

Precise dating of middle to late Villafranchian mammalian paleofaunae from the Upper Allier River valley (French Massif Central) using U–Pb geochronology on volcanic zircons

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1	Precise dating of Middle to Late Villafranchian mammalian paleofaunae
2	from the Upper Allier River Valley (French Massif Central)
3	using U-Pb geochronology on volcanic zircons.
4	
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12	Keywords: U-Pb geochronology; volcanic zircons; Villafranchian; mammals; paleofauna.
13	
14	Abstract
15	The French Massif Central represents one of the rare occurrences in Europe where lower
16	Pleistocene fossil deposits are associated to a substantial volcanic activity. Thanks to the abundance of
17	volcanic zircons in the differentiated products of the Monts-Dore / Guéry stratovolcano, we were able
18	for the first time to use U/Pb geochronology on zircon to precisely date lower Pleistocene fossil
19	deposits. Zircon, a weathering-proof heavy mineral, was dispersed over the landscape through Plinian
20	eruptions, and quickly reworked in fossil-bearing sedimentary deposits. Five Villafranchian fossil sites
21	in the Upper Allier River valley (French Massif Central) have been precisely dated: Chilhac
22	(MNQ17b, 2.285 \pm 0.046 Ma), Mont Coupet (2.274 \pm 0.032 Ma), Senèze (reference locality for

MNQ18, 2.100 \pm 0.029 Ma, confirming the previously determined 2.18-2.10 Ma ⁴⁰Ar/³⁹Ar ages), Blassac-La Girondie (MNQ19, 1.946 \pm 0.029 Ma), and Vazeilles (1.843 \pm 0.028 Ma). These new chronological data constrain the duration of the MNQ18 in central France to about 200 ka. The confirmation of an old age for the Blassac-La Girondie deposit indicates that the MNQ19 biozone started significantly earlier than previously thought.

28

29 **1. Introduction**

Recent evolution of megafaunae in Europe including human arrival is directly linked to ecological 30 31 and climate variations over the last few million years (e.g., Kahlke et al. 2011, Palombo 2014). The Villafranchian mammal age, defined from fossil deposits at Villafranca d'Asti, Italy (Pareto 1865, 32 Rook and Martínez-Navarro 2010) is a biochronological unit based on large mammal species that 33 covers the key period between 3.5 and 1.0 Ma during which the current European fauna was 34 established, including human migration to Europe, likely through the Caucasus region (e.g., Carbonell 35 et al. 2008, Lordkipanidze et al. 2013). Within the Villafranchian, faunal evolution is characterized by 36 the definition of lower level biozones, each transition between biozones being related to first 37 appearance (FAD) or last occurrence (LAD) of key species. The most commonly used 38 biochronological schemes for large European mammals in Europe are the Neogene and Ouaternary 39 Mammal zones (MNQ, Mein 1976; Guérin 1982; Guérin et al. 1990), and the Faunal Units (FU) 40 (Azzarolli 1977, Palombo and Sardella 2007). 41

Biozones are, however, a tool that can only provide relative chronology (biochronology). Absolute chronology constraints are required to tie the faunal evolution to climate variations and compare faunal evolution from different places. The precise timing and duration of Western European mammal biozones is thus still poorly understood, due to the limited number of precise absolute chronological constraints. In this paper, we use zircon crystals to precisely date a series of Early to Middle Villafranchian deposits (MNQ17 to MNQ19 mammal biozones) from the Upper Allier River valley in

central France. Zircon is a highly resistant, high-temperature mineral widely used to date magmatic 48 and metamorphic formations, including silicic volcanic deposits. Compared to other minerals used by 49 absolute geochronology techniques (feldspars, amphiboles, micas), zircon is preserved during 50 weathering of volcanic deposits and subsequent transport and is reworked within secondary 51 sedimentary deposits. Dating of volcanic zircons provide a minimum age for clastic sedimentary 52 deposits, however, if transport processes are fast (cf. Pastre, 1987), the age of the sedimentary deposit 53 will be within error of the age of the volcanic zircons. U/Pb dating of volcanic zircons is thus an 54 excellent tool for dating sedimentary fossil deposits, complementary to the more commonly used 55 40 Ar/ 39 Ar technique (e.g., Nomade et al. 2014b, 2016). 56

All the investigated Middle to Late Villafranchian faunae belong to the Gelasian age (2.588 to 57 1.806 Ma), the earliest part of the Pleistocene. In the French Massif Central, only three volcanic 58 provinces were active during that time, the Devès volcanic field, the Escandorgue volcanic field, and 59 the Mont-Dore / Guéry stratovolcano. The investigated sites are located on the northeastern edge of the 60 Devès volcanic field, formed by a series of Plio-Pleistocene, mostly basanitic, eruptions that produced 61 lava flows, strombolian scoria cones, phreatomagmatic maars and Surtseyan tuff-rings (Mergoil and 62 Boivin 1993). A significant number of eruptions were dated by K/Ar geochronology (see compilation 63 in Mergoil and Boivin 1993), and most of the current chronological constraints on the fossil sites 64 comes from relative chronology between the fossiliferous sediments and the basanitic flows. The 65 existing ages are however imprecise, with uncertainties of at least a few hundred thousand years. 66 While the Devès volcanic field (as well as Escandorgue) exclusively emitted mafic lava, highly 67 explosive, zircon-producing, silicic eruptions also occurred in the Mont-Dore / Guéry stratovolcano, 68 70 km to the northwest. 69

The Mont-Dore massif is a composite edifice formed by two stratovolcanoes (Baubron and Cantagrel, 1980; Nehlig et al., 2001), the Guéry and Sancy stratovolcanoes. The Guéry stratovolcano represents the oldest volcanic center, which emitted a large range of explosive volcanic products between 3.85 and 1.45 Ma (Cantagrel and Baubron, 1983; Pastre and Cantagrel, 2001; Nomade et al.,

2014a). The Sancy stratovolcano (1.1-0.25 Ma, Nomade et al. 2012) is younger than the deposits 74 investigated here. Given the short distance, and the highly explosive activity of the Mont-Dore / Guéry 75 stratovolcano, thin tephra layers likely blanketed the area during each Plinian eruption. Tephra-bearing 76 layers have been found in association with one of the investigated deposits, the Senèze fossil site, and 77 provided a precise age for the faunal association through ⁴⁰Ar/³⁹Ar geochronology on magmatic 78 feldspars (Nomade et al. 2014b). Pastre (1987) performed a detailed study of the repartition of heavy 79 minerals in sediments and slope deposits around the Allier river valley and concluded that heavy 80 minerals deposited by airfalls were quickly reworked into the sedimentary network. For example, 81 during the Fv alluvial cycle, heavy minerals in proximal pyroclastic deposits and in contemporary 82 fluvial sediments are identical, with mineral associations changing every few 10,000 years (Pastre 83 1987). Due to this fast turnover, by dating volcanic zircons within sedimentary or slope deposits, it is 84 possible to date the deposits themselves, with small age uncertainties. 85

86 All 40 Ar/ 39 Ar ages from the literature cited in this paper have been recalculated assuming an age of 87 1.1891 Ma for the ACs standard (Niespolo et al. 2017) and using the Renne et al. (2011) decay 88 constant, following the procedures described by Mercer et al. (2016). K/Ar ages were also corrected 89 according to the decay constants of Renne et al. (2011) although changes are within the uncertainties. 90 All uncertainties have been recalculated at the 2 σ level.

