Geochronology of metamorphism, deformation and fluid circulation: a comparison between Rb-Sr and Ar-Ar phyllosilicate and U-Pb apatite systematics in the Karagwe-Ankole Belt (Central Africa)

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Abstract

This work presents an integrated geochronology study combining step-heating Ar-Ar and in-situ Rb-Sr phyllosilicate geochronology with EPMA elemental maps and U-Pb apatite geochronology in order to determine the timing and duration of regional deformation and fluid circulation processes in the Karagwe-Ankole Belt in Central Africa. The Kibuye-Gitarama-Gatumba study area (West Rwanda) forms part of the

Western Domain of this Mesoproterozoic belt, where the metamorphic and deformation history, geothermometric evolution and mineralization processes (both genesis and geochronology) have been well-documented in previous studies.

Our geochronological results and interpretations show the importance of thermal diffusion throughout the elevated temperature regime present in the Neoproterozoic. During the Ediacaran, metamorphism and fluid alteration in the Gatumba area was associated with deformation, as independently demonstrated by U-Pb apatite and Ar-Ar phyllosilicate geochronology. From the end of the Ediacaran until the Late Cambrian, saline fluid activity is recorded and fluid-induced (re)crystallization processes dominate the Gatumba biotite Rb-Sr isotope record. The direct comparison between Rb-Sr and Ar-Ar geochronology suggests a parentless ^{40}Ar -component is preserved during this fluid-induced (re)crystallization due to its saline, (earth) alkali-rich composition. Additionally, this multi-method approach allows us to place the history of the Western Domain of the Karagwe-Ankole belt in relation to that of the surrounding areas, i.e. the Eastern Domain and the Congo and Tanzania Cratons. Deformation and epidote-amphibolite facies metamorphism (at ~590 – 570 Ma), and fluid fluxes (at ~590 – 495 Ma) occurred in the Kibuye-Gitarama-Gatumba area after the West Gondwana Orogeny but from the onset of the East African Orogeny onwards till after the culmination of the Gondwana amalgamation, demonstrating the progressively eastward-moving orogenic front in this supercontinent assembly.

Key words: Pan-African overprint, Gondwana assembly, geochronological proxies, East African Orogeny, West Gondwana Orogeny

1. Introduction

Geochronological methods are very powerful tools in reconstructing the geological history of metamorphic rocks (e.g. Baxter et al., 2002; Bröcker and Franz, 2006; Schneider et al., 2015; Viete et al., 2011). However, isotopic systematics can be heavily altered or disrupted by thermal diffusion, deformation or fluid activity,

to an extent that is often undefinable (e.g. Allaz et al., 2011; Bloch et al., 2015; Glodny et al., 2008; Henrichs et al., 2018; Villa and Hanchar, 2017). This is especially the case in Precambrian terrains, where subsequent deformation and metamorphism often overprinted the original systematics of mineral geochronometers (Bosse and Villa, 2019), posing challenging conditions to the interpretation of such geochronological data. Numerous new analytical methods are continuously being developed and fine-tuned to circumvent these problems and to improve our ability to date geological events and processes. One such example is the increased interest in in-situ analysis techniques (e.g. Zack and Hogmalm, 2016), as bulk analyses on rock or mineral separates have the inherent drawback that diachronous mineral generations are averaged in geologically meaningless ages (di Vincenzo et al., 2006). These new developments allow detailed comparisons between different techniques, isotope systems and minerals, which can indicate otherwise unnoticed events, and provide additional valuable insights in sensitivity and behavior of different minerals. Phyllosilicate geochronology is typically used to clarify the tectonometamorphic history and geodynamic context of mid- to high-T metamorphic terranes (e.g. Reiser et al., 2017; Smit et al., 2011). Micas are common in many mineral assemblages and often show a clear relationship to the deformation history, sometimes even defining the deformation fabric itself. Additionally, due to the high K-content, most crystals exhibit favorable Ar-contents, as well as Rb/Sr-ratios. These compositional advantages, in combination with micro-sampling or -analyses, enable constraining the age of tectonic and metamorphic processes from phyllosilicates in a quite straightforward way (Bröcker and Franz, 2006; Cliff et al., 2017; di Vincenzo et al., 2006; Freeman et al., 1997). Conceptually, the Rb-Sr and K-Ar systems are very similar. In both systems, the radiogenic daughter elements (Sr and Ar) are incompatible and susceptible to loss by diffusion or recrystallization. Therefore, both Ar-Ar and Rb-Sr ages can document either specific stages of the P-T-t-D path (mineral new growth), variable degrees of incomplete resetting or mixing of different mica generations (Bröcker et al., 2013).

Often, Rb-Sr and Ar-Ar dates (on phyllosilicates) are interpreted as cooling ages, i.e. dating the time when thermal diffusion became insignificant. However, no consensus on the closure temperature of the Rb-Sr system, compared to the K-Ar system, has been attained in literature and quantitative data on diffusive re-equilibration is lacking. Generally, closure of the Rb-Sr system in micas is considered to occur at higher T compared to the K-Ar system, independent of the specific geological situation and sample characteristics (e.g. Cliff et al., 2017; Freeman et al., 1997). However, some studies indicated that the closure temperature could be similar for both systems (Willigers et al., 2004) or that the closure temperature of K-Ar is higher compared to Rb-Sr (e.g. Reiser et al., 2017). Other authors state that significant thermal diffusion of Ar and Sr in micas is inhibited up to temperatures of 600 °C, but that rather strain and fluid availability are responsible for Ar- and Sr-redistribution (Airaghi et al., 2018; Bosse and Villa, 2019; Chafe et al., 2014; Villa, 2006, 1998). Fluid-assisted resetting or new growth additionally offers an explanation for the often observed large geochronological variability on a local scale (Bosse and Villa, 2019). Although more detailed research is required, both isotope systems seem to be controlled differently by these processes (e.g. Bröcker et al., 2013; Freeman et al., 1997; Reiser et al., 2017; Willigers et al., 2004).

Apatite is often the only U-bearing mineral available to date in mafic rocks (Hoskin and Schaltegger, 2003; Piccoli and Candela, 2002; Pochon et al., 2016). U-Pb dating of apatite generally gives more precise results than phyllosilicate dating, but trace mineral geochronology has the drawback that results often cannot be connected to the timing of deformation in a straightforward way (Cliff et al., 2017). However, in combination with geochemistry, apatite geochronology is a versatile tool to determine temporal constraints on either magmatic, metamorphic or hydrothermal processes as trace element contents often allow to distinguish the apatite origin (Glorie et al., 2019; Harlov and Förster, 2002; Henrichs et al., 2018; O'Sullivan et al., 2018; Piccoli and Candela, 2002; Schneider et al., 2015; Spear and Pyle, 2002; Zirner et al., 2015). The original REE-signature is often preserved, except during fluid-associated metamorphism, which can induce REE redistribution (Bosse and Villa, 2019; Harlov, 2015; Janots et al., 2018; Spear and

Pyle, 2002). Similar as for the Ar-Ar and Rb-Sr systems, Pb-loss can be caused by thermal diffusion (Cherniak et al., 1991; Chew et al., 2014; Engi, 2017; Harrison et al., 2002; Kirkland et al., 2017; Willigers et al., 2002), as well as by fluid-induced recrystallization (Bosse and Villa, 2019; Kirkland et al., 2018). Nevertheless, apatite is largely inert and mineralogically stable up to mid-amphibolite facies and generally recrystallizes slower than K-Rb-rich minerals, such as feldspar or micas (Bosse and Villa, 2019; Kirkland et al., 2017; Szopa et al., 2014). In exceptional cases, U-Pb systematics in apatite are observed to be less susceptible to hydrothermal alteration than the K-Ar system (Pochon et al., 2016; Szopa et al., 2014).

This manuscript compares three geochronology methods (Rb-Sr, Ar-Ar and U-Pb) applied on three minerals (white mica, biotite and apatite) in metasilstone, granite and amphibolite rocks of the Western Domain in the Karagwe-Ankole Belt. The geodynamic evolution of this Mesoproterozoic belt is complex and, especially the Neoproterozoic and Phanerozoic part, largely unexplored. The Kibuye-Gitarama-Gatumba area was chosen on the one hand because of its representative character for the Western Domain and previous geochronology work (e.g. Dewaele et al., 2011; Van Daele and Scherer, in revision), as well for the detailed petrography studies characterizing the geothermometric-metamorphic evolution in the area (Van Daele et al., in press). On the other hand, different kinds of Mesoproterozoic host rocks (sediments, granites, dolerites) are present in close spatial association. All these rocks share the same history, and underwent the same regional conditions of deformation and metamorphism. Hence, this area offers a unique setting to compare the sensitivity of different isotope systems, minerals and host rocks. Additionally, this integrated geochronology approach will clarify the youngest part of the history of the Karagwe-Ankole Belt.

2. Geological setting

The Kibuye-Gitarama-Gatumba (KGG) area in West Rwanda geologically belongs to the Karagwe-Ankole Belt (KAB), formerly the Northern Kibara Belt (Tack et al., 2010). This orogenic belt covers the countries Rwanda and Burundi, as well as parts of Uganda, Tanzania and the D.R. Congo. The KAB is situated between

the Archean Tanzania Craton in the east and the Archean–Paleoproterozoic Congo Craton in the west (Fig. 1; Tack et al., 2010). The geodynamic history and formation of this belt is still a matter of debate. Recently proposed geodynamic frameworks range from an intracratonic setting with two short-lived, far-field compressional events to a subduction-collision system (Debruyne et al., 2015; Fernandez-Alonso et al., 2012; Koegelenberg et al., 2015; Koegelenberg and Kisters, 2014). The KAB is divided in two domains; the Eastern Domain (ED) with an Archean basement and the Western Domain (WD) with a Paleoproterozoic basement (Fig. 1; Tack et al., 1994). Each domain is characterized by its own magmatic–metamorphic history and developed independent sedimentary sub-basins (‘aulacogens’) and deposition sequences (Fernandez-Alonso et al., 2012). The KGG study area is part of the Western Domain (Fig. 1).

During the Mesoproterozoic, dominantly terrigenous shallow-water sediments were deposited in various sedimentary basins (Buchwaldt et al., 2008; Fernandez-Alonso et al., 2012; Tack et al., 2010). Within the WD, these sediments are grouped into the Akanyaru Supergroup, which contains four groups. In the KGG area, metasediments of the three oldest groups are represented (Fig. 2), i.e. the Bumbogo and Ndiza Formations (Gikoro Group), Cyurugeyo Formation (Pindura Group) and Gatwaro and Sakinyaga Formations (Cyohoha Group). Except for the youngest Sakinyaga Formation, which dominantly consists of brown to white metasandstone and quartzite, pale brown to grey metasilstone is the most common lithology in the KGG area (Dehandschutter et al., 1988; Tahon et al., 1988a, 1988b). In the Eastern Domain, metasediments are stratigraphically and palaeogeographically divided in the Muyaga, Ruvubu and Bukoba Groups of the Kagera Supergroup (Fernandez-Alonso et al., 2012).

The regional deformation and generally low grade metamorphism in the KAB are characterized by an east to west tectonic vergence and an increase in grade. While the metasediments in the ED are only gently folded and weakly metamorphosed, those of the WD show more intense deformation and regional greenschist to amphibolite facies Barrovian-type metamorphism (Deblond et al., 2001; Fernandez-Alonso and Theunissen, 1998; Klerkx et al., 1987; Koegelenberg and Kisters, 2014; Tack et al., 2010, 1994, 1990;

Van Daele et al., in press). More specifically in the KGG area, biotite, albite, graphite, chlorite, white mica, garnet, staurolite and kyanite represent the prograde regional metamorphic evolution up to amphibolite facies. Younger greenschist metamorphism induced post-deformational crystallization of garnet, biotite, white mica and chlorite (Van Daele et al., in press). Metamorphic zircon rims, interpreted to have grown during peak metamorphism, give Neoproterozoic $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 967 – 964 Ma (Tack et al., 2010). Additionally, three garnet growth episodes are distinguished in the KGG area: > 920 Ma, c. 880 Ma and c. 620 – 600 Ma (Van Daele and Scherer, in revision).

Folding and faulting are omnipresent features in the WD of the KAB. The metasediments often show a discrete, oblique axial planar fabric associated with regional, slightly arcuate, NW-SE to NNE-SSW trending, upright folding, sometimes superimposed on low-angle bedding or layer-parallel fabrics (Fernandez-Alonso et al., 2012; Fernandez-Alonso and Theunissen, 1998; Klerkx et al., 1987, 1984; Rumvegeri, 1991). In exceptional cases, crenulation cleavage developed in schists of the WD (Fernandez-Alonso and Theunissen, 1998). The ED, interpreted as the frontal part of a foreland fold-and thrust belt, shows folding and back-thrusting mostly in its western part, where mylonites and phyllonites developed. The far eastern part is only gently deformed (Fernandez-Alonso and Theunissen, 1998; Koegelenberg et al., 2015). Only the basement and immediately overlying conglomerates of the ED show a schistosity parallel to the bedding as consequence of shearing, while this feature is lacking in the rest of the ED metasediments (Fernandez-Alonso and Theunissen, 1998). Fold-and-thrust tectonics in this part of the KAB have been dated at 1326 ± 10 Ma (Ar-Ar on muscovite; Koegelenberg et al., 2015).

Three main magmatic episodes were distinguished in the WD of the KAB (Tack et al., 2010). Firstly, the Gikoro and Pindura Group metasediments were intruded by widespread bimodal magmatism at c. 1375 Ma, resulting in the (ultra-)mafic Bushveld-type Kabanga-Musongati (KM) alignment close to the boundary between WD and ED, and abundant S-type granite plutons and dolerite bodies (Fig. 1). At c. 1205 Ma, A-type granite bodies were emplaced along NS-oriented shear zones. Lastly, Sn-bearing, S-type leucogranites

intruded the Mesoproterozoic metasediments and older magmatic rocks at c. 986 Ma (Tack et al., 2010). In Rwanda, older denominations for the latter are 'Sn granites' or 'G4-granites', while the first S-type granite generation (part of the bimodal magmatism) was referred to as the 'G1-G3 granites' (Rumvegeri, 1991; Tack et al., 2010). Early Neoproterozoic W-Nb-Ta-Sn mineralization is present in pegmatites and hydrothermal quartz veins that are temporally, spatially and genetically associated with the Sn granites (Hulsbosch et al., 2016, 2014; Pohl, 1994; Pohl et al., 2013; Van Daele et al., 2018). Similar to the metasediments, compressional fabrics such as foliation(s) and exceptional crenulation have been preserved in granitic and mafic bodies (Fernandez-Alonso et al., 1986; Ikingura et al., 1992). In the ED, felsic magmatism is absent. The mafic arcuate Lake Victoria Dyke Swarm (LVDS) was emplaced east of the ED, in the Archean basement of the Tanzania Craton and the Paleoproterozoic Rwenzori Belt contemporaneously with the KM alignment between 1.4 and 1.3 Ga (Fig. 1; Mäkitie et al., 2014).

