Authors' response to reviewers' comments

Manuscript title: Resolving multiple geological events using in situ Rb-Sr geochronology: implications for metallogenesis at Tropicana, Western Australia

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Dear editor,

Please find enclosed comments to the referees comments and your later comments on mineral chemistry. We have brought all key parts in line with the reviewer's constructive comments, particularly the petrographic context as highlighted by both reviewers.

We hope you will now find our manuscript satisfactory for publication. Please do not hesitate to contact us should any further clarification be required. We respond in detail to all reviewers' comments below.

Yours sincerely,

The authors

Editor's comments:

Dear Dr Olierook

I am generally satisfied on how you are planning to address the reviewers' comments. There are however two points that require additional attention and data.

1. The lack of mineral chemistry of the material analysed is not fully addressed. Mineral chemistry can be retrieved also after LA analysis. BSE images are a good start, but mineral chemistry is eventually needed. The same for phengite versus white mica, which can be analyzed after the fact; the petrographic analysis based on grain is not sufficiently robust. I thus request addition of analyses of mica domains beside the LA pits and of white mica versus phengite domains.

AGREE. We have used the mineral chemistry from the automated mineral analyses (TIMA), which is standardized to a Mn standard, to provide semi-quantitative mineral chemistry. These are of course not as robust as getting EPMA (or laser ablation) chemistry, but this at least provides a sense of the type of biotite, muscovite and phengite that was analyzed. We have added representative chemistry measurements in a supplementary table (B), added a new figure (Fig. 5) and added text in the section 5.1 of the results.

2. Composition of standard CK001B. I appreciate that details for this material are in review, but this does not prevent a statement to be added here of the general chemistry of the mica. We do not need the full analyses, which I suppose are included in the other publication, but at least an end members %.

AGREE. In the methods section, we have added "CK009 was collected < 50 km from CK001B, had similar biotite chemistry to CK001 and experienced equivalent Caledonian metamorphism (Kirkland et al., 2007). Biotite in sample CK009 is classified as magnesian siderophyllite according to an mgli-feal diagram (see Fig. 6 in Kirkland et al., 2007)"

Regards
Daniela Rubatto
Associate Editor

Reviewers' comments:

Reviewer #1: Thomas Blenkinsop

The aim of this paper is to demonstrate that in situ Rb/Sr dating has now become sophisticated enough to unravel different geological events. The study uses samples from the Tropicana area, which by now is quite well constrained in terms of regional and deposit scale geochronology. The paper is very clearly written and illustrated, and communicates its message very well. There is no doubt that it shows the power of the method, which is an exciting advance in geochronology and this aspect needs to be published.

We thank the reviewer for their time in reviewing this contribution.

The interpretation of the data with respect to tectonics and mineralisation is more controversial. The older ages agree with previous geochronology (a strength of the paper), but they are interpreted in a new and different way as simple cooling ages rather than relating to the D3 deformation event. This is regarded as having the younger age (1210 Ma). The major reason for this is the interpretation that a single shearing event is seen in the microstructures, unlike the reactivation scenario previously postulated. This is not consistent with the change in kinematics of shear zones from D3 to D4, D5 that is documented in Blenkinsop and Doyle (2014). In that study, D3 shear zones were identified as having only biotite as the phyllosilicate phase, whereas most of the sam- ples in this study have some muscovite/phengite, so they would be classified as D4 or D5 according to the previous work. It could therefore be suggested that none of the samples adequately dated a true D3 shear zone.

PARTLY AGREE. We agree with the disputed aspect of reactivation. This work is not focused on detailed microstructural and petrological study, that is required to assess reactivation scenario. Therefore, it is possible that the reactivation of the greenschist facies D3/D4 shears took place during Mesoproterozoic. We have corrected it in the text, accordingly citing Blenkinsop and Doyle (2014). However, we firmly believe that a low-strain brittle-ductile microstructure we used for dating both Biotite 1 and 2 represents the D3 event as described by Blenkinsop and Doyle (2014). A more discussion to this point is in the following point.

