many parameters  
53 such as epoxy resin, gasses, nylon and metal tubes, mass flow controllers, plastic connectors,  
54 ablation cell, introduction device, etc. This can be achieved by simply enlarging the spot-size  
55 which automatically raises the signal level of radiogenic Pb and allows a precise measurement  
56 of the  $^{238}\text{U}/^{206}\text{Pb}$  ratio. The ability of LA-ICP-MS or SIMS to date very young zircons was  
57 already demonstrated in several recent studies (e.g. Brown and Fletcher, 1999; Dalrymple et  
58 al., 1999; Bacon et al., 2000; Reid and Coath, 2000; Sano et al., 2002; Schmitt et al., 2003;  
59 Brown and Smith, 2004; Bachmann et al., 2007; Wilson et al., 2008; Simon et al., 2009;  
60 Storm et al., 2011; Shane et al., 2012; Guillong et al., 2014; Ito, 2014; Ickert et al., 2015;  
61 Sakata et al., 2017). Obtaining a decent precision for Pleistocene zircon crystals is not a target  
62 itself, but such an analytical age uncertainty may be strongly significant compared to the  
63 timescale of magma chamber activity during volcanic events. Thus, given sufficient analytical  
64 precision, multiple pulses of magma input can be resolved. Indeed, a few percent of the age of  
65 so young zircon grains only corresponds to a few thousand years, which is a very short time at  
66 the geological scale, basically able to constraint the lifetime of a magma chamber. Here, we  
67 tested this concept on the youngest volcanic activity of the Sancy stratovolcano in Central  
68 France.

69

## 70 2 - Geological setting

71

72 The investigated area is part of the Mont-Dore massif, a 35 x 16 km (500 km<sup>2</sup>) and  
73 200 km<sup>3</sup> composite edifice formed by two stratovolcanoes (Baubron and Cantagrel, 1980;  
74 Nehlig et al., 2001). These stratovolcanoes belong to the French Massif Central Province, one  
75 of the volcanic provinces associated with the European Cenozoic Rift System. The European

76 Cenozoic Rift System results from widespread lithospheric extension in the Alpine foreland,  
77 following the formation of the Alps (Michon and Merle 2001, Michon et al. 2003). Large  
78 intraplate alkaline provinces (French Massif Central, Eifel, Vogelsberg, Eger graben...) are  
79 associated with the later stages of rifting. In the French Massif Central, most of the volcanism  
80 occurred in the last 14 Ma, with large stratovolcanoes active until about 250 ka (Cantagrel and  
81 Baubron 1983), and monogenetic edifices forming as late as 6,700 years BP (Juvigné and  
82 Miallier 2016). Alkaline magmas in the French Massif Central are associated with mantle  
83 upwelling, which triggered melting of asthenospheric and lithospheric sources previously  
84 metasomatized during the Variscan orogeny (e.g., Wilson and Downes 1991, Martin et al.  
85 2017).

86 To the north of the Mont-Dore massif, the Guéry stratovolcano represents the oldest  
87 volcanic center, dated between 3.85 and 1.47 Ma (Cantagrel and Baubron, 1983; Pastre and  
88 Cantagrel, 2001; Nomade et al., 2014). The activity of the younger Sancy stratovolcano (Fig.  
89 1) started 1.1 Ma ago and its products form the southern part of the Mont-Dore massif  
90 (Nomade et al., 2012, Cantagrel and Baubron, 1983). According to Cantagrel and Baubron  
91 (1983), the most recent eruptive activity of the Sancy stratovolcano is located in three areas  
92 near the center of the stratovolcano: the Puy de Clergues area, the Montagne de la Platte area  
93 and the Roc de Cuzeau area (Fig. 1). Existing K/Ar ages for the youngest lava flows and  
94 domes in these areas vary between 0.24 and 0.22 Ma with two sigma age uncertainties  
95 between 0.04 and 0.10 Ma (Cantagrel and Baubron, 1983). The most recent known  
96 pyroclastic unit is a distal Plinian deposit sampled in the Bouchet and Praclaux maars and  
97 dated by  $^{40}\text{Ar}/^{39}\text{Ar}$  at  $0.279 \pm 0.011$  Ma (Roger et al., 1999, as recalibrated by Nomade et al.,  
98 2012). Recent fieldwork in the Puy de Clergues area has revealed the existence of a  
99 previously unknown young pyroclastic unit and has highlighted discrepancies between the

100 volcanic stratigraphy observed in the field, and existing K/Ar ages, and was the incentive for  
101 the present study.