91

92 **2.** Villafranchian fossil deposits in the Upper Allier River valley

93 *2.1. Chilhac*

The Chilhac fossil sites are located NE of the village of Chilhac, in the Rabioulet valley, a small tributary of the Allier river. Fossils were first discovered in 1875 by de Morteuil (Boule 1892a, Bout 1960) in slope deposits, but the exact location of the discoveries (referred to as « Chilhac I ») is unknown. Two fossiliferous sites were later excavated, Chilhac II on the right bank of the stream, and Chilhac III on the left bank of the stream (Beden and Guth 1970a; Bœuf 1983). The at least 10 m thick 99 Chilhac II sediments are composed of non-bedded sandstones (containing angular basalt, quartz and 100 gneiss pebbles) and slightly bedded clay- and mica-rich layers. Their exact depositional environment is 101 still debated, and they have been interpreted as sediments from a slow-moving stream (Boivin et al., 102 2010), lacustrine sediments (Fouris et al. 1991), or lahar deposits (Pastre 1987). The Chilhac III 103 deposits are partly disordered and are interpreted as the product of a landslide event affecting the 104 Chilhac II sediments and overlaying pyroclastic and surface deposits (Boivin et al. 2010).

105



Figure 1. Simplified geological map of the investigated area, redrawn from BRGM 1/50 000 maps (Girod et al. 1979; Lasnier et al. 1981; Ledru et al. 1994; Marchand et al. 1986). The Paleozoic basement is partly covered by basanitic lava flows and pyroclasts belonging to the Devès volcanic field. Dashed circles are known maar structures, including the "Fressanges maar" (Vazeilles site, Séguy 1974) which was not known at the time the geological maps were drawn. Fossiliferous sites are contained within clastic sediments or slope deposits.

The two sites produced nearly identical fauna (Table 1, Beden and Guth 1970a, Boeuf 1983) belonging to the MNQ17b biozone (Bœuf 1983, Palombo and Valli 2004). This fauna is more evolved than the Saint-Vallier fauna (MNQ17a reference site, Saint-Vallier Faunal Unit, Guérin 1982, Guérin et al. 2004, Palombo and Valli 2004), and is probably equivalent to the Coste San Giacomo Faunal Unit of Italy (Palombo and Valli 2004, Bellucci et al. 2014). Possible archeological artefacts (choppers) were found in the Chilhac III deposit (Guth 1974, Guth and Chavaillon 1985), but have been later proven to be natural artefacts (Reynal et al. 1995).

The ages of the Chilhac deposits have never been precisely constrained. Based on the faunal association (biostratigraphy), Bœuf (1997) favors an age close to 2.2 Ma. Both sites are arguably younger than the 2.50 ± 0.12 Ma Pié des Varennes basanitic lava flow (K/Ar age from Couthures and Pastre 1983), although the contact between the flow and the deposits is not visible (Boeuf 1997, Boivin et al. 2010).

The Chilhac II site is surmounted by the Sognes basanitic lava flow (Boivin et al. 2010), in turn 126 covered by deposits from the Pié de Bouillergue scoria cone. K/Ar geochronology of the Sognes flow 127 by three different laboratories gives ages of 1.67 Ma (no error reported), 1.88 Ma (no error reported), 128 and 2.02 ± 0.60 Ma (compilation in Boeuf 1983). The age of 1.67 ± 0.10 Ma (Couthures and Pastre 129 1983) is further constrained by a reverse magnetic polarity (Prévôt 1975) that would place it after the 130 Olduvai subchron (i.e. younger than 1.780 Ma, Cohen and Gibbard 2019). More recently, a 131 centimetric, possibly reworked, trachytic tephra layer intercalated within scoria deposits from the Pié 132 de Bouillergue scoria cone, about 10 m above the top of the Chilhac fossil deposits, has been dated by 133 40 Ar/ 39 Ar at 2.34 ± 0.08 Ma (Nomade et al. 2014b). According to this age, the fossil deposits would be 134 older than proposed by Boeuf (1997), between 2.50 and 2.34 Ma. We sampled sediments from the 135 fossiliferous levels of Chilhac II (sample CH2 coming from the Chilhac IIb dig, Table 2) and Chilhac 136 III (sample CH3), as well as the trachytic tephra layer previously dated by Nomade et al. (2014b) 137 (sample CHR). 138

•	•	•					
			U	C	S	В	>
			•	٠	•	٠	•
Proboscidea	Mastodontidae	Anancus arvernensis	х	Х			
	Elephantidae	Mammuthus meridionalis	х	Х	Х	Х	Х
Perrisodactyla	Rhinocerotidae	Stephanorhinus etruscus	х	Х	х	Х	Х
	Equidae	Equus senezensis			Х	Х	
		Equus stenonis guthi	х	Х	Х		
		Equus bressanus (Equus major)		Х	Х	Х	
		Equus stehlini		2	Х		
	Tapiridae	Tapirus arvernensis		?			
Artiodactyla	Cervidae	Libraices gallicus			Х		
		Metacervoceros rhenanus philisi	Х	Х	Х		
		Metacervocerosrhenanus perolensis				Х	
		Croizetoceros ramosus	х	Х	Х		
		Eucladoceros ctenoides	х	Х	Х		
		Eucladoceros tetraceros				х	х
		Alces cf carnutorum				Х	
	Bovidae	Gallogoral meneghinii	х		х		
		Gazellospira torticornis	х	х	х		
		, Hemitragus orientalis			х		
		Leptobos etruscus		х	х	х	?
		Leptobos furtivus			х		?
		Pliotragus ardeus			х		
		Megalovis latifrons			х		
		Procamptoceras brivatense			х		
		Eobison			х		
	Suidae	Sus strozii		?	х		
Carnivora	Hyenidae	Pliocrocuta perrieri	х		х	Х	
		Chasmaporthetes lunensis			х		
	Ursidae	Ursus etruscus			х	х	
		Ursus minimus	Х				
	Canidae	Canis arnensis			х		
		Canis etruscus			х	х	
		Nyctereutes megamastoides	x		х		
		Vulpes alopecoides			х		
	Felidae	Homotherium crenatidens	х	х	х		
		Acinonyx pardinencis			х		
		Megantereon cultridens	х		x	х	
		Felis sp.				х	
Primates	Cercopithecidae	Macaca sylvanus (florentinus)			х		
		Paradolichopithecus arvernensis	1		x		

Table 1. Comparative list of large mammals described in the five investigated fossil deposits. The Chilhac list is reproduced from the compilation of Boivin et al. (2010), the Coupet list from Heintz (1974), the Senèze list from the work of Delson et al. (2006), the Blassac list from Beden and Guth (1970b) and Boeuf et al. (1992), and the Vazeilles list from Séguy (1974).

