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Jean-Louis Paquette, Michel de Saint Blanquat, Guillaume Delpech, Eric Horsman, Abdelmouhcine Gannoun, et al.. Timescales of pluton assembly and growth history of Colorado Plateau lithosphere: geochronology (U-Pb, K-Ar and Ar-Ar) and zircon Hf isotopic study of the. 2024. <insu-04798407>

HAL Id: insu-04798407

<https://insu.hal.science/insu-04798407v1>

Preprint submitted on 22 Nov 2024

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1 **Timescales of pluton assembly and growth history of** 2 **Colorado Plateau lithosphere: geochronology (U-Pb,** 3 **K-Ar and Ar-Ar) and zircon Hf isotopic study of the** 4 **Mount Hillers intrusive center (Henry Mts, Utah,** 5 **USA)**

6
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22 **Highlights**

- 23 - The age of the Mount Hillers Intrusive Center (MHIC) is 25.97 ± 0.11 Ma
- 24 - U-Pb data document an emplacement duration between 220 and 640 kyrs for the MHIC
- 25 - The averaged magmatic flux is estimated between 0.5 and $1.6 \cdot 10^{-4}$ km³/yr
- 26 - Zircon cores show a 1.75-1.6 Ga juvenile signature reworked by a 1.5-1.35 Ga event
- 27 - Zircons from the MHIC diorites document a magmatic legacy spanning 1.5 billion years

28 **Keywords**

29 Henry Mountains
30 Pluton emplacement

31 Proterozoic Colorado Plateau lithosphere

32 Zircon

33 U-Pb and Lu-Hf isotopes

34 Ar-Ar and K-Ar dating

35 **Abstract**

36 We studied the age, history of emplacement, and source of the Mount Hillers intrusive
37 center (MHIC, Henry Mountains, Colorado Plateau), with in-situ U-Pb and Lu-Hf isotopic
38 analysis on the same zircon grains. Inherited cores in all analyzed zircon grains, allowing us
39 to document the Proterozoic history of the Colorado Plateau lithosphere. In addition, K-Ar
40 age dates on feldspars from microgranular matrix and $^{40}\text{Ar}/^{39}\text{Ar}$ age dating on hornblende
41 phenocrysts to compare zircon crystallization and cooling ages. U-Pb data from zircon rims
42 from all samples provide consistent ages with a mean value of 25.97 ± 0.11 Ma. Our field
43 mapping and structural data show that the sample set is representative of the entire history of
44 the MHIC emplacement. We propose that the 220 kyr covered by the analytical uncertainties
45 is the minimum duration of emplacement. The maximum duration is, on the other hand, given
46 by ± 2 SD of the sample population, i.e. 640 kyr. The distinct magmatic pulses identified in
47 the field display similar ages within analytical uncertainties. With these durations, the
48 averaged vertical displacement rate during the MHIC emplacement was around 0.3-0.9 cm/yr.
49 The average magmatic flux was between 0.5 and $1.6 \cdot 10^{-4}$ km³/yr at the scale of both the whole
50 MHIC and individual satellite intrusions. The U-Pb ages of the zircon cores range between
51 1.05 Ga and 2.16 Ga, with a major frequency peak between 1.3 and 1.45 Ga and several
52 minor peaks between 1.6 Ga and 1.75 Ga. The 1.8-1.7 Ga Yavapai and 1.7-1.6 Ga Mazatzal
53 age signatures of are both present beneath this part of the Colorado Plateau. Lu-Hf analyses of
54 most of the zircon rims are consistent with those of the cores and show a lower crustal mafic
55 source derived from a 1.3-1.8 Ga depleted-mantle reservoir, and incorporating variable
56 amounts of recycled continental crust with time from 1.5 Ga. Even if both sources were partly

57 mixed, they still can be observed in the Oligocene rims crystallized during the emplacement
58 of the MHIC. With this core-rim duality, the data tell two stories that might seem totally
59 disconnected, that of the Proterozoic lithosphere and that of the Oligocene magmatism of the
60 Colorado Plateau. But the U-Pb and Lu-Hf data clearly show these two stories are coupled:
61 our data document a magmatic legacy spanning 1.5 billion years. Our work shows
62 unequivocally how important it is to combine robust geochronology based on careful
63 sampling with relative chronology deduced from field-based structural mapping to correctly
64 evaluate the maximum duration or at least to discriminate temporally the different pulses in a
65 pluton.

66

67

68 **1. Introduction**

69 Our understanding of the discontinuous and episodic growth of upper crustal plutons
70 has been greatly improved by documenting the structural record and the detailed spatial and
71 temporal scales of their incremental assembly (Petford et al., 2000; Saint-Blanquat et al.,
72 2001; Coleman et al., 2004; Saint-Blanquat et al., 2006; Matzel et al., 2006; Miller et al.,
73 2007; Morgan et al., 2008; Walker et al., 2007; Michel et al., 2008; Bartley et al., 2008;
74 Horsman et al., 2010; Miller et al., 2011; Saint-Blanquat et al., 2011; Leuthold et al., 2012;
75 Schoene et al., 2012; Davis et al., 2012; Barboni et al., 2015; Paterson and Ducea, 2015;
76 Coleman et al., 2016, and many others). This recent work on upper crustal plutonic systems
77 allow us to examine the link between plutons and magma chambers and the relationship
78 between plutonism, volcanism, and tectonics (Cruden and McCaffrey, 2001; Glazner et al.,
79 2004; Bachmann et al., 2007; Lipman, 2007; Annen, 2009; Saint-Blanquat et al., 2011;
80 Annen, 2011; Glazner et al., 2015; Annen et al., 2015; and references therein).

81 The duration of a given pluton’s assembly is closely tied to its volume, itself related to
82 more or less important magmatic pulses at a particular time scale (Saint-Blanquat et al.,
83 2011); furthermore this relationship seems independent of the tectonic context, and thus may
84 be controlled by the intrinsic dynamics of magmatic processes in the crust. Thus, the observed
85 episodic growth has a different significance at each time/space scale. In small plutons, it is the
86 incremental process of pulse assembly from individual sheet-like bodies. In larger plutons, the
87 incremental process is lost and consists of a cycle of injections at different timescales (the
88 “episodicity” of Pitcher, 1979; see also de Silva et al., 2015 and reference therein). The origin
89 of this pulsing over longer periods of time must be related to lithology and the thermal regime
90 of the upper mantle-lower crust region, itself driving magmatic processes (melting,
91 segregation, transfer) in interactions with geodynamic boundary conditions (e.g. Cruden,
92 2006). Thus, precise quantification of the timescales of magma transfer and emplacement and
93 the determination of the associated magma fluxes (e.g. de Silva and Gosnold, 2007) are
94 critical to improve our global understanding of magmatic processes at crustal scales. Accurate
95 quantitative data on magma dynamics at the upper crustal level is crucial to understand deeper
96 in the crust, e.g. the magma dynamics in the source region, or the mode and rate of magma
97 transfer between the source and the plutonic accumulation level. This is particularly relevant
98 in light of recent models of trans-crustal magmatic columns (e.g. Cashman et al., 2017).

99 The emplacement of a batholith is therefore a record of a relatively long and complex
100 history related to the construction and amalgamation of many plutons through time, a scenario
101 that is now quantifiable using U-Pb geochronology (e.g. Coleman et al., 2004; Demouy et al.
102 2012; Mullen et al., 2018).). However, those component plutons are themselves emplaced
103 through incremental processes, i.e. the injection of pulses, that may operate at (very) fast
104 geologic timescales ($< 10^4$ years; Saint-Blanquat et al., 2011; Cruden et al., 2017; Giorgis et
105 al., 2019) difficult to resolve inside a pluton only with geochronology, even with state-of-the-

106 art methods. It is therefore crucial to combine robust geochronology based on careful
107 sampling with relative chronology deduced from field-based structural mapping to evaluate
108 the maximum duration or at least to discriminate temporally the different pulses in a pluton. .
109 The benefits of this effort will be most evident for a pluton with a very well documented
110 construction history.

111 The Mount Hillers intrusive complex (MHIC) is one of five intrusive centers of the
112 Henry Mountains in southern Utah (USA). It consists of a large central intrusion surrounded
113 by a network of smaller satellite intrusions (Gilbert, 1877; Hunt et al., 1953; Jackson and
114 Pollard, 1988; Horsman et al., 2010 and 2016) (Fig. 1). The map pattern shows that the
115 majority of the satellite intrusions emanate from the central intrusion, similar to how lava
116 flows are connected to their volcano. Previous work clearly documents that the entire MHIC
117 can be considered as a single pluton with a complex 3-d geometry, built from successive
118 injections or cycles of injections dispersed within and around a main intrusion. This well-
119 documented field-based emplacement history (Habert and Saint-Blanquat, 2004; Horsman et
120 al., 2005; Saint-Blanquat et al., 2006; Menand, 2008; Morgan et al., 2008 and 2017; Horsman et
121 al., 2010; Horsman et al., 2016) provides a unique opportunity to study in detail the
122 construction of a plutonic system in the upper crust.

123 The goal of the present work is to obtain the most accurate age data possible on the
124 field-based structural model we have on the construction of the MHIC (Horsman et al., 2010
125 and 2016). Specifically, we attempt to: 1) determine the age of the Mount Hillers Intrusive
126 Complex, 2) determine if there is a sequence to the ages of the satellites versus the central
127 intrusion, 3) determine if there is an age variation from the bottom to the top of component
128 intrusions and, 4) constrain the duration of the construction of both these component
129 intrusions and of the entire MHIC. To achieve these goals, we performed in-situ LA-ICP-MS
130 U-Pb zircon dating on 11 samples covering a complete cross section of the MHIC. We also

131 measured Lu-Hf isotopes on the same zircon grains in order to constrain the nature of the
132 magmatic protolith(s) of the Mount Hillers intrusions. In addition, we performed K-Ar and
133 $^{40}\text{Ar}/^{39}\text{Ar}$ dating of groundmass and hornblendes respectively, to compare to the zircon
134 crystallization and diorite cooling ages. As we have observed inherited cores in all our zircon
135 grains, our data also shed new light on the Proterozoic evolution of the central part of the
136 Colorado Plateau crust. As there are no Proterozoic rocks exposed in this region, our data fill
137 a gap in the geological knowledge of the Colorado Plateau.