102 The field area includes the Roc de Cuzeau itself (1737 m a.s.l.), one of the main  
103 summits of the Sancy stratovolcano, and the area extending to the north down to the “Col de  
104 la Croix Saint Robert” pass (Fig. 1). Detailed field mapping has been combined with previous  
105 existing geological maps to provide an accurate map and stratigraphy of the field area  
106 (Francomme, 2014). At the bottom of the sequence, the Plateau de Durbise is formed by the  
107 superposition of three lava flows. The first flow is a 60 m thick heterogeneous trachytic  
108 coulee that originates from the Puy de Cliergues to the west (Latutrie et al., 2017), and is  
109 dated at  $0.32 \pm 0.06$  Ma (Lavina, 1985). It is overlaid by two basaltic trachyandesitic flows,  
110 each about 20-30 m thick, with the surface of the upper flow making the Plateau de Durbise.  
111 The Roc de Cuzeau itself ( $0.23 \pm 0.04$  Ma, Cantagrel and Baubron, 1983) is a trachyandesitic  
112 dome, possibly emplaced through the basaltic trachyandesitic flows.

113 A fourth basaltic trachyandesite flow crops out in the central part of the Durbise  
114 plateau. This blocky lava flow has very fresh features, including surface ogives and a steep  
115 flow front, and is dated at  $0.25 \pm 0.10$  Ma (Cantagrel and Baubron, 1983). It will be referred  
116 to as the “Upper Durbise Flow” in the following. Field observation and petrology suggest that  
117 it is correlated to another basaltic trachyandesitic outcrop on the eastern flank of Roc de  
118 Cuzeau and is stratigraphically on top of the Roc de Cuzeau dome (Francomme, 2014). This  
119 stratigraphy disagrees with existing K/Ar ages (Cantagrel and Baubron, 1983), but the two  
120 ages largely overlap within a one sigma error. The presence of a basaltic trachyandesite dyke  
121 crosscutting the Roc de Cuzeau dome near its south edge confirms that basaltic  
122 trachyandesites were emplaced after the dome.

123 Finally, a light-colored pyroclastic unit is visible in a 20 m long and 1 m high outcrop  
124 on the northeastern edge of the dome ( $45^{\circ} 33.040' N$ ,  $2^{\circ} 49.987' E$ , 1653 m a.s.l., Fig. 2). This

125 unit may have a higher extent but most of the area is covered with dense grass. This  
126 previously unknown pyroclastic unit is stratigraphically on top of the dome, and on top of the  
127 Upper Durbise Flow. It likely represents the product of the latest eruption in the Roc de  
128 Cuzeau area (and possibly the latest eruption of the Sancy stratovolcano). This deposit is  
129 composed of rounded pumices (5 to 30 cm diameter) and angular plutonic blocks (5 to 40 cm  
130 diameter) in an ash matrix and can be characterized as a pumice-and-ash flow. It will be  
131 referred thereafter as the “Cuzeau Pumice Flow”. Similar pumices and plutonic blocks have  
132 also been observed 1300 m to the south, on a ridge above the Valley de Chaudefour (Fig. 1),  
133 suggesting a larger extent for this unit.