145 2.2. Mont Coupet

The Mont Coupet is a monogenetic volcano belonging to the Devès volcanic field. An initial phreatomagmatic phase grades into a typical Strombolian scoria cone (Bout 1960). On the northern side, a basanitic lava flow emerges at the base of the scoria cone. On the southern flank of the volcano, weathered volcanic scoria forms a slope deposit up to 10-12 m thick (Dorlhac 1854, Bout 1960). This slope deposit contains bones and bone fragments (Dorlhac 1854). A basanitic lava flow originating from the neighboring Mont Briançon covers the lower part of the slope deposits (Bout 1970).

The Mont Coupet fossil deposit was discovered in 1849 (Aymard 1855). The fauna (Dorlhac 153 1854, Boule 1892a, Depéret et al. 1923, Heintz et al. 1974, Table 1) is very similar to the Chilhac 154 fauna and belongs to the MNQ17b biozone (Palombo and Valli 2004).

The lava flow associated with the scoria cone has been dated by K/Ar at 2.14 ± 0.18 Ma (Fouris et al. 1991), providing an approximate upper limit for the age of the slope deposit. Bout (1970) reports a 1.9-1.8 Ma age for a lava flow from the neighboring Mont Briançon that covers the fossiliferous slope deposits. We directly sampled the fossiliferous slope deposits (sample COU) to provide stronger constraints on the age of this fossil site.

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161 2.3. Senèze

The Senèze maar is a 500 m diameter phreatomagmatic crater belonging to the Devès volcanic field. The crater was later filled by at least 123 m of lacustrine sediments comprising a lower layer of sands (at least 43 m) and an upper layer of clays (Ehlai 1969, Roger et al. 2000). The upper sedimentary layers are intercalated with and covered by slope deposits (Pastre et al. 2015).

166 The Senèze fossil deposits (Boule 1892b, Schaub 1943, Delson et al. 2006) are the reference 167 locality for the MNQ18 biozone (Guérin 1982, 1990, 2007). The rich mammalian paleofauna was 168 collected in the upper part of the lacustrine deposits and the associated slope deposits (Pastre et al.

169

2015).

The Lasnier basanitic flow, dated by K/Ar at 2.3 \pm 0.3 Ma (Prévot 1975) or 2.55 \pm 0.12 Ma 170 (Couthures and Pastre 1983), is closely associated with the maar but does not fill it, placing an upper 171 limit on the age of the phreatomagmatic eruption. A core drilled in the lacustrine sediments contained 172 a 5 cm thick tephra layer at a depth of 20.75 m that has been dated by 40 Ar/ 39 Ar at 2.11 ± 0.02 Ma 173 (Roger et al. 2000). Paleomagnetic data indicates that this tephra layer was deposited during the 174 normal Réunion subchron, and since the 19 m upper part of the core show reverse polarity, it is 175 younger than the end of the Réunion subchron at 2.116 Ma (Cohen and Gibbard 2019). This core is 176 177 unfortunately disconnected from the fossil-bearing layers, but the fossil deposits are assumed to be the lateral equivalent of the upper part of the core, i.e. they would be younger than 2.11 Ma (Pastre et al. 178 2015). During the latest excavations of the slope deposits, Pastre et al. (2015) identified several layers 179 enriched in volcanic minerals and closely associated with the fossil deposits. In one trench, a layer 180 located a few decimeters below the main fossiliferous bed (sample SEN1) inside interstratified 181 lacustrine and slope deposits was dated by ${}^{40}\text{Ar}/{}^{39}\text{Ar}$ at 2.104 \pm 0.050 Ma (Nomade et al. 2014b). A 182 short normal polarity anomaly, likely corresponding to the Réunion subchron, has been found just 183 above the dated layer (Sen in Nomade et al. 2014b), further supporting an age younger than 2.116 Ma 184 for the fossil deposit. In another of the recently excavated sites, fossiliferous lacustrine sediments were 185 framed by two layers, below (SEN98) and above (SEN101), dated at 2.176 \pm 0.032 Ma and 2.132 \pm 186 0.042 Ma, respectively (Nomade et al. 2014b). These ages are slightly older, but still consistent within 187 error with the fossiliferous level of the first trench. Two other slope deposits disconnected from the 188 fossiliferous layers were dated at 2.065 ± 0.020 Ma and 2.144 ± 0.044 Ma (Nomade et al., 2014b). We 189 sampled fossiliferous slope deposits on the edge of the crater (sample SEN), to put additional 190 constraints on the youngest possible age of the fossil deposits. The sample comes from a series of 191 alternating clays and sandy levels with centimetric pebbles, located less than 10 m from an outcrop of 192 193 granitic basement.

195 2.4. Blassac-La Girondie

The sedimentary sequence at Blassac-La Girondie crops out along the D585 road. It comprises 196 pebble-rich deposits interpreted as a lacustrine delta (Bout 1960), surmounted by approximately 1.5-197 2.0 m of micaceous sands, in turn covered by 0.5-1.3 m of phreatomagmatic pyroclastic deposits, and a 198 40 m thick basanitic lava flow associated with the Pié Rouge scoria cone. Fossils were discovered at 199 Blassac-La Girondie in 1965 (Beden and Guth 1970b) at the base of the micaceous sand layer. These 200 fossiliferous sands are mostly of granitic origin (quartz-feldspar-biotite-muscovite), but are also 201 enriched in volcanic minerals, including green clinopyroxene, titanite, magnetite and zircon (Pastre 202 203 1987).