138 **2. Geological settings**

139 The Henry Mountains are located in the south-eastern Utah (USA) and are defined by
140 five main peaks, each composed of a sedimentary dome above an igneous laccolith core,
141 surrounded by a zone of satellite intrusions (dikes, sills and minor laccoliths) intruded into
142 sub-horizontal strata (Fig. 1). The five intrusive centers are located on the gently dipping (1-
143 2° West) eastern limb of a North-South trending basin bounded on the west by the east-
144 vergent Waterpocket Fold (Hunt et al., 1953). The intrusive rocks are microgranular
145 porphyritic diorites and quartz diorite porphyries (Engel, 1959) emplaced into Permian
146 through Mesozoic sedimentary formations dominated by sandstones and shales. $^{40}\text{Ar}/^{39}\text{Ar}$ and
147 fission-track dating on the intrusive rocks of the Henry Mountains yield middle to late
148 Oligocene ages (23-31 Ma) for the five intrusion centers, with an age of 29.35 ± 0.33 Ma for
149 Mt Hillers and its satellite intrusions (Sullivan et al., 1991; Nelson et al., 1992; Nelson, 1997;
150 Sullivan, 1997). Murray et al. (2016) provided U-Pb zircon ages on five samples from the
151 Mount Hillers intrusive rocks, ranging from 25.5 ± 1.5 Ma to 26.3 ± 0.7 Ma.

152 The magmatism of the Henry Mountains and other laccoliths of the Colorado Plateau,
153 such as the La Sal and Abajo Mountains, was contemporaneous with the voluminous San Juan
154 and Reno-Marysvale volcanic fields outside the plateau region (Armstrong and Ward, 1991).

155 Although situated far (~1000 km) from the location of the Cenozoic subduction zone, the
156 Henry Mountains appear to be related to a large-scale igneous system with arc-like
157 geochemical affinities (Nelson and Davidson, 1993). The relatively minor volume of mid-
158 Tertiary igneous rocks on the Colorado Plateau (< 500 km³) compared to the
159 contemporaneous regional magmatism may be due to the thick cratonic crust (> 40 and up to
160 50 km) of the Colorado Plateau (Thompson and Zoback, 1979), which could have acted as a
161 structural barrier and hampered the ascent of magma to higher crustal levels (Nelson and
162 Davidson, 1993). A recent petrological and geochemical study of Mount Hillers diorites
163 (Renaudin et al., 2010) suggest that their genesis involved the melting of one heterogeneous
164 or two distinct mafic sources located in the lower part of the Colorado Plateau crust (below 20
165 km). These data question the arc-like geochemical affinities, and suggests that the porphyritic
166 microdiorite may have an inherited arc-like geochemical signature induced by Oligocene
167 melting of lower crustal metabasalts associated with a Proterozoic active continental margin
168 setting.

169 Hypotheses about the geometry and emplacement mechanisms of the intrusive rocks of the
170 Henry Mountains have evolved over time. Gilbert (1877) defined the term “laccolite” (now
171 laccolith) based on his observations there, and presented a growth model involving inflation
172 of an early sill into a domed intrusion that uplifted and rotated overlying host rock. Hunt et al.
173 (1953) reinterpreted the five major intrusions as discordant stocks that radially expanded and
174 fed the satellite intrusions laterally. Almost all subsequent work in the Henry Mountains
175 supports the fundamental laccolith geometry and growth model of Gilbert (1877), as
176 demonstrated by Jackson & Pollard (1988). A similar revision of emplacement model
177 occurred in the nearby La Sal Mountains when the stock hypothesis of Hunt and Waters
178 (1958) was replaced with the laccolith model of Ross (1998).

179 Based on extensive field work throughout the Henry Mountains, Horsman et al. (2016)
180 present a generalized model of the growth of a laccolithic intrusive center. The first stage
181 involves development of a sill and dike network in subhorizontal host rock. The second stage
182 involves growth of a central laccolithic igneous body through injection of multiple magma
183 pulses, which uplifts and rotates overlying host rock and the early sill / dike network. In the
184 third stage, satellite intrusions grow around the margin of the central laccolith and are
185 intruded largely into subhorizontal host rock outside the laccolith dome. Mt Holmes and Mt
186 Ellsworth (each $\sim 20 \text{ km}^3$) developed through the first and second stages, both have no
187 significant satellite intrusions. Both Mt Hillers ($\sim 35 \text{ km}^3$ igneous volume) and Mt Pennell
188 ($\sim 35 \text{ km}^3$) preserve excellent evidence of all three stages, with the central laccolith-cored
189 domes partially surrounded by satellite intrusions. Mt Ellen ($\sim 120 \text{ km}^3$) represents a more
190 advanced degree of the third stage, with dozens of satellite intrusions surrounding the central
191 laccolithic body.

192 This recent work on the Henry Mountains intrusions (Horsman et al., 2010 and 2016 and
193 references therein) has also shown that, across a wide range of intrusion volume, component
194 igneous bodies in each intrusive center were constructed through a series of magma pulses.
195 Each satellite intrusion has a relatively small igneous volume (always $< 3 \text{ km}^3$ and commonly
196 $< 0.5 \text{ km}^3$) but their construction through multiple small-volume stacked magma sheets is
197 documented with detailed field, petrographic, magnetic, geochemical, and textural data.
198 Evidence of sheeted construction in the smallest satellite intrusions, usually sills (Horsman et
199 al., 2005) or small transitional sill-laccoliths (Morgan et al., 2008; Wilson et al., 2016; Giorgis
200 et al., 2019), shows they are built from stacked sheets, usually 1-5 m thick. In larger volume
201 satellite intrusions (e.g. Saint Blanquat et al., 2006), direct evidence of sheeted construction
202 becomes more cryptic.

203 These satellite intrusions are located around the margins of the main central laccolith
204 bodies (Fig. 1 and 2), which have total igneous volumes ranging from $\sim 20 \text{ km}^3$ (Mts
205 Ellsworth and Holmes) to $\sim 120 \text{ km}^3$ (Mt Ellen). Three main laccolith bodies are exposed
206 (Mts. Hillers, Pennell, and Ellen) and each is clearly constructed from multiple magma pulses
207 (Horsman et al., 2016). Mapping of textures throughout an entire intrusive center suggests
208 each main laccolith is constructed from stacking of numerous lobes of igneous rock radiating
209 out from a central region (Horsman et al., 2016, and references therein).

210 The main conclusion of these recent structural works is that the assembly of these
211 igneous intrusions occurs through the amalgamation of numerous pulses of magma, which
212 may be a common occurrence in upper crustal intrusions (e.g. Petford et al., 2000). These
213 emplacement and assembly processes by pulses operate at many spatial and temporal scales
214 (Saint-Blanquat et al., 2011). The emplacement conditions in the Henry Mountains – shallow
215 crustal levels ($< 3 \text{ km}$), low magma volumes and therefore fast cooling rates, no synmagmatic
216 regional deformation – were ideal for the preservation of internal structures (Horsman et al.,
217 2010, 2016). Indeed, the conditions of emplacement and assembly for plutons elsewhere are
218 in general considerably more complex than in the Henry Mountains, which complicates the
219 preservation of primary internal structures recording solely magmatic growth. The Henry
220 Mountains are therefore a valuable end-member case that allows us to study the durations and
221 rates of pluton construction, and particularly to constrain the timescale of magma pulse
222 amalgamation.

223 **3. Analytical techniques**

224 **3.1 U-Pb zircon dating**

225 Zircon grains were separated at the Laboratoire Magmas & Volcans (LMV) using
226 standard techniques of crushing and sieving, followed by Wilfley table, magnetic separation

227 and heavy liquids before handpicking under binocular microscope. They were mounted in
228 epoxy disks, then ground and polished at 0.25 μm to expose crystal interiors.
229 Cathodoluminescence (CL) imaging was conducted at LMV using a JEOL JSM-5910LV
230 SEM. U-Th-Pb isotopic data on zircons were obtained by laser ablation inductively coupled
231 plasma spectrometry (LA-ICPMS) at the LMV (Clermont-Ferrand, France) and are reported
232 in Supplementary Table S2. The analyses involved the ablation of minerals with a Resonetics
233 M-50 Excimer laser system operating at a wavelength of 193 nm. Spot diameters of 44 μm
234 were associated to repetition rates of 3 Hz and fluency of 3 J/cm² resulting in a spot depth of
235 10-12 μm . The ablated material was carried into helium and then mixed with nitrogen
236 (Paquette et al., 2014) and argon before injection into the plasma source of a Thermo Element
237 XR Sector Field high-resolution ICP-MS. The alignment of the instrument and mass
238 calibration were performed before every analytical session using the NIST SRM 612
239 reference glass, by inspecting the signals of ²³⁸U, ²³²Th and ²⁰⁸Pb and by minimizing the
240 ThO+/Th+ ratio. The analytical method for isotope dating with laser ablation ICP-MS is
241 basically similar to that reported in Hurai et al. (2010) where no common Pb correction was
242 applied owing to the large isobaric interference from ²⁰⁴Hg. The ²³⁵U signal is calculated from
243 ²³⁸U on the basis of the ratio ²³⁸U/²³⁵U = 137.818 (Hiess et al., 2012). Single analyses
244 consisted of 30 seconds of background integration with laser off followed by 1 minute
245 integration with the laser firing and a 30 seconds delay to wash out the previous sample and
246 prepare the next analysis (details available in Supplementary Table S1).

247 Data are corrected for U-Pb fractionation occurring during laser sampling and for
248 instrumental mass bias by standard bracketing with repeated measurements of GJ-1 zircon
249 reference material (Jackson et al., 2004). Repeated analyses of zircon 91500 secondary
250 reference material (Wiedenbeck et al., 1995) treated as unknown, independently control the
251 reproducibility and accuracy of the corrections (Concordia age = 1066.2 \pm 2.6 (2SD,

252 MSWDC+E = 0.45, N = 69; to be compared with the reference age of 1065.4 ± 0.3 ;
253 Wiedenbeck et al., 1995).

254 Data reduction was carried out with the software package GLITTER[®] from Macquarie
255 Research Ltd (van Achterbergh et al., 2001; Jackson et al., 2004). Calculated ratios were
256 exported and Concordia ages and diagrams were generated using Isoplot/Ex v. 2.49 software
257 package by Ludwig (2001) and IsoplotR (Vermeesch, 2018). The concentrations in U-Th-Pb
258 were calibrated relative to the certified contents of GJ-1 zircon (Jackson et al., 2004)
259 reference material. A systematic external error is subsequently propagated by quadratic
260 addition of uncertainties on U and Th decay constants as well as of the variability of the
261 primary reference material used for corrections (GJ-1) and of the long term variability of the
262 secondary reference material (91500). According to Horstwood et al. (2016), this systematic
263 external error is added to the 2σ associated to the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages calculation.
264 The zircon analytical results were projected on $^{207}\text{Pb}/^{206}\text{Pb}$ versus $^{238}\text{U}/^{206}\text{Pb}$ diagrams (Tera
265 and Wasserburg, 1972), where the analytical points plot along a mixing line between the
266 common Pb composition in the upper intercept and the zircon age in the lower intercept. This
267 method is commonly used to date Phanerozoic zircons using in situ techniques (Baldwin and
268 Ireland, 1995; Jackson et al. 2004).