Two composite G1-G3 and G4 granite bodies are present in the KGG area, i.e. the large Gitarama batholith southeast of Gitarama, and the smaller Bijojo granite in the northern Gishwati Complex (Fig. 2). Near Gatumba, multiple barren and Nb-Ta-Sn mineralized pegmatites are present. Abundant dolerite sills and dykes intruded the metasediments of the study area, especially around Kibuye and Gatumba (Dehandschutter et al., 1988; Tahon et al., 1988b, 1988a).

3. Methodology

3.1. Sample strategy

Multiple geochronological methods were applied to reconstruct the geological history of the study area and to test/calibrate the chronometers against each other. Therefore, fifteen samples were selected (Table 1), which reflect different deformational, metamorphic, metasomatic and magmatic processes in the Western Domain of the Karagwe-Ankole Belt.

Sample KG89 is a white mica schist of the Bumbogo Formation, sampled just north of Gitarama, along the road to Gatumba. The schist dominantly consists of white mica and minor oxides and is strongly crenulated. Two mica generations are present: the first generation defines a bedding-oblique continuous foliation, which is strongly crenulated by a discrete second foliation. Fe-oxides occur along this second foliation, as well as new-grown white mica, i.e. the second generation (Fig. 3a). In-situ geochronology of these two mica generations could demonstrate if two deformation episodes affected the study area and when. Cm-sized white mica booklets (KG92) from interboudin quartz veins in a pegmatite and biotite (KG98) from interboudin quartz veins in a domino-boudinaged quartz vein (Figs. 4a and 4b, Goscombe et al., 2004) were sampled in order to date the deformational event(s) leading to boudin formation in the Gatumba area.

Sample KG101 represents biotite-garnet zones rimming elliptical, boudin-like, foliation-parallel quartz pockets in gneissic rocks and was sampled at c. 75 m distance of sample KG98 (Figs. 2, 3b and 4c). Biotite crystals also are present dispersed in the host rock. This sample is dated to have more constraints on the timing of gneiss and quartz pocket formation, abundantly observed in the Gatumba area. Sample KG103 is a foliated metasiltstone, sampled in the same Gatumba-Kirengo river section. The foliation is mainly made up by white mica crystals while the biotite crystals, which are often partially chloritized, occur interstitial and are oriented oblique to this foliation (Fig. 3c). Geochronology of both minerals allows to separately date the white mica foliation development, as well as the growth of dispersed biotite. Samples KG123 and KG124 both are quartz veins, which are rimmed by a biotite-garnet zone in the host metasiltstone, sampled from the Magunda-Malirakabibi river transect south of Gatumba (Figs. 3d and 4d). Larger biotite crystals also occur in the quartz vein interior and in the foliated host rock surrounding the vein. Dating the biotite crystals in the vein rims gives a minimum quartz vein age. Metasomatic recrystallization, or pseudomorphism, of metamorphic aluminosilicate porphyroblasts, occurs widespread in the Gatumba area. Two samples representing pseudomorphism were selected for geochronology: white

210 mica KG126 of coarse-grained quartz-white mica lenses in a biotite-rich metasiltstone was analyzed (Fig.
 211 3e) and fine-crystalline white mica pseudomorphs of staurolite (sample KG130, Fig. 3f).

212 Two mica-bearing granite samples from west of the Gitarama city were selected for comparison with
 213 literature data (e.g. Tack et al., 2010) to evaluate if post-magmatic, metamorphic or metasomatic
 214 processes affected the Rb-Sr systematics in mica. Sample KG140 represents a mylonitized G1-G3 granite.
 215 Elliptical quartz-feldspar lenses are surrounded by phyllosilicate-rich layers as in an incipient augen gneiss
 216 texture. Euhedral white mica crystals dominantly define the undulating foliation, the biotite crystals
 217 generally are slightly more anhedral, randomly oriented and occur dispersed in the matrix (Figs. 3g and
 218 4e). Sample KG141 is a leucogranite representing a typical G4-granite without foliation development.
 219 Quartz and feldspar are the dominant minerals and smaller white mica clusters occur dispersed in this
 220 coarse-crystalline matrix (Fig. 4f).

221 Additionally, four amphibolites were selected. Samples KG02-139 and KG02-144 were taken just north of
 222 Gatumba city from the same drill core, sampled at 139 and 144 m, respectively. Samples KG52 and KG53
 223 were sampled in the Kibuye city area along the NS Kibuye – Cyangugu road (Fig. 2). All amphibolite samples
 224 broadly show the same petrographic characteristics. Calcic amphibole (hornblende) occurs abundantly,
 225 mostly as large anhedral, sometimes poikiloblastic, crystals. Feldspar is present as small dispersed crystals
 226 to macroscopic phenocrysts (up to 50 vol%, Fig. 3h). Limited sericitization and occasional saussuritization
 227 affected feldspar, most notably along cleavage planes and in crystal centers. In addition, minor amounts
 228 of biotite and pyrite are present in all samples. Biotite is sometimes partly chloritized. In the Kibuye
 229 samples, quartz is present as well. In addition to apatite, that occurs as trace minerals in all amphibolites,
 230 epidote and tourmaline were observed in the Gatumba amphibolites (Fig. 3h). Apatite geochronology was
 231 applied to obtain temporal constraints on the original intrusion event if trace element and REE data show
 232 the crystals are of magmatic origin. If apatite rather has a metamorphic-metasomatic compositional
 233 affinity, the U-Pb ages indicate the timing of post-magmatic metamorphism or metasomatism (e.g., Glorie

et al., 2019; Harlov and Förster, 2002; Henrichs et al., 2018; O’Sullivan et al., 2018; Piccoli and Candela, 2002; Schneider et al., 2015; Spear and Pyle, 2002; Zirner et al., 2015).

3.2. Geochronology and geochemistry

Step-heating ^{39}Ar - ^{40}Ar analyses were carried out for three phyllosilicate samples of the Gatumba area (KG92, 98 and 101) for which the abundance and crystal size of white mica or biotite made this bulk technique possible. Handpicked separates were prepared by crushing, sieving (250 – 500 μm), MilliQ washing, ultrasound cleaning, magnetic separation and handpicking. These separates were irradiated for 40 hours in the CLICIT facility of the TRIGA reactor at Oregon State University (USA). Simultaneously, Fish Canyon Tuff sanidine was irradiated as neutron flux monitor, for which an age of 28.196 ± 0.038 Ma was assumed (Wotzlaw et al., 2013). At the University of Geneva (Switzerland), the samples subsequently were degassed by step-heating with a rastered CO_2 -IR laser (55W, Photon Machines Inc.). The analytical procedure is that described by Villagómez and Spikings (2013). The gas was cleaned in an extraction line equipped with one GP50 getter, one AP10 (both ST101) getter and a cold finger chilled to - 130 °C. The argon isotopic compositions were measured using a GV Instruments, Argus V multi-collector mass spectrometer equipped with five Faraday collectors with one 1×10^{11} Ohm feedback resistor (mass 40), and four 1×10^{12} Ohm feedback resistors (masses 39 – 36). The mass discrimination correction factor was determined at 0.997 ± 0.051 via analyses of multiple aliquots of air before and after each age spectrum. Data were corrected for blanks, interfering nucleogenic reactions (Ca, K, Cl) and the decay of ^{37}Ar and ^{39}Ar . The ^{40}K decay constant of Steiger and Jäger (1977) was used to calculate the ^{39}Ar - ^{40}Ar ages ($4.962 \times 10^{-10} \text{ yr}^{-1}$). Data reduction was done with the program ArArCalc (Koppers, 2002). Reported uncertainties are always mentioned as 2σ .

For samples that contain smaller crystals or lower proportions of phyllosilicate (KG89, 101, 103, 123, 124, 126, 130, 140 and 141), in-situ techniques are the only possibility to retrieve isotopic compositional and geochronological information. An inherent advantage is that in-situ analyses circumvent the problem of

averaging diachronous mineral generations (e.g. di Vincenzo et al., 2006). Therefore, thick sections (c. 200 μm) were prepared of nine samples from the Gitarama-Gatumba area, with in each up to 38 phyllosilicate crystals selected for analysis of their Rb-Sr systematics by Laser-Ablation Inductively-Coupled-Plasma Triple Quadrupole Mass Spectrometry (LA-ICP-QQQMS). Crystals were selected based on their size (sufficiently large to analyze), absence of impurities such as mineral and fluid inclusions, and representative distribution in the thick section. A new technique was recently developed by Zack and Hogmalm (2016), which successfully separates Rb and Sr ions on-line, overcoming the problem of isobaric interference typically associated with β -decay systems. Analyses were performed at the Chair of Geology and Economic Geology, Montanuniversität Leoben, using an ESINWR (TwoVol2) laser ablation system coupled to an Agilent 8800 ICP-QQQ. The analytical conditions for Rb-Sr dating using N_2O have been described by Hogmalm et al. (2017). The tuning of the system was carried out by ablating NIST SRM 610 (50 μm spot size, $\sim 5 \text{ J/cm}^2$ and a repetition rate of 10 Hz). Standard reference materials NIST SRM 610, BCR2G ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7050$) and Mica-Mg ($^{87}\text{Rb}/^{86}\text{Sr} = 154.6$) nano-powder tablets (Karlsson et al., 2016) were used for quantification of the Rb-Sr ratios for both white mica and biotite. A standard-sample bracketing approach was applied. The precision of the standard reference materials is below 0.65 % (BCR2G), 0.75 % (NIST 612) and 2.66 % (Mica-Mg). The accuracy could not be determined as the available reference materials were used to normalize the element bias of the samples, hence could not be measured as unknowns. Uncertainties (2σ) were taken as 3 % for $^{87}\text{Rb}/^{86}\text{Sr}$ and 1 % for $^{87}\text{Sr}/^{86}\text{Sr}$. Data reduction was done with Excel spreadsheets. About 15% of the data points (43 of 277 analyses) was discarded due to a low or unstable signal obtained, most likely because the mica crystal was smaller than the ablation pit. Additionally, a minor proportion (10 analyses, < 4%) was rejected based on their anomalous, discordant $^{87}\text{Sr}/^{86}\text{Sr}$ or $^{87}\text{Rb}/^{86}\text{Sr}$ composition. All ages were calculated using the ^{87}Rb decay constant of $1.3972 \pm 0.0045 \cdot 10^{-11} \text{ yr}^{-1}$ (Villa et al., 2015) using IsoplotR v2.7 (Vermeesch, 2018). Reported uncertainties are always mentioned as 2σ .

In contrast to phyllosilicates in the metasediment and granite samples, amphibolitic rocks only had apatite as dateable mineral. For four samples (KG02-139, 02-144, 52 and 53), apatite crystals were separated using conventional techniques of crushing (63 – 250 μm), washing, magnetic and heavy liquid separation, and handpicking. Trace element and REE concentrations, as well as U-Pb isotopic compositions, were analyzed by LA-ICP-MS using a RESOLUTION-LR 193 nm excimer laser coupled to an Agilent 7900 ICP-QMS at Adelaide Microscopy, the University of Adelaide (Australia). Instrumental details are the same as reported by Gillespie et al. (2018) and Glorie et al. (2019). Data reduction was done with the VisualAge_Ucompbine (for U-Pb ratios) and X_Trace_Elements_IS (for trace element concentrations) data reduction modules in Iolite (Paton et al., 2011). Discordia ^{238}U - ^{206}Pb ages were calculated with IsoplotR v.2.7 (Vermeesch, 2018) using a ^{238}U -decay constant of $1.55125 \pm 0.00083 \times 10^{-10} \text{ yr}^{-1}$ (Jaffey et al., 1971). The McClure apatite, the secondary reference material, gave a ^{207}Pb -corrected ^{238}U - ^{206}Pb age of $523.4 \pm 3.9 \text{ Ma}$ ($n = 7$), which is in excellent agreement with the published ID-TIMS ^{238}U - ^{206}Pb age of $523.51 \pm 1.47 \text{ Ma}$ (Schoene and Bowring, 2006). Reported uncertainties are always mentioned as 2σ .

Of all samples, semi-quantitative major element maps (Si, Al, Ti, Na, Mg, Ca, Mn, K and Fe) were made of the white mica and biotite crystals with a JEOL JXA-8530F Wavelength Dispersive Spectrometer Field Emission Gun Electron Probe Micro-Analyzer (WDS FEG-EPMA) at the Department of Material Engineering of KU Leuven. An acceleration voltage of 20 kV was used, beam current was 20 nA and dwell times were 50 ms. Depending on the crystal size, the element maps were constructed with a probe diameter and pixel dimension of 2 to 5 μm .

4. Geochronological results

Sample details are given in Table 1 and their locations are shown in Fig. 2.

4.1. Ar-Ar phyllosilicate geochronology

Step-heating Ar-Ar isotopic analyses were performed on three phyllosilicate samples (KG92, 98 and 101) from the Gatumba-Kirengo river section (Table A1, Fig. 5). No samples from Kibuye and Gitarama could be analyzed due to the small crystal size of the phyllosilicates in this area. The Ar-Ar isochron diagrams show a low $^{36}\text{Ar}/^{40}\text{Ar}$ for all temperature steps. This implies that the inverse isochron is mainly constructed based on clustered data points, hence further interpretations will focus on the age spectra (Fig. 5). An Ar-Ar plateau age of 591.2 ± 2.0 Ma (MSWD = 1.87; 80.2 % ^{39}Ar) was obtained for white mica KG92 (Fig. 5a). The youngest Ar-fractions are found in the last part of the spectrum (highest T). Biotite KG98 shows a well-defined Ar-Ar plateau age of 567.2 ± 1.8 Ma (Fig. 5b; MSWD = 0.71; 85.4 % ^{39}Ar). A significantly older plateau age of 625.4 ± 2.0 Ma (MSWD = 0.20; 79.7 % ^{39}Ar) was obtained for biotite of sample KG101 (Fig. 5c). Phyllosilicate crystals in all three samples show a homogeneous major element distribution (KG92 and 98 shown in Figs. 6a and 6b), except for limited solution between the muscovite and paragonite endmembers observed in white mica KG92 (K and Na in Fig. 6a).

4.2. Rb-Sr phyllosilicate geochronology

The two white mica generations in sample KG89 show a similar major element composition. Artefacts in the element maps are due to crystal-boundaries and cleavage relief (Fig. 6c). In general, crystals in this schist are very small (< 50 μm thickness), which imposes analytical challenges to obtain the isotopic composition with high precision. Only few crystals are sufficiently large, and even then the amount of material which can be ablated is limited. Furthermore, limited intra-crystal variation in $^{87}\text{Rb}/^{86}\text{Sr}$ in white mica of both generations results in high uncertainties of the isochron calculation. The oldest generation (wmca1, n = 9) gives an isochron age of 910 ± 287 Ma, with an MSWD of 1.9 and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.729 ± 0.033 (Fig. 7a, full data of all samples can be found in Table A2). The youngest generation (wmca2, n = 13) gives an isochron age of 619 ± 156 Ma (MSWD = 1.7 and initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7672 \pm 0.0186$, Fig. 7b).

