

# Lu-Hf analyses of zircon from the Makoppa Dome and Amalia-Kraaipan area: 1 implications for evolution of the Kimberley and Pietersburg blocks of the Kaapvaal Craton.

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- 3 Kaapvaal Craton.
- 4
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#### 10 Abstract

11 Previously dated zircon crystals from the Amalia-Kraaipan granite-greenstone belts 12 and Makoppa Dome were analysed for their Lu-Hf isotopic characteristics to refine 13 the geological evolution of these areas. Samples from the Makoppa Dome, belonging 14 to the Pietersburg Block, largely fall within the epsilon Hf-age range for granitoids 15 from the eastern part of the block. However, the oldest 3.01-3.03 Ga trondhjemitic 16 gneisses show that reworking of juvenile mafic crust started earlier in the western 17 than the eastern part of the block, suggesting a diachronous tectonic evolution. The 18 three granitoids from the Amalia-Kraaipan area fall within the field for Pietersburg and 19 Kimberley block granitoids. Contribution from older crustal material is seen in a 3.08 20 Ga schist, likely derived from a volcanic protolith, from the Madibe Belt, in the far east 21 of the Kimberley Block, with a mantle extraction age of 3.25-3.45 Ga. The data 22 suggest that the Kimberley Block, like the Pietersburg Block, also contains (minor) 23 ancient crustal components, derived from a depleted mantle source prior to 3.1 Ga. 24 The new data suggest that the Kimberley and Pietersburg blocks underwent a very 25 similar Paleo- to Mesoarchean crustal evolution, with a major crust formation event at 26 3.1-3.0 Ga followed by successive crust reworking until 2.77 Ga. Lavas of the 27 Ventersdorp Supergroup, for which zircons from a ca. 2.75 lapilli tuff give  $\varepsilon$ Hfi of +2, 28 are the first evidence of a juvenile source, after 300 Myr of crustal reworking.

29

#### 30 Introduction

The Kaapvaal Craton is one of the better-studied Archean cratons, thanks to its relatively accessible and well-exposed geological record. Its division into four separate terranes or blocks (Eglington and Armstrong, 2004), based on geochronological data, is now widely accepted (Figure 1), with the Swaziland Block having attracted the most academic attention as it hosts the craton's oldest rocks at 3.66-3.70 Ga (Compston and Kröner, 1988; Kröner et al., 1996; Robb et al., 2006; Zeh et al., 2011). Recorded ages are somewhat younger in the Witwatersrand and

38 Pietersburg blocks (Anhaeusser, 2019) at ≤3.34 Ga (Laurent and Zeh, 2015; Poujol 39 and Anhaeusser, 2001). Because of its extensive cover, the Kimberley Block is the 40 least known, and virtually no ages older than ca. 3.2 Ga have been found (Anhaeusser and Walraven, 1999; Cornell et al., 2018; Poujol et al., 2008). The 41 boundaries between the four terranes are based on geophysically defined 42 43 lineaments, which may or may not have any surface expression, as well as 44 recognisable faults and shear zones, and extensions thereof (Eglington and 45 Armstrong, 2004). As such, they are somewhat dependent on changing 46 interpretations of the geophysical data (Corner and Durrheim, 2018), additional 47 geochronological information and also geochemical data. In the latter respect, the 48 development of the past fifteen years of laser ablation multi-collector inductively 49 coupled mass spectrometry (LA-MC-ICPMS), which permits the determination of the 50 Hf isotopic characteristics of the same zircon grains that provide the age of 51 intrusions, needs to be mentioned. Zircon is the most robust carrier of U-Pb age data, 52 and has therefore been the mineral of choice to obtain reliable geochronological 53 information. Zircon's high contents of the element hafnium, a geochemical twin of 54 zirconium, and limited amount of the radioactive parent element lutetium, makes 55 them also the best carrier of Hf isotopic information. As mantle and crust have 56 contrasting Lu/Hf ratios, they develop different Hf isotope ratios over time. Studying 57 the Hf isotopic compositions of dated zircon crystals therefore allows us to test 58 whether intrusions with the same age also have similar magma sources; and whether 59 these sources were juvenile (mantle-derived), or incorporated older crustal materials. 60 As isotopic information, unlike whole rock geochemistry, is only affected by the 61 sources contributing to the magma, irrespective of crystal fractionation, it is a robust 62 test for similarity among rocks of the same age. This technique has been applied 63 successfully to a number of plutons of the Kaapvaal Craton (see overviews in Kröner 64 et al., 2019 and Laurent et al., 2019, and the many works by Zeh and coworkers (e.g. 65 2009, 2011)), but a great number of intrusives of which the age is known has not

been analysed for the Hf isotopic composition. In addition to providing information on the petrogenesis of the igneous rocks from which the zircon grains are derived, establishing an age-Hf isotopic zircon database for the Kaapvaal Craton is also important for the study of detrital zircon in sedimentary rocks, which provides information on the sediments' provenance.

71 To add to the available information on the geological evolution of the Kimberley and 72 Pietersburg blocks and Kaapvaal Craton zircon age-Hf isotopic database, we 73 performed Lu-Hf isotopic analyses on zircon samples of ten igneous rocks from the 74 Amalia-Kraaipan area of the Kimberley Block and the Makoppa Dome of the 75 Pietersburg Block that were analysed for their U-Pb characteristics previously 76 (Anhaeusser and Poujol, 2004; Poujol et al., 2002; Poujol et al., 2008; Poujol et al., 77 2005). Our new data are compatible with the interpretation that the Makoppa Dome is 78 indeed part of the Pietersburg Block, and provides the earliest evidence for reworking 79 of juvenile mafic material in the region, whereas they add to our relatively poor 80 knowledge of the Kimberley Craton. Additionally, these data are compared to the 81 existing detrital zircon database for Archean-Paleoproterozoic Kaapvaal Craton and 82 provide matches for zircon grains from the Witwatersrand Supergroup and Waterberg 83 Group.

84

#### 85 Geological background

86 The geology of the Pietersburg Block has mainly been studied in its eastern part, 87 between the extension of the Palala Shear Zone and the Thabazimbi-Murchison 88 Lineament (Figure 1c), which are interpreted to be the northern and southern 89 boundary, respectively, of the Pietersburg Block (Eglington and Armstrong, 2004). 90 The Southern Marginal Zone of the Limpopo Belt, which is located north of the Hout 91 River Shear Zone (Figure 1c), is also deemed part of the Pietersburg Block 92 (Eglington and Armstrong, 2004). The western part of the block, in which the 93 Makoppa Dome is located, is separated from the eastern part by the ca. 2.05 Ga

94 Bushveld Complex, which straddles the boundary of the Witwatersrand and 95 Pietersburg blocks. In its eastern part, the Pietersburg Block consists of ENE-WSW 96 running greenstone belts (the Murchison, Giyani and Pietersburg belt), with several 97 generations of granitoids. The oldest of these are the Goudplaats-Hout River tonalite-98 trondhjemite-granodiorite (TTG) gneisses at 3.2-3.43 Ga (Laurent and Zeh, 2015). 99 Further TTG intrusions followed from 3.0 to ca. 2.8 Ga, and more K-rich magmatism 100 from 2.9 to 2.67 Ga (see Laurent et al., 2019 for a review). Magmatism has been 101 interpreted to reflect accretion of several arcs, and a >3.2 Ga continental nucleus, to 102 the proto-Kaapvaal Craton, consisting of the Swaziland and Witwatersrand blocks. 103 The Makoppa Dome straddles the boundary between South Africa and Botswana, 104 with an area of ca. 7600 km<sub>2</sub>. The only published work on the area is the paper by 105 Anhaeusser and Poujol (2004), which also provides the ages of the zircon used for 106 the present study. The rocks of the Makoppa Dome are largely obscured by post-107 Mesozoic sediments, but consist of both granitoids and greenstones (Figure 1b). The 108 latter are amphibolites, serpentinite, talc/chlorite schists and banded iron formations. 109 The granitoids, which were the focus of the U-Pb zircon and whole rock geochemistry 110 study by Anhaeusser and Poujol (2004), are the Vaalpenskraal trondhjemite/tonalite 111 granodiorite/monzogranite gneiss, the Makoppa and the Rooibokvlei 112 granodiorite/monzogranite. Intrusion and deformation relationships define the 113 Vaalpenskraal gneisses to be the oldest felsic rocks in the area.

114 The Kimberley Block of the Kaapvaal Craton has outcrops of Archean rocks only in 115 the Kraaipan-Amalia area, and the area around Marydale. Granitoids from the latter 116 area were recently subject of study by Cornell et al. (2018), who reported ages of ca. 117 2.95 to 2.72 Ga, and xenocrysts up to 3.18 Ga. This work also quotes unpublished 118 ages up to 3.28 Ga from basement samples retrieved during diamond mining. This is 119 similar to the ca. 3.25 Ga unpublished ages quoted by Drennan et al. (1990) for 120 areas west of the Colesberg Lineament, which forms the boundary with the 121 Witwatersrand Block. The Kraaipan area contains greenstone outcrops that occur as

122 three discontinuous NNW-trending belts, the Stella, Kraaipan and Madibe belts, from 123 W to E (Brandl et al., 2006). The greenstones of the Amalia area lie along the 124 extension of the Stella Belt to the south (Figure 1a), and contain interbedded 125 pyroclastic rocks; the discontinuous outcrops may represent tectonically juxtaposed 126 slivers (Brandl et al., 2006). Granitoids, some containing greenstone remnants, occur 127 in the Amalia and Kraaipan areas, but intrusive relationships are unclear because of 128 poor exposures. The rocks of the Amalia area are overlain by Ventersdorp 129 Supergroup Lavas, dated at  $2729 \pm 3$  Ma (Poujol et al., 2005).