269 **3.2 Lu-Hf in-situ analyses**

270 The principles of the Lu-Hf method can be found in Patchett et al. (1981), Vervoort
271 and Blichert-Toft (1999), Bouvier et al. (2008) and Blichert-Toft and Albarède (2008).
272 Hafnium isotope measurements were performed on the same spots as for U-Pb dating using a
273 Thermo Scientific Neptune Plus MC-ICP-MS coupled to a Resonetics M50E 193nm Excimer
274 laser system at the LMV. Data were collected in static mode (^{171}Yb , ^{173}Yb , ^{174}Hf , ^{175}Lu , ^{176}Hf -
275 Yb-Lu , ^{177}Hf , ^{178}Hf , ^{179}Hf), and are reported in Supplementary Table S3. The operating

276 conditions and instrument settings are described in Moyen et al. (2017) and Paquette et al.
277 (2017) and reported in Supplementary Table S1. Mass bias effects on Hf were corrected using
278 an exponential law and a true value for $^{179}\text{Hf}/^{177}\text{Hf}$ of 0.7325 (Patchett et al., 1981; Patchett
279 and Tatsumoto, 1980). Data were reduced based upon user-selected background and sample
280 integration intervals. Outlier Hf isotopic ratios for each analysis were rejected using a two-
281 standard deviation criterion.

282 In order to ensure the accuracy of our Hf isotope results, we checked our analytical
283 reproducibility and correction procedure with systematic measurement of 20 replicates of four
284 synthetic zircons displaying increasing (Y+Lu) content (Supplementary Table S1). Mean and
285 two standard deviation values obtained on MUNZirc 0-2a ($^{176}\text{Hf}/^{177}\text{Hf}=0.28213 \pm 3$),
286 MUNZirc 1-2b (0.28214 ± 2); MUNZirc 3-2b (0.28215 ± 2) and MUNZirc 4-2b ($0.28216 \pm$
287 3) are fully consistent with reference values (Fischer et al., 2011).

288 The $\epsilon\text{Hf}_{(t)}$ value is defined as the deviation of the $^{176}\text{Hf}/^{177}\text{Hf}$ of a sample from the
289 CHUR in parts per 10^4 . It is calculated according to the $\lambda^{176}\text{Lu}$ value = $1.867 \times 10^{-11} \text{ yr}^{-1}$ of
290 Scherer et al. (2001) and the CHUR parameters ($^{176}\text{Hf}/^{177}\text{Hf}=0.282793$; $^{176}\text{Lu}/^{177}\text{Hf}=0.0338$)
291 of Iizuka et al. (2015).

292 **3.3 $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar analyses**

293 $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar dating were performed on two samples from separate satellite
294 intrusions. The $^{40}\text{Ar}/^{39}\text{Ar}$ dating was conducted on hornblende phenocrysts of 150-250 μm
295 from sample 08BM01, a diorite from the top of the Black Mesa bysmalith (Table 1). The K-
296 Ar dating was carried on groundmass (size fraction 80-125 μm , mainly feldspars) of the
297 01MC109 diorite from the top of the Maiden Creek sill. Both samples were crushed and
298 sieved for different size fractions, rinsed and cleaned. A magnetic separation with a hand
299 magnet was then applied on both size fractions of interest prior to heavy liquid separation

300 using diiodomethane or bromoform. Pure hornblende crystals from sample BM01 were mostly
301 separated from denser fractions using diiodomethane, cleaned in an ultrasonic bath, then
302 selected by handpicking under a binocular microscope. The 80-125 μm groundmass from
303 sample 01MC109, mainly constituted of feldspar, was separated from heavier minerals or
304 phenocrysts using bromoforme and concentrated in the lowest density fraction of about 2.65-
305 2.67 g/cm^3 .

306 The K-Ar dating was performed at GEOPS (Geosciences Paris Saclay) using the
307 unspiked Cassinol-Gillot method (Cassinol and Gillot, 1982). Potassium and Ar
308 measurements were acquired in two different aliquots following separate duplicated
309 measurements. The K content for each sample was measured by flame-absorption
310 spectrometry with BCR-2 (Raczek et al., 2001; K = 1.48 wt%) and MDO-G (Gillot et al.,
311 1992; K = 3.51 wt.%) as standard reference material. Argon was measured using a multi-
312 collector 180° sector mass spectrometer by comparing the amount of ^{36}Ar and ^{40}Ar isotopes
313 from the samples and atmospheric aliquots (for details see Germa et al., 2011). ^{40}K decay
314 constants and K isotopic ratio of Steiger and Jäger (1977) have been used in the calculations.
315 Uncertainties reported in Table S4 are quoted at the 2σ level.

316

317 The $^{40}\text{Ar}/^{39}\text{Ar}$ dating was performed at LSCE (CEA, Gif/Yvette) using the method
318 described in Nomade et al. (2010). One gram of pure hornblende phenocrysts of 150-250 μm
319 size was irradiated at the Osiris reactor (CEA Saclay, Gif/Yvette). Following their irradiation,
320 single crystals were individually transferred into a stainless-steel sample holder and then
321 loaded into a differential vacuum Cleartran® window. After a slight leaching using a 25W
322 CO_2 laser (Synrad®) at 2.5% of the full laser power, the hornblende crystals were fused at
323 about 15% of the full laser power. Ar isotopes were analysed using a VG5400 mass
324 spectrometer equipped with a single ion counter (Balzers® SEV 217 SEN) following the

325 procedure outlined in Nomade et al. (2010). Neutron fluence (J) was monitored by co-
326 irradiation of Fish Canyon Tuff (FCT) together with the hornblende separates. The J value (J=
327 0.00279150; Supplementary Table S4) was calculated using the FCT age of 28.02 Ma (Renne
328 et al., 1998) and the total decay constant of Steiger and Jäger (1977). Recent revisions of
329 decay and monitor constants for FCT suggest values older by about 1% (Kuiper et al. 2008;
330 28.201 Ma) and 1.0% (Renne et al. 2010; 28.305 Ma). Mass discrimination correction was
331 monitored by weekly measurement of the air argon (see the full experimental description in
332 Nomade et al. 2010). Uncertainties reported in Table S4 are quoted at the 2σ level.

333 **4. Results**

334 **4.1 Samples and zircon description**

335 The location of samples are reported in Figure 2 and their principal characteristics and
336 U-Pb age are listed in Table 1. All the Mount Hillers intrusive rocks are composed of
337 microgranular porphyritic diorite (Fig. 3). The samples are composed of 30-55% phenocrysts
338 (20-40% plagioclase, 5-20% amphibole, 1-5% accessory minerals: epidote, clinopyroxene,
339 titanite, oxides, quartz, apatite, calcite) in a microgranular matrix mainly composed of
340 plagioclase, quartz and potassium feldspar (Renaudin et al., 2010). The samples can be
341 divided in two textural families (Renaudin et al., 2010): the most abundant is a texture
342 characterized by 0.5-2 cm phenocrysts of lozenge-shaped plagioclase and stocky 1-5 mm
343 amphibole called hereafter the coarse-grained texture (CGT; Fig. 3b and d). The second
344 textural group, hereafter called the fine-grained texture (FGT; Fig. 3c and e) has smaller
345 phenocrysts with plagioclase <1 cm, more elongated and tabular, and the amphibole thinner
346 and longer, 0.2-0.5 mm thick and up to 4-5 mm long. Magmatic epidote and clinopyroxene
347 are present in the CGT and FGT respectively, and never coexist in the same sample. Each

348 satellite intrusion is composed of a single textural and mineralogical family, but the central
349 intrusion displays both textural-mineralogical types and some intermediate families.

350 In this study, we analyzed 3 samples from the FGT and 8 from the CGT (Fig. 2). BM-
351 01 and BM-02 were sampled near the base and BM-03 near the top of the Black Mesa
352 bysmalith (BMB) (Habert and Saint-Blanquat, 2004; Saint-Blanquat et al., 2006). BM-01 and
353 02 exhibits the regular FGT but BM-03 is more fine-grained (Fig. 3e). The BMB is 250 m
354 thick and is one of the thickest satellite intrusions of the MHIC. CS-02 comes from the
355 Copper Spring sill which is located on the south margin of the Mount Hillers Central
356 Intrusion. The sill is vertical, concordant, 10-20 m thick, and made of CGT microdiorite (Fig.
357 3d). HI-01 and 04 were sampled in the central intrusion of Mount Hillers, respectively at the
358 summit and on the NNW-SSE ridge of the Mount Hillers Central Intrusion, SE of the summit;
359 both belong to the FGT group (Fig. 3c). HI-02 was sampled SE of the Mount Hillers summit
360 on a NNW-SSE ridge and belongs to the CGT group (Fig. 3b). MC-01 and MC109 are CGT
361 microdiorites sampled close to the top of the Maiden Creek sill (MCS), a sill composed of
362 multiple superimposed magma injections (Horsman et al., 2005; Morgan et al., 2017). SP-01
363 is a CGT microdiorite sampled in the middle part of the Saddle Pass sill located between the
364 BMB and the central intrusion. SR-01 and SR-02 are both CGT microdiorites sampled near
365 the base and the top of the Sawtooth Ridge conduit (SRC), which is a long and tubular
366 intrusion, with a mapped connection to the central intrusion. TM-02 is a CGT microdiorite
367 sampled near the base of the Trachyte Mesa laccolith (TML) (Morgan et al., 2008). The TML
368 is the furthest satellite intrusion (Fig. 2 and 3), at 10 km from the NE margin of the central
369 intrusion, fed by a narrow pipe-like conduit (Morgan et al., 2008; Wetmore et al., 2009).