Biotite of sample KG101, which also was analyzed by step-heating Ar-Ar, gives a Rb-Sr age of 530.5 ± 3.3 Ma (n = 30, MSWD = 1.3, initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7866 \pm 0.0094$, Fig. 7c), while the obtained Ar-Ar age is 625.4

± 2.0 Ma (Fig. 5c). Rb-Sr signatures of biotite of the biotite-garnet rim zone and biotite dispersed throughout the host rock are concordant and both categories fit on one isochron. Similar to sample KG101, biotite crystals of sample KG103 show a homogeneous major element composition, while white mica displays limited solid solution between paragonite and muscovite (Fig. 6d), which has also been observed in sample KG92. For KG103 white mica, a reasonable isochron age could only be determined after excluding four anomalous analyses (unfilled ellipses in Fig. 7d). This selection did not affect the age nor the initial $^{87}\text{Sr}/^{86}\text{Sr}$ to a great extent. An age of 703 ± 73 Ma was obtained ($n = 25$, MSWD = 1.8, initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7708 \pm 0.0153$, Fig. 7d). Unchloritized biotite from the same sample gives a more precise age of 494.1 ± 6.6 Ma ($n = 9$, MSWD = 0.26, initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7967 \pm 0.0112$, Fig. 7e). No Rb-Sr age difference could be observed between the different biotite types (in the biotite-garnet rim, quartz vein or metasilstone) of samples KG123 and KG124. Including all analyzed biotite crystals, both samples give – within uncertainty – a similar and precise age: 512.1 ± 4.1 Ma ($n = 25$, MSWD = 0.98, initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.696 \pm 0.103$) for sample KG123 and 516.0 ± 7.3 Ma ($n = 26$, MSWD = 0.5, initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.70 \pm 0.22$) for sample KG124 (Figs. 7f and 7g).

An Early Neoproterozoic Rb-Sr age of 973 ± 69 Ma was obtained for white mica in KG126 ($n = 23$, MSWD = 2.1, initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.705 \pm 0.026$, Fig. 7h). In KG130, except for three ablation spots with a very low signal intensity, the (isotopic) composition is very homogeneous over multiple white mica lenses. When these three low $^{87}\text{Rb}/^{86}\text{Sr}$ outliers are excluded, an imprecise isochron age of 586 ± 198 Ma ($n = 19$, MSWD = 0.54; initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.778 \pm 0.042$, Fig. 7i) is obtained.

In both granite samples (KG140 and 141), white mica shows different domains with a distinctively heterogeneous composition, representing more muscovitic versus more phengitic domains according to Tschermak substitution [$2\text{Al} \leftrightarrow \text{Si} + (\text{Mg}, \text{Fe})$] (Fig. 6e). The white mica crystals show a low, rather homogeneous $^{87}\text{Rb}/^{86}\text{Sr}$, resulting in an imprecise age of 940 ± 135 Ma ($n = 13$, MSWD = 1.2; Fig. 7j) for sample KG140. A much larger spread in $^{87}\text{Rb}/^{86}\text{Sr}$ is observed for the biotite crystals ($n = 9$), as well as a

much younger and more constrained age: 519 ± 15 Ma (MSWD = 2.2; initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.71 \pm 0.27$; Fig. 7k).

For sample KG141, an isochron age of 918 ± 75 Ma is obtained ($n = 18$, MSWD = 1.1; Fig. 7l)

The Rb-Sr systematics in the Gitarama-Gatumba samples show clear differences between white mica and biotite. While the biotite all gives precise Cambrian isochron ages between 531 and 494 Ma (Figs. 7c, 7e, 7f, 7g and 7k), the white mica isochrons show more imprecise Early to Late Neoproterozoic ages (973 – 586 Ma; Figs. 7a, 7b, 7d, 7h-j and 7l).

4.3. U-Pb apatite geochronology

The U-Pb apatite ages obtained from the amphibolite samples of the Kibuye and Gatumba areas, are tabulated in Table A3 and presented in Tera-Wasserburg diagrams in Fig. 8. For all samples, all data fit on one discordia isochron, for which the age was calculated. Within uncertainty, all samples yield similar Late Neoproterozoic ages. Sample KG02-139 gives a precise U-Pb apatite age of 589.6 ± 9.2 Ma ($n = 12$, MSWD = 1.2, $(^{207}\text{Pb}/^{206}\text{Pb})_i = 0.972 \pm 0.203$, Fig. 8a) and sample KG02-144 an age of 589 ± 17 Ma ($n = 13$, MSWD = 1.5, $(^{207}\text{Pb}/^{206}\text{Pb})_i = 0.63 \pm 0.27$, Fig. 8b). The Kibuye apatite ages are more imprecise compared to the Gatumba ages and show a larger variation: 577 ± 64 Ma ($n = 23$, MSWD = 1.3, $(^{207}\text{Pb}/^{206}\text{Pb})_i = 0.873 \pm 0.058$, Fig. 8c) for sample KG52 and 546 ± 37 Ma ($n = 23$, MSWD = 0.68, $(^{207}\text{Pb}/^{206}\text{Pb})_i = 0.854 \pm 0.049$, Fig. 8d) for sample KG53.

Apatite trace elements, including REE, were analyzed by LA-ICP-MS for 10 crystals of each sample to support the geochronological interpretations. Results were normalized to the CI-chondritic values recommended by McDonough and Sun (1995). Typically, the inter-crystal variation in trace element content within one sample is limited, while the geochemical variation between the different samples is slightly higher (Fig. 9, Tables A4 and A5). Figures 9a-d show that Kibuye apatite (KG52 and 53) clearly has a distinct geochemical signature compared to that of Gatumba (KG02-139 and 02-144). Kibuye apatite is relatively enriched in Th, Sr, Si, Zr and Y, but depleted in Mn and Cl in comparison to the Gatumba samples.

Regarding the REE patterns, the same groups can be distinguished (Fig. 9e). Samples KG52 and KG53 (Kibuye) have the most REE-enriched apatite, showing a flat or slightly concave REE pattern with no to minor LREE fractionation. In contrast, apatite from the KG02-139 and KG02-144 samples (Gatumba) is REE-depleted, specifically for the LREE's. Apatite of these samples displays an overall, though slightly asymmetric, concave REE-signature (Figs. 9e and 9f). Except for one outlier of sample KG02-139, all apatite crystals analyzed have a slightly negative Eu-anomaly ($\text{Eu}_\text{N}/\text{Eu}_\text{N}^* = 0.5 - 1.1$) (Fig. 9g).

5. Interpretation and discussion

This section discusses the geochronological data and processes they represent in chronological order, which grosso modo corresponds with the different analytical and mineral groups: Rb-Sr white mica, Ar-Ar for biotite and white mica, U-Pb apatite and Rb-Sr biotite, respectively.

5.1. Elevated temperature regime during the Neoproterozoic

All Rb-Sr white mica dates of the Gitarama-Gatumba area are characterized by high uncertainties (3.5 – 31.5 %) and scatter ($\text{MSWD} = 0.96 - 2.1$, except for one value of 0.54; Fig. 7). The dates obtained range from the Early to Late Neoproterozoic (973 – 586 Ma). While the high uncertainties can be explained by the limited variability in $^{87}\text{Rb}/^{86}\text{Sr}$ amongst the white mica crystals (Glodny et al., 2008), the high scatter and regional discrete and extended age range indicate disequilibrium. Such characteristics are often found in systems affected by thermal diffusion, whether or not in combination with new mineral growth (e.g. Bröcker and Franz, 2006; Moghadan et al., 2017; Villa and Hanchar, 2017; Willner et al., 2015). Sr^{2+} is susceptible to loss by diffusion, as long as the temperature remains higher than the so-called closure temperature, depending on cooling rate and crystal size (Dodson, 1973; Fletcher et al., 1997; Villa, 2006). This diffusion affects the Rb/Sr-ratio of a rock or mineral sample and consequently alters the geochronological data obtained. Full isotopic equilibration by volume diffusion among all phases or crystals only occurs in thermally extreme situations (Glodny et al., 2008). Geochronological interpretations

of overprinted metamorphic rocks are hence complicated by incomplete resetting of which the extent is indefinable, preventing solid conclusions about regional processes.

Fluid- or deformation-assisted dissolution-recrystallization is a much faster and more efficient process in disturbing isotope systematics than volume diffusion (Bosse and Villa, 2019; Villa et al., 2014) and can lead to multiple, diachronous and heterochemical mica generations, even on the scale of a single thin section (Bröcker et al., 2013; Cliff et al., 2017; Willner et al., 2015). Typically, the presence of fluids only induces local resetting near the fluid pathways (Glodny et al., 2008), which also could explain the local variability observed in the white mica Rb-Sr dataset of the KGG area. However, rocks that underwent (partial) recrystallization due to deformation or fluid circulation, and associated isotopic inheritance, can, typically, be recognized by patchy or dendritic replacement structures, most notably for the elements Si and Al (Villa, 2016). Except for limited paragonite-muscovite solid solution, the metasiltstone white mica EPMA maps show no distinct geochemical variation within or between white mica crystals for a single sample of the KGG area (Figs. 6c and 6d). Therefore, fluid- or deformation-assisted mica recrystallization seems unlikely in the metasiltstone samples.

The closure temperature for the Rb-Sr system in white mica typically is between 500 and 550 °C (Eberlei et al., 2015; Freeman et al., 1997; van Blanckenburg et al., 1989). Petrographic observations demonstrate that metamorphism at the start and end of the Neoproterozoic was associated with temperatures up to 630 and 520 °C in the KGG area, respectively (Van Daele et al., in press). This means that, at least during these two metamorphic events, the regional temperature exceeded the closure temperature, allowing thermal diffusion to have a significant influence on the Sr isotope systematics of white mica. Therefore, based on the high MSWD-values, homogeneous white mica composition and postulating temperatures ≥ 520 °C during the Neoproterozoic, it can be inferred that the metasiltstone white mica Rb-Sr dataset dominantly reflects thermal diffusion processes. This unfortunately implies that no detailed conclusions

can be made on the foliation development and related deformation (KG89 and 103), metasomatism (KG126) or retrograde white mica pseudomorphism (KG130).

In contrast to the other samples, white mica in granite (KG140 and KG141) displays a heterogeneous composition, especially for Al (Fig. 6e), which is indicative of at least two white mica growth generations, most probably primarily magmatic and secondary metamorphic overgrowth. Based on the initial strontium ratios in granitic rocks, Fernandez-Alonso et al. (1986) already suggested a long time lag between magmatism and isotopic closure. More reliable and precise SHRIMP $^{207}\text{Pb}/^{206}\text{Pb}$ zircon ages determined the intrusion age of the G1-G3 granites at 1380 – 1375 Ma, and that of the G4 granites around 986 Ma ($n = 8$ and $n = 1$ respectively; Tack et al., 2010). Bulk Rb-Sr geochronology has given ages of 951 ± 12 Ma and 976 ± 10 Ma for G4 granite samples (Cahen and Ledent, 1979). In our study, both the G1-G3 and G4 granite white mica Rb-Sr age are younger than indicated by previous studies (KG140: 940 ± 135 Ma, KG141: 918 ± 75 Ma). In combination with the EPMA maps, it can therefore be concluded that the Rb-Sr isotope systematics of white mica in these samples do not represent the original age of granite intrusion, but rather a partially reset or mixture date between intrusion and metamorphism. Hence we interpret for samples KG140 and KG141 that multiple mineral growth generations, possibly complemented by thermal-induced isotopic resetting, are the primary cause for the large data scatter, leading to the imprecise isochron ages obtained for granitic white mica.

5.2. Deformation during the Ediacaran

Mica from inter-boudin quartz veins (KG92 and 98) indicates a local extensional regime with layer-parallel stretching during the Ediacaran. The ‘domino’ boudin context of sample KG98 demonstrates an additional shear-component acted during this extension (Twiss and Moores, 2007). Possibly, boudinage took place during the regional compressive stress regime as far-field effect of the East African Orogeny (Fernandez-Alonso et al., 2012), but this cannot be confirmed without additional structural analyses. White mica (KG92: 591.2 ± 2.0 Ma; Figs. 5a), although typically having a higher Ar-retentivity and T_c , shows younging

ages towards the end of the spectrum and a less well-developed plateau than biotite (KG98: 567.2 ± 1.8 Ma; Fig. 5b). Ar-Ar spectra as of sample KG92, with younger ages at the high T end, were also observed in hornblende of mafic intrusive rocks in the southeastern part of the KAB (Deblond et al., 2001) and in muscovite from the ED of the KAB (Koegelenberg et al., 2015). These authors assigned this specific spectrum morphology to a younger event in which percolating fluid or stress-related minor recrystallization occurred which disturbed the K-Ar systematics (Villa, 2010). The Ar-spectrum of sample KG92 also resembles that of white mica strongly overprinted during the second of two deformational events, as observed by Villa et al. (2014). No detectable ^{37}Ar was observed and ^{38}Ar could not be analyzed, which could have confirmed the occurrence of multiple, chemically resolvable white mica generations. The EPMA maps neither show distinct major element composition variation in both samples (sample KG92 in Fig. 6a), hence suggesting younger deformation-induced disturbance rather than fluid-induced recrystallization and resetting in the boudin veins of sample KG92. The plateau age of sample KG98 (567 Ma) is interpreted to represent the actual crystallization age of biotite in the quartz veins, hence the formation age of the domino boudins and time of local extensional shear deformation .

The biotite age of gneiss KG101 shows a difference of 58 Myr with the nearby sampled boudin biotite Ar-Ar age (sample KG98 at 75 m, Fig. 2). Although the biotite crystals in gneiss KG101 are significantly smaller compared to quartz vein biotite KG98 ($< 300 \mu\text{m}$ thick versus cm-sized, respectively), the latter gives the youngest Ar-Ar age. The geographical location of these samples precludes a largely different thermal evolution, and the homogeneous EPMA maps of biotite in sample KG101 (Fig. 6b) exclude partial recrystallization processes. Following the classical closure temperature concept, the KG101 Ar-Ar results would suggest that the regional temperature dropped below the biotite Ar-closure temperature of $280 - 345^\circ\text{C}$ (Harrison et al., 1985) as early as 625 Ma. This is however impossible regarding the regional greenschist metamorphic conditions ($T = 520^\circ\text{C}$) in the KGG at that time (Van Daele et al., in press). The older KG101 biotite age is, therefore, explained by a component of parentless ^{40}Ar (see § 5.5).