130

#### 131 Sample description and ages

Table 1 gives an overview of the samples analysed. All background information,including cathodoluminescence images, can be found in the referenced papers.

#### 134 Pietersburg Block

The five samples from the Makoppa Dome, in the western part of the Pietersburg Block, have been described by Anhaeusser and Poujol (2004), and the following is based on their findings. All samples have undergone some degree of sericitisation, but no other evidence of metamorphism was noted, apart from the gneissosity of the oldest samples.

140 Samples MK10 and MK11 were taken from the Vaalpenskraal trondhjemitic gneiss, 141 along the Crocodile River in the north central part of the dome (Figure 1b). The zircon 142 crystals are yellowish to pink in colour, elongated to prismatic, with some rounded 143 edges. Cathodoluminescence imaging showed apparent core-rim structures, with 144 brighter cores and darker rims; rare crystals showed simple igneous zoning. Dating 145 of sample MK10 was done by LA-ICP-MS and yielded a weighted average 207Pb/206Pb age of 3013 ± 11 Ma, measured mostly on the bright cores. This was 146 147 interpreted to represent the age of intrusion. Zircon rims gave a poorly constrained 148 upper intercept age of ca. 2.6 Ga, interpreted to reflect a later metamorphic event.

Sample MK11 was also dated by LA-ICP-MS, but gave poor results with an older age, likely igneous, of  $3034 \pm 64$  Ma, and a likely resetting event at  $2842 \pm 35$  Ma.

Sample MK5 represents the Makoppa granodiorites/monzogranites and was taken near the town of the same name. These relatively large, yellow to amber crystals, showed simple zoning in CL imaging. Zircon crystals from this sample were analysed by ID-TIMS and define an upper intercept age of 2886 +3/-2 Ma, which was interpreted to reflect the intrusive age of this phase.

156 Samples MK2 and MK3 represent the Rooibokvlei granodiorite/monzogranites. MK2 157 yielded pink to metamict zircon grains, of which many showed complex zoning in CL 158 imaging, but few crystals with simple igneous zoning were also present. ID-TIMS 159 dating yielded an upper intercept age of 2777 ± 2 Ma. This was confirmed by LA-ICP-160 MS dating, which yielded an upper intercept age of 2777 ± 35 Ma. Many of the more 161 complexly zoned crystals showed much younger ages, trending towards a lower 162 intercept of ca. 800 Ma. Sample MK3 yielded crystals that were similar in character to 163 those of MK2, and ID-TIMS dating gave an upper intercept age of  $2797 \pm 2$  Ma. This 164 is regarded as the emplacement age of this granitoid.

165

#### 166 *Kimberley Block*

All five samples analysed come from the Kraaipan-Amalia area of the Kimberley
Block. Three of them (Madibe1, MAD1 and KP5; Poujol et al., 2002; Poujol et al.,
2008) come from the Kraaipan area (Figure 1c); these samples show limited
sericitisation and epidotisation (Anhaeusser and Walraven, 1999). Two others (AL3,
BOT1; Poujol et al., 2002; Poujol et al., 2005) come from near Amalia.

Sample Madibe-1 (Poujol et al., 2008) is a lower greenschist-facies quartz-sericite schist that has been interpreted, based on its whole rock geochemistry, as a calcalkaline lava from the Madibe belt in the easternmost part of the Kraaipan area. The sample was taken in the hanging wall of the orebody of the Madibe gold mine. This borehole sample is located very close to the Colesberg Lineament (Figure 1c), which

177 is interpreted to run through Mahikeng (McCarthy et al., 2018). Zircon crystals in this 178 drill core sample were rare, but those present are euhedral and have well-defined 179 oscillatory zoning. Eight concordant SIMS analyses yielded a weighted average 180  $_{207}Pb/_{206}Pb$  emplacement age of 3083 ± 6 Ma, whereas one older xenocrystic grain 181 gave a concordant  $_{207}Pb/_{206}Pb$  date of  $_{3201} \pm 4$  Ma.

Sample KP5 (Poujol et al., 2002), a pink granodiorite, was taken near the Kraaipan railway siding. Zircon crystals are prismatic, and show well-developed zoning in cathodoluminescence (CL) imaging. The ion microprobe analyses gave a weighted mean  $_{207}Pb/_{206}Pb$  age of 2913 ± 17 Ma for the emplacement of this granodiorite, without any evidence of inheritance.

187 Sample MAD1 was taken near the town of Madibogo and consists of a grey 188 granodiorite. Zircon grains look similar to those in KP5, and their ion microprobe 189 emplacement age is also indistinguishable at 2917  $\pm$  9 Ma. Some grains appear to 190 have suffered Pb-loss with 207Pb/206Pb apparent ages down to 2629  $\pm$  23 Ma.

191 Sample BOT1 was taken between Amalia and Schweizer-Reneke (Poujol et al., 192 2005) and consists of a little-deformed accretionary lapilli tuff, which still contains 193 fresh volcanic glass (Jones and Anhaeusser, 1993). Two types of zircon crystals 194 were extracted: prismatic, euhedral zircon with simple, CL-dark internal structures, 195 and smaller, more rounded grains with a very bright CL-response. When analysed by 196 ion microprobe, the latter type gave Mesoproterozoic dates (1038  $\pm$  48 Ma and 1538 197  $\pm$  50), and the former a weighted mean 207Pb/206Pb age of 2754  $\pm$  5 Ma interpreted as 198 the emplacement age.

Sample AL3 (Poujol et al., 2002) was taken to the SSE of Amalia and represents a fine-grained leuco-trondhjemite gneiss, interpreted to be representative of the earliest basement in this area. Zircon crystals are euhedral to subhedral, pink, and CL imaging shows zoning and potential core-rim structure. Ion microprobe analyses, however, show a largely homogeneous age group with a weighted mean  $_{207}Pb/_{206}Pb$ emplacement age of 2939 ± 10 Ma, although Pb-loss towards a lower intercept

around 1.25 Ga was also observed. Only one core gave a near-concordant
 207Pb/206Pb apparent age of 3178 ± 10 Ma.

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208 More detailed descriptions of the samples, as well as CL images of the zircon 209 crystals, are given in the cited publications.

210

#### 211 Analytical techniques

212 LA-MC-ICPMS analyses for Lu-Hf were done on the same mounts that were imaged 213 in the course of the geochronological investigations. The images and age results 214 were used as a guide for the ablations, but not all zircon grains used for the study 215 had been analysed for their U-Pb isotopic characteristics. The 207Pb/206Pb ages 216 quoted in the previous section were used for the calculation of initial isotope ratios. 217 The Lu-Hf analyses were done at the Department of Geology, University of 218 Johannesburg, using a NPII MC-ICP-MS and ASI Resolution laser ablation system. 219 The spot size used was 50-70 µm, and ablations were done at a repetition rate of 6-7 220 Hz; these parameters were adjusted to match the size and expected depth of the 221 domain to be ablated. The fluence was ca. 4.6 J/cm<sub>2</sub>. For details on the data 222 reduction, including interference corrections, see Jacobs et al. (2017). Reference 223 materials analysed during the course of the study gave results within uncertainty 224 (quoted at the 2 sigma level) of published values for 176Hf/177Hf (Mud Tank: 0.282495 225 ± 0.000018, n=16; TEM-2: 0.282658 ± 0.000034, n=13; LV11: 282814 ±0.000016, n= 226 8). Additionally, the quality of the analyses for the unknowns was monitored by 227 measuring their invariant 178Hf/177Hf and 174Hf/177Hf ratios, which yielded averages of 228  $1.467277 \pm 0.000053$  and  $0.008661 \pm 0.000060$ , respectively. All results can be found in Electronic Supplement 1. 229

The measured 176Hf/177Hf ratios for the unknowns were calculated to their initial value using the measured 176Lu/177Hf ratios, a 176Lu decay constant of 1.867\*10-11 year-1 (Scherer et al., 2007) and the emplacement ages obtained during previous studies

(Table 1). The calculations of epsilon Hf were done with a present-day chondritic
176Hf/177Hf value of 0.282785 and 176Lu/177Hf of 0.0336 (Bouvier et al., 2008).
Depleted mantle parameters are 176Hf/177Hf 0.28325 and 176Lu/177Hf of 0.0388,
following Griffin et al. (2000).

237

#### 238 Results

Full results can be found in Electronic Supplement 1; averages are given in Table 1.

#### 240 Pietersburg Block

For trondhjemitic gneiss sample MK10, twelve ablations were performed, with two targeting younger rims. The ten analyses on the igneous cores gave  $_{176}$ Hf/<sub>177</sub>Hf<sub>3013</sub> 0.28094-0.28099 (Figure 2a), corresponding to a  $\epsilon$ Hf<sub>3013</sub> of +3.5 to +5.5 (Figure 2b), with an average (mean) of +4.1 ± 1.2 (2 standard deviations). The two younger rims gave only marginally higher initial Hf isotope ratios.