134

### 135 3 - Analytical techniques

136

#### 137 3.1. U-Pb dating

138

139 Zircons were separated at the Laboratoire Magmas et Volcans (LMV) using standard  
140 techniques of crushing and sieving, followed by Wilfley table, magnetic separation and heavy  
141 liquids before handpicking under binocular microscope. They were mounted in epoxy disks  
142 (EPO-TEK<sup>®</sup> 301 from Epoxy Technology Inc.) and ground and polished at 0.25 $\mu$ m to expose  
143 crystal interiors. Cathodoluminescence (CL) and EDS imaging were conducted at LMV using  
144 a JEOL JSM-5910LV SEM. U-Th-Pb isotopic data on zircons were obtained by laser ablation  
145 inductively coupled plasma spectrometry (LA-ICP-MS) at the LMV (Clermont-Ferrand,  
146 France) and reported in Table 1. The analyses involved the ablation of minerals with a  
147 Resonetics M-50 laser system operating at a wavelength of 193 nm. Spot diameters of 73  $\mu$ m  
148 were associated to repetition rates of 3 Hz and fluency of 3.5 J/cm<sup>2</sup> resulting in a spot depth of  
149 12-15  $\mu$ m. This set up allows to significantly improve the signal intensity with a large spot-

150 size since the increase of the spot-size from 20  $\mu\text{m}$  to 73  $\mu\text{m}$  multiplies the signal intensity by  
151 a factor of ten, while laser-induced elemental fractionation effects are minimized by using low  
152 fluency and repetition rate. The ablated material was carried into helium and then mixed with  
153 nitrogen and argon before injection into the plasma source of a Thermo Element XR Sector  
154 Field high-resolution ICP-MS. The alignment of the instrument and mass calibration were  
155 performed before every analytical session using the NIST SRM 612 reference glass, by  
156 inspecting the signals of  $^{238}\text{U}$ ,  $^{232}\text{Th}$  and  $^{208}\text{Pb}$  and by minimising the  $\text{ThO}^+/\text{Th}^+$  ratio. The  
157 analytical method for isotope dating with laser ablation ICPMS (see Supplemental Data SD1  
158 for details) is basically similar to that reported in Hurai et al. (2010), Paquette et al. (2014)  
159 and Mullen et al. (2018). The  $^{235}\text{U}$  signal is calculated from  $^{238}\text{U}$  on the basis of the ratio  
160  $^{238}\text{U}/^{235}\text{U} = 137.818$  (Hiess et al., 2012). Single analyses consisted of 30 seconds of  
161 background integration with laser off followed by 1 minute integration with the laser firing  
162 and a 30 seconds delay to wash out the previous sample and prepare the next analysis.

163 Data are corrected for U-Pb fractionation occurring during laser sampling and for  
164 instrumental mass bias by standard bracketing with repeated measurements of GJ-1 zircon  
165 standards (Jackson et al., 2004). Repeated analyses of 91500 zircon reference material  
166 (Wiedenbeck et al., 1995) during each analytical session and treated as unknown,  
167 independently control the reproducibility and accuracy of the corrections. Data reduction was  
168 carried out with the software package GLITTER<sup>®</sup> from Macquarie Research Ltd (van  
169 Achterbergh et al., 2001; Jackson et al., 2004). Common Pb and initial disequilibria caused by  
170  $^{230}\text{Th}/^{238}\text{U}$  and  $^{231}\text{Pa}/^{235}\text{U}$  fractionation in the zircon/melt system were corrected according to  
171 Sakata et al. (2015) and Sakata (2018) method and related Microsoft Excel spreadsheet.  
172 Whole-rock Th and U contents and calculated  $\text{Th}/\text{U}_{\text{melt}}$  values of the studied samples (Table  
173 2) were determined following the technique described in Vlastelic et al. (2015). The  
174 concentrations in U-Th-Pb were calibrated relative to the certified contents of GJ-1 zircon



175 (Jackson et al., 2004) reference material. The available fractionation factor of Pa/U in a  
176 zircon-melt system of rhyolitic composition roughly shows agreement with a value of  $2.9 \pm$   
177 1.0 (Sakata, 2018). This value and related uncertainty is propagated into the calculations for  
178 the three samples. The isotopic ratios and ages together with all of the uncertainties were  
179 corrected from elemental and isotopic fractionation, common Pb contribution and Th/U  
180 disequilibria correction. Weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  ages and Concordia diagrams were  
181 generated using Isoplot/Ex v. 2.49 software package by Ludwig (2001).