5.3. Regional fluid-assisted metamorphism during the Ediacaran

The isochron regressions of the U-Pb apatite data from the amphibolite bodies of the KGG area show Ediacaran ages (~590 – 550 Ma; Fig. 8). The trace elements, especially the Rare Earth Element content, shows that apatite has in all cases a metamorphic origin. Compared to the average mafic rock apatite (not associated with mineralization) of Piccoli and Candela (2002), all apatite from the KGG area is depleted in Sr, U, Th, Y, ΣREE_N and LREE_N , which is a typical characteristic for metamorphic apatite (Gillespie et al., 2018; Henrichs et al., 2018; Schneider et al., 2015; Spear and Pyle, 2002). During fluid-assisted metamorphism, mainly LREE are redistributed, which is often due to the crystallization of epidote or zoisite (Janots et al., 2018). Epidote was indeed observed in the amphibolite samples from the Gatumba area KG02-139 and KG02-144 (Fig. 3h). Moreover, epidote content is closely linked to the extent of LREE-depletion and shows a strong negative correlation with the total REE-content in apatite (Fig. 9e, also see Glorie et al., 2019). It is, therefore, very likely that authigenic apatite in the Gatumba area crystallized from metamorphic fluids. Apatite growth is widespread in metapelites and metabasic rocks from the upper greenschist facies onwards (Henrichs et al., 2018), conditions that were reached in the KGG area during Late Neoproterozoic metamorphism (Van Daele et al., in press). Epidote (and hence apatite in the KGG amphibolite samples) typically crystallizes at epidote-amphibolite facies conditions, which occur at the transition between greenschist and amphibolite facies metamorphism (Klein and Dutrow, 2007; Turner, 1981; Winkler, 2013).

Epidote has not been observed in the Kibuye amphibolites (KG52 and 53). Additionally, apatite from these samples shows a different geochemical signature and generally younger U-Pb ages compared to Gatumba apatite (Figs. 8 and 9). These differences suggest the Kibuye area was not affected by the fluid alteration event that took place in the Gatumba area. However, interaction with hot (> 250 °C), acidic, Na-, Ca- and Cl-rich brines can selectively deplete LREE in apatite without the formation of REE-minerals, such as epidote or monazite (Cave et al., 2018; Harlov et al., 2002; Migdisov et al., 2016). The younger ages can

also be caused by increased thermal diffusion of Pb in the Kibuye area due to a longer elevated temperature regime or slower uplift than the Gatumba area. Even though apatite is rather inert to recrystallization during overprinting metamorphism and can be stable up to amphibolite facies conditions, U-Pb isotope systematics in apatite can be controlled by diffusion (Kirkland et al., 2017; Szopa et al., 2014; Willigers et al., 2002). The closure temperature for the U–Pb system in apatite is generally estimated between 450 and 550 °C (Cherniak et al., 1991; Chew et al., 2011; Harrison et al., 2002; Schneider et al., 2015). For 250 µm large apatite crystals, this can further be constrained between 480 and 525 °C, for cooling rates of 1 to 10 °C/Myr, respectively (Barfod et al., 2005). In view of the geothermometric evolution in the WD of the KAB during the Neoproterozoic, as postulated by Van Daele et al. (in press), thermal Pb diffusion could have affected the Pb-budget of apatite in the Kibuye amphibolites, explaining these results as ‘cooling’ ages. However, without additional knowledge on the fluid type or the detailed temperature evolution in both the Gatumba and Kibuye areas, it is not possible to decide between a cooling or fluid-induced recrystallization origin of the U-Pb apatite data from the Kibuye area.

5.4. Early Cambrian biotite new growth

The biotite Rb-Sr ages (KG101, 103, 123, 124 and 140) are all Cambrian (494.1 – 530.5 Ma), which is significantly younger than all other ages obtained in this study. Additionally, generally lower uncertainty and scatter is associated with these isochrons ($< \pm 15$ Ma, mostly $< \pm 6.6$ Ma, MSWD = 0.26 – 1.3 Ma, exceptionally 2.2; Fig. 7). Two factors can explain these young biotite ages. Firstly, as the closure temperature for Sr in biotite (300 – 400 °C; Jenkin et al., 2001; Willigers et al., 2004) is significantly lower than that for Sr in white mica (500 – 550 °C; Eberlei et al., 2015; van Blanckenburg et al., 1989) and for Pb in apatite (480 – 525 °C; Barfod et al., 2005), such young ages are not unexpected in case they represent cooling ages. Secondly, young biotite ages also can indicate late biotite growth or alteration by retrograde reaction mechanisms, e.g. chloritization (Bosse and Villa, 2019; Smit et al., 2011).

Two samples, KG103 and 140, for which both the white mica and biotite Rb-Sr isotope compositions were analyzed, allow a direct and detailed comparison. Rb-Sr dating of white mica in G1-G3 granite KG140 yields an imprecise early Neoproterozoic age (940 ± 135 Ma), which is affected by multiple growth generations and possibly partial resetting by diffusion (§5.1). Rb-Sr analyses on biotite from the same rock reveal an early Cambrian age. Similar observations were found for metasilstone KG103. The mineral paragenesis, as determined by petrography, explains the divergent mineral ages. Syn-foliation white mica isotopic systematics were partly disturbed and partly retained from the Mesoproterozoic until the Cambrian when, amongst others, post-foliation biotite crystallized in dispersed clusters (Figs. 5c and 5g). Moreover, biotite of sample KG103 shows a significantly younger Rb-Sr age than all other biotite samples. This difference with the other biotite Rb-Sr ages probably is linked to different host rock lithologies, characterized by temporally differential biotite growth. While the other biotite samples are either a granite or gneiss with quartz pockets or veins, KG103 represents an 'ordinary' foliated metasilstone. The good quality of the biotite isochrons (in comparison to those of white mica) additionally supports the hypothesis of biotite new growth during the Cambrian rather than that of thermal diffusion.

5.5. The role of fluid activity

Biotite of sample KG101 was analyzed both for its Ar-Ar and Rb-Sr isotopic composition (Figs. 3c and 7c), which allows a direct comparison between the two geochronological systems. The Ar-Ar age obtained is 625.4 ± 1.9 Ma, while the Rb-Sr age is c. 95 Myr younger: 530.5 ± 3.3 Ma. All biotite EPMA maps, including those of sample KG101, show a very homogeneous major element composition of the biotite crystals (Fig. 6b), excluding partial recrystallization processes. Additionally, if full recrystallization due to hydrothermal fluid circulation took place at conditions cooler than c. 280 °C, corresponding Ar-Ar and Rb-Sr ages are expected. If (re)crystallization occurred at temperatures exceeding the closure temperatures, thermal diffusion should have had an impact on the isotope systematics. Largely similar thermal diffusion behavior is expected for Ar and Sr in mica (Hart, 1964; Purdy and Jäger, 1976; Villa, 2016). Nevertheless, based on

the ion size and charge, Sr^{2+} diffuses slower through the crystal lattice than Ar (Bosse and Villa, 2019). This is reflected in a partially overlapping, but slightly higher closure temperature of the Rb-Sr system in biotite (300 – 400 °C; Jenkin et al., 2001; Willigers et al., 2004) compared to the biotite Ar-Ar closure temperature (280 – 345 °C, Harrison et al., 1985). This implies that in case of recrystallization at a temperature higher than 280 °C, which was the case in the KGG area during the Ediacaran (Van Daele et al., in press), older Rb-Sr ages are expected. Additionally, it is generally accepted that the closure temperature concept is not readily applicable to metamorphic rocks that were subjected to a complex P-T, deformation or fluid circulation history (Challandes et al., 2008; Moghadan et al., 2017).

Therefore, the age discrepancy between the Rb-Sr and Ar-Ar results cannot be explained by thermal diffusion in a simple scenario of regional cooling or by partial recrystallization. An alternative cause has to be found to why the K-Ar system in biotite acted as a closed system from an earlier stage onwards, compared to the Rb-Sr system. In complex geological settings, metasomatism, metamorphism or alteration are often of much larger importance (Villa and Hanchar, 2017). Substantial fluid circulation in the Satinsyi Complex west of Gatumba was already envisaged by the abundant occurrence of tourmaline and white mica aggregates, as staurolite pseudomorphs and coarse-crystalline quartz-muscovite lenses (Van Daele et al., in press). Therefore, the possibility of fluid-induced resetting certainly cannot be ignored in the KGG area.

Different independent studies have demonstrated extensive hydrothermal activity at the end of the Neoproterozoic in Rwanda and the Kivu region (Cahen et al., 1984; Dewaele et al., 2011; Goldmann, 2016; Melcher et al., 2015). Varying degrees of hydrothermal alteration traditionally have been invoked to cause discrete and partial resetting of the K-Ar, Ar-Ar and Rb-Sr isotopic systems in the KAB (Ernst et al., 2013; Fernandez-Alonso et al., 2012; Midende et al., 2014). The younger Rb-Sr biotite ages can be caused by circulation of a high salinity, (earth) alkali-rich fluid. (Re)crystallization from such a fluid would allow the Rb-Sr isotopic composition of biotite to be more easily disturbed than its K-Ar isotope systematics, as the

solubility of Ar in aqueous fluids decreases with increasing salinity (di Vincenzo et al., 2006; Jenkin et al., 2001). This would lead to an increased importance of back-diffusion and retention of Ar compared to Sr. This specific fluid alteration induces a back-diffused component of parentless or excess ^{40}Ar in the biotite crystals, resulting in artificially old Ar-Ar ages (Cliff et al., 2017; di Vincenzo et al., 2006; Willigers et al., 2004). It furthermore corresponds with the general assumption that in mountain belts with multiple deformational and metamorphic events, such as the Karagwe-Ankole Belt, the condition of no 'initial' radiogenic ^{40}Ar usually is not met (Freeman et al., 1997; Villa et al., 2014). Moreover, the presence of fluids with the potential to affect the Rb-Sr isotopic systematics to a larger extent than those of K-Ar in Western Rwanda has been demonstrated by earlier studies. The Pan-African hydrothermal alteration of metabasic and phyllitic rocks northwest of Kibuye resulted in the formation of talc(-chlorite) schists and quartz veins (Prochaska et al., 1992). Fluid inclusion studies indicated highly saline NaCl-CaCl₂-CO₂-rich fluids were the responsible factor for this talcification, which was accompanied by a complete loss of (earth)alkalis, silicification, Fe-mobilization and actinolite formation (Prochaska et al., 1992). Saline fluids (4.3 wt% NaCl_{eq}) also have been observed in bedding-parallel quartz veins in the transect Kibuye-Cyangugu (Van Daele et al., 2018). Additionally, based on age-corrected Sr isotope ratios of multiple G4-granites samples, post-igneous alkali mobility has been determined in the KAB (Debruyne et al., 2015). Furthermore, apatite geochemistry from the Kibuye area potentially indicates LREE-depletion without formation of REE-minerals, suggesting to be the consequence of alteration by saline Na- and Ca-rich fluids (§5.3).

5.6. Integration in the geodynamic setting

Due to the high uncertainties associated with the white mica Rb-Sr data, these results unfortunately do not provide detailed information on the Meso- or Neoproterozoic deformation and metasomatism events in West Rwanda and, by extension, the Western Domain of the KAB (Fig. 10). These data, however, confirm the elevated temperature regime during the Neoproterozoic, as already demonstrated by the

petrographic study of Van Daele et al. (in press). Nevertheless, the biotite and apatite geochronology give important insights in the geological history of the KAB during the Ediacaran and Cambrian periods.

During the Ediacaran, deformation, metamorphism and associated fluid activity has been recognized based on the U-Pb apatite and phyllosilicate Ar-Ar ages. The local extensional deformation, in some cases complemented with oblique shear, is following shortly after greenschist facies metamorphic processes (520 °C), resulting in garnet growth in metasilstones at c. 620 – 602 Ma (Van Daele and Scherer, in revision) and is contemporaneous with epidote-amphibolite facies metamorphism at c. 590 Ma. The study area lies in West Gondwana, on the eastern side of the Congo Craton (Oriolo et al., 2017). West of the study area, the final assembly of West Gondwana, the West Gondwana Orogeny, already took place between 630 and 600 Ma (Oriolo et al., 2017). Ages of 620-570 Ma in the Kibuye-Gitarama-Gatumba area (this study) partially overlap with the timing of the West Gondwana Orogeny and corresponds to the onset of the East African Orogeny. Collisional processes of the East African Orogeny have been widely recognized in the eastern part of the Congo Craton from 570 Ma onwards (De Waele et al., 2008). The front of this orogeny lies c. 550 km more to the east (Tanzania – Mozambique; De Waele et al., 2008) and continues southwards, where it is called the Kuunga Orogeny (Malawi – Zambia; Fritz et al., 2013). Its main phase took place between 570 and 530 Ma, ending with the collision between East and West Gondwana (De Waele et al., 2008; Fritz et al., 2013). The Ediacaran deformation and metamorphism from the KGG area hence fit very well in the progressively eastwards moving tectonic front finally ending in the amalgamation of the Gondwana supercontinent (Fig. 10). Multiple samples in our study confirm the first occurrence of far-field effects of the Gondwana assembly and associated tectonic activity in West Rwanda around 590 Ma, slightly older than previously estimated (e.g. Fernandez-Alonso et al., 2012), but corresponding with the white mica Ar-Ar plateau age obtained by Dewaele et al. (2011).

Extensive fluid circulation was especially important at the start of the Cambrian (530 – 510 Ma), as evidenced by the young Rb-Sr biotite ages observed in the Gatumba area. These dates are slightly younger

than the climax of the compressional overprint in the KAB as far-field effect of the East African Orogeny, which traditionally has been put around 550 Ma (De Waele et al., 2008; Dewaele et al., 2011; Fernandez-Alonso et al., 2012). This delay possibly reflects the process of aqueous fluxes percolating through underthrust fault systems towards the west as the result of final collision tectonics and associated crustal thickening more to the east (Buchwaldt et al., 2008; Fig. 10). The saline, reactive fluids circulating throughout the WD affected the Rb-Sr systematics of biotite, while muscovite and the Ar-Ar signature of biotite were left largely unaffected.

While a Pan-African overprint also has been recognized in the WD of the KAB by earlier studies (e.g. Dewaele et al., 2011; Klerkx et al., 1984), this has not been the case for the Eastern Domain (ED) so far (Koegelenberg et al., 2015). Mesoproterozoic muscovite Ar-Ar ages of 1326 ± 10 Ma were obtained in mylonites and phyllonites, which represent the main phase of shortening and fold-and-thrust tectonics in the ED. The younger ages in the WD correspond with an increasing grade and intensity of regional metamorphism and deformation from east to west in the KAB (Klerkx et al., 1987; Koegelenberg and Kisters, 2014; Tack et al., 1994) and nicely reflect the strong dependence of geochronological results on metamorphic peak temperatures and deformation intensity, as illustrated in detail by Villa et al. (2014). Our study suggests that metamorphism and deformation at the end of the Neoproterozoic, and associated fluid activity and isotopic resetting, was restricted to the WD of the KAB. This difference is maybe related to the presence of two contrasting basements in the KAB (Fernandez-Alonso et al., 2012): the strong Archean Tanzania Craton in the ED versus the weaker Paleoproterozoic basement in the WD.