Ten zircon grains were analysed for the other sample of trondhjemitic gneiss, MK11,

from the same area, and the results are consistent with the other sample, giving an average  $\epsilon$ Hf<sub>3034</sub> of 4.9 ± 1.3.

249 Sample MK5 from the Makoppa monzogranite is represented by ten analyses.

250 176Hf/177Hf2886 varies from 0.28093 to 0.28101, corresponding to εHf2886 of 0 to +3.0,

with an average of  $\pm 1.6 \pm 1.9$ .

Twelve zircon crystals were analysed for the MK3 Rooibokvlei monzogranite. These give  $_{176}$ Hf/ $_{177}$ Hf $_{2797}$  0.28095-0.28105, or  $\epsilon$ Hf $_{27976}$  -1.2 to +2.2, and an average  $\epsilon$ Hf $_{2797}$ +0.1 ± 2.

Ten analyses were done on the other Rooibokvlei monzogranite sample, MK2, of which the eight analyses with igneous ages gave results indistinguishable from sample MK3, with average  $\varepsilon$ Hf<sub>2777</sub> -0.4 ± 1.5. The two areas with younger 207Pb/206Pb apparent ages are indistinguishable in their initial 176Hf/177Hf ratios from the older grains.

260

#### 261 Kimberley Block

For quartz-sericite schist sample Madibe-1, fourteen zircon crystals were analysed, 262 263 with one spot per zircon. This also included the one older zircon xenocryst at 3.2 Ga. 264 Excluding the latter, 12 grains gave initial 176Hf/177Hf values of 0.28077 to 0.28089, 265 which translates into epsilon-Hf<sub>3083</sub> values of -0.8 to +3 (Figure 2a,b). The one dated 266 older zircon gave a lower 176Hf/177Hf3201 of 0.280728, corresponding to  $\epsilon$ Hf3201 = +0.4. One of the undated grains gave a similarly low value, and could therefore also 267 268 represent an older grain. The average of the 12 zircon grains is  $\varepsilon$ Hf<sub>3083</sub> +1.2 ± 3 269 (2SD).

For granodiorite sample KP5, eleven analyses were performed, giving  $_{176}$ Hf/ $_{177}$ Hf $_{2913}$ from 0.28096 to 0.28100, and a range of  $\epsilon$ Hf $_{2913}$  of +1.8 - +4.5. The average is  $\epsilon$ Hf $_{2913}$ of +2.8 ± 1.5.

Fourteen analyses were done on zircon from granodiorite sample MAD1, including two analyses on a single grain, of which the rim had given a younger age. Excluding this grain, twelve analyses gave 176Hf/177Hf2917 from 0.28092 to 0.28099, or  $\epsilon$ Hf2917 of +0.6 - +3.0, resulting in an average  $\epsilon$ Hf2917 of +2.8 ± 1.5, which is indistinguishable from the previous sample. For the grain that had given a ca. 2.63 Ga rim age, both core and rim gave somewhat lower initial Hf isotopic values, indicating that there might have been some overlap between the two domains during the analyses.

For accretionary lapilli tuff sample BOT1 from the Amalia area, thirteen zircon crystals were analysed. Ten of these constitute a homogeneous group, with  $176Hf/177Hf_{2754}$  0.28106-0.28110, or  $\epsilon Hf_{2754}$  of +1.6 - +3.2, with average  $\epsilon Hf_{2754}$  of +2.3 ± 1.0. Three undated grains gave much higher 176Hf/177Hf ratios (0.2817-0.2824) and are assumed to be part of the Mesoproterozoic population (ca. 1-1.5 Ga) described by Poujol et al. (2005). As these analyses cannot give any information on the

Archean evolution of the Kaapvaal Craton, which is the subject of this paper, they willnot be discussed further.

Sixteen grains were analysed from leuco-trondhjemite sample AL3. Thirteen of these cluster at  $_{176}$ Hf/ $_{177}$ Hf $_{2939}$  0.28096-0.28101, corresponding tor  $\epsilon$ Hf $_{2939}$  of +2.4 - +4.4, with an average of +3.2 ± 1. The one older xenocryst gave significantly lower  $_{176}$ Hf/ $_{177}$ Hf $_{3178}$  of 0.28087 ( $\epsilon$ Hf $_{3178}$  = +5). Two undated grains also give substantially lower  $_{176}$ Hf/ $_{177}$ Hf than the main group (0.28084), so zircon grains with older ages could potentially be more common in sample AL3 than detected by Poujol et al. (2002).

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296

#### 297 Discussion

To facilitate the interpretation of the data, the average epsilon Hf values for the ten analysed samples are shown in Figure 3a, together with similarly averaged literature data. The two older xenocrystic cores are shown separately. In this diagram, all other Kimberley Block Hf isotopic data points are from Cornell et al. (2018), whereas the Pietersburg Block data are those used in the recent review paper by Laurent et al. (2019). All references to the literature data are given in Electronic Supplement 2.

304

#### 305 Pietersburg Block

The general geochemistry and ages of the granitoids of the Makoppa Dome in the Pietersburg Block were found to be similar to the data from the area to the east of the Bushveld Complex (Laurent et al., 2019). Our new zircon Hf isotope data confirm this finding for the ca. 2.9-2.8 Ga samples from the Rooibokvlei (MK2, 3) and Makoppa (MK5) granodiorite/monzogranite. These three samples overlap in terms of age and Hf isotopic composition with the various biotite-(muscovite) granites from the eastern part of the Pietersburg Block. The two samples from the Vaalpenskraal trondhjemitic

gneisses are, however, slightly different. Apart from three samples of tonalite-313 314 trondhjemite-granodiorite (TTG) of 3.35-3.25 Ga that have been interpreted to form 315 the nucleus of a separate 'crustal nucleus' (Laurent et al., 2019), the Vaalpenskraal 316 trondhjemite is the oldest TTG in the Pietersburg Block of which Hf isotope data have 317 been obtained. The samples are slightly older than the ca. 2.97 Free State Tonalite 318 of the Rooiwater Complex and Rubbervale felsic volcanics, both in the Murchison 319 Belt, for which the strongly superchondritic data were reported by Zeh et al. (2013). 320 Similarly, the Vaalpenskraal trondhjemitic gneisses also record initial epsilon Hf3.0Ga 321 values of +4 - +5. These age-epsilon Hf values overlap with a single older zircon 322 reported in a 2.88 Ga trondhjemite sampled just north of the Rooiwater Complex by 323 Laurent and Zeh (2015). A slightly older zircon xenocryst (at 3.115 Ga) with an even 324 higher initial epsilon Hf value (+6) was reported by the same authors from a 2.83 Ga 325 biotite granite north of the Hout River Shear zone.

326 The trend in the linear age-epsilon Hf array for the eastern part of the Pietersburg 327 Block has been interpreted by Laurent and Zeh (2015) and Laurent et al. (2019) as 328 reflecting partial melting of depleted mantle at 3.15-2.97 Ga, followed by reworking of 329 the mafic rocks to TTGs at 2.97-2.88 Ga. Subsequently, the TTG-type crust with a 330 176Lu/177Hf ratio of 0.0022 was internally further transformed into grey gneisses and 331 biotite-granites, with only very minor contributions from older crust. Our new data 332 from the Makoppa Dome show that formation of felsic crust (Vaalpenskraal 333 trondhjemite, with SiO<sub>2</sub> contents of 69-75%, Anhaeusser and Poujol, 2004) already 334 started 3.03-3.01 Ga ago. Assuming a mafic protolith with 176Lu/177Hf=0.022, the Hf 335 isotope data give a mantle extraction age of 3.15-3.10 Ga (Figure 3a, Table 1), in agreement with the estimate by Laurent et al. (2019). The three samples from the 336 337 two younger granitoids fall within the 176Lu/177Hf=0.0022 array that envelops the Pietersburg Block intrusives from the eastern side. All five samples fall towards the 338 339 lower part of the array, in agreement with the old mantle extraction age of the earliest 340 samples compared to those from the eastern side of the block. Note that none of the

samples fall below the array, which would reflect a contribution of older continental
crust (Figure 3a). This is in agreement with their distal position relative to the old
continental nucleus on the eastern side, and the lack of older inherited zircon.

344 The average 176Lu/177Hf ratio of the zircon crystals is plotted in Figure 3b (in contrast 345 to the previously discussed 176Lu/177Hf ratios of the protoliths that define the arrays), showing that our samples also plot in the same field as previously analysed zircon 346 347 grains from the Pietersburg Block. The two younger samples, of the Rooibokvlei 348 monzogranite have higher 176Lu/177Hf than the other three samples, which matches 349 their whole rock composition, with Lu concentrations 3-8 times higher in the 350 Rooibokvlei samples (Anhaeusser and Poujol, 2004). This adds to recent discussions 351 whether zircon trace element data can be used to determine the composition of the 352 magma it crystallised from (e.g. Chapman et al., 2016; Reimink et al., 2020). In this 353 case, this appears to hold, on the assumption that the whole rock compositions are 354 representative for the liquid composition.