182

### 183 3.2. Whole rocks major and trace element compositions

184

185 Whole rock major element compositions were obtained by Inductively Coupled Plasma  
186 Atomic Emission Spectroscopy (ICP – AES). Samples were fused using a  $\text{LiBO}_2$  flux and  
187 dissolved in  $\text{HNO}_3$ . Calibration was performed using reference materials GH (for Si, Na and  
188 K) and BR (for other elements), both from CRPG, Nancy, France (Centre de Recherches  
189 Petrographiques et Geochimiques), prepared in the same way as the unknown samples.

190 Whole-rock U and Th concentrations were obtained by Inductively Coupled Plasma Mass  
191 Spectrometry (Agilent Technologies ICP-MS 7500 Series) at LMV (see Vlastelic et al. 2015). The  
192 signal was calibrated against international standards BHVO-2 and BEN. The external  
193 reproducibility and the accuracy, estimated from repeated measurements of the standards, are  
194 lower than 10 %. The U and Th values obtained for the three investigated samples are shown in  
195 Table 2.

196

## 197 4 – Sample description and petrography

198

### 199 4.1. Roc de Cuzeau trachyandesitic dome (sample RC-03)

200

201           The Roc de Cuzeau dome is composed of a mesocratic to leucocratic trachyandesite, with  
202 a porphytic microlitic texture. Large (up to 5 cm) sanidine megacrysts and amphibole,  
203 clinopyroxene and plagioclase phenocrysts are set in a groundmass that also contains biotite,  
204 magnetite, apatite and zircons. At the outcrop scale, the trachyandesite is heterogeneous, and  
205 contains numerous quenched mafic enclaves, indicative of magma mixing, which is a widespread  
206 phenomenon in the eruptive history of the Sancy stratovolcano (Gourgaud and Maury, 1984).  
207 Evidence of magma mixing is also present at the thin section scale, including partial resorption of  
208 the sanidine megacrysts which have rounded edges. The selected sample comes from the Western  
209 end of the Roc de Cuzeau (45° 32.972' N, 2° 49.730 E, 1725 m a.s.l.), and is the one that shows  
210 the least evidence of magma mixing.

211

#### 212 4.2. Juvenile pumices from the Cuzeau Pumice Flow pyroclastic unit (sample RC-09a)

213

214           Juvenile pumices have a hyaline porphyritic texture, with phenocrysts of biotite, green  
215 clinopyroxenes, sanidine, plagioclase, and minor apatite, zircon and magnetite in a glassy  
216 matrix (Fig. 3a). Most phenocrysts are euhedral and unzoned, although inclusion of rounded  
217 plagioclase crystals in sanidine phenocrysts may be indicative of some amount of magma  
218 mixing.

219

#### 220 4.3. Syenite xenolith from the Cuzeau Pumice Flow (sample RC-09b1)

221

222           Numerous angular syenitic fragments are present in the pumice deposit. Their size  
223 vary from a few cm to about 40 cm. The representative sample investigated here is a quartz-  
224 syenite with a holocrystalline granular texture. Mafic and accessory minerals (clinopyroxene,  
225 amphibole, magnetite, titanite, biotite, apatite, zircon) are mostly grouped in clusters (~9 % of  
226 the sample, Fig. 3b), surrounded by mm-sized crystals of sanidine (~56 %) and plagioclase

227 (~27 %). A small number of interstitial quartz crystals (~8 %) are present around mafic  
228 mineral clusters.