6. Conclusion

This integrated geochronology study of the Kibuye-Gitarama-Gatumba area demonstrates the multitude of events and processes occurring in the Western Domain of the Karagwe-Ankole Belt (Fig. 10). During the prograde greenschist to amphibolite facies metamorphic conditions throughout the Meso- and Neoproterozoic, thermal diffusion severely affected the Sr-budget in white mica to such an extent that Rb-

Sr white mica data are not suitable to temporally pinpoint any events during the Neoproterozoic. Additionally, multiple, heterochemical white mica generations were observed in the Mesoproterozoic granites. Apatite U-Pb ages demonstrate fluid-assisted metamorphism in the Gatumba area at c. 590 Ma. Simultaneously (c. 590 – 570 Ma), local extension and minor shearing took place, resulting in (domino) boudin formation (biotite and muscovite Ar-Ar ages). Lastly, biotite (re)crystallized in the metasilstones under the influence of circulating saline, (earth) alkali-rich fluid during the Cambrian. The homogenous EPMA elemental maps suggest this is correctly recorded in the Rb-Sr geochronological results, while the Ar-Ar isotope systematics appear to contain a parentless ^{40}Ar component.

In view of the geodynamics, the Western Domain of the Karagwe-Ankole Belt had the unique geographical position to record processes from the onset till after the culmination of the East African and Kuunga Orogenies. The local extensional(-shear) deformation followed by important fluid migration, possibly induced by the final Gondwana amalgamation at the East African front, strongly affected the Western Domain during the Late Neoproterozoic and Cambrian (Fig. 10). This is in strong contrast to the Eastern Domain of the Karagwe-Ankole Belt and has previously largely been overlooked in metamorphic and geodynamic models of this Mesoproterozoic belt. The results of this study indicate that the metamorphic history and its elevated temperature regime, as well as the belt-wide geodynamic deformation and fluid circulation, are recorded in the Neoproterozoic geochronological record of the Karagwe-Ankole Belt.

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Conflict of interest

The authors can confirm that there is no disclosure of potential conflicts of interest, no research involving neither human participants nor animals.

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1015 **7. Appendix**

1016 Tables A1 – A5

1017 **Figure captions**

1018 **Figure 1:** Geological position of the Karagwe-Ankole Belt and Kibuye-Gitarama-Gatumba study area (WD
1019 = Western Domain, ED = Eastern Domain, D.R. Congo = Democratic Republic of Congo). Based on
1020 Fernandez-Alonso et al. (2007) and Koegelenberg and Kisters (2014).

1021 **Figure 2:** Geological map of the Kibuye-Gitarama-Gatumba study area with indication of the samples
1022 studied in this manuscript (based on Dehandschutter et al., 1988; Tahon et al., 1988b, 1988a).

1023 **Figure 3:** Thin section petrography of the samples analyzed. (a) Two white mica generations in white mica
1024 schist KG89. (b) Biotite-garnet rim in sample KG101. (c) Metasiltstone KG103 with white mica defining the
1025 host rock foliation and dispersed biotite. (d) A quartz vein, rimmed by a biotite-garnet zone, in finely
1026 laminated metasiltstone KG123. (e) Boundary between the biotite- and white mica-rich, foliated
1027 metasiltstone and coarser, unfoliated white mica-quartz lens in sample KG126. (f) Fine-crystalline white
1028 mica lenses (staurolite pseudomorphs) in foliated metasiltstone KG130. (g) G1-G3 granite KG140: the
1029 mylonite foliation is primarily defined by white mica; biotite rather occurs dispersed throughout the
1030 matrix. (h) Hornblende, plagioclase and epidote in amphibolite KG02-139. Mineral abbreviations after
1031 Siivola and Schmid (2007) (see Table 1, plag = plagioclase).

1032 **Figure 4:** Field work and handsample petrography of the samples analyzed. (a) White mica KG92 in quartz
1033 veins in boudinaged pegmatite. (b) Biotite KG98 in quartz veins from a domino-boudinaged quartz vein.
1034 (c) Biotite in the gneissic metasiltstone and biotite-garnet rim of an elliptical quartz pod in sample KG101.
1035 (d) Sample KG123 containing a quartz vein, rimmed by a biotite-garnet zone, in finely laminated

1036 metasiltstone. (e) G1-G3 granite KG140: the mylonite foliation is primarily defined by white mica; biotite
1037 rather occurs dispersed throughout the matrix. (f) Leucogranite (G4-generation) KG141 with quartz,
1038 plagioclase, K-feldspar and muscovite. The pencil has a length of 15 cm and a diameter of 1 cm, the coin
1039 has a diameter of 2 cm. Mineral abbreviations after Siivola and Schmid (2007) (see Table 1, plag =
1040 plagioclase, Kfs = K-feldspar).

1041 **Figure 5:** Plateau ages in the Ar-Ar age spectra of samples KG92, KG98 and KG101.

1042 **Figure 6:** Selection of EPMA elemental and backscattered electron (BSE-compo) maps made of
1043 phyllosilicate samples analyzed for Ar-Ar and Rb-Sr geochronology. (a) White mica KG92 from quartz veins
1044 in a boudinaged pegmatite. (b) Biotite in the biotite-garnet rim of a quartz pocket in metasiltstone KG101.
1045 (c) Two white mica generations in white mica schist KG89. (d) Biotite and a small proportion of white mica
1046 (lower right corner) of sample KG103. (e) White mica aggregate in G4-granite KG141. Color scales
1047 represent relative (semi-quantitative) counting intensities (dwell times of 50 ms per pixel).

1048 **Figure 7:** White mica and biotite Rb-Sr ages of the Gitarama-Gatumba area. Unfilled ellipses are not taken
1049 into account for the isochron age calculations.

1050 **Figure 8:** U-Pb ages of apatite in amphibolite of the Kibuye -Gatumba area.

1051 **Figure 9:** Trace element (including REE) contents of apatite from amphibolites in the Kibuye-Gatumba area.
1052 (a) – (d) Trace element content of apatite crystals, all values are in ppm. (e) Average REE-patterns of apatite
1053 in amphibolite, normalized to the CI chondritic values of McDonough and Sun (1995). (f) Normalized total
1054 REE content versus fractionation degree for all apatite crystals analyzed. (g) Normalized total REE content
1055 versus Eu-anomaly for all apatite crystals analyzed.

1056 **Figure 10:** Overview of the Ediacaran-Cambrian events and processes in the Western Domain of the
1057 Karagwe-Ankole Belt recognized in this study and how they relate to the regional Gondwana assembly. [1]
1058 Oriolo et al. (2017). [2] in correspondence with Debruyne et al. (2015); Prochaska et al. (1992); Van Daele

1059 et al. (2018). [3] Van Daele and Scherer (in revision). [4] in correspondence with Van Daele et al. (in press).
 1060 [5] De Waele et al (2008). [6] Fritz et al. (2013). [7] Fernandez-Alonso et al. (2012).

1061 **Table captions**

Sample	Location	Latitude (°S)	Longitude (°E)	Rock type	Group
KG02-139	Gatumba	1° 55' 17"	29° 39' 15"	amphibolite	Cyohoha (St)
KG02-144	Gatumba	1° 55' 17"	29° 39' 15"	amphibolite	Cyohoha (St)
KG52	Kibuye	2° 05' 31"	29° 19' 55"	amphibolite	Pindura (Cy)
KG53	Kibuye	2° 06' 09"	29° 20' 07"	amphibolite	Pindura (Cy)
KG89	Gitarama	1° 59' 47"	29° 42' 43"	schist	Gikoro (Bu)
KG92	Gatumba	1° 55' 36"	29° 39' 09"	quartz vein	Cyohoha (St-Ga)
KG98	Gatumba	1° 55' 42"	29° 39' 01"	quartz vein	Cyohoha (St-Ga)
KG101	Gatumba	1° 55' 42"	29° 38' 58"	metasiltstone	Cyohoha (St-Ga)
KG103	Gatumba	1° 55' 44"	29° 38' 57"	metasiltstone	Cyohoha (St-Ga)
KG123	Gatumba	1° 56' 55"	29° 39' 21"	QGB vein	Cyohoha (St-Ga)
KG124	Gatumba	1° 56' 55"	29° 39' 20"	QGB vein	Cyohoha (St-Ga)
KG126	Gatumba	1° 56' 43"	29° 39' 09"	metasiltstone	Cyohoha (St-Ga)
KG130	Gatumba	1° 56' 55"	29° 39' 17"	metasiltstone	Cyohoha (St-Ga)
KG140	Gitarama	2° 04' 38"	29° 43' 03"	granite	/
KG141	Gitarama	2° 04' 40"	29° 43' 04"	granite	/

Sample	Mineralogy	chrono
KG02-139	am, fsp (sericitized), bt, minor amounts of chl, ep, qtz, tur, py	U-Pb
KG02-144	am, fsp (sericitized), bt, minor amounts of chl, ep, qtz, tur, py	U-Pb
KG52	am, fsp, qtz, minor amounts of bt, py, ap	U-Pb
KG53	am, fsp, minor amounts of qtz, bt, py, ap	U-Pb
KG89	crenulated wmca schist (minor qtz and oxides)	Rb-Sr
KG92	wmca of intermullion qtz vein of a mullioned pegmatite	Ar-Ar
KG98	bt of intermullion qtz vein of a bookshelf mullioned quartz vein	Ar-Ar
KG101	qtz lens with bt-grt rim in gneiss (qtz, gr, bt, wmca, tur, chl)	Ar-Ar, Rb-Sr
KG103	metasiltstone (qtz, wmca, chl, bt, py) with few large mica aggregates	Rb-Sr
KG123	quartz vein with biotite-garnet rim in metasiltstone (qtz, bt, fsp, chl, grt, tur)	Rb-Sr
KG124	quartz vein with biotite-garnet rim in metasiltstone (qtz, bt, tur)	Rb-Sr
KG126	metasiltstone (qtz, bt, wmca, tur) with coarse qtz-wmca lenses	Rb-Sr
KG130	metasiltstone (qtz, wmca, chl, bt) with large white mica aggregates	Rb-Sr
KG140	granite (qtz, fsp, wmca and bt-chl) with (mylonite) foliation	Rb-Sr
KG141	leucogranite (qtz, fsp, wmca)	Rb-Sr

1062
 1063 **Table 1:** Sample details on location, lithology, formation, mineralogy and applied geochronological
 1064 method. Mineral abbreviations after Siivola and Schmid (2007) (fsp = feldspar, am = amphibole, bt =

1065 biotite, py = pyrite, ep = epidote, qtz = quartz, ap = apatite, tur = tourmaline, chl = chlorite, wmca = white
 1066 mica, grt = garnet, gr = graphite).

	Heating step	⁴⁰ Ar x 10 ⁻¹⁴ mol	⁴⁰ Ar/ ³⁹ Ar	±2σ	³⁶ Ar/ ³⁹ Ar	±2σ	⁴⁰ Ar*/ ³⁹ Ar	±2σ	⁴⁰ Ar*	³⁹ Ar	cum ³⁹ Ar	Age	±2σ
									%	%	%	Ma	Ma
KG92-wmca, J=0.011563±0.000012	1	2.136	36.8597	0.1681	0.0104	0.0003	33.7742	0.1743	91.6	2.9	2.9	594.8	2.6
	2	6.636	35.4094	0.1650	0.0043	0.0001	34.1381	0.1622	96.4	9.5	12.5	600.2	2.4
	3	8.103	34.4040	0.1471	0.0027	0.0001	33.6118	0.1452	97.7	12.0	24.4	592.3	2.2
	4	5.722	34.0459	0.1577	0.0016	0.0001	33.5797	0.1567	98.6	8.5	33.0	591.9	2.4
	5	6.849	34.1816	0.1493	0.0019	0.0001	33.6088	0.1482	98.3	10.2	43.2	592.3	2.2
	6	10.140	33.9754	0.1405	0.0013	0.0000	33.6006	0.1395	98.9	15.2	58.3	592.2	2.1
	7	6.428	34.4835	0.1544	0.0035	0.0001	33.4589	0.1526	97.0	9.5	67.8	590.0	2.3
	8	10.292	34.0187	0.1423	0.0022	0.0000	33.3772	0.1405	98.1	15.4	83.2	588.8	2.1
	9	11.099	33.5024	0.1506	0.0011	0.0000	33.1895	0.1496	99.1	16.8	100.0	586.0	2.3
KG98-bt, J=0.011635±0.000012	1	1.763	30.3775	0.1375	0.0064	0.0002	28.4806	0.1473	93.8	2.1	2.1	516.3	2.3
	2	1.166	32.0096	0.1608	0.0020	0.0003	31.4142	0.1768	98.1	1.3	3.4	562.0	2.7
	3	4.871	32.0575	0.1536	0.0023	0.0001	31.3747	0.1524	97.9	5.5	8.9	561.4	2.3
	4	5.067	32.1526	0.1514	0.0012	0.0001	31.7881	0.1511	98.9	5.7	14.6	567.8	2.3
	5	6.462	31.5876	0.1372	0.0005	0.0000	31.4320	0.1373	99.5	7.4	22.0	562.3	2.1
	6	4.049	32.0748	0.1647	0.0006	0.0001	31.9049	0.1652	99.5	4.6	26.6	569.5	2.5
	7	10.828	31.7756	0.1610	0.0003	0.0000	31.6985	0.1608	99.8	12.3	38.9	566.4	2.5
	8	12.441	31.7398	0.1634	0.0000	0.0000	31.7388	0.1636	100.0	14.2	53.1	567.0	2.5
	9	6.511	31.7610	0.1466	0.0000	0.0001	31.7600	0.1474	100.0	7.4	60.5	567.3	2.3
	10	6.758	31.6995	0.1367	0.0000	0.0000	31.6985	0.1374	100.0	7.7	68.2	566.4	2.1
	11	6.369	31.7618	0.1505	0.0000	0.0001	31.7608	0.1514	100.0	7.3	75.5	567.3	2.3
	12	8.961	31.7683	0.1361	0.0000	0.0000	31.7673	0.1363	100.0	10.2	85.7	567.4	2.1
	13	12.568	31.7027	0.1614	0.0000	0.0000	31.7017	0.1615	100.0	14.3	100.0	566.4	2.5
KG101-bt, J=0.011470±0.000012	1	0.711	36.3023	0.1647	0.0062	0.0004	34.4621	0.1940	94.9	1.4	1.4	600.9	2.9
	2	1.972	36.1140	0.1866	0.0008	0.0001	35.8651	0.1903	99.3	4.0	5.4	621.6	2.8
	3	3.039	36.1628	0.1808	0.0000	0.0001	36.1617	0.1841	100.0	6.1	11.5	626.0	2.7
	4	3.176	36.6389	0.1900	0.0000	0.0001	36.6379	0.1942	100.0	6.3	17.8	632.9	2.8
	5	5.972	36.1137	0.1591	0.0000	0.0000	36.1127	0.1597	100.0	12.0	29.8	625.2	2.3
	6	9.186	36.1025	0.1507	0.0000	0.0001	36.1014	0.1515	100.0	18.5	48.3	625.1	2.2
	7	9.742	36.0734	0.1513	0.0000	0.0000	36.0724	0.1518	100.0	19.6	68.0	624.7	2.2
	8	8.428	36.1518	0.1527	0.0000	0.0000	36.1508	0.1531	100.0	17.0	84.9	625.8	2.2
	9	1.042	36.1332	0.1524	0.0000	0.0004	36.1322	0.1956	100.0	2.1	87.0	625.5	2.9
	10	5.201	36.1698	0.1660	0.0000	0.0001	36.1688	0.1672	100.0	10.5	97.5	626.1	2.4
	11	0.684	36.4959	0.1714	0.0000	0.0005	36.4949	0.2275	100.0	1.4	98.8	630.8	3.3
	12	0.591	36.5662	0.1813	0.0000	0.0006	36.5652	0.2557	100.0	1.2	100.0	631.9	3.7

1067
 1068 **Table A1:** Analytical data for the separate incremental heating steps of the Gatumba samples analyzed for
 1069 Ar-Ar geochronology.