355 Although a connection between the Murchison Belt Free State Tonalite + Rubbervale 356 Volcanics and the Vaalpenskraal Trondhjemite seemed possible based on the age 357 and Hf isotopic characteristics of the zircons, the zircon 176Lu/177Hf ratios (Fig. 3b) are 358 much higher for the three Murchison Belt samples than for the Makoppa Dome 359 samples. This is a reflection of the whole rock geochemistry, with flat normalised 360 REE patterns for the Rubbervale Volcanics (Schwarz-Schampera et al., 2010), and 361 steeply downward sloping patterns for the Vaalpenskraal Trondhjemite (Anhaeusser 362 and Poujol, 2004). It therefore seems that the Makoppa Dome samples reflect crustal 363 reworking, which must have taken place very shortly after juvenile crust formation, based on the Hf isotopic signature. The Murchison Belt samples, on the other hand, 364 365 are evidence of juvenile crust formation, rather than reworking.

366

#### 367 *Kimberley Block*

368 Sample AL3, a fine-grained trondhjemitic dyke from the Amalia area has an age that 369 is ca. 20 Ma older than the two more K-rich granitoids from the Kraaipan area, MAD1 370 and KP5, but the three samples are indistinguishable in terms of 176Hf/177Hf and 371 176Lu/177Hf (Figure 3a,b). They fall within the same array as the Pietersburg Block 372 intrusives, with epsilon Hf values of +1 to +2 at ca. 2.9 Ga, and also overlap with 373 some of the granitoids from the Marydale area described by Cornell et al. (2018). The 374 one older zircon in sample AL3, at ca. 3.18 Ga, falls slightly off the array for the 375 Pietersburg Block. It plots very close to the depleted mantle line, and therefore gives 376 a mantle extraction age of ca. 3.2 Ga, assuming a mafic protolith.

377 Schist sample Madibe-1, presumably a metamorphosed volcanic rock, has an 378 igneous age of ca. 3.08 Ga, and lies completely off the Pietersburg array, with an 379 initial epsilon Hf value just above 0. If this isotopic signature reflects reworking of 380 mafic crust with 176Lu/177Hf 0.022, then the mantle extraction age is ca. 3.43 Ga 381 (Table 1); this age would fit with 3.43 Ga zircon found in a volcano-sedimentary 382 sample from the same area (Poujol et al., 2008). However, if this is part of a TTG 383 array, with 176Lu/177Hf 0.0022, then mantle extraction would be around 3.25 Ga. Here, 384 it must be noted that the scatter of Hf isotope data for this sample is larger than for 385 the other samples analysed in this study (Fig. 2a), and the data show a rough 386 negative correlation between 176Lu/177Hf ratio and initial 176Hf/177Hf ratio (not shown). 387 As zircons can take up HREE during alteration processes (Pidgeon et al., 2019), it is 388 possible that the spread towards lower 176Hf/177Hf ratios is related to this effect. In 389 that case, the mantle extraction ages quoted here are over-estimates. Either way, the 390 one older grain of 3.2 Ga that was analysed for its Hf isotopic composition actually 391 has a 176Hf/177Hf ratio that is lower than that of the main population, which is the 392 opposite of what would be expected if this zircon had been derived from 3.45-3.25 Ga juvenile crust that was the protolith to the Madibe-1 lava. As such, the one older 393 394 zircon plots close to the data for the Pietersburg 'old continental nucleus' of the 395 Goudplaats-Hout River gneiss, although a single older zircon may be of limited

396 significance. The main zircon population of sample Madibe-1 shows most similarity in 397 terms of its Hf isotopic composition and Lu/Hf ratio to samples from the adjacent 398 Witwatersrand Block (Figure 3a,b), such as the granites studied by Frimmel et al. 399 (2009) from a borehole west of Carletonville. Considering that this is only a single 400 sample, it is hard to say whether this can be interpreted as the Madibe greenstone 401 area having a greater affinity to the Witwatersrand than the Kimberley Block, but, 402 considering its location so close to the Colesberg Lineament, this possibility cannot 403 be excluded.

404 Sample BOT1 also plots away from the other Kimberley Block samples, but now on 405 the young, higher-epsilon Hf side. It shows some similarities in its Hf isotopic 406 composition to the slightly older Pietersburg Block biotite granite samples GH-2 and 407 GHBR-2 analysed by Laurent and Zeh (2015). Its signature is however significantly 408 different from similarly aged granitoids from the Marydale area analysed by Cornell et 409 al. (2018). The 2.75 Ga age of lapilli tuff sample BOT1, interpreted to be part of the 410 greenstone basement, was discussed at length by Poujol et al. (2005), since it 411 appears rather young for the age of the greenstone succession in the area, 412 especially in the light of the ages of the granitoids of 2.8-3.0 Ga. Some granitoids in 413 the Marydale area of the Kimberley Block have provided similar ages, which Cornell 414 et al. (2018) related to crustal melting in connection with plume activity of the 415 Ventersdorp Supergroup lavas. Although the Ventersdorp volcanism was long 416 assumed to have started at ca. 2.71 Ga (Armstrong et al., 1991), more recent work 417 has shown activity at 2791-2779 (Klipriviersberg Group), 2754-2709 (Platberg 418 Group) and 2709-2683 Ma (Allanridge Group) (Gumsley et al., 2020). Indeed, a 419 felsic porphyry sample from the Platberg Group of the Ventersdorp Supergroup in the Amalia area was dated at 2729 ± 3 Ma (U-Pb zircon SHRIMP upper intercept age) by 420 421 Poujol et al. (2005). This porphyry was interpreted to overlie the granite-greenstone 422 succession. It is therefore likely that the lapilli tuffs from which sample BOT1 was 423 derived are also part of the Ventersdorp Supergroup, rather than the greenstone

424 basement. This ties in with the work by de Kock et al. (2012), who sampled 425 accretionary lapilli-bearing tuffs near Taung, 50 km to the SW of sample BOT-1, of 426 the Mohle Formation, which is a local correlative of the Kameeldoorns Formation of 427 the Platberg Group of the Ventersdorp Supergroup. Zircons from these tuffs gave a 428 concordia age of  $2735 \pm 3$  Ma. Although no Hf isotope data are available for the 429 Ventersdorp Supergroup, the Nd isotopic characteristics for the Platberg Group 430 appear to be subchondritic (see Humbert et al., 2019 for an overview of the existing 431 isotope data), which does not agree with the decidedly superchondritic Hf isotope 432 values of the zircon grains of BOT1. Although the Klipriviersberg Group might provide 433 a match with marginally superchondritic Nd isotope values, the age of  $2754 \pm 5$  Ma 434 for BOT1 appears to preclude this. More information on the isotopic composition of 435 the Ventersdorp Supergroup is therefore needed to resolve this matter further. It is, 436 however, the first evidence of tapping of a juvenile source after ca. 300 Myr of crustal 437 reworking in the area.

438

#### 439 Comparison to detrital zircon data

In as far as our new data overlaps with previously published analyses for granitoids from the Kaapvaal Craton, they only broaden the choice of provenance areas for detrital zircon data. However, our data for the Makoppa Vaalpenskraal trondhjemite and Amalia lapilli tuff have quite a distinct age-epsilon Hf signature, and can therefore provide a possible match for detrital zircon grains of which the protosource has remained elusive.

As Figure 4 shows, our three 'uncommon' samples (BOT-1, MK10, MK11) only show limited overlap with published detrital zircon data (see Electronic Supplement 2 for full references of literature data) from Archean successions, the Magaliesberg Formation from the Paleoproterozoic Pretoria Group or the Waterberg Group. However, some overlap is noted between the Vaalpenskraal trondhjemite samples MK10 and 11 and detrital zircon from the Eldorado Reef in the upper part of the

Witwatersrand Supergroup (Koglin et al., 2010). This is in agreement with 452 453 paleocurrent direction from the north and west (Frimmel et al., 2009), and the 454 connection between the Pietersburg and Witwatersrand blocks (Zeh et al., 2013; 455 Laurent et al., 2019) around the time of deposition of the upper Witwatersrand 456 Supergroup at 2.9-2.78 Ga. The characteristics of the accretionary lapilli tuff from the 457 Amalia area provide a match for zircon from the Svaershoek Formation of the 458 Waterberg Group (Andersen et al., 2019). It is however doubtful that this equates to 459 direct derivation of the sediment from these outcrops, considering the depositional 460 age of ca. 2.05 Ga for the Syaershoek Formation, which is 700 Ma younger than the 461 Amalia lapilli tuff. This time gap would leave sufficient time for several cycles of 462 erosion and redeposition to take place. Moreover, if this lapilli tuff indeed belongs to 463 the Ventersdorp Supergroup rather than the greenstone basement, the potential 464 protosource area would have had a large areal extent; and, within analytical 465 uncertainty, the zircon grains from the Waterberg Group also overlap with granitoids 466 from the Pietersburg Block, so this derivation is ambiguous.

467

#### 468 **Conclusions regarding the evolution of the Kaapvaal Craton**

469 Our new data show that the Makoppa Dome is indeed part of the Pietersburg Block, 470 despite being separated from the eastern granitoids by the Bushveld Complex, which 471 itself is obscured by the Paleoproterozoic sedimentary rocks of the Waterberg Group. 472 The Makoppa Dome samples also provide the first Hf-in-zircon evidence that 473 reworking of juvenile mafic material started as early as 3.01-3.03 Ga, immediately 474 after formation of the mafic crust from a depleted mantle source. This is ca. 50 million years younger than what is known for the eastern Pietersburg Block (Laurent and 475 Zeh, 2015; Zeh et al., 2013), where the TTGs of the Groot Letaba-Duivelskloof 476 477 Domain provide the first evidence for this. This could mean that the tectonic scenario 478 sketched in Laurent et al. (2019) is actually diachronous, with an earlier onset of 479 events on the western side of the Pietersburg Block.