229

## 230 5. LA-ICP-MS zircon dating

231

232 The zircon crystals from RC-09b1 syenite and RC-03 trachyandesite are large,  
233 medium elongated, colourless and display a continuous euhedral growth (Fig. 4a). The large  
234 size and their apparent textural consistency all along the growth of the zircon crystals confirm  
235 that using large spot-size is a valuable strategy in this case. Cathodo-luminescence images are  
236 poorly contrasted and display a fine oscillatory zoning (Fig. 4a) with some dark melt  
237 inclusions, mostly sub-spherical blobs. In few grains from the syenite, dark centre domains  
238 are evidenced that can be interpreted as a U and Th-enriched early growth phase. In the  
239 syenite, most Th and U content are ranging from 200 to 400 ppm with maximum values of  
240 2800 and 1600 ppm respectively. In the trachyandesite, Th and U content are lower, generally  
241 ranging from 100 to 300 ppm. In the three dated samples, Th/U ratios yield constant  
242 magmatic values of  $1.1 \pm 0.2$ . In the RC-09a trachyte pumice, the zircon morphology looks  
243 similar than in the two other samples, nevertheless under binocular microscope the crystals  
244 appear less translucent, milkier with an irregular surface. In cathodo-luminescence (Fig. 4b),  
245 oscillatory and sector zoning are combined. The same zircon grain imaged in backscattered  
246 electrons mode (Fig. 4c) clearly shows that the light grey crystal faces are embedded by an  
247 irregular darker phase. We performed EDS chemical mapping of both phases (Fig. 4h).  
248 Unsurprisingly, the zircon crystal in the middle is enriched in Zr, Hf and Si (Fig. 4d and 4e).  
249 The irregular overgrowth obviously contains more silica than zircon (Fig. 4e), as well as  
250 significant amounts of Al, K and Na (Fig. 4f and 4g), which approximately corresponds to the  
251 composition of the melt. This demonstrates that the zircons were already crystallized into the

252 liquid and, at the vicinity of the eruption time, this latter quenched rapidly and irregularly at  
253 the zircon surface producing this trachyte glass mantle. Similar features have already been  
254 reported in volcanic zircons (Miller and Wooden, 2004; McCormack, 2009; Schmitt et al.,  
255 2011).

256 The analytical results are reported in the Table 1. 59 spots were performed on the  
257 zircon grains from the RC-09b1 syenite and 56 common Pb and Th/U disequilibria-corrected  
258 zircon analyses yield a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  concordant age of  $277.6 \pm 3.2$  ka (Fig. 5a).  
259 This age is interpreted as the crystallization age of the zircons in the magma chamber. In the  
260 RC-03 trachyandesite, 41 spots were performed on individual zircons and 25 analyses yield a  
261 weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  concordant age of  $284.4 \pm 4.2$  ka (Fig. 5b) taking into account the  
262 common Pb and Th/U disequilibria correction. This age, equivalent within error limits to the  
263 former one, is also interpreted as the crystallization age of the zircons. Analytical points of the  
264 trachyandesite are often more discordant than those of the syenite owing to their lower U  
265 content, producing lower radiogenic Pb content. Consequently, this low radiogenic Pb vs.  
266 common Pb ratio moves the points toward the common Pb upper intercept and increase the  
267 correction, discarding some points from the age calculation. For the RC-09a trachyte pumice,  
268 32 analyses on 37 zircon spots yield a weighted mean  $^{206}\text{Pb}/^{238}\text{U}$  concordant age of  $260.1 \pm$   
269  $3.6$  ka (Fig. 5c), taking into account the common Pb and Th/U disequilibria correction. Owing  
270 to the peculiar character of the zircon morphology developed in the former paragraph, this age  
271 characterizes the crystallization of the zircon, which should be very close to the eruption time.  
272 In the three studied samples, no xenocrystic zircons and related inherited ages were  
273 evidenced. The lack of zircon xenocryst may reflect limited assimilation of the basement or  
274 resorption of zircon by Zr-undersaturated magma.

275

276 6. Discussion

277

278 6.1. *Dating the latest magmatic activity of the Sancy stratovolcano*

279

280 This new precise dating is well integrated to the rare dataset of geochronological  
281 informations about the final activity of the Sancy stratovolcano (Cantagrel and Baubron,  
282 1983; Lavina, 1985; Nomade et al., 2012; Pastre and Cantagrel, 2001). These new dates  
283 improve the precision on the ages of the latest eruptive activity by a factor of ten and resolve  
284 significant inconsistencies between field observation and the existing inaccurate age data.