370 In all samples, crystals of zircon are observed as free grains within the fine-grained
371 groundmass of the microdiorite. The zircon crystals are large (generally 300-400 μ m, up to

372 500 μm), euhedral, light pink in color and moderately elongated. Their morphology and inner
373 structure is similar in all the samples from the central intrusion and the different satellites. The
374 complete (unbroken) zircons are all composed of an irregular inherited core surrounded by a
375 zoned rim (Fig. 4 a-f), so in-situ U-Pb dating techniques are required. The boundaries between
376 core and rim domains sometimes display complex shapes suggesting the replacement of an
377 older generation of zircon by younger material. These cores can be of variable size (rarely less
378 than 50-100 μm ; Fig. 4a and b), but are systematically rounded with an irregular shape and
379 often darker in color than the rims, suggesting a higher U content. Cathodoluminescence
380 images of the cores vary from grain to grain, some illustrating the lack of any visible texture
381 (Fig. 4d) and others exhibiting very complex morphologies (Fig. 4e), sometimes including
382 oscillatory or sector-zoned parts (Fig. 4f). In some cases, the core constitutes the largest part
383 of the zircon with thin rims in the order of 50 μm but generally the rim is larger (more than
384 100-200 μm) and systematically displays sector-zoning as illustrated in Fig. 4. This sector
385 zoning is regular and suggests growth was continuous from the inherited cores up to the outer
386 edges. There are no detectable dissolution-precipitation features, suggesting the crystal rim
387 growth occurred during a single magmatic episode rather than multiple time-differentiated
388 episodes

389 Uranium contents range from 9 to 5500 ppm, but 72% of the analyses yield U
390 concentrations lower than 500 ppm. Th/U ratios are generally low with 84% and 22% of the
391 grains displaying values lower than 0.35 and 0.1, respectively. In a [Th] versus [U] diagram
392 (Fig. 5 and Supplementary Figure S1), two main sample groups can be distinguished for the
393 zircon rims. The first group is characterized by the largest Th and U contents ([Th] > 10 ppm
394 and [U] > 100 ppm) associated to Th/U ratios higher than 0.1. This group comprises zircon
395 grains from the Mount Hillers (HI) central laccolith and the Black Mesa (BM) satellite
396 intrusion. The second group comprises most of the other satellite intrusions: Maiden Creek

397 (MC), Sawtooth Ridge (SR), Trachyte Mesa (TM) and Saddle Pass (SP), and is characterized
398 by the lowest Th and U concentrations of the zircons ($[Th] < 5$ ppm and $[U] < 100$ ppm) as
399 well as Th/U ratios lower than 0.1 and mostly lower than 0.05. A single sample, the Copper
400 Spring satellite intrusion, yields an intermediate position in this diagram with high U-Th
401 contents but low Th/U ratios. In general, such low Th/U ratios (lower than 0.05) like in these
402 zircon rims are often considered characteristic of metamorphic zircons (Chen et al., 2010),
403 however in the Mount Hillers samples the zircon rims are unambiguously of magmatic origin
404 and crystallized from the dioritic melt. This highlights that very low Th/U ratios resulting
405 from dissolution-recrystallization of zircons are not systematically good markers of
406 metamorphic overprint (see Yakymchuk et al., 2018). The cores of the FGT and CGT zircons
407 have similar compositions, with Th/U ranging from 1 and 0.1 (Fig. 5a). The cores and rims of
408 zircons from FGT samples have a similar composition (Fig. 5c), whereas the zircons from
409 CGT samples are characterized by cores and rims of different composition, with Th/U mainly
410 above and below 0.1 for the cores and the rims respectively (Fig. 5d).

411 **4.2 U-Pb zircon dating**

412 **4.2.1 Cenozoic rims**

413 A total of 396 zircon rims were analyzed out of 11 rock samples; their U-Pb results are
414 reported in Supplementary Table S2. The reported age for each sample (n=25 to 48 grains)
415 corresponds to their concordia mean age on a Terra-Wasserburg plot ($^{207}Pb/^{206}Pb$ vs.
416 $^{206}Pb/^{238}U$) in Figure 6.

417 Individual age results demonstrate a very short time-span for the crystallization of the
418 zircons from the whole Mount Hiller central laccolith and related satellite intrusions between
419 26.19 ± 0.35 Ma (HI-04+HI-01 Fig.6b) and 25.66 ± 0.32 Ma (SR-01 Fig.6h). For the Black
420 Mesa intrusion, the sample from a late dike crosscutting the intrusion roof was dated at 26.09
421 ± 0.39 Ma (BM-03 Fig.6d), whereas the sample located in a magmatic pulse at the base of the

422 intrusion was dated at 26.04 ± 0.33 Ma (BM-02 Fig.6c). For the Sawtooth Ridge satellite
423 intrusion, the pattern is the same, with the sample from a magmatic pulse constituting the top
424 of the intrusion dated at 26.08 ± 0.35 Ma (SR-02 Fig.6g), and the one located in a pulse
425 constituting the bottom of the intrusion dated at 25.66 ± 0.32 Ma (SR-01 Fig.6h). Figure 7
426 shows the age pattern of all the dated samples, showing consistent ages with each other and a
427 mean value of 25.97 ± 0.11 Ma.

428 Finally, even if the oldest age is from a FGT sample and the youngest one from a CGT
429 sample, our data show that these two type of magmas were emplaced synchronously, within
430 the time resolution of our U-Pb data, so there is no discernable relationship between age,
431 composition, and textural characteristics of samples (Fig. 7).

432 ***4.2.2 Proterozoic cores***

433 A total of 234 cores from the 11 selected samples were analysed. Raw data are
434 reported in Supplementary Table S2 and plotted in Supplementary Figure S2. Among these
435 234 core analyses, 33 $^{207}\text{Pb}/^{206}\text{Pb}$ ages fall in the range between 1.5 to 1.6 Ga, a period of
436 tectonic lull and magmatic quiescence in the area with no known activity despite many studies
437 This period correspond to a period of stabilization of North American lithosphere (Anderson,
438 1983; Bowring and Karlstrom, 1990; Whitmeyer et Karlstrom 2007; Johansson et al., 2022).
439 Crowley et al. (2006) also reported zircon U-Pb ages from lower crustal xenoliths in the
440 Navajo volcanic field about 200 km south of the Mount Hillers within this 1.5-1.6 Ga period
441 using high precision ID-TIMS. However, these ages are discordant and lie on a discordia with
442 lower and upper intercepts of about 1.65 and 1.40 Ga, implying these grains are mixture of
443 two different domains with different ages. Thus it is very likely that the ages we report in the
444 1.5-1.6 Ga time interval also have no geological meaning and represent mixtures of complex
445 cores with different U-Pb isotopic compositions sampled during laser ablation, even though
446 some ages are concordant. Therefore these data are not further considered in the discussion.

447 The remaining U-Pb dating results of the cores (N = 161) are very similar from sample
448 to sample; therefore the core population was therefore treated as a global dataset for all
449 samples. These 161 analyses represent 70% of the whole analyses and display less than 5%
450 discordance, most probably related to recent Pb-loss, thus the apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages can be
451 considered as representative of the ages of these cores (Fig. 8a). The whole population of
452 zircon cores ranges in age from 1.2 to 1.8 Ga with the exception of two analyses, one being
453 concordant at 1.1 Ga and the other discordant at 2.45 Ga. The major frequency peak for the
454 zircon cores is centered around 1.4 Ga with two minor peaks ranging between 1.60 and 1.75
455 Ga (Fig. 8b).

456 **4.3 Lu-Hf isotopes in zircon**

457 A set of 164 analyses was performed for Lu-Hf isotopes comprising 92 Cenozoic rims
458 and 72 Proterozoic U-Pb concordant cores (Supplementary Table S3).

459 ***4.3.1 Cenozoic rims***

460 The analyzed zircon rims overlap on a large range of initial $\epsilon\text{Hf}_{(t)}$ values from +4 to -
461 25 (Fig. 9 and 10). A careful examination of the Lu-Hf results of the zircon rims sample by
462 sample (8-10 analyses per sample) shows that most analyses (90%) range from chondritic
463 values to $\epsilon\text{Hf}_{(t)}$ of about -10 (Fig. 10). In the FGT suite, excluding the most negative $\epsilon\text{Hf}_{(t)}$ (-
464 16 to -25; n=6/92), most zircon rims from the central laccolith (samples HI-02-04; n=12/18)
465 and from the Black Mesa (BM-02-03; n=12/17) satellite intrusion seem to have distinctive
466 mean initial $\epsilon\text{Hf}_{(t)}$ values, those from the central intrusion having $\epsilon\text{Hf}_{(t)}$ around +1 to -4
467 whereas those from Black Mesa mainly have lower -6 to -11, implying slightly different
468 sources. Six outliers over the 92 zircon rims analysed display even more negative values
469 between -16 and -25 (Fig. 10), which are not found in any other satellite intrusions. Although
470 very minor in the dataset (6%), these low $\epsilon\text{Hf}_{(t)}$ values could either suggest a different/older

471 magma source for these few zircon rims of the FGT suite having high Th/U ratios, or possibly
472 an Hf composition and U-Pb age mismatch for these few grains (analytical bias). In the CGT
473 suite, most samples have their initial $\epsilon\text{Hf}(t)$ values between -2 and -6 although some samples
474 display more heterogenous compositions than others (eg. TM-02 vs. MC-01). Likewise, the
475 zircon rims from the Copper Spring satellite intrusion (CS-02), which have intermediate
476 chemical compositions between both major groups in Figure 5 (high U contents and low Th/U
477 < 0.1), show initial $\epsilon\text{Hf}(t)$ ranging from -2 up to +3 (Fig. 10), indicating a more mantle-
478 derived Hf isotopic signature than in other samples. Nevertheless, the sub-synchronous
479 crystallization of all the zircon rims does not provide any constrain on the timing of the
480 isotopic heterogeneity.

481 ***4.3.2 Proterozoic cores***

482 All the cores except two analyses yielded positive initial $\epsilon\text{Hf}(t)$ values ranging from 0
483 to +12 for a time period between 1.3 to 1.8 Ga (Fig. 9). Only two analyses from Black Mesa
484 satellite intrusion (sample BM-03) give sub-chondritic initial $\epsilon\text{Hf}(t)$ values up to -1.3. These
485 results indicate that the Proterozoic rocks in the lower part of the Colorado Plateau crust were
486 originally mostly derived from a (depleted) mantle reservoir with minor contribution of a
487 continental crust component. These Proterozoic basement rocks then melted in the Cenozoic
488 to produce the parental magmas for the MHIC diorites. In the Hf dataset (Supplementary
489 Table S3), eleven zircon cores returned variable $\epsilon\text{Hf}(t)$ (+2 to +9) associated to $^{207}\text{Pb}/^{206}\text{Pb}$ ages
490 between 1.5 and 1.6 Ga. These analyses are suspected to result from mixing of different
491 domains of complex cores with variable ages during laser ablation of the composite core (see
492 section 4.2.2 above, section 5.4 below, and Supplementary Fig. S2.). As already stated above,
493 in the Yavapai province, there is no record of magmatic activity between about 1.5 and 1.6
494 Ga, therefore these data have no geological meaning and are not further considered in the
495 discussion and do not appear in related figures.