480 The data from the three granitoids of the Amalia-Kraaipan area of the Kimberley 481 block fall within the same epsilon-Hf – age space as Pietersburg granitoids – as do 482 the granitoids from the Marydale area analysed by Cornell et al. (2018). Therefore, 483 the Hf isotopic evolution of the two blocks is starting to look remarkably similar, 484 including evidence for the involvement of older crust (at least as old as 3.2 Ga, based 485 on near-concordant analyses of older zircon). The schist sample from the Madibe area could potentially bear evidence of this older crust - although its igneous age is 486 487 ca. 3.08 Ga, the Hf isotopic composition of the zircon necessitates a mantle 488 extraction age of 3.25-3.43 Ga, depending on the assumed protolith. However, 489 another possibility is that the area, which is very close to the Colesberg Lineament, 490 bears a closer resemblance to the Witwatersrand Block, for which an older crustal 491 history is more evident than for either the Kimberley or Pietersburg Block. The 492 previously reported ca. 2.75 age for a lapilli tuff in the Amalia Belt (Poujol et al., 493 2005), which was interpreted as reflecting the age of the greenstone belt, likely 494 reflects magmatism associated with the Ventersdorp Supergroup, although the Hf 495 isotopic signature of the latter is not known, so direct comparisons cannot be made.

496

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504

506 **Figure captions**:

507 Figure 1: Overview location map (a), showing boundaries between the blocks after 508 Eglington and Armstrong (2004); locations for the samples from the Makoppa Dome 509 (after Anhaeusser and Poujol, 2004) in the Pietersburg Block (b) and from the 510 Kraaipan-Amalia area (after Poujol et al., 2002) of the Kimberley Block (c). The white 511 areas in panel (c) are mainly lavas of the Ventersdorp Supergroup. HRSZ = Hout 512 River Shear Zone; TML: Thabazimbi-Murchison Lineament; PSZ = Palala Shear 513 Zone; CL= Colesberg Lineament

514

Figure 2: Obtained Hf isotope data for the Amalia-Kraaipan (triangles) and Makoppa Dome (squares) samples in initial 176Hf/177Hf (a) and epsilon Hf (b) versus age space. All data are calculated for the time of igneous zircon crystallization. The inset shows the data including the younger Archean zircon domains, interpreted to reflect later reworking or Pb-loss. The typical uncertainties (2 SD) are based on multiple analyses of reference materials.

521

522 Figure 3: a. Average  $\varepsilon$ Hfi versus age for the samples from this study (large symbols), 523 together with pluton-averages for published analyses, plus single analyses for 524 inherited (older) zircon grains within the granitoids (references in Electronic 525 Supplement 2). Trendlines for mafic crust (176Lu/177Hf = 0.022) and typical TTG 526 (176Lu/177Hf = 0.0022) are also shown. The depleted mantle line is following Griffin et 527 al. (2000). Note that tuff sample BOT1 is more primitive than any other sample, and 528 likely represents volcanism associated with the Ventersdorp Supergroup. See text for 529 further discussion.

b. Zircon 176Lu/177Hf (pluton averages) versus age for the same samples as in a. Note
that the zircons from the Rubbervale Volcanics and Free State Tonalite from the
Murchison Belt (Zeh et al., 2013) have much higher 176Lu/177Hf than the Makoppa
Dome samples, despite their ages and Hf isotopic compositions being similar. The

534 former are evidence of juvenile crust formation, whereas the latter, together with 535 slightly younger samples of the Groot Letaba-Duivelskloof (GLD) TTGs (Laurent and 536 Zeh, 2015) are a result of crustal reworking.

537

Figure 4: As Figure 3a, but with the addition of detrital zircon data from Archean successions, Waterberg Group and Magaliesberg Formation (see Electronic Supplement 2 for references). Our new Hf isotope data widen the possible provenance areas for Archean sedimentary rocks, and could explain some of the yet unmatched grains in the Eldorado Reef of the Witwatersrand Supergroup and Waterberg Group.

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Figure 2 Elburg & Poujol



Figure 3 Elburg & Poujol



Table 1: Overview of analysed samples.

Sample name Pietersburg B	Area Slock	Reference	Rock type	Age ± 2 SD (Ma)	Type of age	Dating technique	mean <sup>176</sup> Hf/ <sup>177</sup> Hf <sub>i</sub>	mean εHf <sub>i</sub> (± 2 SD)	T <sub>DM</sub> mafic	T <sub>DM</sub> tonalitic
MK10	Makoppa Dome	Anhaeusser and Poujol (2004)	Vaalpenskraal trondhjemitic gneiss	3013 ± 11	wtd. av. 7/6	LA-ICP-MS	0.28096	4.2 ± 1.2	3.15	3.08
MK11	Makoppa Dome	Anhaeusser and Poujol (2004)	Vaalpenskraal trondhjemitic gneiss	3034 ± 64	wtd. av. 7/6	LA-ICP-MS	0.28096	4.9 ± 1.3	3.10	3.07
MK2	Makoppa Dome	Anhaeusser and Poujol (2004)	granodiorite/ monzogranite	2777 ± 2	upper intercep	t ID-TIMS	0.28099	-0.4 ± 1.5	3.34	3.05
МКЗ	Makoppa Dome	Anhaeusser and Poujol (2004)	granodiorite/ monzogranite	2797 ± 2	upper intercep	t ID-TIMS	0.28099	0.1 ± 2	3.31	3.05
MK5	Makoppa Dome	Anhaeusser and Poujol (2004)	granodiorite/ monzogranite	2886 +3/-2	upper intercep	tID-TIMS	0.28097	1.6 ± 1.9	3.26	3.07
Kimberley Blo	ock									
MADIBE1	Kraaipan	Poujol et al. (2008)	quartz-sericite schist core	3083 ± 6 3201 ± 4	wtd. av. 7/6 <sup>207</sup> Pb/ <sup>206</sup> Pb	SHRIMP SHRIMP	0.28083 0.28073	1.2 ± 3.0 0.4 ± 0.9	3.43 3.72	3.25 3.40
BOT1	Amalia	Poujol et al. (2005) Poujol et al	accretionary lapilli tuff grov	2754 ± 5	wtd. av. 7/6	SHRIMP	0.28108	2.3 ± 1.0	3.11	2.93
MAD1	Kraaipan	(2002) Poujol et al	granodiorite	2917 ± 9	wtd. av. 7/6	SHRIMP	0.28096	2.0 ±1.8	3.25	3.08
KP5	Kraaipan	(2002)	pink granodiorite leuco-	2913 ± 17	wtd. av. 7/6	SHRIMP	0.28098	2.8 ± 1.5	3.19	3.05
AL3	Amalia	Poujol et al. (2002)	trondhjemite gneiss core	2939 ± 10 3178 ± 10	wtd. av. 7/6 <sup>207</sup> Pb/ <sup>206</sup> Pb	SHRIMP SHRIMP	0.28098 0.28087	3.2 ± 1.0 5.0 ± 1.0	3.22 3.20	3.08 3.19

wtd. av. 7/6 = weighted average  ${}^{207}$ Pb/ ${}^{206}$ Pb age  $T_{DM}$  = depleted mantle extraction age in Ga; calculated with  ${}^{176}$ Lu/ ${}^{177}$ Hf = 0.022 for mafic protoliths, and 0.0022 for felsic protoliths