285 The age of  $260.1 \pm 3.6$  ka for the Cuzeau Pumice Flow is significantly younger than  
286 existing ages for silicic pyroclastic activity from the Sancy stratovolcano. The latest  
287 pyroclastic cycle of the Sancy stratovolcano (phase III of Pastre and Cantagrel, 2001, cycle IV  
288 of Nomade et al., 2012) is characterized by trachytic products with phenocrysts of green  
289 clinopyroxene, biotite, two feldspars and titanite (Pastre and Cantagrel, 2001), very similar to  
290 the pyroclastic unit investigated here. There are only two recent accurate ages for this  
291 pyroclastic cycle, both obtained by  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of sanidine crystals:  $392 \pm 14$  ka for the  
292 Barbier unit (Nomade et al., 2012), and  $279 \pm 11$  ka for a distal Plinian deposit sampled in the  
293 Lac du Bouchet and Praclaux maars (Roger et al., 1999, as recalibrated by Nomade et al.,  
294 2012). Pastre and Cantagrel (2001), however, list a few poorly dated units around 0.3 Ma. The  
295 260.1 ka - old Cuzeau Pumice Flow is thus the youngest pyroclastic deposit of the Sancy  
296 stratovolcano and marks the end of the pyroclastic cycle IV of Nomade et al. (2012), which  
297 lasted at least 144 ka.

298 Field evidence (Francomme, 2014) indicates that the Cuzeau Pumice Flow is younger  
299 than the Upper Durbise Flow that was so far considered the youngest volcanic activity in this  
300 area (Cantagrel and Baubron, 1983). This lava flow is dated at  $0.25 \pm 0.10$  Ma by K/Ar  
301 (Cantagrel and Baubron, 1983). Due to the significant error on this value, the two ages of the

302 Cuzeau Pumice Flow and the Upper Durbise Flow largely overlap. According to our new  
303 results and taking into account their respective uncertainties, the Upper Durbise flow is  
304 younger than 288.6 ka (oldest possible age of the Cuzeau dome) and older than 256.5 ka  
305 (youngest possible age of the Cuzeau Pumice Flow), giving a more likely age of  $273 \pm 16$  ka.  
306 Other young mafic lava flows in the Sancy stratovolcano have been dated at  $0.24 \pm 0.06$  Ma  
307 (Puy de Clergues, Cantagrel and Baubron, 1983) and  $0.22 \pm 0.04$  Ma (Montagne de la Platte,  
308 Cantagrel in Lavina 1985), all within error of the ages of the Upper Durbise Flow. Those  
309 three mafic flows crop out on the upper slopes of the volcano, but the Upper Durbise flow has  
310 fresher morphologies than the two other flows. Given the fact that ages are indistinguishable  
311 within error, and that all three flows have similar chemistries, it is reasonable to assume that  
312 all three flows have almost the same age, and that the Upper Durbise Flow is slightly younger  
313 than the other two because of its fresher morphologies. This would indicate that silicic and  
314 mafic magmas were both emplaced near the end of the stratovolcano activity, and that activity  
315 ended around  $260.1 \pm 3.6$  ka, after a lifetime of about 950 ka for the Sancy stratovolcano.

316 The zircon age of  $284.4 \pm 4.2$  ka places an upper limit on the age of the Roc de  
317 Cuzeau dome emplacement. There is no constraint to establish if the zircon crystallization  
318 began significantly before the eruption. This age is older but in reasonable agreement with the  
319  $230 \pm 40$  Ma K/Ar age determined by Cantagrel in Lavina (1985). The new age of the Roc de  
320 Cuzeau dome is also within  $2\sigma$  error of the  $279 \pm 11$  ka age of the distal fall deposits reported  
321 from sedimentary sequences in the Bouchet and Praclaux maars (Roger et al., 1999). Given  
322 their age range and mineralogy, these tephra are very likely to originate from the Sancy  
323 stratovolcano but no proximal deposit of this age has been found so far. It is possible that  
324 these distal fall deposits correspond to an early Plinian magmatic phase of the Roc de Cuzeau  
325 system, before dome emplacement, whose proximal deposits are hidden by the dome and  
326 have not been sampled yet.