KG89	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$	KG101	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$
b_wmca1_1	9.096	0.273	0.84419	0.00844	bt_1	4887.983	146.639	38.57818	0.38578
b_wmca1_2	9.444	0.283	0.86706	0.00867	bt_2	607.165	18.215	5.31390	0.05314
b_wmca1_4	8.943	0.268	0.85437	0.00854	bt_3	4646.466	139.394	36.19349	0.36193
b_wmca1_5	9.366	0.281	0.83879	0.00839	bt_4	5008.863	150.266	38.91860	0.38919
b_wmca1_6	7.856	0.236	0.83201	0.00832	bt_5	719.127	21.574	6.19094	0.06191
b_wmca1_9	7.937	0.238	0.83542	0.00835	bt_6	2450.696	73.521	19.13677	0.19137
b_wmca1_10	6.766	0.203	0.81532	0.00815	bt_7	256.832	7.705	2.68038	0.02680
b_wmca1_11	6.909	0.207	0.81663	0.00817	bt_8	1837.779	55.133	14.54594	0.14546
b_wmca1_12	7.736	0.232	0.82439	0.00824	bt_9	3024.812	90.744	23.87686	0.23877
b_wmca1_13	7.892	0.237	0.82742	0.00827	bt_10	4365.931	130.978	33.30772	0.33308
					bt_11	756.680	22.700	6.37252	0.06373
a_wmca2_1	9.309	0.279	0.84142	0.00841	bt_12	3668.577	110.057	28.55607	0.28556
a_wmca2_2	9.353	0.281	0.84301	0.00843	bt_13	2228.043	66.841	17.16102	0.17161
a_wmca2_3	8.404	0.252	0.83329	0.00833	bt_14	3516.224	105.487	27.21710	0.27217
a_wmca2_4	8.842	0.265	0.84973	0.00850	bt_15	5372.724	161.182	41.18684	0.41187
a_wmca2_5	9.376	0.281	0.84239	0.00842	bt_16	554.430	16.633	4.87820	0.04878
a_wmca2_6	9.129	0.274	0.85658	0.00857	bt_17	1691.778	50.753	13.34190	0.13342
a_wmca2_7	10.018	0.301	0.84101	0.00841	bt_18	1691.778	50.753	13.34190	0.13342
a_wmca2_8	9.785	0.294	0.85286	0.00853	bt_19	4099.956	122.999	31.14039	0.31140
a_wmca2_9	10.478	0.314	0.84375	0.00844	bt_20	4735.089	142.053	34.48167	0.34482
a_wmca2_10	7.973	0.239	0.84208	0.00842	bt_21	138.560	4.157	1.82906	0.01829
a_wmca2_11	8.538	0.256	0.84336	0.00843	bt_22	1137.087	34.113	9.20436	0.09204
b_wmca2_1	7.229	0.217	0.83236	0.00832	bt_23	240.603	7.218	2.49549	0.02495
b_wmca2_2	6.630	0.199	0.82566	0.00826	bt_24	7092.708	212.781	52.94656	0.52947
b_wmca2_3	9.346	0.280	0.85016	0.00850	bt_25	6787.027	203.611	51.20933	0.51209
b_wmca2_4	10.730	0.322	0.84611	0.00846	bt_26	14.232	0.427	0.89418	0.00894
b_wmca2_9	5.691	0.171	0.81365	0.00814	bt_27	5381.795	161.454	40.15745	0.40157
					bt_28	5577.103	167.313	41.93593	0.41936
					bt_29	4621.391	138.642	34.91311	0.34913
					bt_30	3104.083	93.122	23.52921	0.23529

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KG103	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$	KG103	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$
wmca_1	14.193	0.426	0.90776	0.00908	bt_1	1537.737	46.132	11.39350	0.11394
wmca_2	11.744	0.352	0.88640	0.00886	bt_2	3614.372	108.431	25.79056	0.25791
wmca_3	17.769	0.533	0.95153	0.00952	bt_3	2251.404	67.542	16.48766	0.16488
wmca_4	16.613	0.498	0.93387	0.00934	bt_4	13.861	0.416	0.89273	0.00893
wmca_5	15.202	0.456	0.91743	0.00917	bt_5	3724.335	111.730	26.34964	0.26350
wmca_6	16.075	0.482	0.95013	0.00950	bt_6	2221.820	66.655	16.27352	0.16274
wmca_7	12.667	0.380	0.90421	0.00904	bt_7	2769.901	83.097	20.20675	0.20207
wmca_8	14.076	0.422	0.90750	0.00907	bt_8	1435.953	43.079	10.78657	0.10787
wmca_9	24.109	0.723	0.97603	0.00976	bt_9	3815.991	114.480	26.95617	0.26956
wmca_10	16.260	0.488	0.92946	0.00929					
wmca_11	13.775	0.413	0.91065	0.00911					
wmca_12	10.830	0.325	0.88462	0.00885					
wmca_13	14.993	0.450	0.91981	0.00920					
wmca_14	13.850	0.416	0.90355	0.00904					
wmca_15	15.061	0.452	0.91762	0.00918					
wmca_16	18.090	0.543	0.95894	0.00959					
wmca_17	15.401	0.462	0.90861	0.00909					
wmca_18	12.038	0.361	0.88516	0.00885					
wmca_19	17.435	0.523	0.94685	0.00947					
wmca_20	13.656	0.410	0.91102	0.00911					
wmca_21	17.495	0.525	0.92325	0.00923					
wmca_22	22.805	0.684	1.02625	0.01026					
wmca_23	14.263	0.428	0.90604	0.00906					
wmca_24	14.138	0.424	0.91581	0.00916					
wmca_25	18.891	0.567	0.96802	0.00968					
wmca_26	14.039	0.421	0.90612	0.00906					
wmca_27	14.108	0.423	0.91597	0.00916					
wmca_28	18.671	0.560	0.94024	0.00940					
wmca_29	15.143	0.454	0.91157	0.00912					

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KG123	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$	KG124	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$
bt_1	5512.614	165.378	40.34760	0.40348	bt_1	2895.696	86.871	21.38443	0.21384
bt_2	4048.110	121.443	30.15189	0.30152	bt_2	2664.568	79.937	20.10296	0.20103
bt_3	4529.138	135.874	33.37456	0.33375	bt_3	989.615	29.688	7.93545	0.07935
bt_4	4544.024	136.321	34.42300	0.34423	bt_4	701.447	21.043	5.56297	0.05563
bt_5	3978.068	119.342	29.19581	0.29196	bt_5	962.149	28.864	7.72552	0.07726
bt_6	385.650	11.569	3.47357	0.03474	bt_6	2874.106	86.223	21.09074	0.21091
bt_7	5630.381	168.911	39.55158	0.39552	bt_7	3614.722	108.442	27.01014	0.27010
bt_8	4251.301	127.539	31.41301	0.31413	bt_8	2234.365	67.031	16.82654	0.16827
bt_9	4295.895	128.877	31.70745	0.31707	bt_9	2998.496	89.955	22.80370	0.22804
bt_10	6107.812	183.234	44.48249	0.44482	bt_10	1629.617	48.889	12.26356	0.12264
bt_11	5245.624	157.369	39.59213	0.39592	bt_11	1802.643	54.079	13.09040	0.13090
bt_12	5348.825	160.465	39.76248	0.39762	bt_12	2082.091	62.463	15.80375	0.15804
bt_13	5035.065	151.052	36.77770	0.36778	bt_13	1481.741	44.452	11.04786	0.11048
bt_14	5944.009	178.320	41.75410	0.41754	bt_14	2373.478	71.204	17.78155	0.17782
bt_15	4892.722	146.782	35.96575	0.35966	bt_15	1476.664	44.300	11.27961	0.11280
bt_16	4748.024	142.441	34.90549	0.34905	bt_16	2998.496	89.955	22.80370	0.22804
bt_17	3783.395	113.502	27.83197	0.27832	bt_17	3237.866	97.136	24.20758	0.24208
bt_18	2718.589	81.558	19.88657	0.19887	bt_18	4511.418	135.343	33.13181	0.33132
bt_19	5681.809	170.454	40.05593	0.40056	bt_19	3028.028	90.841	22.79282	0.22793
bt_20	6602.935	198.088	48.53571	0.48536	bt_20	2332.769	69.983	17.30036	0.17300
bt_21	6764.084	202.923	48.73128	0.48731	bt_21	2457.813	73.734	18.57698	0.18577
bt_22	3986.183	119.585	29.36245	0.29362	bt_22	3104.468	93.134	23.37297	0.23373
bt_23	6336.818	190.105	46.11955	0.46120	bt_23	4228.369	126.851	31.44720	0.31447
bt_24	3569.267	107.078	26.48744	0.26487	bt_24	4372.974	131.189	32.48818	0.32488
bt_25	4487.947	134.638	33.43351	0.33434	bt_25	2091.055	62.732	15.59524	0.15595
bt_26	8167.421	245.023	59.49439	0.59494	bt_26	4531.969	135.959	33.09908	0.33099
bt_27	2900.575	87.017	20.86725	0.20867	bt_27	1553.999	46.620	11.59729	0.11597
bt_28	3780.723	113.422	27.04777	0.27048	bt_28	4126.197	123.786	30.67191	0.30672
					bt_29	3930.247	117.907	28.00838	0.28008
					bt_30	3378.359	101.351	25.25940	0.25259
					bt_31	4307.887	129.237	31.86187	0.31862

KG126	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$	KG130	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$
wmca_1	23.664	0.710	1.03021	0.01030	wmca_1	14.272	0.428	0.89746	0.00897
wmca_2	26.402	0.792	1.06638	0.01066	wmca_2	15.515	0.465	0.90487	0.00905
wmca_3	29.773	0.893	1.10848	0.01108	wmca_3	13.765	0.413	0.89147	0.00891
wmca_4	27.340	0.820	1.09643	0.01096	wmca_4	15.148	0.454	0.90256	0.00903
wmca_5	23.931	0.718	1.05020	0.01050	wmca_5	15.236	0.457	0.90335	0.00903
wmca_6	21.570	0.647	0.99892	0.00999	wmca_6	16.788	0.504	0.91311	0.00913
wmca_7	23.947	0.718	1.04424	0.01044	wmca_7	13.943	0.418	0.89240	0.00892
wmca_8	25.685	0.771	1.06400	0.01064	wmca_8	15.109	0.453	0.89378	0.00894
wmca_9	28.133	0.844	1.07211	0.01072	wmca_9	15.106	0.453	0.90754	0.00908
wmca_10	33.542	1.006	1.16690	0.01167	wmca_10	1.156	0.035	0.70348	0.00703
wmca_11	31.352	0.941	1.13697	0.01137	wmca_11	1.142	0.034	0.71156	0.00712
wmca_12	27.414	0.822	1.07010	0.01070	wmca_12	1.151	0.035	0.71232	0.00712
wmca_13	25.712	0.771	1.02474	0.01025	wmca_13	15.748	0.472	0.90207	0.00902
wmca_14	33.515	1.005	1.09364	0.01094	wmca_14	15.980	0.479	0.91276	0.00913
wmca_15	29.682	0.890	1.07641	0.01076	wmca_15	15.746	0.472	0.91317	0.00913
wmca_16	27.840	0.835	1.09148	0.01091	wmca_16	14.378	0.431	0.89166	0.00892
wmca_17	29.613	0.888	1.06080	0.01061	wmca_17	14.468	0.434	0.89913	0.00899
wmca_18	24.598	0.738	1.02447	0.01024	wmca_18	14.468	0.434	0.89913	0.00899
wmca_19	25.951	0.779	1.03851	0.01039	wmca_19	15.999	0.480	0.90915	0.00909
wmca_20	26.156	0.785	1.07958	0.01080	wmca_20	14.037	0.421	0.89323	0.00893
wmca_21	30.692	0.921	1.05316	0.01053	wmca_21	14.819	0.445	0.89904	0.00899
wmca_22	23.368	0.701	1.03438	0.01034	wmca_22	13.576	0.407	0.88979	0.00890
wmca_23	35.649	1.069	1.10258	0.01103					
wmca_24	32.374	0.971	1.14304	0.01143					
wmca_25	27.978	0.839	1.01361	0.01014					
wmca_26	36.937	1.108	1.19837	0.01198					
wmca_28	26.252	0.788	1.05876	0.01059					
wmca_29	23.899	0.717	1.03061	0.01031					
wmca_30	26.271	0.788	1.05960	0.01060					
wmca_31	27.041	0.811	1.07509	0.01075					
wmca_32	22.140	0.664	0.99134	0.00991					