	H8	""Hf s	ε '	"H0" 'Hf	SE	""HD" "HI	SE	"HD.,H	SE	~~Lu/~?	f se	"Yb/"7Hf	SE	AGE (years)	Initial ""H0""H	f INITIAL EPSILC	3N average	250	average epsilon H	f 25D epalon i	Hf median i	median epsilon M	f TDM2a (Ga)	TDM25 (G	a) <sup>176</sup> H9 <sup>177</sup> HfDM <sup>176</sup> Lu/ <sup>177</sup> HfDM <sup>176</sup> Lu/ <sup>177</sup> Hfcrust	TDM2a 0.28325 0.0388 0.022	TDM25 0.28325 0.0388 0.0022
MADIBE1-01	0.28	3859 0.00	0008 (	0.008859	0.000008	1.467286	0.000012	1.886852	0.000030	0.0010	0.00000	0.032922	0.000078	3.083E+09	0.280802	0.3	0.280828	8.34057E-05	1.2	3.0	0.280809	0.5	3.43	3.25		3.499	3.255
MADIBE1-08 MADIBE1-11	0.28	224 0.00 220 0.00	0009 0	0.008666	0.000008	1.467275 1.467302	0.000013	1.886802 1.886807	0.000028	0.0008	0.00000	0.022453 0.054102	0.000133 0.000236	3.083E+09 3.083E+09	0.280879 0.280822	3.0 1.0										3.284 3.443	3.182 3.260
MADIBE1-A MADIBE1-B	0.28	2933 0.00 2913 0.00	0010 0	0.008715	0.000011 0.000017	1.467265	0.000014	1.886846	0.000034	0.0007	0.00001	0.023107 0.025872	0.000307	3.083E+09 3.083E+09	0.290891 0.290863	3.4 2.4										3.252	3.165
MADIBE1-C MADIBE1-D	0.28	3872 0.00	0009 0	0.008856	0.000008	1.467283	0.000012	1.886874	0.000026	0.0011	0.00000	0.038333	0.000099	3.083E+09 3.083E+09	0.290809	0.5										3.480	3.278
MAD(BE1-E MAD(BE1 E	0.28	3848 0.00	0008 0	0.008869	0.000008	1.467252	0.000010	1.886811	0.000022	0.0010	0.00000	0.031665	0.000090	3.083E+09	0.290789	-0.2										3.535	3.305
MADIBEI-P MADIBEI-G	0.28	227 0.00	0010 0	0.008958	0.000009	1.467290	0.000012	1.886772	0.000034	0.0008	0.00000	0.028802	0.000123	3.083E+09	0.280880	-0.5										3.263	3.181
MADIBE1-1 MADIBE1-L	0.28	3885 0.00 2913 0.00	0010 0	0.008649 0.008646	0.000009	1.467274 1.467303	0.000013	1.886826 1.886817	0.000027	0.0014	0.00002	0.050544 0.041687	0.000525	3.083E+09 3.083E+09	0.290801 0.290840	0.2										3.504	3.290
MADIBE1-K-core MADIBE1-J	0.280	1802 0.00 1797 0.00	0010 0	0.008655	0.000012 0.000010	1.467271 1.467277	0.000016	1.896847 1.896817	0.000033	0.0013	0.00005	0.047083 0.039394	0.001760	3.083E+09 3.201E+09	0.280724 0.280728	-2.5										3.718	3.395
BOT1-01 BOT1-A	0.28	222 0.00	0009 0	0.008670	0.000012 0.000010	1.467301 1.467276	0.000012	1.886867	0.000025	0.0029	0.00001	0.109723 0.119893	0.000570 0.000196	2.754E+09 2.754E+09	0.281069	2.0	0.251076	2.83753E-05	2.3	1.0	0.281077	2.3	3.11	2.93		3.132	2.939
BOT1-B BOT1-C	0.28	209 0.00	0010 0	0.008865	0.000012	1.467274	0.000012	1.886847	0.000027	0.0023	0.00000	0.088091	0.000155	2.754E+09 2.754E+09	0.251055	2.7										3.080	2.913
BOT1-D	0.28	199 0.00	0013 0	0.008685	0.000014	1.467322	0.000014	1.886851	0.000031	0.0027	0.00002	0.096995	0.000346	2.754E+09	0.281056	1.6										3.168	2.956
BOT1-F	0.28	246 0.00	0011 0	0.008632	0.000013	1.467292	0.000013	1.886801	0.000029	0.0035	0.00000	0.144254	0.000329	2.754E+09	0.251050	1.7										3.159	2.952
BOT1-H BOT1-I	0.28	178 0.00	0012 0	0.008717	0.000012	1.467346	0.000018	1.886918	0.000026	0.0017	0.00001	0.065582	0.000122	2.754E+09 2.754E+09	0.281086	2.6										3.085	2.916
BOTI-L BOTI-J	0.28	181 0.00	0017 0	0.008685	0.000016	1.467289	0.000023	1.886877	0.000034	0.0019	0.00004	0.056612	0.001310	2.754E+09 2.754E+09	0.281079	2.4										3.104	2.925
8011-K 8071-M	0.282	1750 0.00	0010 0	0.008705 008653328	0.000010	1.467299	0.000015	1.886930	0.000033	0.0005	0.00001	0.017131 0.03511386	0.000188	2.754E+00 2.754E+00	0.282392	42.1 24.5											
MAD1-A MAD1-B	0.28	013 0.00	0013 0.0	008660115	0.0000117	1.467303	0.0000158	1.886823	0.000033	0.0003	0.00000	0.01465444 0.03208008	0.00028	2.917E+09 2.917E+09	0.280994	3.2	0.280961	4.96988-05	2.0	1.8	0.280958	2.3	3.25	3.08		3.156	3.034
MAD1-C MAD1-D	0.28	2958 0.00	0009 0.0	008671111	0.00000831	1.467317	0.0000131	1.886959	0.0000283	0.0003	0.00000	0.01197282	0.000102	2.917E+09 2.917E+09	0.280970	2.3										3.221	3.065
MAD1-E	0.28	2987 0.00	0009 0.0	008665994	0.00000937	1.467286	0.0000115	1.886794	0.0000246	0.0012	0.00001	0.0520325	0.000426	2.917E+09	0.280922	0.6										3.358	3.133
MAD 1-P MAD 1-G	0.28	1022 0.00	0013 0.0	008671968	0.0000123	1.467274	0.0000175	1.886883	0.000037	0.0006	0.00000	0.02296585	0.000152	2.917E+09	0.280986	2.9										3.109	3.040
MAD1-H MAD1-I	0.28	2965 0.00	0010 0.0	008665103	0.0000107	1.467308	0.0000141	1.886885	0.0000309	0.0005	0.00000	0.01720286	0.0000122	2.917E+09 2.917E+09	0.280955	1.8										3.263	3.087
MAD1-J MAD1-K	0.28	035 0.00	0015 0.0	008625743	0.000015	1.467235	0.0000181	1.886839	0.0000388	0.0012	0.00002	0.05037008	0.000961 0.000163	2.917E+09 2.917E+09	0.280968	2.3										3.227	3.069
MAD1-L MAD1-15-CORE	0.28	2995 0.00 1878 0.00	0009 0.0	008693356	0.00000941	1.467259	0.0000128	1.886815	0.0000308	0.0003	0.00000	0.01204885	0.0000748	2.917E+09 2.917E+09	0.280977	2.6										3.204	3.057
MAD1-15.RM KP5.01	0.28	957 0.00	0010 0.0	008851547	0.00000891	1.46727	0.000012	1.88678	0.0000278	0.0008	0.00000	0.03149061	0.000183	2.629E+09 2.913E+09	0.280918	-62	0 280985	4 330378-05	2.8	15	0 280983	27	3.19	3.05		3.704	3.154
KPS-A voc p	0.28	2993 0.00	0012 0.	00862756	0.0000124	1.467244	0.0000152	1.886796	0.0000343	0.0005	0.00000	0.02052981	0.000064	2.913E+09	0.290967	2.1						-				3.236	3.071
KP5-C	0.28	013 0.00	0013 0.0	008640955	0.0000135	1.467279	0.0000173	1.886842	0.0000375	0.0008	0.00001	0.0327433	0.000467	2.913E+09	0.290970	23										3.226	3.065
KP5-E	0.28	2215 0.00	0010 0.0	008628596	0.0000103	1.467261	0.0000128	1.88682	0.0000298	0.0005	0.00000	0.02235855	0.000215	2.913E+09	0.280964	2.0										3.259	3.083
KPS-F KP5-G	0.28	1047 0.00	0011 0.0	008634253 008520501	0.0000102	1.467257 1.467199	0.0000139	1.886743 1.8867	0.0000312 0.000034	0.0008	0.00001	0.03500648	0.000232 0.00067	2.913E+09 2.913E+09	0.281004 0.280963	3.5										3.130 3.190	3.020 3.049
KP5-H KP5-I	0.28	1010 0.00	0010 0.0	008661451 008496207	0.00000995	1.467319	0.0000147	1.88693	0.0000306	0.0005	0.00000	0.02264225	0.000218 0.000474	2.913E+09 2.913E+09	0.290990 0.281035	2.6										3.198	3.053
KPS-J AL3-13CORE	0.28	015 0.00	0012 0.0	008853422	0.0000133	1.467322	0.0000162	1.886862	0.0000337	0.0004	0.00001	0.01902001	0.000357	2.913E+09 2.939E+09	0.290992 0.290981616	3.0	0.280981	2,936196-05	3.2	1.0	0.280979	3.2	3.22	3.08		3.165	3.036
AL3-01CORE	0.28	007 0.00	0011 0.0	008656562	0.0000112	1.467276	0.0000137	1.886827	0.0000342	0.0009	0.00000	0.03105382	0.000142	2.939E+09	0.280957313	2.4										3.232	3.083
AL3-A	0.28	030 0.00	0008 0.1	008682347	0.00000777	1.467282	0.0000106	1.886879	0.0000249	0.0009	0.00002	0.03045036	0.000779	2.939E+09	0.280979174	3.2										3.171	3.053
AL3-0	0.28	1041 0.00	0007 0.1	008658987	0.00000588	1.467257	0.00000988	1.886829	0.0000204	0.0010	0.00001	0.03363031	0.000355	2.939E+09	0.280982549	3.3										3.152	3.045
AL3-E AL3-F	0.28	1048 0.00	0005 0.0	008654814	0.00000655	1.467293	0.0000107	1.886843	0.0000193	0.0013	0.00000	0.02873864	0.000962	2.939E+09 2.939E+09	0.280974203 0.280981044	3.0										3.185	3.059