327

328 *6.2. Dating of the timescale of a small chamber producing discrete batches of magma.*

329

330 Magma storage timescale vary from  $10^2$  to  $10^6$  years in silicic systems due to the age,  
331 composition and structural characteristics of the host region (Brown and Smith, 2004;  
332 McCormack et al., 2009). Storage timescales can be constrained using the crystallization age  
333 of zircon and later crystallizing minerals. Complicated and discontinuous age spectra indicate  
334 phenocrysts, antecrysts and xenocrysts present in a single eruption (Charlier et al., 2005). It is  
335 assumed that this difference between zircon age spectra is the results of different geological  
336 conditions. The Roc de Cuzeau is a small-volume dome associated to pyroclastic units. It is  
337 characterized by a different temporal evolution of magmatic processes compared to large-  
338 volume silicic volcanic systems.

339 All the investigated samples plot in the general differentiation trend of the Sancy  
340 stratovolcano. The trachyandesitic lava of the Roc de Cuzeau dome is already differentiated  
341 (56.0 wt% SiO<sub>2</sub>, Mg# 36.4, Table 2). However, significant additional differentiation occurred  
342 between the trachyandesite and the trachytic pumice (61.4 wt% SiO<sub>2</sub>, Mg# 27.3, Table 2).  
343 The bulk composition of the syenite is difficult to interpret: it may have crystallized “en-  
344 masse” and its bulk composition is the composition of a liquid, but since it is coarse grained,  
345 melt extraction and/or crystal accumulation cannot be excluded. Its bulk composition is,  
346 however, close to the bulk composition of the trachytic pumice (62.9 wt% SiO<sub>2</sub>, Mg# 32.0,  
347 Table 2). It thus cannot be a cumulate counterpart to either the trachyandesite or the trachyte,  
348 and most likely represent a plutonic equivalent of the trachyte, possibly crystallized on the  
349 edges of the magma chamber after the dome-forming eruption. Similar compositions, close  
350 geographic association, and closely spaced ages strongly suggest all three samples belong to  
351 the same magmatic system.

352 Syenite xenoliths and the neighbouring trachyandesitic lava were dated at  $277.6 \pm 3.2$   
353 ka and  $284.4 \pm 4.2$  ka, respectively. Both magmatic events cannot be distinguished within  
354 uncertainties. A late trachytic pumice was emplaced at  $260.1 \pm 3.6$  ka. Considering the ages  
355 and related analytical precision obtained on the three different samples, the timescale of the  
356 magmatic activity is estimated at  $24 \pm 8$  ka, which is a minimum evolution time for a small  
357 magma chamber associated to a low volume of magma for this late volcanic event. Such a  
358 duration is obviously not related to an accumulation of large amounts of rhyolitic magmas  
359 over slightly longer timescales. Similar age within error limits for the syenite and the  
360 trachyandesite demonstrates a non-resolvable residence time of the zircon in the magma  
361 chamber between crystallization and eruption. Nevertheless, the syenite does not represent the  
362 cumulate counterpart of the synchronous trachyandesite. Consequently, this 24 ka duration  
363 should be considered as a minimum estimate because older rocks from this magmatic system  
364 may be present at depth. We do not observe any remobilization of xenocrystic zircon from the  
365 magma chamber and/or the volcanic and plutonic basement. No complex growth history of  
366 the zircon crystals characterized by the older cores-younger rims evolution frequently  
367 observed in the large volcanic systems was recorded here. The lack of any inherited zircon is  
368 in agreement with a lithospheric mantle source without significant crustal contamination  
369 (Briot, 1990).

370

## 371 7. Conclusion

372

373 We performed U-Pb zircon dating on one of the latest volcanic event from the Sancy  
374 stratovolcano located in the French Massif Central. Precise LA-ICP-MS dating of Pleistocene  
375 magmatic zircons was obtained with uncertainties of 3-4 ka and allow to clearly distinguish  
376 the evolution of these late magmatic events within the complex volcanic activity of this large



377 stratovolcano. Syenite xenoliths and the neighbouring trachytic lava were dated at  $277.6 \pm 3.2$   
378 ka and  $284.4 \pm 4.2$  ka, respectively, whereas a late trachyandesitic pumice was emplaced at  
379  $260.1 \pm 3.6$  ka.