496 4.4 $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar dating

497 The $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar results are reported in Supplementary Table S4 and Figures
498 S3 and S4. The 150-250 μm hornblende phenocrysts of sample BM-01 gave a plateau age of
499 26.31 ± 0.33 Ma (2σ). The plateau and inverse isochron ages are similar and the $^{36}\text{Ar}/^{40}\text{Ar}$
500 given by the inverse isochron method is 291.4 ± 4.9 Ma (Supplementary Fig. S3). This value
501 is similar to the atmospheric ratio of 295.5 indicating the sample was totally outgassed hence
502 the $^{39}\text{Ar}/^{40}\text{Ar}$ age is not affected by the occurrence of excess Ar in this sample (Supplementary
503 Fig. S3). However previous attempts to precisely date the emplacement of the Mount Hillers
504 and other laccolith intrusions on the Colorado Plateau using $^{40}\text{Ar}/^{39}\text{Ar}$ dating on amphibole
505 have shown difficulties in calculating a precise Ar-Ar or K-Ar crystallization age due to the
506 frequent occurrence of excess Ar and xenocryst contamination (e.g. Nelson et al., 1992;
507 Sullivan, 1997). Incorporation of excess Ar or xenocryst contamination produces older
508 apparent ages such as the $^{40}\text{Ar}/^{39}\text{Ar}$ age of 29.35 ± 0.66 Ma for a hornblende separate from the
509 Mount Hillers reported by Nelson et al. (1992), which appears about 3.5 Ma older than the
510 mean U-Pb age given by zircons from this study. The $^{40}\text{Ar}/^{39}\text{Ar}$ age is thus interpreted as the
511 cooling age of the hornblende grains and indicate the time at which the hornblende
512 phenocrysts within the cooling crystallized magma was at a temperature below the closure
513 temperature of 580-490°C (Harrison, 1982). This plateau age of 26.48 ± 0.33 Ma
514 (recalculated using the FCT value of 28.201 Ma of Kuiper et al., 2008, see above) is within
515 analytical uncertainties of the mean U-Pb ages for the Black Mesa zircons of 26.04 ± 0.33 Ma
516 and very close to the mean U-Pb age of 25.97 ± 0.11 Ma for all diorites from the MHIC.

517 The K-Ar dating on the 80-125 μm feldspar groundmass of the top Maiden Creek sill
518 (MC109) returned a mean age of 25.05 ± 0.72 Ma (2σ). This age is also identical to the mean
519 U-Pb age for the Maiden Creek sill zircons of 25.98 ± 0.30 Ma and very close to the mean U-
520 Pb age of 25.97 ± 0.11 Ma (2σ) for all diorites from the MHIC (Supplementary Fig. S4). The

521 K-Ar age of 25.05 ± 0.72 Ma is interpreted as the cooling age of the feldspar-rich groundmass
522 and indicate the time at which the Maiden Creek sill intrusions were at a temperature of about
523 200-400°C or even slightly below (Harrison and Lovera, 2013) at the end of the cooling
524 process. The consistency between the K-Ar, Ar-Ar and U-Pb ages on different samples show
525 that the feldspar groundmass was totally outgassed and does not contain any excess Ar hence
526 the K-Ar age is considered robust. This is not the case for the K-Ar age of the groundmass
527 analysed in sample 08HI03 which returned an age of 29.4 ± 0.8 Ma, older by 3.5 Ma than the
528 mean U-Pb age of 25.97 ± 0.11 Ma (2σ) given by zircons. This older age is similar to other
529 $^{40}\text{Ar}/^{39}\text{Ar}$ ages on hornblende phenocrysts (e.g Nelson et al., 1992) and also likely indicate the
530 occurrence of excess Ar or xenocryst contamination in this groundmass sample. This age is
531 not further considered in the discussion.

532 **5. Discussion**

533 **5.1 Age of the Mount Hillers Intrusive Center**

534 The average U-Pb zircon rim age of the 11 samples ages is 25.97 Ma \pm 0.11 Ma (2σ)
535 which is interpreted as the age of the Mount Hillers intrusive center (Fig. 7). This age is in
536 very good agreement with the U-Pb zircon rim age mean value of 25.84 ± 0.32 Ma from five
537 Mount Hillers samples (3 from satellites intrusions and 2 from the central intrusion) reported
538 by Murray et al. (2016; Table DR2). As outlined previously, the mean U-Pb age for the whole
539 MHIC is also identical to the $^{40}\text{Ar}/^{39}\text{Ar}$ age on the hornblende separate and just slightly older
540 than the K-Ar age of the groundmass, 26.48 ± 0.66 Ma and 25.1 ± 0.7 Ma respectively. The
541 consistency in ages between the high temperature U/Pb chronometer and the lower
542 temperature $^{40}\text{Ar}/^{39}\text{Ar}$ or K-Ar chronometers indicate that the magma cooling process
543 occurred quickly within the shallow crust and that the mean U-Pb age of 25.97 ± 0.11 Ma on
544 zircon rims can be considered as the crystallization age of the zircons rims very close or

545 during magma emplacement at upper crustal levels. This conclusion is also consistent with the
546 only available titanite fission track age (FT) reported by Sullivan et al. (1991) of 25.6 ± 3.3
547 Ma, which is imprecise, but for a chronometer in a temperature range similar to that of K-Ar
548 on feldspar (ca. 300°C). However, two other FT ages on zircon reported by Sullivan et al.
549 (1991) appear much older or younger (29.2 and 21.2 Ma) than the new U-Pb, Ar-Ar and K-Ar
550 geochronological constraints from this study. As mentioned earlier, previous attempts to
551 constrain the age of crystallization using the $^{40}\text{Ar}/^{39}\text{Ar}$ (or K-Ar) methods on separate
552 minerals (hornblende and feldspar) have failed in many cases for the Colorado laccolith
553 intrusions (La Sal Mountains, Henry Mountains; see Nelson et al., 1992, this study) because
554 of the occurrence of excess Ar or xenocryst contamination, in part due to the contamination of
555 primary magmas by lower Proterozoic crust (Nelson et Davidson, 1993).

556 *At the scale of the Henry Mountains*

557 In-situ zircon U-Pb data are available for three of the five intrusive centers of the
558 Henry Mts (Fig. 11), from north to south, Mount Ellen (3 samples from the central intrusion:
559 27.8 ± 0.58 , 27 ± 0.66 , and 27.4 ± 0.9 Ma, Murray et al., 2016; mean value 27.44 ± 0.77 Ma),
560 Mount Pennell (two samples from the central intrusion and one from a satellite, respectively
561 25.6 ± 0.33 , 25.5 ± 0.37 , and 25.7 ± 1 Ma, Murray et al., 2016; mean value 25.56 ± 0.47 Ma),
562 and Mount Hillers (3 samples from the central and 8 from the satellites intrusions : $25.97 \pm$
563 0.11 , this study, Fig. 7). In summary, the three main intrusive centers of the Henry Mountains
564 were probably emplaced close in time, in 3 Ma, between 28 and 25 Ma, the oldest being
565 Mount Ellen and the youngest Mount Pennell, with Mount Hillers between the two (Fig. 11).

566 In the Henry Mountains, Ar-Ar dating of hornblende for Mount Ellsworth and Mount
567 Ellen diorites have been unsuccessful in giving apparent too old ages (e.g. > 27 Ma; Nelson et
568 al., 1992). However, the U/Pb zircon age of 25.56 ± 0.47 Ma obtained for Mount Pennell by
569 Murray et al. (2016) is only slightly older than the average $^{40}\text{Ar}/^{39}\text{Ar}$ age of 24.8 ± 0.9 Ma

570 measured on hornblendes on the same intrusive center (Nelson et al., 1992; Nelson, 1997),
571 which suggests the same interpretation for Mount Hillers i.e. crystallization of the zircon rims
572 during or shortly before emplacement in the upper crust, followed by a rapid cooling.

573 *At the scale of the central Colorado Plateau*

574 Nelson and Davidson (1993) suggest that all the intrusive complexes of the central
575 Colorado Plateau are part of a widespread late Paleogene magmatic episode in the North
576 American Cordillera. Although late Paleogene volcanism was voluminous around the margins
577 of the Colorado Plateau (Armstrong and Ward 1991), plutonism on the plateau includes only a
578 few hundred cubic kilometers of igneous rock, a considerable portion of which is now
579 exposed in the laccolithic intrusive centers of the Henry, La Sal and Abajo Mountains. U-Pb
580 age of Mount Hillers (this work and Murray et al., 2016) are much younger than the recent U-
581 Pb ages on zircons recently reported for the La Sal Mountains (120km ENE of MHIC) at 29.1
582 ± 0.3 Ma from Rønnevik et al. (2017), who conducted U-Pb analyses of zircons for one
583 sample from Middle Mountain laccolith. Apatite fission tracks on 6 samples of the same
584 laccolith have a reported age of 29.7 ± 2.1 Ma, consistent with the U-Pb zircon age (Rønnevik
585 et al., 2017). Despite the absence of published U-Pb ages for the Abajo Mountains (100 km E
586 of MHIC; dated between 28.6 and 22.6 by $^{40}\text{Ar}/^{39}\text{Ar}$ on hornblende, Nelson et al., 1992), our
587 data and the available ages on these laccolithic intrusions allow us to propose a provisional
588 age of the Oligocene upper crustal plutonic activity on the Colorado Plateau that lasted ~ 5
589 Ma, between 24.8 ± 0.4 and 29.1 ± 0.3 Ma (Fig. 11).

590 **5.2 Timescales of the construction of the Mount Hillers Intrusive Center**

591 In this section, our U-Pb dataset is used to discuss the constraints on (1) the duration
592 of MHIC emplacement, (2) the respective timing of satellites versus central intrusion, and (3)
593 the magmatic fluxes associated to the MHIC emplacement.

594 Concerning the duration of emplacement of the MHIC, we must consider if our
595 sampling covers all phases of MHIC construction. This question is complex, but field
596 evidence provides some constraints. Our structural work shows that the actual summit of the
597 MHIC is very close to its upper contact (Figure 3b in Horsman et al., 2016). As the older
598 emplaced injections could constitute a rigid barrier which impedes the passage of younger
599 magma bodies (e.g. Menand, 2008), a construction by under accretion is the most simple
600 model, and the Mount Hillers summit may then represent the oldest emplaced magmas. But
601 under accretion is not the only model, as shown by our structural data on satellite intrusions,
602 where we have found both under accretion (Black Mesa bysmalith: Habert and Saint-Blanquat
603 2004, Saint-Blanquat et al., 2006), upper accretion (Maiden Creek sill: Horsman et al., 2005),
604 and more complex patterns (Trachyte Mesa laccolith: Morgan et al., 2008).

605 Some of our samples likely record the beginning of MHIC construction. For example,
606 sample CS-02 from the Copper Spring area in the southern margin of the MHIC was collected
607 in a concordant sill located within rotated subvertical host strata. Our structural mapping
608 shows that it is really a concordant sill and not a vertical dike (Hunt, 1953; Jackson and
609 Pollard, 1988 and 1990; Horsman et al., 2016). It has therefore likely undergone a rotation
610 after its emplacement and crystallization, due to the formation of the central intrusion growth.
611 Paleomagnetic data from several steeply dipping sills in this same portion of the MHIC
612 suggest they were emplaced while host strata were subhorizontal, implying that the
613 underlying main laccolith grew later (Jackson & Pollard, 1988). Consequently, this sample
614 can reasonably be interpreted as very early stage of the formation of the MHIC.