The Blassac fauna (Beden and Guth 1970b, Guth 1975) is younger than the MNQ18 fauna of 204 Senèze and has been correlated with the MNQ19 fauna of Peyrolles, based on the presence of Cervidae 205 remains similar to Metacervoceros perolensis (Beden and Guth 1970b, Heintz et al. 1974, Palombo 206 207 and Valli 2004). This interpretation was later challenged by the attribution of the remains to another species, Metacervoceros rhenanus (Bœuf et al. 1992). Metacervoceros perolensis and Metacervoceros 208 rhenanus might actually belong to the same species (de Vos et al. 1995). A cluster analysis performed 209 by Palombo et al. (2006) indicates a very strong similarity between the Blassac-La Girondie and 210 Peyrolles fauna. Other evidence for Blassac-La Girondie belonging to MNQ19 includes the association 211 of Stephanorhinus etruscus and Eucladoceros tetraceros. 212

The basanitic flow overlying the fossil deposit has been dated by K/Ar at 2.06 ± 0.10 Ma (Couthures and Pastre 1983) and 2.14 ± 0.12 Ma (Fouris et al. 1991), placing a lower limit on the age of the Blassac-La Girondie fauna. A paleomagnetic study of the same flow gives a normal polarity (Prévot 1975), suggesting it erupted during either the Olduvai subchron (1.925 to 1.728 Ma, Cohen and Gibbard 2019), or the Réunion subchron (2.137 to 2.116 Ma, Cohen and Gibbard 2019). There is an ongoing controversy between the geochronology data suggesting an old age, and the paleontological data suggesting a correlation with the MNQ19 Peyrolles fauna that is assumed to be much younger (1.449 \pm 0.024; Nomade et al. 2014b). We sampled zircons from the fossiliferous level (sample BLA) to get a more precise age for this deposit.

222

223 *2.5. Vazeilles*

The Vazeilles deposit (also called Vazeilles-Limandre or Fix-Saint-Geneys) was discovered during construction work on the N102 road between Brioude and Le Puy-en-Velay in 1974 (Séguy 1974). A sequence of lacustrine sediments (Figure 2) fills the crater of a maar volcano ("Fressanges maar") belonging to the Devès volcanic province (Séguy 1974; Fouris et al. 1991). The deposit is comprised mostly of layers of clay, silt, sand, gravel, and diatomite with a steep bedding plane (17 to 45-degree dip towards the west). At the top of the deposit, a clay layer is covered by a basanitic lava flow (Fouris et al. 1991).

Only a preliminary description of the paleofauna has been provided (Séguy, 1974): the sediments contained fossils of *Stephanorhinus etruscus*, a molar of *Mammuthus meridionalis*, a few bovidae bones (part of an astragalus and part of a tibia), and a molar from a large cervidae, possibly *Eucladoceros*.

The basanitic lava flow situated on top of the deposit has been dated by K/Ar at 1.31 ± 0.12 Ma (Fouris et al. 1991). The fossiliferous sediments have a normal magnetic polarity (Thouveny 1983), whereas the polarity around 1.31 Ma was reverse (Matuyama chron). The youngest possible age for the sediments thus corresponds to the Olduvai subchron (1.925 to 1.780 Ma). We sampled a layer of gravel near the site were most fossils were discovered (sample VAZ1, Figure 2), and another sample at the top of the sedimentary sequence (VAZ2), 1 m below the basanitic lava flow dated by Fouris et al. (1991).



Figure 2. Cross-section of the Vazeilles deposits along the N102 road, redrawn from Séguy (1974).

245

246 **3. U-Pb geochronology**

247 *3.1. Analytical technique*

Between 1 and 10 kg of sediments were collected at each site. The sediment samples were cleaned 248 and sieved, and zircons were separated from the 0.16-0.50 mm fraction by panning, magnetic 249 separation and density separation using heavy liquids before handpicking under a binocular 250 microscope. Zircons were then mounted in epoxy disks, ground, and polished with 0.25 µm diamond 251 grit to expose crystal interiors. U-Th-Pb isotopic data on zircons were obtained by laser ablation 252 inductively coupled plasma mass spectrometry (LA-ICP-MS) at LMV (Laboratoire Magmas & 253 Volcans, Clermont-Ferrand, France). The analyses involved ablation of minerals with a Resonetics M-254 50 laser system operating at a wavelength of 193 nm. Spot diameters of 60 µm, repetition rates of 3 Hz 255 and fluence of 3.0 J/cm² resulted in a spot depth of 12 um (details in Supplementary Table S1). The 256 ablated material was carried into helium and then mixed with nitrogen (Paquette et al., 2014) and 257 argon before injection into the plasma source of a Thermo Element XR Sector Field high-resolution 258 ICP-MS equipped with the jet interface pumping device. The alignment of the instrument and mass 259 calibration were performed before every analytical session using the NIST SRM 612 reference glass, 260 by inspecting the signals of 238 U, 232 Th and 208 Pb and by minimising the ThO⁺/Th⁺ ratio. The analytical 261 method for isotope dating with laser ablation ICP-MS is basically similar to that reported in Hurai et 262

al. (2010) and Paquette et al. (2019). The ²³⁵U signal is calculated from ²³⁸U based on the ratio $^{238}U/^{235}U = 137.818$ (Hiess et al., 2012). Single analyses consisted of 30 seconds of background integration with laser off followed by 60 seconds integration with the laser firing and a 30 seconds delay to wash out the previous sample and prepare the next analysis.

Data were corrected for U-Pb fractionation occurring during laser sampling and for instrumental mass bias by standard bracketing with repeated measurements of GJ-1 zircon primary standard (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).

Schärer (1984) demonstrated that most zircons are affected during their growth by deficits and excesses of both ²³⁰Th and ²³¹Pa relative to the initial Th/U secular equilibrium. In order to obtain accurate crystallization ages for young zircons (<10 Ma), it is necessary to correct for the effect of initial disequilibria caused by intermediate nuclides in the ²³⁸U and ²³⁵U decay series. Sakata et al. (2017) and Sakata (2018) propose a simplified correction model and a related Microsoft Excel spreadsheet based on the mathematical framework of Wendt and Carl (1985) using the following equations:

280
$${}^{206}\text{Pb}^{*/238}\text{U} = (e^{\lambda_{238} t} - 1) + \lambda_{238}/\lambda_{230} (f_{\text{Th/U}} - 1) (1 - e^{-\lambda_{230} t}) e^{\lambda_{238} t}$$

281
$${}^{207}\text{Pb}^{*/235}\text{U} = (e^{\lambda_{235} t} - 1) + \lambda_{235}/\lambda_{231} (f_{\text{Pa/U}} - 1) (1 - e^{-\lambda_{231} t}) e^{\lambda_{235} t}$$

The concentrations in U-Th-Pb are 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, Paquette et al., 2019). Owing to the lack of any available magmatic protolith for the zircon sources, an estimated Th/U_{melt} value of 4.0 (Paquette et al., 2019) was systematically considered in the calculations as well as 50% uncertainties for the resulting individual (Th/U_{zircon})/(Th/U_{melt}) ratios. The isotopic

288	ratios and 2σ level uncertainties were corrected from elemental and isotopic fractionation, as well as
289	Pa/U and Th/U disequilibria. A systematic external error is subsequently propagated by quadratic
290	addition of uncertainties on U and Th decay constants as well as of the variability of the primary
291	reference material used for corrections (GJ-1) and of the long term variability of the secondary
292	reference material (91500). According to Horstwood et al. (2016), this systematic external error is
293	added to the 2σ error associated to the weighted mean $^{206}Pb/^{238}U$ ages calculation. The Tera and
294	Wasserburg (1972) diagrams were generated using Isoplot/Ex v. 2.49 software package by Ludwig
295	(2001).