This study has the advantage of the TIMA images which may have revealed additional aspects of shear zones not seen in the 2014 study, so it may be that the petrographic distinction claimed previously is not real. However, there is a clear morphological difference between the shear zones with biotite and pyrite and those with phengite - the latter are generally wider, with much stronger fabrics. This can be seen for example in the differences between Fig. 7, a and b compared to c and d in Blenkinsop and Doyle (2014) There is clear structural evidence for shear zones that cross cut earlier biotite fabrics in the drill core, and there are clearly sets of shear zones with different kinematics (Blenkinsop and Doyle Fig. 14). It would be very strange if this was not the case in such a polymetamorphic setting, although that is not a strong argument. So it is a bold claim that there is no evidence for reactivation and that all deformation textures belong to a single event. To substantiate the new interpretation, it would be useful to see some more microstructural analysis with kinematics and some more detailed photomicrographs of the dated samples.

DISAGREE. We went through the paper of Blenkinsop and Doyle (2014) carefully again. Unfortunately, none of the figures shows a clear cross-cutting relationship between D3 and

D4 textures. Also, it is quite intriguing that both events show the same kinematics of NE-SW shortening in their paper (Table 1 for D3 event and see text in Page 198 for the D4 event). It is necessary to emphasise that the work of Blenkinsop and Doyle (2014) is based on a structural analysis of drill holes when pits were not open. Consequently, it is likely that a spatial and temporal relationship between D3 extensional textures and D4 shears could not have been adequately assessed.

We see a possibility that a variable amount of muscovite/phengite might be a function of variable plagioclase content of the host syenitic gneiss. An easy breakdown of plagioclase to micas localises strain within anastomosing and simple shear-dominated D4 ductile shears, while K-feldspar dominated domains show a more brittle response within an apparent low-strain and pure shear-dominated domain. A presence of carbonate and euhedral pyrite in both microstructures support the coincident development of the D3 and D4 microstructures. If only a single shearing event is implicated, this would have to occur during the formation of mineral assemblage 2 (i.e., 1210 Ma). Although the question of a possible reactivation is not the primary goal of this paper, it is likely that some reactivation of D3-D4 fabric might occur during localised D5 event as suggested by Blenkinsop and Doyle (2014). A presence of carbonate and euhedral pyrite in both microstructures support the coincident development of the D3 and D4 microstructures.

In the end this debate is much less important than the geochronological aspects of the paper, which seem really solid. The tectonic interpretation could therefore be presented with a more nuanced discussion, acknowledging the points above. It would be good to see this paper published, after dealing with this point. Tom Blenkinsop

AGREE. We thank the reviewer again for his constructive comments. We appreciate his knowledgeable insights to the geology of Tropicana deposit very much during this review as well as at the time when he worked on kinematics from drill holes. We realise how difficult it is to resolve the structural story in a remote and very poorly known area without outcrops and open pit observations. We have corrected our discussion to reflect this appreciation.

Reviewer #2: Thomas Zack

This manuscript is a very good illustration of the new opportunities of in-situ Rb-Sr dat- ing. It combines a range of state-of-the-art techniques relevant to mineral exploration (e.g., automated full thin section mineral identification) with texturally controlled in-situ Rb-Sr dating of micas. In the following a range of suggestions are presented how to improve this contribution. As it is a fully public review (something I need to get used to), I hope I can also convince other colleagues to follow some of those suggestions.

We thank the reviewer for their time to provide insightful comments for this paper.

1.) Novelty of contribution: As it is stated in the introduction, it is not the first publi- cation dating two generations of mineral assemblages in the same sample. Therefore please remove "for the first time" in line 16 in the abstract. Instead, it could be stressed stronger that this study demonstrates that in-situ Rb-Sr dating allows tying microtex- tures to several geological events, as correctly stated in the last line of the abstract.

AGREE. This has been removed.

2.) Better microtextural documentation: although a big strength of this manuscript is the combination of microtexture and dating, this connection could and should easily be improved by adding BSE images of selected areas where LA-ICP-MS spots are visible. In general, BSE images give a clearer overview of where exactly spots were drilled and if any fractures, veinlets, inclusions were accidentally hit. In this study specifically, it is important for the reader to judge independently if a biotite 1 or 2 domain was sampled. A critical question is: are those mixed ages (in between 2.5 and 1.2 Ga) due to a partly resetting or by a mixed analysis? Figure 3c is a good example. The biotite 2 looks "bleached"- well, it could be different chemistry (less Fe and/or Ti), finer grain size or even a mixture of different minerals. This can only be solved by showing higher magnification images by BSE (alternatively reflected light can suffix; however, if there is a change in chemistry, this may be visible by a change in gray scale).