615 A second important point to consider is the respective timing of satellites versus
616 central intrusion emplacement. Our field data and interpretation of the map pattern at the scale
617 of the Henry Mountains (Horsman et al., 2010 and 2016) suggest that the five intrusive
618 centers can be collectively interpreted as a series of snapshots of the progressive growth of an

619 igneous system in the shallow crust, and this is confirmed by geochronological data (see
620 above). Moreover, the two smallest volume intrusive centers, Mounts Ellsworth and Holmes,
621 are entirely constituted of a central laccolithic intrusion with no evidence for peripheral
622 satellite intrusions. A logical conclusion that can be drawn is that the construction of each
623 center begins with an early sill / dike network that is rotated by growth of the central
624 intrusion, and that the distant satellite intrusions are late in the construction of each center. A
625 physical explanation of this interpretation was provided by Horsman et al (2016) writing that
626 “the emplacement of satellite intrusions proceeds only when the main laccolithic dome has
627 grown enough that further bending and uplift of host rock to accommodate emplacement of
628 new magma becomes mechanically unfavorable compared to injection around the heavily
629 fractured lower hinge region. This general spatial and temporal pattern was observed by
630 Henry et al. (1997) in the Solitario lacco-caldera of the Trans-Pecos region. There
631 emplacement of satellite intrusions occurred during the final stage in the episodic magmatic
632 history of the intrusive center and was localized in the vicinity of the ring fault bounding an
633 earlier caldera.”

634 To summarize, field relationships and structural data show that our sample collection
635 spans the earliest (Copper Spring sill rotated to vertical after emplacement, Mount Hillers
636 summit ridge) and latest (the several satellite intrusions, e.g. Trachyte Mesa) emplaced
637 portions of MHIC construction. We are therefore confident that our sampling is representative
638 of the whole MHIC emplacement. Despite its complex map pattern and 3-d geometry, the
639 MHIC can be considered as a “single” pluton, and it corresponds to a single magmatic event,
640 as suggested by the continuity of oscillatory zoning observed in zircon rims (this work, Fig. 4
641 and section 4.1).

642 The absence of significant age differences between samples together with the lack of
643 correlation between inferred emplacement sequence and mean crystallization age (e.g. some

644 samples have older mean ages than CS-02, and younger mean ages than TM-02) suggests the
645 absolute duration of pluton emplacement is likely shorter than individual age uncertainties.
646 Therefore, we interpret our population of mean crystallization ages to represent a near-random
647 sampling of the mean crystallization age of the entire pluton within uncertainties, exactly the
648 same way a population of individual zircon ages represent a near-random sampling of the
649 mean crystallization age of a single sample. This is confirmed by the MSWD value of 0.96
650 obtained when calculating the mean age of our sample population, which indicates that
651 statistically it represents a single event and near-random dispersion with respect to individual
652 sample age uncertainties.

653 In this case, it is relevant to calculate the uncertainty on the mean crystallization age of
654 the entire pluton (25.97 Ma) using 2 standard error of the mean (0.22 Ma). We therefore
655 propose this value of 220 kyr as the possible duration for the crystallization of all our samples,
656 i.e. of the MHIC, including all the satellite intrusions. Although this is obviously the
657 minimum duration we can calculate from this dataset, it is entirely possible the actual duration
658 of pluton construction was shorter than 220 kyr. The maximum duration is, on the other hand,
659 given by +/- 2 SD of the population, i.e. 640 kyr. Given the 2000 meters of vertical uplift
660 associated to the MHIC emplacement (Jackson and Pollard, 1988 and 1990, Horsman et al.,
661 2016), these durations suggest an averaged vertical intrusion growth rate around 0.3-0.9
662 cm/yr.

663 The total igneous volume of the MHIC is estimated to be around 35 km³ (Jackson and
664 Pollard, 1988; Horsman et al., 2016). With a 220 - 640 ka duration of construction, we obtain
665 a averaged magmatic flux –taking into account both the real duration of magma injection plus
666 the repose time between the successive injections – between 0.5 and 1.6*10⁻⁴ km³/yr for the
667 MHIC. Comparison with other plutonic systems cannot be easily established owing to the low
668 number of available similar complete datasets, i.e. examples of plutons for which we have

669 both a reasonably constrained estimation of the volume and a geochronological dataset
670 constrained by a structural model of emplacement. Most of the available complete dataset are
671 represented in Figure 12. Our results are consistent with other similarly studied plutons,
672 notably with the Torres del Paine pluton, a well-studied Miocene intrusion from southern
673 Patagonia which has a volume of 88 km^3 and was emplaced episodically in $162 \pm 11 \text{ ka}$ (Fig.
674 12) (Michel et al., 2008; Leuthold et al., 2012), for an average magma flux on the order of 10^4
675 km^3/yr .

676 At the scale of the satellite intrusions, we dated two samples of the Black Mesa and
677 Sawtooth Ridge intrusions, one at the base and one at the top of each intrusion. For both
678 intrusions, the two ages are indistinguishable within analytical uncertainties. A consequence is
679 that the U-Pb in-situ dating method applied to these zircon grains is unable to distinguish the
680 successive magma injections at this timescale of $\sim 220 \text{ ka}$. The imprecision of this duration
681 estimate is entirely related to analytical uncertainties. Another approach must therefore be
682 used to determine the duration of emplacement. Detailed structural work on the Black Mesa
683 satellite intrusion, along with thermal modelling and microstructural observations (Habert and
684 Saint-Blanquat, 2004; Saint-Blanquat et al., 2006; Saint-Blanquat et al., 2011), suggests this
685 small intrusion of 0.6 km^3 was likely emplaced very short time on the order of 100 years. In
686 addition, Giorgis et al. (2019) used paleomagnetic techniques and examined variation in
687 position of the geomagnetic (paleo) pole of the individual sheets comprising the Trachyte
688 Mesa (TM) laccolith, which has an estimated igneous volume of 0.05 km^3 . If this paleosecular
689 variation from sheet to sheet in the Oligocene is assumed to occur at the same rate as secular
690 variation in the Holocene, then the Trachyte Mesa laccolith was emplaced in a minimum of
691 750 years. Black Mesa and Trachyte Mesa are two small plutons of similar volume and
692 composition, emplaced at the same time and in the same context. Synthesizing these two
693 estimates, one with a maximum duration (100 yrs, Black Mesa) and the other with a minimum

694 duration (750 yrs, Trachyte Mesa), we can propose that the order of magnitude of the
695 construction duration of these small satellite intrusions of less than one cubic kilometer could
696 be in the order of 100 to 1000 years. This corresponds to a magmatic flux between $0.7 \cdot 10^{-4}$
697 (TM) and $6 \cdot 10^{-3}$ (BM) km^3/yr . This flux is quite similar to the flux we propose at the MHIC
698 scale ($0.5\text{-}1.6 \cdot 10^{-4}$ km^3/yr). This suggests the MHIC grew in at a relatively consistent rate
699 throughout its emplacement.

700 Figure 12 illustrates the magmatic fluxes obtained for active intrusive bodies
701 constrained through geophysical data, and also fossil plutons for which we have a complete
702 construction model (from beginning to end), a geochronological dataset constrained by this
703 structural model, and a good estimate of the volume. There are not many plutons and active
704 intrusive bodies for which we have all this information, but we can nevertheless observe a
705 correlation between magma fluxes and the method used to assess the duration of
706 emplacement. The fluxes estimated with geochronological data are the lowest ($< 10^{-3}$ km^3/yr),
707 the fluxes obtained from geophysical observation of actual living magmatic systems are
708 generally higher ($> 10^{-2}$ km^3/yr), and in between we have the flux obtained from numerical
709 modelling constrained by field relationships (around 10^{-3} to 10^{-1} km^3/yr). This is easy to
710 understand if we consider that the fluxes obtained from present-day living systems likely
711 record a single pulse injection, that is instantaneous on a geological timescale, and that the
712 fluxes obtained from fossil systems by geochronology are average fluxes, which include
713 quiescent periods between injections. The three examples for which numerical modelling was
714 used are intermediate because hypothesis were made about the injection scenario (duration of
715 quiescent periods) in order to satisfy internal structure criteria observed in the field like
716 contact metamorphism intensity and spatial repartition, or textural change associated to
717 internal contacts.

718 The similarity of magma flux across several orders of magnitude of intrusive volume
719 and duration is surprising. Many igneous bodies, across a wide range of spatial and temporal
720 scales, that grow through injection of component magma pulses have a step-wise growth
721 history, with relatively brief periods of injection separated by longer periods of little or no
722 injection (e.g. Saint-Blanquat et al., 2011). When calculating the magma flux for such a
723 pluton, the rate is thus a time-averaged value. In larger intrusions, the component pulses we
724 can resolve with geochronology, structural or petrologic observations, etc. tend to be
725 correspondingly larger. The pulses observable at smaller spatial scales (and operating on
726 shorter temporal scales) tend to be masked at larger spatial scales. The real challenge is now
727 to quantify the duration of magmatic lull between successive injections.

728 This also suggests that the dynamics of present-day magmatic systems can tell us
729 something about the 'instantaneous' dynamics of fossil magmatic systems. A striking example
730 is the construction in 2011 in one month of a 0.8 km³ laccolith similar in shape, volume, and
731 emplacement mechanism (roof lifting) to the Henry Mountains satellite intrusions. This
732 intrusion was emplaced between 200 and 400 m depth in one month, in association with a
733 rhyolitic eruption of the Cordon Caulle volcano (Castro et al., 2016). The associated
734 magmatic flux is therefore in the order of 10 km³/yr (Fig. 12).

735 In light of this evidence, our interpretation of a duration of 220 – 640 kyrs for the
736 emplacement duration of the MHIC may therefore be conservative, even if this does not
737 preclude that the duration of the MHIC construction was shorter than 220 kyr.

738 The high (3-5 orders of magnitude) contrast in magmatic flux between single pulse
739 injections and entire plutons built from multiple pulses separated by magmatic lulls highlights
740 the importance of collecting detailed datasets (geochronology, structural and petrologic
741 observations, etc.) that span the full duration of intrusion emplacement, and to propose careful
742 interpretation of those data in light of the full emplacement history.