3.2. U-Pb zircon results

The investigated samples are either sediments or slope deposits, and zircons are reworked either from distal volcanic ash-falls, or from the local Variscan basement. Volcanic zircon crystals are light pink, most often euhedral and may contain undetermined translucent inclusions. Variscan grains are rather yellow with rounded shapes. The main analytical results are reported in Table 2.

302

303 <u>3.2.1. Chilhac fossil deposits</u>

For the Chilhac II sample, U and Th concentrations in the volcanic zircons are highly variable, from 58 to 1050 ppm and from 39 to 5511 ppm, respectively. Th/U ratios are mostly higher than 1 up to values about 5. Sixty spots were performed on the zircon grains including 39 spots in Pliocene volcanic crystals and 21 spots in basement grains. A set of 34 Th/U disequilibria-corrected analyses yields a weighted mean 206 Pb/ 238 U age of 2.285 ± 0.046 Ma (Fig. 3a), interpreted as the crystallization age of the zircons. Crystals from the basement range from Carboniferous to Neo-Proterozoic (Fig. 5) with one additional Neoarchean grain.

In the Chilhac III sample, U (59 to 886 ppm) and Th (55 to 3906 ppm) contents as well as Th/U 311 values (0.9 to 4.4) are broadly similar than in the previous Chilhac II sample. The fifty-four laser spots 312 were performed in 23 Pleistocene volcanic grains and 31 basement zircons. The volcanic zircons are 313 divided into two populations; the 17 younger ones yield a Th/U disequilibria-corrected mean 314 206 Pb/ 238 U age of 2.262 ± 0.057 Ma (Fig. 4b), whereas six other zircons give an older mean 206 Pb/ 238 U 315 age of 2.53 ± 0.10 Ma (Fig. 4b). Finally, the basement crystals provide the same age ranges than in 316 Chilhac II sample, from Carboniferous to Mesoarchean (Fig. 5a and b). The age of 2.26 Ma is 317 interpreted as the time of crystallization of the zircons in the magma chamber just preceding the 318 volcanic eruption. The age of 2.53 Ma could represent zircon grains related to an older unconstrained 319 event, or may also be the effect of data scatter resulting from U-decay induced damaged zircon crystal 320 parts. Even if this 2.53 Ma-old population mostly comprises low Th and U contents (<100 ppm), 321 additional dating of thermally and chemically annealed zircon crystals would be required to solve this 322 question (Von Quadt et al., 2014). 323

The upper trachytic airfall deposit contains only Neogene volcanic zircons for which the U (404 \pm 118 ppm) and Th contents (419 \pm 220 ppm), as well as the Th/U ratios (1.0 \pm 0.4) are more selfconsistent than in the two previous samples. Twenty-one of the twenty-three analysed laser spots yield a Th/U disequilibria-corrected mean ²⁰⁶Pb/²³⁸U age of 1.727 \pm 0.028 Ma (Fig. 4c). Interestingly, a single zircon crystal at 2.56 Ma is synchronous within uncertainties with the older volcanic population of the Chilhac III sample dated at 2.53 Ma.

330

331 <u>3.2.2. Mont Coupet slope deposits</u>

In the Mont Coupet sample, the variable U (43 to 991 ppm) and Th (33-2483 ppm) contents are comparable to that of the Chilhac II and III samples. Similarly, Th/U ratios (0.7 to 3.1) also display significantly high values. Thirty-nine of the forty-one spot analyses yield a Th/U disequilibriacorrected mean 206 Pb/ 238 U age of 2.274 ± 0.032 Ma (Fig. 3d), which is also, within uncertainties, consistent with the ages measured on Chilhac II and III zircons. No other zircon crystals were recovered in that sample.



339

338

Figure 3. U/Pb diagrams for the investigated zircons from Chilhac and Mont Coupet fossils deposits.
(a) and (b) are bulk sediments from the Chilhac deposits, (c) is the upper trachytic airfall located 10 m
above the Chilhac III deposit, and (d) are slope deposits from Mont Coupet.

343

344 <u>3.2.3. Senèze upper slope deposits</u>

In the Senèze sample, U (85-1103 ppm) and Th (71-2651 ppm) are still variable as well as Th/U ratios (0.7 to 2.7). Fifty-two spots were performed on Pleistocene volcanic zircons and yield a Th/U disequilibria-corrected mean 206 Pb/ 238 U age of 2.100 ± 0.029 Ma (Fig. 4a). Again, no basement zircons were recovered in that sample.

349

350 <u>3.2.4. Blassac-La Girondie sand</u>

In the Blassac-La Girondie zircon crystals, U (59-450 ppm) and Th (45-542 ppm) contents are lower than in the other samples and associated with rather constant Th/U (1.1 ± 0.4) values. Twentyfive of the twenty-nine spots performed on the Pleistocene volcanic zircons yield a Th/U disequilibriacorrected mean 206 Pb/ 238 U age of 1.946 \pm 0.029 Ma (Fig. 4b). Eight basement zircons consistent with the age range defined by the Chilhac samples (Fig. 5a and b) have been analysed.

356

357 <u>3.2.5. Vazeilles sediments</u>

In the zircon crystals from the Vazeilles fossiliferous sediments, the U (93-796 ppm) and Th (103-1808 ppm) contents are high and comparable to those of Chilhac and Le Coupet samples with varied igneous Th/U values (0.6-2.6). On the thirty-nine analyzed Pleistocene zircons, thirty-four grains yield a Th/U disequilibria-corrected mean 206 Pb/ 238 U age of 1.843 ± 0.028 Ma (Fig. 4c). The five older zircon crystals range between 320 Ma and 670 Ma.

In the Upper Level sample, the U (37-1077 ppm) and Th (51-2854) as well as Th/U ratios (0.7-2.6) display varied and high values, similarly to the former sample. A large group of 42 on 46 analyses yields a Th/U disequilibria-corrected mean 206 Pb/ 238 U age of 1.648 ± 0.025 Ma (Fig. 4d). The three remaining zircon grains recorded ages of 580, 610 and 640 Ma, respectively (Fig. 5a).



369

Figure 4. U/Pb diagrams for the investigated zircons from Senèze, Blassac-La Girondie and Vazeilles
fossils deposits.