AGREE. We thank the reviewer for raising this point – it has yielded some interesting discoveries. BSE images have been added as a new figure (4) and across the transects. Biotite 1 in the ca. 2.5 Ga samples is really 'clean', whereas biotite 1 in the other three samples with younger apparent isochron dates show exsolution lamellae of rutile that probably occurred during the formation of biotite 2. Thus, these laser spots have hit physical mixtures of biotite 1 and 2, with the ages younger than 2.5 Ga having no geological significance.

3.) Combination of ages and chemistry: do you have any additional information on the chemistry of the dated micas? Again, there could (should?) be a difference in chemistry if there are different mica generations (here perhaps visible in different Fe and/or Ti contents). This is not only relevant for distinguishing biotite 1 and 2, but also I do wonder why you distinguish between muscovite (s.s.) and phengite? Is it based on the Si-content? In this case microprobe data must exist, and it would be important to report. If not, then how? Unfortunately no other major (except Ca) and trace elements were measured along with the Rb and Sr isotopes by LA-ICP-MS. This is a pity as it is one of the unique advantages of quadrupole ICP-MS to combine dating and concentration determination (for the future. . .).

AGREE. In retrospect, additional chemistry would have been a useful technique to help discriminate between the two biotite phases. Unfortunately, this was not done. For the biotite chemistry, see above point. For muscovite and phengite, the differentiation was purely petrographic, with muscovite being in larger sheets (e.g., Fig. 3h) and phengite being microcrystalline (Fig. 3f). We have stated this now in various places in the results section.

4.) How many age domains? Are there really "only" two significant ages extractable from the biotite data? A close inspection of figure 4b and 4d seems to show a clear linear trend of your "biotite 1" that falls on an isochron somewhere between the 2.5 Ga and 1.2 Ga. It could well be in this 1.8-1.6 Ga interval mentioned in chapter 2.1.   I strongly recommend replotting the data from figure 4 in a histogram where x-axis is single spot model ages (like kernel density plots typical for detrital zircons). With a bit of statistics it can be tested if this third age is significant. For me it looks to regular   to be a product of partial resetting (in contrast, the scatter visible by the grey circles   in Figure 4a is a convincing example of partial resetting). IF such a third age can be established, the next question is: what distinguishes "biotite1" from samples in fig 4b and d from biotite from samples in fig 4a?

AGREE. As the above points, these dates younger than 2.5 Ga are physical mixtures and geologically meaningless.

5.)   Closure vs formation ages: as far as I can see, the difference between closure   and formation ages has been handled in a succinct matter. Still, I think the manuscript will benefit by giving this topic a bit more prominence (e.g., defining those topics in the introduction and devoting a chapter in the discussion). It is currently a hot topic ("petrochronology" vs "thermochronology"), not always trivial to say which process is dominating in specific cases. Here you have (at least) two age populations of biotite not governed by volume diffusion (still, it is worth mentioning grain size effects on closure temperatures). Furthermore, muscovite is supposed to have higher closure temperatures than biotite, yet muscovite is younger than biotite 1, a clear indication that muscovite ages are formation ages.

PARTLY AGREE. The muscovite ages have high uncertainties (+/- 170 Ma) that overlap with biotite 1; thus, it is not possible to say that the biotite 1 is younger than the muscovite. Thus, we find it difficult to comment on the closure temperature and formation ages.

Specific edits:
-       abstract, line 16: instead of "K- and Rb-bearing", say "K-rich" or "Rb-bearing".

AGREE. Changed.

-       abstract, line 20: replace "second assemblage" with "younger assemblage" (second and first are not defined in abstract)

AGREE. Changed.

-       introduction, line 47: papers by Wolfgang Muller are good examples for texturally-controlled micromilling Rb-Sr dating (e.g., EPSL 180, 385-397).

AGREE. This paper has been cited.