743 **5.3 Magmatic sources for the Oligocene Mount Hillers Intrusive Complex**

744 The range in Hf isotopic compositions recorded by the 26 Ma zircon rims allows to
745 discuss the magmatic source(s) involved in the formation of the MHIC. The majority of the
746 $\epsilon\text{Hf}_{(t)}$ varies between +4 and -10, with a few outliers having much more negative values (-17
747 to -24). Most samples exhibit a range between 0 and -10 except the diorites from Cooper
748 Spring which extend to slightly more depleted isotopic signature (CS-02; -2 to +4). The
749 absence of juvenile material at 26 Ma (depleted MORB mantle (DMM) around +18) indicates
750 that either such source was not involved in the formation of the MHIC, or that the mantle-
751 derived signature was strongly overprinted during the formation of the MHIC, possibly during
752 mixing with older crustal material during magma formation. The spread in $\epsilon\text{Hf}_{(t)}$ for the
753 majority of zircon rims in Fig. 10 (+4 to -10) may be explained by re-melting of Proterozoic
754 mafic crust material having variable time-integrated Lu/Hf ratios (0.029 to 0.02; green field of
755 Fig. 9). This mafic crust probably formed during the Proterozoic magmatic events between
756 1.3 and 1.8 Ga (or even older) recorded by the zircon cores in all intrusions. These
757 observations are consistent with the model of Nelson and Davidson (1992), which involves
758 interaction of mantle-derived magmas with Proterozoic mafic continental crust to produce the
759 geochemical and isotopic diversity observed in the Henry Mountains. This agrees with the
760 proposition by Renaudin et al. (2010), who suggested the Mount Hillers microdiorites has an
761 inherited arc-like geochemical signature induced by the melting during the Oligocene of old
762 lower crustal metabasalts emplaced in a Proterozoic active continental margin setting. The
763 removal of the Farallon slab and the resulting heat supplied to the upper mantle and lower
764 crust (Humphreys, 1995; Roy et al., 2009) is a plausible hypothesis as a heat source for the
765 Oligocene magmatism in agreement with the data presented here.

766 In summary, the chemical and isotopic compositions of the zircon rims, which
767 crystallized during the formation of the MHIC, are inherited from their protolith sources,
768 extracted during the multiple Proterozoic magmatic events between 1.3 and 1.8 Ga (or even
769 older) as indicated by the U-Pb ages of zircon cores (Fig. 8b and 9). Most of the zircon rims,
770 and consequently the Mount Hiller microdiorites, were derived from a mafic crust that
771 separated from a 1.3-1.8 Ga depleted-mantle reservoir. A recycled continental crust
772 component (with ~ 0 or negative $\epsilon\text{Hf}_{(t)}$) could have been added in variable amounts to that
773 mantle source to derive all the observed samples.

774 **5.4 Evolution of the Colorado Plateau Proterozoic lithosphere**

775 The U-Pb-Hf data from zircon cores can be used to constrain the formation and
776 evolution of the Proterozoic lithosphere below this part of the Colorado Plateau. Zircons cores
777 with the highest $\epsilon\text{Hf}_{(t)}$ values (+10-12) indicate they were mainly formed within juvenile
778 material extracted from a depleted mantle source whereas zircons cores having sub-chondritic
779 to slightly negative $\epsilon\text{Hf}_{(t)}$ values could have been formed in a source that contains more
780 recycled continental crust (from crustal older material) than depleted mantle materials (Fig.
781 9). The large variations in $\epsilon\text{Hf}_{(t)}$ at a given U-Pb age (e.g. ~ 1.4 Ga) suggest mixing between
782 these two different sources was an important process during Proterozoic magmatic events.
783 The evolution from values typical of the DMM ($\epsilon\text{Hf}_{(t)} \sim +7$ to $+11$) at 1.6 - 1.75 Ga toward
784 more chondritic values ($\epsilon\text{Hf}_{(t)} \sim -1$ to $+7$) at 1.3 - 1.45 Ga in zircon cores indicates a change in
785 source composition through time for the zircon cores. The ca. 1.75 Ga zircons from the oldest
786 Paleoproterozoic protoliths mainly crystallized as juvenile material extracted from a depleted
787 mantle source with little input from a recycled crustal source component, whereas the

788 increasing number of zircon cores with sub-chondritic $\epsilon\text{Hf}_{(t)}$ from the younger Meso-
789 Proterozoic protoliths (1.6 - 1.4 Ga) indicate a source with an increasing contribution of
790 recycled continental material between 1.7 and 1.4 Ga.

791
792 According to numerous previous studies on the nature of the crust below the Colorado
793 Plateau, the Henry Mountains are located within the so-called Yavapai province, a northeast-
794 trending crustal block that was defined as a wide zone of 1.80 to 1.70 Ga dominantly juvenile
795 arc crust that extends through Arizona, SE Utah, NW New Mexico, to Colorado south of the
796 Cheyenne belt (Bowring and Karlstrom, 1990; Karlstrom and Bowring, 1993; Karlstrom and
797 Humphreys, 1998 ; Whitmeyer and Karlstrom, 2007; Johansson et al., 2022). The Yavapai
798 province is described as the product of collisional accretion of a serie of juvenile arcs from
799 1.78 to 1.72 Ga, with an orogenic peak ca. 1.74–1.68 Ga (Yavapai orogeny), that resulted in a
800 progressive amalgamation of Yavapai crust to Laurentia (Karlstrom and Bowring, 1988). On
801 its SE side, the Yavapai province is in contact with the younger Mazatzal province, a 1.7-1.6
802 Ga juvenile arc crust accreted to the margin of southern Laurentia – i.e. to the Yavapai
803 province – during the 1.65-1.60 Mazatzal orogeny (Karlstrom and Bowring, 1988; Whitmeyer
804 and Karlstrom, 2007; Holland et al., 2020).

805 Figure 13 shows a compilation of the U-Pb vs. Lu-Hf data for zircon cores from this
806 study compared to other available zircon or monazite data for the Yavapai and Mazatzal
807 provinces (either magmatic or detrital supracrustal minerals). Except one isolated date at 2.44
808 Ga, the new in-situ U-Pb data for zircon cores range in age from 1.08 Ga to 1.76 Ga (Fig. 6a)
809 and represent two major periods of magmatism. The major frequency age peak is centered
810 between 1.3 and 1.45 (almost 50% of the data; Fig. 6b) with another statistically less
811 important peak between ca. 1.6 Ga to 1.75 Ga.

812 Two observations can be drawn from the new U-Pb and Lu-Hf results:

813 (1) The (lower-middle) Yavapai crust below the MHIC represented by the zircon cores has a
814 complex Paleoproterozoic origin and records both the Yavapai and the younger Mazatzal
815 juvenile arc accretion events with ages between 1.8 and 1.6 Ga as previously recognised in the
816 literature (Bickford et al., 2015). During both periods of accretion/orogeny, juvenile magmas
817 from the depleted mantle were mixed with crustal materials and/or recycling of earlier crustal
818 material, e.g older Yavapai crustal material was likely recycled during the Mazatzal orogeny
819 as indicated by the variation in $\epsilon\text{Hf}_{(t)}$ between 1.6-1.75 Ga. The new U-Pb ages also agree
820 with the few U-Pb ages on zircon cores from La Sal Mountains (Rønnevik et al., 2017), about
821 120 km ENE of the MHIC, interpreted as xenocrysts from the lower crust which yield
822 Proterozoic ages in the range of 1.76 to 1.66 Ga.

823 (2) The dominant age peak in the zircon core dataset is represented by the 1.45–1.3 Ga event.
824 Consequently, the Yavapai crust below the MHIC with its mixed Paleoproterozoic origin was
825 also strongly reworked during the widespread Mesoproterozoic crustal tectono-magmatic and
826 metamorphic event that affected the southern provinces of Laurentia, identified as the Picuris
827 orogeny (Crowley et al., 2006; Daniel et al., 2013). This event has been documented near the
828 boundary between the Mojave/Yavapai (Wooden et al., 2012; Holland et al., 2018) or the
829 Yavapai/Mazatzal provinces (Karlstrom et al., 2002) but its occurrence in the Henry
830 Mountains has not been documented before. The large $\epsilon\text{Hf}_{(t)}$ and Th/U variations in the
831 inherited zircon cores from the MHIC diorites during this period (Fig. 5 and 13) are however
832 very similar to those in metamorphic and magmatic zircons from lower crustal xenoliths
833 (granulites) of similar age (1.36-1.42 Ga) from the Navajo volcanic field, about 200 km south-
834 east from the MHIC near the boundary between Mazatzal and Yavapai provinces ($\epsilon\text{Hf}_{(t)} = -$
835 0.7 to +13.6; Crowley et al., 2006). Although the depth of origin and protoliths of the
836 inherited zircon cores are unknown, the large $\epsilon\text{Hf}_{(t)}$ and Th/U variability around 1.4 Ga may

837 suggest the zircon cores grew from a variety of melts or fluids mainly derived from reworking
838 of older magmatic/metamorphic portions of lower/middle Yavapai or Mazatzal crusts or even
839 older crust ($\epsilon\text{Hf}(t) = +7$ to -1.3) including mafic crust (green field of Fig. 9) but only rare
840 unmodified mantle-derived juvenile melts. The few zircon inherited cores with elevated $\epsilon\text{Hf}(t)$
841 in Figure 13 (>10 ; this study; Crowley et al., 2006) however suggest some rare mantle-
842 derived juvenile melts escaped mixing with Proterozoic crust and played a role during the 1.4
843 Ga magmatic and metamorphic event. These data are also consistent with those on Colorado
844 Plateau mantle xenoliths from the Navajo Volcanic Field (Marshall et al., 2017) showing
845 evidence of resetting of the Sm-Nd isotopic system at 1.4 Ga, providing evidence for the
846 formation of melts with a lithospheric mantle source at this time. Therefore, this intra-cratonic
847 portion of the Yavapai crust below the MHIC requires a mechanism of formation and
848 evolution in which an important magmatic/metamorphic event involved intense
849 reworking/recycling of earlier (lower) Paleoproterozoic crust occurred around 1.4 Ga during
850 anatexis, as previously envisaged for other locations closer to the Mazatzal province (e.g.
851 Mako et al., 2015; Holland et al., 2020). The new data support a model in which heat was
852 supplied by mantle-derived melts ponded at the base of the crust such as during basaltic
853 underplating in response to subduction and could trigger anatexis of the older
854 Paleoproterozoic crust situated above (e.g. Shaw et al., 2005; Crowley et al., 2006; Goodge
855 and Vervoort, 2006; Bickford et al., 2015; Marshall et al., 2017), although a model involving
856 delamination cannot be excluded (Holland et al., 2020).

857 **6. Conclusion**

858 To investigate the spatial and temporal patterns of emplacement within the Mount
859 Hillers intrusive center (Henry Mts, Utah, USA), we used U-Pb dating of zircons from 11

860 samples along a cross section of the intrusion as well as Ar-Ar dating on amphibole
861 phenocryst and K-Ar on the groundmass (mainly feldspars) dating on two samples.