372

373 <u>3.2.6. Older zircons from the Variscan basement</u>

Sixty-eight zircons from the Chilhac II and III, as well as Blassac-La Girondie and Vazeilles samples are derived from the crystalline basement of the French Massif Central (Figure 5) and were either associated with the Neogene volcanic zircons during the volcanic eruptions or have been incorporated as detrital grains by late sedimentary processes. About half of this population (Figure 5b) defines a sharp Cambro-Ordovician (~480 Ma) peak, whereas a subordinate Carboniferous peak most probably records the crystallization of Hercynian granites. The Cambro-Ordovician ages are typical of the protoliths of the Variscan Upper Gneiss Unit (e.g. Chelle-Michou et al., 2017), which constitutes the basement of the Chilhac area, and crops out upstream of the Blassac deposits, strongly suggesting that these zircons are detrital. An Ediacaran peak associated to the occurrence of Cryogenian and Archean grains is typical of the detrital zircon record related to the geodynamic evolution of the north Gondwana margin (e.g. Couzinié et al., 2019).

385

sample	Х	Y	Z	Age	2σ error
				(Ma)	(Ma)
CH 2(II)	45°09'33.3''N	3°26'37.2''Е	550 m	2.285	0.046
CH 3(III)	45°09'36.6''N	3°26'41.6''Е	585 m	2.262	0.057
CHR	45°09'43.3''N	3°26'45.5''Е	580 m	1.727	0.028
COU	45°07'12.7''N	3°32'39'8'' Е	615m	2.274	0.032
SEN	45°14'23.6''N	3°28'57.9''Е	630 m	2.100	0.029
BLA	45°10'41.2''N	3°24'08.1''E	490 m	1.946	0.029
VAZ1	45°07'38.8''N	3°41'34.9''Е	987 m	1.843	0.028
VAZ2	45°07'56.8''N	3°41'26.3''Е	1010m	1.648	0.025

386

Table 2. Sample location and U/Pb chronological data for the investigated fossil sites.

388

4. Discussion

4.1. Constraining the age of sedimentary and slope deposits with volcanic zircons

Since the investigated zircons are reworked from distal volcanic ash-falls, we should expect one or more zircon populations, with the youngest population providing a lower age for the sedimentary deposit. Proximal slope deposits (our samples from Mont Coupet and Senèze), indeed contain one single population of volcanic zircons with a well-constrained magmatic age (Figure 3d and 4a).



396

Figure 5. Older ages measured in pre-Cenozoic zircons from the fossiliferous sediments a) The Tera-Wasserburg plot represents the Proterozoic and Phanerozoic ages; the Concordia diagram in inset shows the Archean ages; b) Cumulative probability ages histogram plot.

397

Sediments sampling a large, active, river basin (Allier river sediments at Blassac-La Girondie) still contain a dominant zircon population with a single magmatic age, and a small proportion of older zircons (volcanic and from the basement). A more complicated history emerges from the Chilhac deposits, which were formed in a small drainage system that eroded a variety of metamorphic and volcanic deposits. The zircon population is, however, still characterized by a predominance of the younger population age. These results confirm the conclusions of Pastre (1987) that heavy minerals
deposited by airfalls are quickly reworked into the sedimentary network. Given this fast renewal, and a
likely near-continuous volcanic activity from the Mont-Dore / Guéry stratovolcano, the highly
dominant youngest zircon population in each sample provides an age very close to the deposition age
of the sediment.

412

413 *4.2. New age constraints on major fossil deposits in volcanic context*

414 <u>4.2.1.Chilhac fossil deposits</u>

Zircons from both fossiliferous layers have statistically identical ages of 2.285 \pm 0.046 Ma for 415 Chilhac II and 2.262 ± 0.057 Ma for Chilhac III, in agreement with the 2.2 Ma age proposed by Bœuf 416 (1997) based on the biochronological attribution to the MNO17b biozone. Although no proximal 417 pyroclastic layer has been precisely dated in the Mont-Dore / Guéry stratovolcano between 2.5 Ma 418 (debris avalanches and lahars of the Perrier Plateau) and 2.07 Ma (Guéry tephra, Nomade et al. 2014a), 419 relative chronology of trachytic pyroclastic deposits in the Vendeix stream and the Bouay waterfall 420 sections indicate ages close to 2.3 Ma (Pastre and Cantagrel, 2001). These 2.27 Ma old zircons are thus 421 interpreted as products of a Plinian eruption whose deposits are present but have not yet been precisely 422 dated in the central part of the stratovolcano. 423

For the Chilhac samples, the number of old zircons is high (21/60 for Chilhac II, 31/54 for Chilhac III), pointing to a significant sedimentary component from the metamorphic basement, in agreement with the abundance of quartz and micas in the sediments. The Chilhac III sample also contains a significant amount of reworked volcanic zircons crystals (2.53 Ma).

Nomade et al. (2014b) dated a trachytic tephra located stratigraphically above the Chilhac III deposits by Ar/Ar and obtained an age of 2.34 ± 0.08 Ma, which would thus be a minimum age for the deposit. However, zircon U/Pb ages for this deposit are significantly younger (1.727 \pm 0.028 Ma), suggesting that the feldspars dated by Ar/Ar might be xenocrysts older than the trachytic layer. This is

not uncommon and has been already described in the Monts-Dore for the «Grande Nappe» 432 pyroclastic unit (Nomade et al. 2017). Also, the presence of metamorphic garnet, a mineral not seen in 433 the proximal Mont-Dore deposits but widespread in the basement rocks of the Chilhac area might 434 suggest that this unit is not a pristine ash-fall deposit and has been reworked. Our new results date this 435 pyroclastic unit, and thus also the age of the Pié de Bouillergue scoria cone in which the layer is 436 intercalated at 1.727 ± 0.028 Ma. This age is consistent with the K/Ar (1.67 ± 0.10 Ma. Couthures et 437 Pastre 1983) and paleomagnetic (< 1.78 Ma, Prévôt 1975) age of the Sogne basanitic flow, and 438 precisely constrains the age of the Pié de Bouillergue volcanic eruption. Once again, there are no 439 known proximal pyroclastic deposits of that age in the Mont-Dore / Guéry stratovolcano, but no proof 440 of an activity gap at that time either. 441

The new ages of 2.285 ± 0.046 Ma and 2.262 ± 0.057 Ma, identical within error (average 2.27 Ma), are much more consistent with previous paleontological estimates (e.g., Bœuf et al. 1992) than the > 2.34 Ma age proposed by Nomade et al. (2014b). They are in excellent agreement with the age of the similar Coste San Giacomo fauna of Italy (estimated at 1.95-2.2 Ma by Bellucci et al. 2014), confirming the equivalence of the MNQ17b biozone and the Coste San Giacomo Faunal Unit.