ALS-G ALS-H	0.28	1059 0.00	0013 0.0	008713671 .00867414	0.0000014 0.00000692	1.467328 1.467284	0.0000176	1.886766 1.886856	0.0000365	0.0008	0.00000	0.02928768 0.03631203	0.000122 0.0000443	2.939E+09 2.939E+09	0.281014701 0.280967881	4.4										3.071 3.146	3.004 3.041
AL3-1 AL3-J	0.28	040 0.00	0009 0.1	008696171 008655202	0.00000925	1.467277	0.0000138 0.0000141	1.88688 1.886762	0.0000313 0.0000291	0.0008	0.00003	0.02754151 0.0361459	0.00118	2.939E+09 2.939E+09	0.280997231 0.280972008	3.8										3.120 3.191	3.028
AL3-L AL3-C-core	0.28	1018 0.00	0009 0.1	008657296	0.00000735	1.467272	0.0000119	1.886826	0.0000229	0.0009	0.00001	0.02939025 0.119943	0.0003	2.939E+09 2.939E+09	0.280968808 0.280843823	2.8										3.200	3.067
AL3-K-core AL3-12	0.280	1958 0.00 1976 0.00	0007 0.0	008673709 008712668	0.00000789	1.467307	0.00000976	1.886932 1.886898	0.0000211	0.0020	0.00001	0.05622789 0.0635719	0.000377 0.000577	2.939E+09 3.178E+09	0.280843053 0.280870757	-1.7 5.0										3.552	3.240
MK11-02CORE MK11-A	0.28	021 0.00	0010 0.	00865807	0.0000107 0.0000147	1.467252 1.467285	0.0000128	1.886808	0.0000323	0.0008	0.00000	0.03311846 0.05280675	0.000108	3.034E+09 3.034E+09	0.280971777 0.280932937	5.2 3.5	0.250964	3.526398-05	4.9	1.3	0.280954	4.9	3.10	3.07		3.082 3.191	3.057
MK11-B MK11-C	0.28	053 0.00	0011 0.	00871028	0.0000108	1.467285	0.0000129	1.886799	0.0000316	0.0010	0.00001	0.04195169 0.02588409	0.000409	3.034E+09 3.034E+09	0.280992076 0.280974024	5.9										3.025	3.029
MK11-D MK11-F	0.28	015 0.00	0010 0.0	008637293	0.00000983	1.467288	0.0000137	1.886901	0.0000269	0.0009	0.00001	0.03306196	0.000412	3.034E+09 3.034E+09	0.280959598	4.7										3.116	3.074
MK11-F	0.28	022 0.00	0013 0.0	008665755	0.0000138	1.467271	0.0000146	1.886941	0.000036	0.0012	0.00000	0.03959787	0.0000923	3.034E+09	0.290953943	4.5										3.132	3.082
MK11-H	0.28	045 0.00	0009 0.1	008665337	0.00000975	1.467279	0.0000124	1.886888	0.0000276	0.0011	0.00000	0.03793004	0.00011	3.034E+09	0.290961623	5.5										3.054	3.044
MKS-A	0.28	2993 0.00	0012 0.0	008653005	0.0000101	1.46729	0.0000138	1.886771	0.000032	0.0008	0.00001	0.02834525	0.000369	2.886E+09	0.28094989	0.9	0.250959	5.24925E-05	1.6	1.9	0.280967	1.5	3.26	3.07		3.314	3.095
MK5-D MK5-C	0.28	1007 0.00	0008 0.0	008669968	0.00000818	1.467268	0.0000134	1.886875	0.0000285	0.0006	0.00000	0.02193006	0.000182	2.886E+09	0.280973139	1.7										3.140	3.014
MKS-D MKS-E	0.28	1060 0.00	0010 0.1	008714261	0.00000948	1.467303	0.0000134	1.886865	0.0000286	0.0012	0.00000	0.04238175 0.02514613	0.000425	2.886E+09 2.886E+09	0.280996649	2.5										3.185	3.032
MK5-F MK5-G	0.28	2222 0.00	0010 0.0	008643025 008681263	0.000000957	1.467269	0.0000122 0.0000143	1.886876	0.0000277	0.0008	0.00000	0.03034146 0.02829921	0.000132 0.000213	2.886E+09 2.886E+09	0.280955479 0.280997515	1.1										3.299	3.055
MKS-H MKS-I	0.28	2994 0.00 1083 0.00	0011 0.0	008647666	0.0000106	1.46725	0.0000145	1.886825	0.0000295	0.0008	0.00000	0.03177566 0.08419213	0.000138	2.886E+09 2.886E+09	0.280947312 0.280961851	0.8										3.322 3.281	3.099
MKS-J MK3-M	0.28	0072 0.00	0011 0.	00859856	0.0000112	1.467246	0.0000137	1.886839	0.0000317	0.0008	0.00000	0.03130875	0.0000679	2.886E+09 2.797E+09	0.280925414 0.280964873	0.0	0.280987	5.7418E-05	0.1	2.0	0.280985	0.0	3.31	3.05		3.383 3.376	3.130 3.080
MICS-A MICS-B	0.28	1063 0.00	0011 0.0	008680162	0.0000114	1.467278	0.0000145	1.886789	0.000033	0.0014	0.00001	0.05252635	0.000501	2.797E+09 2.797E+09	0.290967879 0.290991772	0.1										3.311	3.049
MK3-C MK3-D	0.28	011 0.00	0008 0.0	008827835	0.00000749	1.467243	0.0000108	1.886843	0.0000255	0.0011	0.00002	0.03929636	0.000634	2.797E+09	0.290949907	-1.2										3.418	3.101
MKG-L MKG-E	0.28	102 0.00	0009 0.1	008862932	0.00000883	1.467295	0.0000112	1.886922	0.0000218	0.0024	0.00003	0.09101119	0.00107	2.797E+09	0.280974915	-0.3										3.348	3.067
MG-F	0.28	000 000	0010 0.0	008893788	0.0000101	1.467262	0.0000122	1.886887	0.000025	0.0024	0.00001	0.08136618	0.000388	2.797E+09	0.280958268	-0.9										3.394	3.009
MK3-G MK3-H	0.28	169 0.00	0007 0.0	008674303	0.00000113	1.467277	0.0000126	1.886885	0.00002273	0.0013	0.00002	0.08349571	0.000145	2.797E+09 2.797E+09	0.281017843 0.281046352	1.2										3.227	2.965
MK3-I MK3-J	0.28	133 0.00	0009 0.	00864061	0.0000101	1.467215	0.0000119 0.0000105	1.886821 1.886908	0.0000275 0.0000249	0.0022	0.00001	0.0820808	0.000326	2.797E+09 2.797E+09	0.281017465 0.280991098	1.2										3.228 3.302	3.005
MK10-04-02 MK10-A	0.28	1018 0.00	0008 0.0	008671822	0.00000807	1.467265 1.467301	0.0000116	1.886851 1.886834	0.0000241 0.000027	0.0011	0.00000	0.04382395 0.04682708	0.000202 0.000147	3.013E+09 3.013E+09	0.280955105	4.1	0.280958	3.46384E-05	4.2	1.2	0.280959	4.2	3.15	3.08		3.153 3.129	3.082
MK10-B MK10-C	0.28	1006 0.00	0008 0.0	008859644	0.00000905	1.467261	0.0000117	1.88685	0.0000249	0.0010	0.00001	0.04195067 0.08625252	0.000443	3.013E+09 3.013E+09	0.280947841 0.280964919	3.8										3.173	3.092
MK10-E	0.28	015 0.00	0013 0.0	008835829	0.0000123	1.467302	0.000015	1.886894	0.0000322	0.0015	0.00001	0.05525993	0.00044	3.013E+09	0.280929895	3.2										3.223	3.116
MK10-G MK10-I	0.28	014 0.00	0009 0.1	008890074	0.00000932	1.467283	0.0000118	1.886852	0.000025	0.0005	0.00001	0.03672857	0.000284	3.013E+09 3.013E+09	0.280958308	4.2										3.144	3.077
I-DEXMA L-DEXMA	0.28	0.00 0.00	0009 0.0	008658589	0.00000872	1.467285	0.0000112	1.8869	0.0000267	0.0010	0.00001	0.04199073 0.08754873	0.000306	3.013E+09 3.013E+09	0.28036446	4.2										3.141 3.127	3.069
MK10-K <u>MK10-04-02-bis</u>	0.28	1113 0.00	0012 0.0	00868212	0.0000113	1.467342 1.467233	0.0000175 0.0000146	1.886888 1.886767	0.0000322 0.0000322	0.0008	0.00001	0.02856003	0.000259 0.000261	3.013E+09 2.615E+09	0.280938711 0.281056035	3.5										3.199	3.104
AK(10-14 MK2-13.1	0.28	001 0.00	0010 0.0	006656418	0.00000922	1.467234 1.467285	0.0000135	1.886828 1.886875	0.0000291	0.0007	0.00000	0.02412591	0.0000448	2.592E+09 2.777E+09	0.280965818	-0.4	0.280986	4.26047E-05	-0.4	1.5	0.280984	-0.4	3.34	3.05		3.339	3.091
MK2-13.2 MK2-A	0.28	139 0.00	0011 0.0	008865703	0.0000114	1.467234	0.0000143	1.88686	0.000031	0.0015	0.00001	0.05592822 0.1009259	0.000302	2.777E+09 2.777E+09	0.281024041	1.0										3.233 3.310	3.000
MR2-9 MR2-8	0.28	1006 0.00	0008 0.	00865222	0.00000752	1.467252	0.0000115	1.886784	0.0000257	0.0007	0.00002	0.02671534	0.000708	2.777E+09 2.777E+09	0.290967457	-1.1										3.392	3.078
MC2-B	0.28	1096 0.00	0012 0.0	008687851	0.0000127	1.46726	0.0000143	1.88686	0.0000324	0.0021	0.00002	0.08219682	0.000742	2.777E+09	0.290962523	-0.5										3.350	3.057
MK2-0	0.28	1033 0.00	0010 0.0	008652979	0.0000102	1.467272	0.0000124	1.886811	0.0000268	0.0014	0.00002	0.04856023	0.00062	2.777E+09	0.290960636	-1.3										3.411	3.087
MR12.1 MR2-12.2	0.28	074 0.00	0014 0.1	008626283	0.0000146	1.467277	0.0000175	1.886826	0.0000469	0.0010	0.00001	0.0510428	0.00046	2.082E+00	0.281018602	-0.4 -15.9										4.024	1045