862 (1) U-Pb dating of the zircon rims showing sector zoning allow us to propose an age of
863 25.97 ± 0.11 Ma for the emplacement of the Mount Hillers intrusive center. Since our
864 previous structural work shows that our sample collection is representative of the whole
865 MHIC emplacement, we propose a duration of emplacement around 220 - 640 kyrs. This
866 duration and an estimated volume of 35 km^3 , suggest an average magmatic flux around 0.5-
867 $1.6 \cdot 10^{-4} \text{ km}^3/\text{yr}$ at the scale of the whole MHIC. Magmatic flux for the satellite intrusions are
868 of the same order of magnitude, suggesting the MHIC grew at a relatively consistent rate
869 throughout its emplacement. The time span between the structurally defined oldest and
870 youngest magmatic pulses of two satellite intrusions could not be determined since it lies
871 within analytical uncertainties. The averaged vertical intrusion growth rate during the MHIC
872 emplacement was around 0.3-0.9 cm/yr.

873 (2) The available U-Pb geochronological data on the Henry and La Sal Mountains
874 show that the central Colorado Plateau intrusive event lasted for about 5 My, between 29 and
875 24 Ma, and that the three main intrusive centers of the Henry Mts (Ellen, Pennell and Hillers)
876 were probably emplaced close in time, in 3 Ma, between 28 and 25 Ma, with a progression of
877 magma intrusion from north to south.

878 (3) U-Pb dating of zircon cores from the MHIC yield a range in age from 1.1 Ga to
879 2.45 Ga. The major frequency peak is centered between 1.3 and 1.45, with several minor
880 peaks ranging from 1.45 Ga to 1.75 Ga. The Yavapai and Mazatzal age signatures of 1.8-1.7
881 and 1.7-1.6 Ga respectively are both present but are not the dominant signatures in the dataset,
882 which is the 1.5 – 1.3 Ga event. Consequently, the crust below the MHIC has a mixed
883 Paleoproterozoic Yavapai and Mazatzal ‘juvenile’ signature and was significantly reworked
884 during the Mesoproterozoic crustal tectono-magmatic event.

885 (4) Lu-Hf isotopic analyses on the same zircon cores can be interpreted in terms of an
886 accumulation of underplating mantle-derived material between 1.75 and 1.5 Ga, followed by
887 the input and mixing over time of more and more continental crust between 1.5 and 1.3 Ga.
888 Lu-Hf analyses indicate most zircon rims are consistent with those of the cores and can be
889 derived from a mafic crust separated from a 1.3 - 1.8 Ga depleted-mantle reservoir
890 incorporating variable amount of a recycled continental crust component with time.

891 The uniqueness of our work lies in the composition and texture of the zircons of the
892 Henry Mountains diorites, and their core-rim duality. In fact, our data tell two stories that
893 might seem totally disconnected, that of the Proterozoic lithosphere and that of the Oligocene
894 magmatism of the Colorado Plateau. However, as the U-Pb-Th and Lu-Hf data clearly show,
895 these two stories are coupled: our data document a magmatic legacy spanning 1.5 billion
896 years, and help us to understand and quantify the associated magmatic processes.

897 Our work shows unequivocally how important it is to combine robust geochronology
898 based on careful sampling with relative chronology deduced from field-based structural
899 mapping to evaluate the maximum duration or at least to discriminate temporally the different
900 pulses in a pluton.

901 **Acknowledgements**

902 This study was funded by the CNRS-INSU-3F PULSE project (PI M. de Saint-
903 Blanquat) and supported by the French Government Laboratory of Excellence initiative n°
904 ANR-10-LABX-0006. This is Laboratory of Excellence ClerVolc contribution number 660.
905 This manuscript was considerably improved by the thoughtful reviews of Mark Holland and
906 the careful review and editorial work of Associate Editor Emilie Bruand. We thank Oscar
907 Laurent for discussions about the statistical interpretation of the U-Pb rim data. We thank F.
908 de Parseval for thin section preparation and A.-M. Cousin for her assistance with drawing the
909 figures. S. Nomade is thanked for his help during Ar-Ar analysis at LSCE (Gif/Yvette). The

910 sampling for this project was completed in 2008 by Jean-Louis Paquette and most co-authors
911 of this manuscript. He left us at the beginning of the writing of this article before its first
912 submission. We hope that we have respected his ideas, and that our interpretations have
913 captured the very essence of his high-quality dataset.

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1297 **Figure captions**

1298 Figure 1: location and simplified geologic map of the Henry Mts, modified from Horsman et
1299 al., 2016. Longitude and latitude are in UTM WGS84, 12S zone.

1300

1301 Figure 2: Mount Hillers geologic map with samples location, modified from Horsman et al.,
1302 2016. Longitude and latitude are in UTM WGS84, 12S zone. Circles and squares represent
1303 CGT and FGT respectively.

1304

1305 Figure 3: field view and sample texture. a. general view of the Mount Hillers (MH), with the
1306 location of some of the studied satellite intrusions, note the light-colored rotated (steeply
1307 dipping) Mesozoic sandstone around the Mt Hillers central intrusion ; b. central intrusion
1308 CGT, sample HI-02; note the mafic xenolith ; c. central intrusion FGT, sample HI-04,
1309 summit of the Mt Hillers ; note the late quartz veins; d. Copper Spring satellite intrusion
1310 CGT, sample CS-02 ; e. – Black Mesa satellite intrusion FGT, location close to sample
1311 BM- 03, note the xenolith of sandstone wallrock. Scale bar is 2 cm.

1312

1313 Figure 4: Cathodoluminescence images of representative zircon crystals from the studied
1314 samples. a. large composite core from MC-01; b. small composite core from MC-01; c.
1315 core-free sector-zoned zircon crystal from TM-02; d. large and unzoned zircon core from
1316 CS-02; e. convolute zoning in a large zircon core from MC-01; f. nested complex core
1317 structure from BM-02.

1318

1319 Figure 5: plots of the [Th] (ppm) versus [U] (ppm) data of the analyzed zircons, represented
1320 by sample and separately for cores, rims and the two fine- and coarse-grained textures.
1321 Symbols with white borders are for cores, and with black borders for rims; circles and

1322 squares are for CGT and FGT respectively. At first order, the FGT samples (cores and
1323 rims) and the CGT cores have Th/U ratio > 0.1, and the CGT rims < 0.1, with the
1324 exception of the HI-02 sample.

1325

1326 Figure 6: Terra-Wasserburg plots of the zircon rims ages from the studied samples.

1327

1328 Figure 7: Synthesis of $^{206}\text{Pb}/^{238}\text{U}$ ages measured on the zircon rims. Orange is for CGT and
1329 blue for FGT samples. Bold contours are for Central Intrusion samples.

1330

1331 Figure 8: U-Pb zircon cores data reported in a/ a Tera-Wasserburg U-Pb diagram and b/ a
1332 relative probability plot of the $^{207}\text{Pb}/^{206}\text{Pb}$ apparent ages.

1333

1334 Figure 9: ϵ_{Hf} versus time diagram for the studied zircons. $^{176}\text{Lu}/^{177}\text{Hf}$ ratios for mafic and
1335 average continental crust were reported from Griffin et al. (2004), Blichert-Toft and
1336 Albarède (2008), O'Neil et al. (2012) and reference therein. Grey triangles : data from the
1337 lower crustal xenoliths from the Navajo volcanic field (Crowley et al., 2006). Same
1338 symbology than figure 5

1339

1340 Figure 10 : plot of the ϵ_{Hf} values obtained on the rims of analyzed zircon of the studied
1341 samples, grouped by intrusion except for the central intrusion which contains the two
1342 textures. Same symbology than figure 5.

1343

1344 Figure 11 : Synthesis of U-Pb ages measured on the zircon rims in intrusive rocks from the
1345 Henry and La Sal Mts.

1346

1347 Figure 12 : averaged magmatic flux for the Mount Hillers Intrusive Complex and other
1348 intrusions, plotted against the method used to constrain emplacement time. Only plutons
1349 for which an emplacement model and volume estimate are available are plotted. Mount
1350 Hillers Intrusive Complex: this work; Black Mesa bysmalith: Saint-Blanquat et al. 2006;
1351 Buckhorn Ride sill: Horsman, pers. com.; Papoose Flat pluton: Saint-Blanquat et al. 2001;
1352 Torres del Paine pluton: Leuthold et al. 2012; Monte Capanne pluton: Barboni et al. 2015;
1353 2011 Cordon Caulle laccolith: Castro et al. 2016; Laguna del Maule : Le Mével et al.,
1354 2016.

1355

1356 Figure 13 : comparison between the ϵ_{Hf} versus time data obtained on the analyzed zircon cores
1357 of this study with other similar data from recent bibliography. See text for explanation.

1358

1359 **Tables content**

1360 Table 1: coordinates, structural position, texture and age of all the analysed samples.

1361

1362 **Supplementary material**

1363 Supplementary Figure S1 : [Th] (ppm) versus [U] (ppm) diagram of all the analyzed from all
1364 our samples. In the sample name, “c” is for core “ and “r” for rim. The FGT samples are
1365 in ‘cold’ colors, (mainly blue), and the CGT cores are in warm colors (red, orange,
1366 yellow...). Rims symbols have have a black border, core symbols have a white border.

1367 Supplementary Figure S2 : U-Pb zircon data analyzed in the zircon cores reported in a/ Tera-
1368 Wasserburg U-Pb diagram and b/ a relative probability plot of the $^{207}\text{Pb}/^{206}\text{Pb}$ apparent
1369 ages. All 234 data without filtering.

1370 Supplementary Figure S3 : results of $^{40}\text{Ar}/^{39}\text{Ar}$ dating of hornblende phenocrysts from diorite
1371 BM-01.

1372 Supplementary Figure S4 : Comparison of Ar-Ar and K-Ar results with U-Pb ages on zircon
1373 rims.

1374 Supplementary Table S1: Detail of analytical conditions for U-Pb and Lu-Hf isotope analysis
1375 by *insitu* Laser Ablation ICP-MS. Lu-Hf isotope data on natural GJ-1, 91500 and Mud
1376 Tank zircon reference materials and synthetic zircons doped with hafnium and rare earth
1377 elements (Fischer et al., 2011) are included.

1378 Supplementary Table S2 : Zircon U-Th-Pb data from the analysed zircon crystals obtained by
1379 *in situ* Laser Ablation ICP-MS. c/r is for core / rim.

1380 Supplementary Table S3 : Zircon Lu-Hf isotope data obtained by *in situ* Laser Ablation MC-
1381 ICP-MS.

1382 Supplementary Table S4 : $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar data obtained on hornblende phenocrysts and
1383 groundmass.

1384