447

448 <u>4.2.2. Mont Coupet slope deposits</u>

The fossil deposits at Mont Coupet contain zircons with the exact same age as the Chilhac fossil 449 sites, 2.274 ± 0.032 Ma. They were thus deposited during the same time period, a finding consistent 450 with the presence of a very similar paleofauna (Table 1). Heavy mineral contents in the Mont Coupet 451 slope deposits are dominated by kaersutitic amphibole, magnetite and titanite, a mineralogy identical 452 to that observed in the Chilhac samples, further supporting a common origin for the Plinian deposit 453 that was reworked at both sites (same eruption or clustered eruptions belonging to the same eruptive 454 phase). Our age is consistent with the 2.14 \pm 0.18 Ma age of a basanitic lava flow associated with the 455 Mount Coupet activity (Fouris et al., 1991), providing that the flow was emplaced during the older 456

2.32-2.24 part of the age bracket since the fossil-bearing slope deposits must be younger than the
volcanic activity. Together with Chilhac, Mont-Coupet is one of the last occurence of *Anancus arvernensis* (a forest-dwelling species), replaced by *Mammuthus meridionalis* (an open land species)
in younger sites. Global cooling and the advent of glacial cycles starting at about 2.5 Ma in Western
Europe (e.g., Shackleton et al., 1984, Kahlke et al., 2011) resulted in the progressive disappearance of
large forests, replaced by a more open landscape. The two biotopes still coexisted in the Chilhac and
Coupet area around 2.27 Ma.

464

465 <u>4.2.3. Senèze fossil deposits</u>

The upper slope deposit sampled in this study is dated at 2.100 ± 0.029 Ma, consistent with an age younger than 2.104 ± 0.050 Ma for some of the recent fossil finds (Nomade et al., 2014b). A second fossil layer dated between 2.176 ± 0.032 Ma and 2.132 ± 0.042 Ma by Nomade et al. (2014b), also provides consistent ages within errors. Whether these fossil layers were deposited at the same time, or indicate a longer duration for the deposition process, or two different faunae are present as suggested by Azzaoli et al. (1997), is beyond the scope of this study.

472

473 4.2.4. Blassac-La Girondie sand

The site of Blassac-La Girondie is the richest French fossil site of the MNQ19 period, and its age can put key constraints on the beginning of this biozone. Sediments collected inside the fossil deposit give an age of 1.946 ± 0.029 Ma, in agreement with previous rough estimates based on the local geology (Bœuf et al. 1992). This new data, however, favors an old age for the beginning of the MNQ19, which would start much earlier than the younger 1.47 Ma age proposed for the Peyrolles MNQ 19 reference fossil deposit (Nomade et al. 2014b). The sedimentary zircons could possibly be tied to pyroclastic deposits from the central part of the Guéry stratovolcano (La Morangie tephra, dated

- 481 at 1.92 ± 0.04 Ma by Féraud et al., 1990), however, a detailed correlation between distal sedimentary
- deposits and proximal units is beyond the scope of this study.
- 483



Figure 6: comparison of our new ages with existing ages for the Senèze and Chilhac deposits, European land mammal zones, paleomagnetic chrons, and oxygen isotope variations. U/Pb ages from this study, Ar/Ar ages from Nomade et al. (2014b) and Roger et al. (2000). Red circles are ages of fossiliferous sediments, white triangles ages of tephra-bearing layers above (down-pointing) or below (up-pointing) fossiliferous sediments, and squares for non-fossiliferous sediments or tephra-bearing layers disconnected from the fossil deposits.

484

492 <u>4.2.5. Vazeilles sediments</u>

The Vazeilles fossiliferous sediments, dated at 1.818 ± 0.028 Ma, are slightly younger than the Blassac-La Girondie deposit. This age is consistent with the normal polarity of the sediments (Olduvai subchron between 1.925 and 1.780 Ma, Thouveny 1983). Only preliminary paleontological investigations have been performed on this site (Séguy 1974), however, the new age places this site firmly within the MNQ19 biozone. Given the paucity of fossil sites belonging to this time period in central France, this poorly known site is thus of significant interest for the understanding of faunal evolution during the late Villafranchian and would be worth further investigation. The sedimentary sequence could also provide a record of at least 200 ka of geologic history since the top of the sequence has been dated around 1.648 ± 0.025 Ma.

502

503 *4.3. Age constraints on late Villafranchian mammal biozones*

504 <u>4.3.1. Duration of the MNQ18 biozone</u>

The new U-Pb zircon dating places further constraints on the age and duration of faunal biozones in Central France. The five investigated neighboring sites provide a ~500 ka record of land mammal evolution during the Middle Villafranchian (2.3-1.8 Ma), including significant faunal changes.

- The transition between biozones MNQ17b (latest site Chilhac III at 2.262 \pm 0.057 Ma) and MNQ18 (earliest possible age for the Senèze fossil deposits at 2.176 \pm 0.032 Ma, Nomade et al. 2014b) is precisely constrained at 2.22 \pm 0.09 Ma.
- The transition between biozones MNQ18 (latest fossiliferous level from Senèze at 2.100 ± 0.029
 Ma) and MNQ19 (Blassac-La Girondie at 1.946 ± 0.029 Ma) is precisely constrained at 2.02 ± 0.10
 Ma.

These two boundaries are consistent with paleomagnetic constraints from the MNQ18 faunae Fonelas P-1 and Puebla de Valverde from Spain (Sinusìa et al. 2004, Arribas et al. 2009), which were deposited during the inverse polarity period separating the Réunion and Olduvai normal subchrons, i.e. between 2.116 and 1.925 Ma. They would also be consistent with a possible equivalence between MNQ18 and the Olivola F.U. of Italy dated around 2.10 ± 0.05 Ma (Napoleone 2013), as suggested by Rook et al. (2010). The average duration of the MNQ18 biozone is 200 ka, with a maximum possible duration of 400ka, the maximum permissible time between the MNQ17b Chilhac III deposit (2.262 ± 0.057 Ma) and the MNQ19 Blassac-La Girondie deposit (1.946 ± 0.029 Ma).

523

524 <u>4.3.2. Age of the MNQ19 biozone</u>

Only a small number of fossil sites have been attributed to the MNO19 biozone in Central France. 525 Aside from the reference locality of Peyrolles (Heintz et al. 1974, Valli et al. 2006), the only sites are 526 Blassac-La Girondie and La Sartanette (Palombo and Valli 2004). The age of the Pevrolles deposit has 527 been estimated at 1.40 ± 0.20 Ma (Lo Bello 1988), and further refined at 1.449 ± 0.024 Ma (Nomade et 528 al. 2014b) based on indirect evidence from neighboring pyroclastic deposits. Paleomagnetism data 529 constrain the age of the sediments at La Sartanette to the Olduvai-Jaramillo inverse polarity interval 530 (Thouveny et al. 1984), i.e. between 1.78 and 1.07 Ma. A statistical study by Palombo et al. (2006) 531 confirms the similarity of the Peyrolles and Blassac-La Girondie fauna - La Sartanette was not 532 included in their analysis. 533