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	176Hf/177Hf	SE	174Hf/177Hf	SE	178Hf/177Hf	SE	180Hf/177Hf	SE	176Lu/177Hf	SE	176Yb/177Hf	SE	AGE	INITIAL
TRA_Data_39409-MT-1.csv	0.282490	0.000005	0.008656	0.000004	1.467277	0.000009	1.886812	0.000020	0.000017	0.000000	0.000722	0.000006	732000000	0.28249
TRA_Data_39411-MT-2.csv	0.282507	0.000005	0.008671	0.000004	1.467273	0.000008	1.886830	0.000019	0.000011	0.000000	0.000450	0.000003	732000000	0.28251
TRA_Data_39437-MT-03.csv	0.282481	0.000005	0.008651	0.000004	1.467266	0.000009	1.886837	0.000020	0.000011	0.000000	0.000446	0.000003	732000000	0.28248
TRA_Data_39438-MT-04.csv	0.282494	0.000005	0.008663	0.000004	1.467272	0.000009	1.886817	0.000019	0.000028	0.000000	0.001174	0.000003	732000000	0.28249
TRA Data 39442-MT-05.csv	0.282494	0.000005	0.008656	0.000004	1.467275	0.000009	1.886832	0.000021	0.000027	0.000000	0.001145	0.000003	732000000	0.28249
TRA Data 39443-MT-06.csv	0.282497	0.000005	0.008670	0.000004	1.467273	0.000009	1.886822	0.000018	0.000028	0.000000	0.001182	0.000003	732000000	0.28250
TRA Data 39463-MT-07.csv	0.282505	0.000005	0.008666	0.000004	1.467271	0.000010	1.886841	0.000021	0.000025	0.000000	0.001044	0.000003	732000000	0.28250
TRA Data 39482-MT-08.csv	0.282488	0.000005	0.008672	0.000004	1.467263	0.000009	1.886836	0.000020	0.000035	0.000000	0.001494	0.000003	732000000	0.28249
TRA Data 39498-MT-09.csv	0.282490	0.000005	0.008650	0.000004	1.467273	0.000009	1.886823	0.000020	0.000030	0.000000	0.001301	0.000003	732000000	0.28249
TRA_Data_39504-MT-10 csv	0 282496	0.000005	0.008668	0 000004	1 467268	0.000009	1 886839	0.000021	0.000036	0.000000	0.001582	0.000003	732000000	0 28250
TBA Data 39506-MT-11 csv	0.282501	0.000005	0.008672	0.000004	1 467246	0.000009	1 886873	0.000018	0.000023	0.000000	0.000977	0.000003	732000000	0.28250
TBA Data 39522-MT-12 csv	0.282510	0.000005	0.008671	0.000004	1 467248	0.000009	1 886772	0.000021	0.000032	0.000000	0.001374	0.000003	732000000	0.28251
TRA_Data_39550-MT-13_csv	0.282487	0.000005	0.008653	0.000004	1 467257	0.000000	1 886859	0.000019	0.000035	0.000000	0.001535	0.000003	732000000	0.28249
TPA_Data_39565_MT_14_cov	0.202400	0.000005	0.0000000	0.000004	1.467266	0.000000	1 996930	0.000013	0.000031	0.000000	0.001319	0.000003	732000000	0.20240
TRA_Data_39505-WIT-14.csv	0.202499	0.000005	0.008640	0.000004	1.407200	0.000009	1.000039	0.000021	0.000031	0.000000	0.001318	0.000003	732000000	0.20200
TRA_Data_39565-WIT-15.CSV	0.202470	0.000005	0.000049	0.000004	1.407270	0.000008	1.000003	0.000018	0.000039	0.000000	0.001737	0.000003	732000000	0.20240
TRA_Data_39597-WIT-16.csv	0.282497	0.000005	0.008657	0.000004	1.467245	0.000009	1.886799	0.000021	0.000028	0.000000	0.001208	0.000003	732000000	0.28250
	0.282495	0.000018												
TRA_Data_39413-LV11-1.csv	0.282807	0.000004	0.008666	0.000004	1.467282	0.000006	1.886830	0.000014	0.001226	0.000003	0.065179	0.000201	290000000	0.28280
TRA_Data_39439-LV11-02.csv	0.282815	0.000009	0.008664	0.000010	1.467282	0.000010	1.886801	0.000021	0.002678	0.000002	0.149247	0.000064	290000000	0.28280
TRA_Data_39464-LV11-03.csv	0.282810	0.000009	0.008651	0.000011	1.467235	0.000011	1.886799	0.000022	0.002607	0.000001	0.147064	0.000132	290000000	0.28280
TRA_Data_39483-LV11-04.csv	0.282825	0.000010	0.008688	0.000011	1.467303	0.000010	1.886830	0.000022	0.002911	0.000006	0.171454	0.000417	290000000	0.28281
TRA_Data_39499-LV11-05.csv	0.282814	0.000009	0.008681	0.000011	1.467278	0.000010	1.886876	0.000024	0.002975	0.000000	0.174036	0.000096	290000000	0.28280
TRA_Data_39507-LV11-06.csv	0.282812	0.000007	0.008686	0.000007	1.467274	0.000009	1.886775	0.000021	0.001691	0.000001	0.099293	0.000209	290000000	0.28280
TRA_Data_39551-LV11-07.csv	0.282825	0.000009	0.008650	0.000011	1.467296	0.000008	1.886898	0.000022	0.003909	0.000063	0.221444	0.003350	290000000	0.28280
TRA_Data_39584-LV11-08.csv	0.282803	0.000006	0.008663	0.000007	1.467246	0.000009	1.886796	0.000019	0.001726	0.000003	0.099349	0.000119	290000000	0.28279
	0.282814	0.000016												
TRA Data 39414-TEM2-1.csv	0.282649	0.000015	0.008691	0.000013	1.467354	0.000017	1.886870	0.000038	0.001544	0.000006	0.052991	0.000074	417000000	0.28264
TRA Data 39416-TEM2-02.csv	0.282673	0.000007	0.008647	0.000007	1.467299	0.000010	1.886780	0.000021	0.001202	0.000003	0.043976	0.000064	417000000	0.28266
TRA Data 39440-TEM2-03.csv	0.282627	0.000009	0.008662	0.000010	1.467286	0.000012	1.886905	0.000029	0.002307	0.000017	0.069269	0.000242	417000000	0.28261
TRA_Data_39441-TEM2-04_csv	0 282649	0.000009	0.008651	0.000009	1 467310	0.000012	1 886880	0.000029	0.001418	0.000007	0.044299	0.000080	417000000	0 28264
TRA Data 39465-TEM2-05 csv	0.282679	0.000008	0.008666	0.000000	1 467279	0.000011	1 886881	0.000025	0.001393	0.000008	0.050914	0.000201	417000000	0.28267
TRA_Data_39484-TEM2-06.csv	0.282664	0.000000	0.0000000	0.0000000	1 467304	0.000011	1 886920	0.000020	0.001000	0.000000	0.000014	0.000186	417000000	0.28265
TRA Data 39497-TEM2-07.cov	0.282695	0.000010	0.008647	0.000000	1 467292	0.000012	1 886929	0.000020	0.001063	0.000043	0.070860	0.001300	417000000	0.28267
TPA Data 20509 TEM2 09 cov	0.202000	0.000010	0.000047	0.000009	1 46729	0.000013	1 996922	0.000027	0.001303	0.000043	0.064344	0.0001000	417000000	0.20207
TPA Data 20535 TEM2 00.05V	0.202034	0.000000	0.008659	0.000009	1.40720	0.000011	1.000032	0.000024	0.001756	0.000003	0.064344	0.000090	417000000	0.20204
TDA Data 20526 TEM2 10 anu	0.202030	0.000010	0.0000003	0.000010	1.40/311	0.000012	1.000930	0.000028	0.001208	0.000020	0.045644	0.0000080	417000000	0.20203
TDA Data 39330-1EW2-10.0SV	0.202040	0.000008	0.000009	0.000009	1.40/322	0.000012	1.000912	0.000020	0.001013	0.000003	0.000614	0.000132	417000000	0.20203
TRA_Data_39539-TEM2-11.CSV	0.282662	0.000009	0.008683	0.000010	1.467264	0.000012	1.886867	0.000026	0.002216	0.000010	0.080522	0.000312	417000000	0.28264
TRA_Data_39564-1EM2-12.CSV	0.282671	0.000007	0.008670	0.000008	1.467255	0.000011	1.886878	0.000025	0.000985	0.000004	0.034351	0.000136	41/000000	0.28266
IRA_Data_39598-TEM2-13.csv	0.282662	0.000007	0.008686	0.000008	1.467278	0.000010	1.886817	0.000023	0.001383	0.000005	0.047327	0.000088	417000000	0.28265

0.282658 0.000034

Data for figure 3:

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