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KG140	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$	KG141	$^{87}\text{Rb}/^{86}\text{Sr}$	$\pm 2\sigma$	$^{87}\text{Sr}/^{86}\text{Sr}$	$\pm 2\sigma$
wmca_1	84.977	2.549	1.82294	0.01823	wmca_1	180.097	5.403	2.94026	0.02940
wmca_2	83.888	2.517	1.82190	0.01822	wmca_2	156.077	4.682	2.70394	0.02704
wmca_3	75.717	2.272	1.74527	0.01745	wmca_3	144.928	4.348	2.57073	0.02571
wmca_4	97.260	2.918	1.97496	0.01975	wmca_4	132.725	3.982	2.01699	0.02017
wmca_5	98.712	2.961	2.03708	0.02037	wmca_5	166.615	4.998	2.90522	0.02905
wmca_7	83.755	2.513	1.84990	0.01850	wmca_6	161.331	4.840	2.81422	0.02814
wmca_8	65.913	1.977	1.55838	0.01558	wmca_7	138.158	4.145	2.52042	0.02520
wmca_9	79.777	2.393	1.74616	0.01746	wmca_8	91.821	2.755	1.72299	0.01723
wmca_11	86.787	2.604	1.80929	0.01809	wmca_9	108.045	3.241	2.00374	0.02004
wmca_12	81.682	2.450	1.78985	0.01790	wmca_10	101.537	3.046	1.88596	0.01886
wmca_13	81.266	2.438	1.75663	0.01757	wmca_11	137.284	4.119	2.41584	0.02416
wmca_14	82.011	2.460	1.73396	0.01734	wmca_12	127.458	3.824	2.29523	0.02295
wmca_15	89.235	2.677	1.84473	0.01845	wmca_13	157.010	4.710	2.74090	0.02741
wmca_16	91.720	2.752	1.92530	0.01925	wmca_14	172.172	5.165	2.92889	0.02929
wmca_17	84.343	2.530	1.76864	0.01769	wmca_15	154.196	4.626	2.69305	0.02693
wmca_18	87.242	2.617	1.82329	0.01823	wmca_16	143.240	4.297	2.46540	0.02465
wmca_19	91.732	2.752	1.90740	0.01907	wmca_17	176.829	5.305	2.96246	0.02962
wmca_20	87.245	2.617	1.78551	0.01786	wmca_18	147.683	4.430	2.55063	0.02551
wmca_21	93.111	2.793	1.90257	0.01903	wmca_19	157.655	4.730	2.72430	0.02724
wmca_22	86.602	2.598	1.85212	0.01852	wmca_20	142.841	4.285	2.59266	0.02593
wmca_25	70.934	2.128	1.57098	0.01571	wmca_21	128.469	3.854	2.34969	0.02350
wmca_26	80.100	2.403	1.71190	0.01712	wmca_22	140.737	4.222	2.28086	0.02281
wmca_27	85.931	2.578	1.79070	0.01791	wmca_23	135.839	4.075	2.47634	0.02476
wmca_28	83.502	2.505	1.82970	0.01830	wmca_24	132.320	3.970	2.33081	0.02331
wmca_29	104.295	3.129	2.04840	0.02048	wmca_25	135.684	4.071	2.39372	0.02394
wmca_30	101.023	3.031	1.99768	0.01998	wmca_26	148.305	4.449	2.58786	0.02588
wmca_31	89.422	2.683	1.87596	0.01876	wmca_27	118.068	3.542	1.95859	0.01959
wmca_32	73.745	2.212	1.58370	0.01584	wmca_28	189.798	5.694	3.18190	0.03182
					wmca_29	129.056	3.872	2.20614	0.02206
bt_1	1091.156	32.735	8.26944	0.08269	wmca_30	168.405	5.052	2.88710	0.02887
bt_2	3056.099	91.683	22.56671	0.22567	wmca_31	157.215	4.716	2.63473	0.02635
bt_3	732.666	21.980	6.10168	0.06102	wmca_32	142.888	4.287	2.39380	0.02394
bt_4	1086.837	32.605	8.52313	0.08523	wmca_33	126.869	3.806	2.29067	0.02291
bt_5	2762.661	82.880	20.71296	0.20713	wmca_34	134.526	4.036	2.40702	0.02407
bt_6	1118.953	33.569	9.03958	0.09040					
bt_7	3025.874	90.776	23.04456	0.23045					
bt_8	1085.958	32.579	8.70331	0.08703					
bt_9	2021.351	60.641	15.58224	0.15582					

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1075 **Table A2:** Rb-Sr isotope systematics of the individual spots analyzed by LA-ICP-MS. Analyses not included
1076 in the isochron calculation are crossed out.

	U (ppm)	±2σ	²³⁸ U/ ²⁰⁶ Pb	±2σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±2σ	ρ		U (ppm)	±2σ	²³⁸ U/ ²⁰⁶ Pb	±2σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±2σ	ρ
02-139-4	11.8	0.6	10.010	0.401	0.101	0.012	0.2142	52-1	5.5	0.3	3.676	0.176	0.582	0.024	0.4434
02-139-6	17.6	0.8	9.794	0.422	0.084	0.008	0.4355	52-2	5.3	0.3	3.788	0.230	0.595	0.029	0.0344
02-139-7	21.7	1.0	10.142	0.401	0.075	0.007	0.2947	52-3	5.6	0.2	4.115	0.186	0.582	0.024	0.3674
02-139-8	18.9	0.7	9.681	0.422	0.083	0.006	0.0365	52-4	6.3	0.3	4.202	0.194	0.538	0.024	0.2735
02-139-12	8.0	0.3	9.709	0.471	0.125	0.015	0.2275	52-5	6.5	0.3	4.261	0.176	0.543	0.021	0.4042
02-139-13	11.3	0.6	9.718	0.406	0.115	0.013	0.0257	52-6	7.1	0.3	4.505	0.185	0.516	0.024	0.4848
02-139-14	54.0	3.0	10.406	0.314	0.069	0.004	0.1667	52-8	4.1	0.2	3.247	0.148	0.646	0.033	0.6277
02-139-15	12.1	0.7	9.940	0.435	0.121	0.011	-0.0469	52-9	5.3	0.2	3.472	0.157	0.599	0.026	0.1610
02-139-16	36.7	1.5	10.438	0.327	0.070	0.005	0.1829	52-11	6.4	0.3	4.032	0.195	0.551	0.023	0.5216
02-139-22	12.9	0.7	10.030	0.473	0.096	0.010	0.2259	52-12	5.6	0.3	3.597	0.168	0.591	0.028	-0.0136
02-139-24	34.3	1.3	10.526	0.299	0.073	0.006	0.0570	52-13	4.6	0.2	3.425	0.152	0.641	0.027	0.3010
02-139-26	7.7	0.4	7.930	0.377	0.282	0.020	0.2061	52-14	7.1	0.6	3.817	0.262	0.539	0.029	-0.1784
								52-15	7.0	0.3	4.697	0.218	0.534	0.027	0.5636
02-144-1	11.8	0.5	9.911	0.442	0.094	0.010	0.1834	52-16	8.7	0.3	5.028	0.192	0.512	0.024	0.5052
02-144-3	6.0	0.4	9.337	0.506	0.140	0.016	0.2666	52-17	6.3	0.4	4.202	0.212	0.584	0.028	0.5053
02-144-4	13.6	0.6	9.681	0.309	0.089	0.008	0.0261	52-19	6.1	0.3	3.846	0.178	0.581	0.027	0.6012
02-144-8	22.1	1.1	10.010	0.301	0.085	0.008	0.1351	52-20	8.2	0.4	5.438	0.242	0.478	0.025	0.2389
02-144-12	15.1	0.6	9.747	0.408	0.096	0.010	0.3592	52-21	5.3	0.3	3.584	0.193	0.607	0.027	0.4901
02-144-15	10.8	0.5	9.294	0.432	0.108	0.015	0.2762	52-22	5.3	0.3	3.717	0.193	0.573	0.028	0.3783
02-144-20	15.8	0.7	10.363	0.365	0.090	0.009	-0.0676	52-23	7.2	0.4	4.895	0.204	0.477	0.026	0.4808
02-144-23	10.3	0.5	9.862	0.477	0.109	0.013	-0.0465	52-25	7.3	0.4	4.305	0.167	0.543	0.028	0.3407
02-144-26	16.3	0.8	10.020	0.442	0.097	0.011	0.3271	52-26	6.2	0.3	4.098	0.202	0.564	0.032	0.3053
02-144-30	8.5	0.5	9.174	0.404	0.104	0.012	0.2319	52-27	9.1	0.6	4.817	0.211	0.501	0.024	0.4150
02-144-31	78.0	11.0	10.267	0.274	0.067	0.004	0.1104								
02-144-34	19.1	0.9	10.000	0.380	0.090	0.007	0.0933	53-1	11.2	0.6	5.688	0.233	0.458	0.019	0.1368
02-144-39	22.1	1.0	9.804	0.384	0.089	0.007	0.1096	53-2	13.8	0.6	6.527	0.243	0.407	0.015	0.2227
								53-3	8.9	0.5	5.023	0.202	0.514	0.023	0.2965
								53-6	8.6	0.5	4.955	0.189	0.518	0.023	0.3271
								53-8	10.0	0.6	5.336	0.228	0.479	0.025	0.1340
								53-9	13.2	0.7	6.068	0.247	0.420	0.017	0.1980
								53-10	9.4	0.4	5.023	0.194	0.479	0.021	0.4212
								53-11	8.3	0.4	4.812	0.188	0.503	0.020	0.3563
								53-12	8.5	0.4	4.701	0.181	0.537	0.021	0.4503
								53-13	9.2	0.4	5.277	0.214	0.484	0.019	0.5705
								53-14	11.1	0.5	5.615	0.202	0.459	0.022	0.3251
								53-15	14.2	0.8	6.219	0.213	0.396	0.018	0.0188
								53-16	7.5	0.3	4.050	0.153	0.570	0.021	0.4621
								53-19	8.0	0.4	4.662	0.187	0.535	0.030	0.4494
								53-20	9.6	0.5	4.794	0.214	0.513	0.025	0.3087
								53-21	7.9	0.4	4.427	0.174	0.533	0.020	0.2846
								53-23	8.8	0.5	4.808	0.231	0.521	0.028	0.4833
								53-24	9.1	0.5	4.585	0.196	0.517	0.019	0.1875

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1078 **Table A3:** U-Pb systematics analyzed by LA-ICP-MS in apatite from amphibolite of the Kibuye-Gatumba
1079 area.

	Si		P ₂ O ₅		Cl		V		Mn		Sr		Y		Zr		Th		U	
	ppm	±2σ	wt%	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ
02-139_4	490	120	34.8	2.7	4.58E+03	3.70E+02	1.24	0.14	451	19	141	6	109	4	< L.O.D		2.44	0.19	11.3	0.7
02-139_6	307	83	34.6	1.6	4.19E+03	3.80E+02	2.30	0.17	444	16	142	5	102	4	< L.O.D		1.53	0.14	13.0	1.0
02-139_7	382	94	36.2	3.2	4.07E+03	3.50E+02	0.80	0.10	432	22	129	6	126	6	0.06	0.02	3.33	0.27	22.8	1.6
02-139_8	357	99	35.7	1.8	4.27E+03	3.90E+02	1.25	0.13	418	12	136	5	99.1	4.1	0.02	0.02	0.55	0.09	10.4	0.6
02-139_12	357	79	34.1	1.5	3.96E+03	3.00E+02	2.06	0.18	397	14	135	5	94.8	3.2	< L.O.D		0.11	0.03	7.02	0.40
02-139_13	286	98	34.8	1.7	4.11E+03	3.70E+02	0.78	0.11	437	17	138	6	105	4	0.02	0.01	0.91	0.12	8.88	0.59
02-139_14	440	170	39.9	4.4	4.35E+03	4.70E+02	3.08	0.43	438	31	141	8	268	26	0.15	0.05	28.3	2.9	123	10
02-139_15	2.40E+04	1.90E+04	35.5	2.0	4.70E+03	1.00E+03	29.0	14.0	585	74	135	9	111	8	0.04	0.25	0.61	0.26	10.3	1.4
02-139_16	300	110	36.0	2.2	3.94E+03	4.00E+02	0.89	0.13	413	20	139	7	116	5	< L.O.D		0.85	0.10	9.61	0.80
02-139_22	345	97	35.3	1.6	3.74E+03	3.70E+02	0.67	0.09	419	16	139	5	177	7	0.03	0.02	3.87	0.55	27.4	1.7
average	2726	7475	35.7	1.6	4.19E+03	2.95E+02	4.21	8.75	443	52	137	4	131	54	0.05	0.05	4.25	8.54	24.4	35.3
02-144_1	< L.O.D		34.4	1.9	3.06E+03	3.30E+02	1.20	0.13	423	16	139	5	154	6	0.07	0.03	1.99	0.19	20.9	1.2
02-144_3	260	130	33.0	1.8	2.95E+03	5.00E+02	0.53	0.16	402	21	130	7	92.3	4.9	< L.O.D		0.81	0.15	4.87	0.49
02-144_4	337	89	33.9	2.3	3.14E+03	3.00E+02	0.56	0.09	389	23	140	8	208	12	0.02	0.02	2.93	0.28	19.6	1.7
02-144_8	570	120	36.2	4.6	2.79E+03	4.00E+02	1.31	0.16	500	34	163	12	138	9	0.11	0.04	7.37	0.67	47.5	3.5
02-144_12	8.60E+03	1.70E+03	33.2	2.7	3.07E+03	3.20E+02	12.9	2.4	528	27	144	5	51.5	1.9	0.09	0.04	0.65	0.08	9.47	0.61
02-144_15	460	120	34.1	3.2	3.20E+03	3.60E+02	0.54	0.10	440	30	150	14	203	12	0.03	0.02	1.56	0.20	18.3	2.0
02-144_20	380	110	40.6	5.5	2.87E+03	2.80E+02	0.82	0.13	466	15	150	5	60.1	2.0	< L.O.D		0.53	0.06	11.1	0.7
02-144_23	300	85	38.0	4.4	3.43E+03	2.60E+02	0.57	0.10	440	14	149	5	76.5	2.6	0.02	0.01	0.93	0.11	9.59	0.59
02-144_26	429	89	34.8	2.5	3.21E+03	2.40E+02	2.92	0.20	429	22	131	5	116	6	0.03	0.02	3.59	0.38	22.1	1.6
02-144_30	305	78	32.3	1.3	3.20E+03	2.90E+02	1.41	0.15	448	17	140	5	62.0	1.9	< L.O.D		0.38	0.08	7.02	0.35
average	1293	2742	35.1	2.5	3.09E+03	1.87E+02	2.28	3.80	447	42	144	10	116	58	0.05	0.04	2.07	2.15	17.0	12.3
52_1	1.33E+03	2.00E+02	36.9	3.4	1.29E+03	3.70E+02	9.32	0.62	332	16	195	9	906	39	6.39	0.64	13.6	1.2	6.19	0.47
52_2	1.42E+03	1.80E+02	37.1	3.0	9.50E+02	1.90E+02	8.89	0.53	318	16	189	9	871	50	8.90	1.00	15.8	1.2	7.39	0.39
52_3	1.20E+03	1.60E+02	34.1	2.7	7.90E+02	2.00E+02	9.66	0.60	340	13	195	9	824	27	7.51	0.95	13.3	0.8	4.68	0.41
52_4	1.07E+03	1.40E+02	36.2	2.7	1.10E+03	2.30E+02	8.89	0.51	304	14	186	10	864	44	18.7	6.0	12.9	0.9	5.54	0.43
52_5	1.41E+03	1.80E+02	37.6	3.4	9.20E+02	2.30E+02	8.87	0.48	319	14	186	8	982	45	6.34	0.51	12.9	0.8	6.69	0.42
52_6	1.26E+03	1.70E+02	35.5	2.2	8.40E+02	1.90E+02	8.69	0.40	304	12	176	8	1022	41	15.3	2.4	14.6	0.7	7.10	0.46
52_8	1.12E+03	1.40E+02	37.1	3.7	1.02E+03	2.30E+02	9.99	0.62	326	14	192	10	730	34	5.95	0.51	12.1	0.7	3.77	0.27
52_9	1.39E+03	1.90E+02	35.7	2.7	1.21E+03	3.20E+02	8.57	0.58	340	14	189	7	1095	72	6.73	0.52	16.0	1.0	5.89	0.39
52_11	6.60E+03	3.90E+02	37.1	3.0	1.33E+03	2.20E+02	21.4	0.8	345	15	193	7	931	36	11.4	0.9	16.1	1.0	4.96	0.32
52_12	1.14E+03	1.70E+02	37.8	3.2	8.50E+02	2.80E+02	9.53	0.59	349	15	207	10	798	44	5.64	0.43	12.0	0.8	3.99	0.36
average	1794	1693	36.5	1.1	1.03E+03	1.94E+02	10.4	3.9	328	16	191	8	902	109	9.28	4.48	13.9	1.6	5.62	1.26
53_1	1.71E+03	1.40E+02	34.1	1.7	1.10E+03	1.50E+02	6.98	0.43	347	8	204	6	761	24	11.6	0.8	19.5	0.7	7.61	0.36
53_2	4.44E+03	6.30E+02	32.5	1.6	1.28E+03	1.90E+02	8.00	0.78	368	12	209	7	1231	38	14.8	2.2	27.5	1.1	9.82	0.59
53_3	1.80E+03	1.50E+02	34.8	1.4	1.08E+03	1.80E+02	6.81	0.50	362	11	204	7	1255	77	13.7	1.0	36.1	3.3	13.2	0.7
53_6	4.30E+03	1.70E+03	33.0	1.4	1.15E+03	1.70E+02	7.60	1.30	368	17	197	7	1303	45	7.04	0.42	22.6	1.0	8.83	0.48
53_8	6.30E+03	2.30E+03	33.2	2.0	1.11E+03	1.80E+02	13.7	4.9	367	18	187	7	991	46	5.65	0.43	13.7	1.0	9.80	0.47
53_9	3.59E+03	2.40E+02	32.8	2.3	1.05E+03	1.50E+02	7.29	0.36	356	15	197	7	1517	61	14.9	1.3	30.6	1.7	14.5	0.8
53_10	1.61E+03	1.60E+02	31.2	1.2	1.53E+03	2.30E+02	7.34	0.39	362	11	204	7	792	24	10.6	0.8	19.4	0.9	7.22	0.39
53_11	2.55E+03	3.60E+02	34.4	2.2	1.15E+03	1.80E+02	4.25	0.29	356	16	203	8	945	33	19.7	6.5	15.9	0.8	12.6	0.7
53_12	1.57E+03	1.40E+02	35.3	2.1	1.20E+03	2.20E+02	8.76	0.36	378	13	207	5	866	28	14.4	0.6	28.9	1.1	8.82	0.44
53_13	1.57E+03	1.60E+02	35.3	2.5	1.01E+03	1.80E+02	8.05	0.40	377	17	201	8	881	33	11.6	1.0	22.8	1.0	8.51	0.51
average	2944	1643	33.7	1.3	1.17E+03	1.49E+02	7.88	2.37	364	10	201	6	1054	255	12.4	4.1	23.7	7.0	10.1	2.5

