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Jean-Louis Paquette, Etienne Médard, Justine Francomme, Patrick Bachèlery, Jean-Marc Hénot. LA-ICP-MS U/Pb zircon timescale constraints of the Pleistocene latest magmatic activity in the Sancy stratovolcano (French Massif Central). *Journal of Volcanology and Geothermal Research*, 2019, 374, pp.52-61. 10.1016/j.jvolgeores.2019.02.015 . hal-02057053

HAL Id: hal-02057053

<https://uca.hal.science/hal-02057053>

Submitted on 10 Dec 2019

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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).**

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Abstract

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

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

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

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

1 - Introduction

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

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

2 - Geological setting

The investigated area is part of the Mont-Dore massif, a 35 x 16 km (500 km²) and 200 km³ composite edifice formed by two stratovolcanoes (Baubron and Cantagrel, 1980; Nehlig et al., 2001). These stratovolcanoes belong to the French Massif Central Province, one of the volcanic provinces associated with the European Cenozoic Rift System. The European

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

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

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

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

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

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

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

3 - Analytical techniques

3.1. U-Pb dating

Zircons were separated at the Laboratoire Magmas et Volcans (LMV) using standard techniques of crushing and sieving, followed by Wilfley table, magnetic separation and heavy liquids before handpicking under binocular microscope. They were mounted in epoxy disks (EPO-TEK[®] 301 from Epoxy Technology Inc.) and ground and polished at 0.25μm to expose crystal interiors. Cathodoluminescence (CL) and EDS imaging were conducted at LMV using a JEOL JSM-5910LV SEM. U-Th-Pb isotopic data on zircons were obtained by laser ablation inductively coupled plasma spectrometry (LA-ICP-MS) at the LMV (Clermont-Ferrand, France) and reported in Table 1. The analyses involved the ablation of minerals with a Resonetics M-50 laser system operating at a wavelength of 193 nm. Spot diameters of 73 μm were associated to repetition rates of 3 Hz and fluency of 3.5 J/cm² resulting in a spot depth of 12-15 μm. This set up allows to significantly improve the signal intensity with a large spot-

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

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

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

3.2. Whole rocks major and trace element compositions

Whole rock major element compositions were obtained by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP – AES). Samples were fused using a LiBO_2 flux and dissolved in HNO_3 . Calibration was performed using reference materials GH (for Si, Na and K) and BR (for other elements), both from CRPG, Nancy, France (Centre de Recherches Petrographiques et Geochimiques), prepared in the same way as the unknown samples.

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

4 – Sample description and petrography

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

The Roc de Cuzeau dome is composed of a mesocratic to leucocratic trachyandesite, with a porphyritic microlitic texture. Large (up to 5 cm) sanidine megacrysts and amphibole, clinopyroxene and plagioclase phenocrysts are set in a groundmass that also contains biotite, magnetite, apatite and zircons. At the outcrop scale, the trachyandesite is heterogeneous, and contains numerous quenched mafic enclaves, indicative of magma mixing, which is a widespread phenomenon in the eruptive history of the Sancy stratovolcano (Gourgaud and Maury, 1984). Evidence of magma mixing is also present at the thin section scale, including partial resorption of the sanidine megacrysts which have rounded edges. The selected sample comes from the Western 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 the least evidence of magma mixing.

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

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

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

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

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

5. LA-ICP-MS zircon dating

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

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

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

6. Discussion

6.1. Dating the latest magmatic activity of the Sancy stratovolcano

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

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

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

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

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

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

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

All the investigated samples plot in the general differentiation trend of the Sancy stratovolcano. The trachyandesitic lava of the Roc de Cuzeau dome is already differentiated (56.0 wt% SiO₂, Mg# 36.4, Table 2). However, significant additional differentiation occurred between the trachyandesite and the trachytic pumice (61.4 wt% SiO₂, Mg# 27.3, Table 2). The bulk composition of the syenite is difficult to interpret: it may have crystallized “en-masse” and its bulk composition is the composition of a liquid, but since it is coarse grained, melt extraction and/or crystal accumulation cannot be excluded. Its bulk composition is, however, close to the bulk composition of the trachytic pumice (62.9 wt% SiO₂, Mg# 32.0, Table 2). It thus cannot be a cumulate counterpart to either the trachyandesite or the trachyte, and most likely represent a plutonic equivalent of the trachyte, possibly crystallized on the edges of the magma chamber after the dome-forming eruption. Similar compositions, close geographic association, and closely spaced ages strongly suggest all three samples belong to the same magmatic system.

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

7. Conclusion

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

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

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

Acknowledgments:

Claire Fonquernie is warmly thanked for her help with mineral separation, Pierre Boivin for processing the DEM and Shuhei Sakata from Gakushuin University Tokyo for kindly providing advices and spreadsheet for Th/U disequilibria calculation. Critical reviews by Rian B. Ickert and Gilles Chazot greatly improved this manuscript.

This research was financed by the French Government Laboratory of Excellence initiative n° ANR-10-LABX-0006, the Region Auvergne and the European Regional Development Fund. This is Laboratory of Excellence ClerVolc contribution number 332.

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Figure Captions:

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

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

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

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

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

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

Tables content:

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

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