380 Comparison between the ages of a series of trachyandesitic lava, trachytic pumice and  
381 cognate syenitic cumulates allows to determine a minimum evolution time of about  $24 \pm 8$  ka  
382 for a small magma chamber. It corresponds to the lifetime of a reduced magma chamber  
383 associated to a low volume of magma for this late volcanic event, which should be compared  
384 to the hundreds of thousands of years reported for large volcanic systems. These data also  
385 constrain the latest activity of the Sancy stratovolcano, one of the largest and youngest  
386 stratovolcano in the Western European Rift System, with the last eruptive phases around 250  
387 ka.

388

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590 Figure Captions:

591

592 Figure 1. Geographic extension of the deposits of the Sancy stratovolcano (redrawn after  
593 Brousse et al. 1989, 1990, Cantagrel and Baubron 1983, Nomade et al. 2017). The three  
594 youngest flow are drawn in grey: 1. Highest flow in the Puy de Clergues area dated at  $0.24 \pm$   
595  $0.06$  Ma (Cantagrel and Baubron, 1983); 2. Upper Durbise Flow dated at  $0.25 \pm 0.10$  Ma  
596 (Cantagrel and Baubron, 1983) or  $258 \pm 13$  ka (this study); 3. Cinder cone and flow of  
597 Montagne de la Platte dated at  $0.22 \pm 0.04$  Ma (Cantagrel in Lavina, 1985). An enlarged  
598 topographic map of the Durbise-Cuzeau area shows the location of the investigated samples  
599 (RC30 marks the second outcrop of the Cuzeau Pumice Flow) on the 10-m DEM of France  
600 (IGN).

601

602 Figure 2. Main outcrop of the Cuzeau Pumice Flow (outcrop RC-09, picture taken September  
603 2015).

604

605 Figure 3. (a, b) Texture and mineralogy of sample RC-09b1 (syenite xenolith) seen in plane-  
606 polarized light (a) and cross-polarized light (b). (c) Texture and mineralogy of sample RC-09a  
607 (trachytic pumice) seen in plane-polarized light.

608

609 Figure 4. Scanning Electron Microscope images of the zircon crystals. a) cathodo-  
610 luminescence (CL) image of a zircon crystal from the RC-09b1 syenite showing an oscillatory  
611 zoning and an U and Th-enriched dark inner domain. b) CL image of a zircon crystal from the  
612 RC09a trachyte pumice showing an oscillatory zoning and the laser spot. c) Backscattered  
613 (BSE) image of the former zircon crystal. An irregular dark grey rim covering the zircon  
614 crystal is evidenced with a thin white outline. d-e-f-g) Zr, Si, Al and K chemical maps of the

615 zircon crystal and its outer irregular rim obtained by energy dispersive X-ray spectroscopy  
616 (EDS). h) Cumulative chemical map showing a Zr-Si purple euhedral zircon crystal  
617 surrounded by a Si-Al-K orange rim of volcanic glass. The thin outline appears Al-enriched.

618

619 Figure 5. Concordia diagrams of the dated samples are plotted on the left column. Individual  
620 uncorrected analyses are represented by error ellipses and common Pb and U-Th disequilibria  
621 corrected weighted means are represented by red squares on the Concordia curve.  
622 Corresponding detailed diagrams of individual  $^{206}\text{Pb}/^{238}\text{U}$  corrected ages are represented on  
623 the right column.

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627 Tables content:

628

629 Table 1. Zircon U-Th-Pb data from the dated samples obtained by in *situ* Laser Ablation ICP-  
630 MS.

631

632 Table 2. Whole rock major elements and concentrations of U and Th in the investigated  
633 trachyandesite (RC-03), trachytic pumice (RC-09a) and syenite (RC-09b1) of the Sancy  
634 volcano.

635

636