The 1.946 ± 0.028 Ma age of the Blassac-La Girondie site thus indicates that the MNQ19 biozone 534 started much earlier than previously thought and solves the mystery of the absence of paleontological 535 deposits in Central France between 2.1 and 1.5 Ma. However, existing ages for Blassac-la Girondie 536 and Peyrolles, would suggest a very long duration for the MNQ19 biozone of about 500 ka. This 537 period corresponds to at least two, possibly three Italian faunal units (Tasso F.U. dated around 1.7-1.8 538 Ma; Farneta F.U. dated around 1.6-1.7 Ma, and probably also Pirro F.U., Napoleone et al. 2013). This 539 time period is still poorly known in Central France, and further research is needed to understand 540 mammal evolution during the late Villafranchian. 541

- 542
- 543 *4.4. Implications for the tephrostratigraphy of the Mont-Dore stratovolcano*

The precise chronology of the Mont-Dore stratovolcano during the early Pleistocene is still poorly 544 constrained. Following the major destructive stage that produced a series of four debris avalanches or 545 debris flows (Bernard et al. 2009) at ~2.6 Ma (Cantagrel and Briot 1990, Nomade et al. 2014b), Pastre 546 and Cantagrel (2001) identified at least five major pyroclastic phases during their « middle trachytic 547 cycle » (G3 and G4 cycles of Nomade et al. 2014a). The sites investigated in this study provide an 548 excellent record of the distal tephrochronology of the Mont-Dore stratovolcano during that period and 549 show the existence of at least nine distal tephra deposits that were reworked in the fossiliferous 550 sediments $(2.53 \pm 0.10 \text{ Ma}; 2.274 \pm 0.032 \text{ Ma}; 2.176 \pm 0.032 \text{ Ma}; 2.144 \pm 0.044 \text{ Ma}; 2.100 \pm 0.029 \text{ Ma}; 2.100 \pm 0.0$ 551 Ma; 1.946 ± 0.029 Ma; 1.818 ± 0.028 Ma; 1.727 ± 0.025 Ma; 1.648 ± 0.025 Ma). This list of nine 552 different pyroclastic events capable of producing distal deposits ~70 km from the Guéry stratovolcano 553 is a conservative estimate since deposits with identical ages might represent different deposits with 554 ages separated by a time shorter than the analytical uncertainty of the U/Pb and ⁴⁰Ar/³⁹Ar dating 555 556 techniques. Four of these pyroclastic events were previously unknown (2.27 Ma; 1.82 Ma; 1.73 Ma; 1.65 Ma). The three youngest ages fall within the 1.9 to 1.5 Ma gap between the pyroclastic cycles III 557 and IV of Nomade et al. (2014a) and confirms the observations of Pastre and Cantagrel (2001) of a 558 rather continuous trachytic activity between 2.6 and 1.5 Ma. 559

560

561 **5. Conclusions**

Given the fast turnover of heavy mineral populations in sediments of the Upper Allier River basin, it is possible to precisely date fossil-bearing sedimentary deposits using U/Pb ages on volcanic zircons originating from Plinian activity of the neighboring Mont-Dore / Guéry stratovolcano. We obtained volcanic zircons ages covering the entire Early Pleistocene, from 2.6 to 1.4 Ma, included during a possible activity gap between pyroclastic cycles III and IV of Nomade et al. (2014a). This indicates that there was no long-duration break in volcanic activity during the history of the volcano.

Five paleontological deposits have been precisely dated using U/Pb dating on volcanic zircons. 568 The new data reconciles biochronological and absolute ages for the Chilhac II deposit (2.285 \pm 0.046 569 Ma) and a new precise age for Blassac-La Girondie (1.946 \pm 0.029 Ma) indicates that the MNQ19 570 biozone started earlier than previously thought. These new U-Pb zircon dates place absolute 571 constraints on the age and duration of the MNQ18 mammal biozone in Central France, and possibly by 572 extension in Western Europe. Since the differentiated volcanic activity in the Mont-Dore area lasted at 573 574 least from 3.85 to 0.25 Ma (Nomade et al. 2014a), further analyses can be used to provide an absolute geochronological framework for MNO mammal biozones defined in Central France. 575

576

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859 **Figure Captions:**

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Figure 1. Simplified geological map of the investigated area, redrawn from BRGM 1/50 000 maps (Girod et al. 1979; Lasnier et al. 1981; Ledru et al. 1994; Marchand et al. 1986). The Paleozoic basement is partly covered by basanitic lava flows and pyroclasts belonging to the Devès volcanic field. Dashed circles are known maar structures, including the "Fressanges maar" (Vazeilles site, Séguy 1974) which was not known at the time the geological maps were drawn. Fossiliferous sites are contained within clastic sediments or slope deposits.

868	Figure 2. Cross-section of the Vazeilles deposits along the N102 road, redrawn from Séguy (1974).
869	
870	Figure 3. U/Pb diagrams for the investigated zircons from Chilhac and Mont Coupet fossils deposits.
871	(a) and (b) are bulk sediments from the Chilhac deposits, (c) is the upper trachytic airfall located 10 m
872	above the Chilhac III deposit, and (d) are slope deposits from Mont Coupet.
873	
874	Figure 4. U/Pb diagrams for the investigated zircons from Senèze, Blassac-La Girondie and Vazeilles
875	fossils deposits.
876	
877	Figure 5. Older ages measured in pre-Cenozoic zircons from the fossiliferous sediments a) The Tera-
878	Wasserburg plot represents the Proterozoic and Phanerozoic ages; the Concordia diagram in inset
879	shows the Archean ages; b) Cumulative probability ages histogram plot.
880	
881	Figure 6: comparison of our new ages with existing ages for the Senèze and Chilhac deposits,
882	European land mammal zones, paleomagnetic chrons, and oxygen isotope variations. U/Pb ages from
883	this study, Ar/Ar ages from Nomade et al. (2014b) and Roger et al. (2000). Red circles are ages of
884	fossiliferous sediments, white triangles ages of tephra-bearing layers above (down-pointing) or below
885	(up-pointing) fossiliferous sediments, and squares for non-fossiliferous sediments or tephra-bearing
886	layers disconnected from the fossil deposits.
887	
000	Tables content:
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889	

890	Table 1. Comparative list of large mammals described in the five investigated fossil deposits. The
891	Chilhac list is reproduced from the compilation of Boivin et al. (2010), the Coupet list from Heintz
892	(1974), the Senèze list from the work of Delson et al. (2006), the Blassac list from Beden and Guth
893	(1970b) and Boeuf et al. (1992), and the Vazeilles list from Séguy (1974).
894	
895	Table 2. Sample location and U/Pb chronological data for the investigated fossil sites.
896	
897	Table 3. Zircon U-Th-Pb data from the dated samples obtained by in situ Laser-Ablation-ICP-MS.
898	
899 900	Supplementary Table S1: LA-ICP-MS U-Th-Pb dating methodology
901	