	La		Ce		Pr		Nd		Sm		Eu		Gd		Tb		Dy		Ho		Er		Tm		Yb		Lu		ΣREE _n	La _n /Yb _n	Eu/Eu*
	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ	ppm	±2σ			
02-139_4	5.46	0.41	26.7	1.3	6.29	0.36	46.9	2.3	17.7	0.9	4.63	0.25	21.5	1.3	3.20	0.20	18.8	1.0	3.73	0.22	10.2	0.6	1.36	0.09	9.05	0.50	1.46	0.09	985	0.43	0.72
02-139_6	3.39	0.16	18.3	0.6	4.66	0.21	39.1	1.8	16.8	0.8	5.22	0.34	21.2	1.1	3.06	0.16	18.4	0.9	3.69	0.19	9.65	0.48	1.31	0.08	8.44	0.51	1.34	0.10	912	0.29	0.84
02-139_7	9.64	0.69	56.9	3.4	11.7	0.6	75.5	4.5	22.3	1.5	7.20	0.42	25.0	1.5	3.77	0.22	22.2	1.4	4.42	0.25	12.6	0.7	1.79	0.13	12.4	0.8	2.06	0.13	1376	0.56	0.93
02-139_8	1.98	0.11	13.2	0.6	3.69	0.16	33.9	1.5	16.1	0.7	4.51	0.25	21.4	0.9	3.19	0.18	17.4	0.9	3.54	0.18	9.12	0.47	1.20	0.06	7.60	0.43	1.26	0.08	841	0.19	0.74
02-139_12	1.96	0.14	11.2	0.8	2.94	0.20	23.9	1.7	11.6	0.6	4.53	0.27	17.7	1.1	2.78	0.12	16.6	0.8	3.37	0.18	9.20	0.46	1.17	0.07	7.95	0.41	1.25	0.07	745	0.18	0.97
02-139_13	3.26	0.17	14.7	0.6	3.21	0.16	24.6	1.1	12.4	0.7	4.19	0.25	18.0	0.8	2.92	0.15	17.8	0.7	3.66	0.20	9.76	0.48	1.32	0.09	8.86	0.54	1.32	0.07	793	0.26	0.86
02-139_14	8.93	0.82	51.1	4.8	13.1	0.9	107	8	47.1	4.7	13.8	1.2	58.8	6.1	8.43	0.82	50.2	5.1	10.15	0.97	26.6	2.5	3.48	0.32	22.0	2.3	3.75	0.38	2497	0.29	0.80
02-139_15	2.15	0.36	11.1	1.1	3.60	1.90	19.5	2.4	10.7	1.8	4.33	0.58	18.4	2.5	2.96	0.37	19.1	2.0	3.81	0.47	9.90	1.10	1.18	0.30	7.80	1.30	1.27	0.26	765	0.20	0.94
02-139_16	1.76	0.12	10.9	0.6	3.24	0.20	32.2	1.6	19.4	1.2	5.08	0.35	26.1	1.7	3.83	0.25	21.9	1.3	4.25	0.26	11.0	0.6	1.42	0.12	8.60	0.59	1.43	0.10	962	0.15	0.69
02-139_22	8.41	0.78	42.5	3.6	9.05	0.69	66.0	4.7	22.4	1.2	9.31	0.49	31.1	1.6	4.79	0.19	28.8	1.1	6.17	0.26	16.7	0.7	2.36	0.11	15.3	0.8	2.56	0.14	1534	0.39	1.08
average	4.69	3.17	25.7	17.9	6.14	3.79	46.9	28.0	19.7	10.5	6.28	3.10	25.9	12.3	3.89	1.70	23.1	10.2	4.68	2.08	12.5	5.5	1.66	0.74	10.8	4.6	1.77	0.82	1141	0.29	0.86
02-144_1	9.41	0.45	46.7	2.0	10.3	0.5	72.5	2.7	26.3	1.5	7.65	0.42	31.9	1.6	4.71	0.29	27.3	1.2	5.34	0.24	14.9	0.8	2.04	0.11	13.8	0.7	2.30	0.14	1508	0.49	0.81
02-144_3	4.97	0.38	23.2	1.5	4.80	0.34	35.9	2.2	15.0	1.3	5.15	0.36	18.9	1.4	2.78	0.20	16.0	1.1	3.24	0.22	8.47	0.56	1.13	0.10	8.20	0.65	1.28	0.12	854	0.43	0.93
02-144_4	4.15	0.26	20.5	1.4	5.09	0.42	45.0	2.2	25.4	1.9	9.35	0.58	39.1	2.2	6.17	0.37	36.9	2.2	7.74	0.51	19.4	1.2	2.50	0.20	16.9	1.1	2.65	0.21	1584	0.18	0.90
02-144_8	33.9	2.6	146	15	25.9	2.4	152	12	36.9	2.9	9.19	0.73	34.1	2.5	4.34	0.30	24.7	1.7	4.85	0.36	12.6	1.0	1.62	0.16	10.8	0.8	1.89	0.15	2122	2.25	0.78
02-144_12	8.41	0.51	40.1	2.0	8.09	0.38	51.2	2.9	12.7	0.8	3.21	0.22	12.7	0.8	1.68	0.10	9.0	0.5	1.78	0.10	4.9	0.3	0.59	0.06	4.13	0.38	0.76	0.06	715	1.46	0.77
02-144_15	7.37	0.56	36.4	3.1	8.03	0.61	59.6	4.2	27.8	2.2	9.80	0.81	37.7	2.6	5.95	0.46	34.8	2.2	6.81	0.43	19.0	1.3	2.59	0.18	16.6	1.3	2.79	0.24	1677	0.32	0.93
02-144_20	5.77	0.34	28.3	1.2	6.17	0.30	42.5	1.7	12.5	0.9	3.51	0.18	13.8	0.7	1.99	0.12	10.8	0.6	2.18	0.14	5.6	0.4	0.78	0.06	4.88	0.38	0.79	0.06	695	0.85	0.81
02-144_23	6.29	0.26	31.6	1.2	6.72	0.29	44.3	2.1	12.9	0.6	4.17	0.26	16.4	0.7	2.27	0.11	13.3	0.7	2.78	0.13	7.27	0.35	0.93	0.08	6.60	0.45	1.01	0.07	801	0.68	0.88
02-144_26	15.9	0.8	85.9	3.7	16.3	0.8	101	5	26.1	1.5	6.74	0.39	26.4	1.5	3.49	0.21	20.1	1.2	4.11	0.24	11.3	0.7	1.70	0.12	12.2	0.8	2.10	0.14	1545	0.94	0.78
02-144_30	2.19	0.14	9.01	0.47	1.84	0.10	14.3	0.8	6.78	0.46	2.83	0.18	11.6	0.5	1.84	0.10	11.2	0.4	2.27	0.11	5.76	0.31	0.76	0.06	4.67	0.33	0.79	0.06	480	0.34	0.97
average	9.83	9.23	46.8	40.5	9.33	6.98	61.8	39.2	20.2	9.5	6.16	2.73	24.3	10.8	3.52	1.69	20.4	10.1	4.11	2.04	10.9	5.4	1.46	0.74	9.88	4.89	1.64	0.80	1198	0.79	0.86
52_1	84.0	23.0	241	48	37.8	5.3	243	27	108	7	36.2	2.2	178	11	28.2	1.6	169	9	33.1	1.7	87.4	5.7	11.2	0.7	72.0	5.2	10.9	0.6	7687	0.84	0.79
52_2	34.6	3.6	132	12	25.5	1.9	182	12	91.1	5.3	34.1	1.9	157	10	25.4	1.6	160	11	33.2	1.9	87.6	5.0	11.2	0.7	71.8	4.5	10.9	0.8	6684	0.35	0.86
52_3	64.1	3.0	217	11	38.6	1.8	258	11	104	4	31.0	1.5	164	8	25.0	1.0	151	6	31.3	1.4	78.2	3.2	10.5	0.6	64.8	3.0	9.75	0.52	7057	0.71	0.72
52_4	35.3	1.9	143	9	28.6	1.8	202	12	97.4	6.3	30.7	1.5	162	9	26.0	1.5	161	9	32.1	1.8	82.6	4.5	10.9	0.7	70.3	4.2	10.5	0.6	6726	0.36	0.74
52_5	38.1	3.1	142	8	27.4	1.5	198	9	105	5	34.9	1.8	176	10	29.3	1.7	178	9	36.1	2.0	93.5	5.0	12.2	0.6	78.5	3.7	11.8	0.7	7338	0.35	0.78
52_6	36.1	1.6	139	6	27.5	1.1	198	7	102	5	37.0	1.4	181	7	30.3	1.4	187	8	39.0	1.7	101	4	13.6	0.6	84.6	3.7	12.7	0.6	7658	0.31	0.82
52_8	12.2	6	338	18	53.2	2.4	321	15	107	6	27.8	1.6	151	8	23.5	1.4	138	7	27.5	1.3	72.6	3.9	8.73	0.45	56.3	3.1	8.20	0.49	7320	1.55	0.67
52_9	102	11	323	37	51.9	4.8	338	30	134	10	38.7	2.4	208	13	31.9	2.0	195	13	40.2	2.5	105	7	13.3	0.9	84.1	5.2	13.3	1.0	9284	0.87	0.71
52_11	79.2	3.2	251	11	43.1	1.5	294	13	118	5	35.7	1.6	180	7	27.8	1.2	170	7	33.7	1.4	89.9	4.0	11.8	0.6	74.6	3.6	10.8	0.6	7964	0.76	0.75
52_12	199	17	516	50	74.1	6.0	403	29	124	9	28.7	2.0	164	9	25.5	1.5	149	9	29.8	1.8	73.7	4.5	9.41	0.65	58.8	3.9	8.71	0.59	8725	2.43	0.62
average	79.4	52.1	244	122	40.8	15.4	266	74	109	13	33.5	3.7	172	16	27.3	2.7	166	18	33.6	3.9	87.1	10.7	11.3	1.5	71.6	9.6	10.8	1.6	7644	0.85	0.75
53_1	76.9	4.2	271	14	49.0	2.1	334	14	117	4	29.9	1.0	160	6	22.7	0.8	135	4	28.0	0.8	73.2	2.3	9.56	0.37	62.3	2.0	10.2	0.5	7279	0.89	0.67
53_2	256	11	699	30	114	4	669	21	206	7	40.0	1.3	266	10	37.8	1.6	220	8	44.7	1.7	119	4	15.5	0.7	96.3	4.1	15.4	0.6	13350	1.91	0.52
53_3	153	13	513	42	87.0	6.3	558	35	195	12	41.7	2.2	263	14	38.3	2.2	223	12	46.2	2.6	121	8	15.4	0.9	96.9	5.7	15.7	0.9	12108	1.13	0.56
53_6	126	7	439	17	78.1	2.9	525	18	195	7	40.8	1.5	280	10	41.2	1.4	244	9	48.8	1.7	125	5	15.0	0.5	95.5	3.4	14.9	0.6	11954	0.94	0.53
53_8	76.0	10.0	276	25	50.2	3.0	338	19	138	7	37.1	1.9	195	10	28.8	1.4	170	8	36.3	1.7	98.4	4.6	12.8	0.6	82.3	3.8	13.9	0.7	8719	0.66	0.69
53_9	137	6	478	22	87.4	4.1	575	26	216	9	52.8	2.2	304	14	44.9	2.3	265	10	54.0	2.4	147	6	19.3	0.8	124.2	4.9	20.0	1.0	13672	0.79	0.63
53_10	179	6	507	16	78.7	2.8	476	19	144	5	26.3	1.0	190	8	26.8	1.0	152	5	30.2	1.1	76.0	2.0	9.18	0.33	55.1	2.0	8.76	0.39	9088	2.32	0.49
53_11	55.2	3.0	195	8	43.1	2.0	291	12	121	6	25.3	1.0	188	8	29.0	1.3	175	8	35.6	1.6	90.8	4.4	11.1	0.5	68.0	2.9	10.7	0.5	7672	0.58	0.51
53_12	175	5	511	18	82.1	2.5	511	14	160	5	29.5	1.1	210	6	29.6	1.0	168	5	33.7	1.2	85.7	2.6	10.3	0.3	64.9	2.5	9.80	0.31	9851	1.93	0.49
53_13	168	10	480	2																											