-       methods, line 193: instead "zero counts" (which do not exist), rather say "< xx cps".

AGREE. We have changed this to <7 cps.

- methods, line 217: please say a few more words on the biotite secondary standard CK001B. What chemistry does it have (annite vs phlogopite, etc)? Micas are a very large group with very different chemistry- it may turn out that "matrix" effects may even operate within a mica group, so it is good to have the chemistry specified.

We currently have another paper under review that specifically characterises this secondary standard.

- results, line 237-243: out of curiosity: do you have any constraints on the temperature conditions during mylonite formation? Would be nice to state if you can, as it will give important constraints that biotite 1 can statically survive a certain heating episode without diffusional resetting.

AGREE. Unfortunately, we have no calculation of temperature based on petrology. We believe that a mineralogy of the Assemblage 2 indicates ingress of fluids during the shearing and demonstrates an open thermodynamic system, which makes any PT calculations unreliable. Textural evidence shows brittle deformation of K-feldspar supporting greenschist facies temperatures.

- results, line 271: "fractures were intercepted". Again, this is not clearly visible in the petrographic image. A BSE or reflected light image would be better.

AGREE. Following the comment above, we have taken selected BSE images to demonstrate this.

- discussion, line 313-316: please delete the last two sentences, as they are too speculative!! You can ask Steve Reddy how messy cite occupancy of radiogenic isotopes are on an atomic level. Unless somebody is doing AFM on a mica, we simply do not know.

AGREE. We have deleted these.

- figure 1b: please note that yellow diamonds are gold occurrences. Best wishes,

AGREE. This has been added to the legend map.

Resolving multiple geological events using in situ Rb-Sr geochronology: implications for metallogenesis at Tropicana, Western Australia

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Abstract. Dating multiple geological events in single samples using thermochronology and geochronology is relatively common but it is only with the recent advent of triple quadrupole LA-ICP-MS that in situ Rb-Sr dating has become a more commonly applied and powerful tool to date K-rich or~~and~~ Rb-bearing minerals. Here, we date ~~, for the first time,~~ two generations of mineral assemblages in individual thin sections using the *in situ* Rb-Sr method. Two distinct mineral assemblages, both probably associated with Au mineralization, are identified in samples from the Tropicana gold mine in the Albany–Fraser Orogen, Western Australia. For Rb-Sr purposes, the key dateable minerals are two generations of biotite, and additional phengite associated with the younger~~second~~ assemblage. Our results reveal that the first, coarse-grained generation of biotite grains records a minimum age of 2535 ± 18 Ma, coeval with previous $^{40}Ar/^{39}Ar$ biotite, Re-Os pyrite and U-Pb rutile results. The second, fine-grained and recrystallized generation of biotite grains record an age of 1207 ± 12 Ma across all samples. Phengite and muscovite yielded broadly similar results at ca. 1.2 Ga but data is overdispersed for a single coeval population of phengite and shows elevated age uncertainties for muscovite. We propose that the ca. 2530 Ma age recorded by various geochronometers represents cooling and exhumation, and that the age of ca. 1210 Ma is related to major shearing associated with the regional deformation associated with Stage II of the Albany–Fraser Orogeny. This is the first time that an age of ca. 1210 Ma has been identified in the Tropicana Zone, which may have ramifications for constraining the timing of mineralization in the region. The *in situ* Rb-Sr technique is currently the only tool capable of resolving both geological events in these rocks.

1.0 Introduction

The ability to date multiple events in individual samples has important consequences for developing a comprehensive understanding of the geological history of complex terranes. The U-Pb method has long been employed to date crystallization, metamorphism and hydrothermal events, often by targeting cores and rims in individual grains. Many U-bearing minerals have recorded multiple ages due to their ability to participate in metamorphic/hydrothermal reactions or become (partially) reset by events above mineral closure temperatures, including zircon (Liu et al., 2012), monazite (Rasmussen et al., 2007), titanite (Kirkland et al., 2020; Olierook et al., 2019b), rutile (Olierook et al., 2019a; Zack and Kooijman, 2017) and apatite (Kirkland et al., 2018). However, not all geological events are associated with (partial) reset or new growth of U-bearing minerals. In these scenarios, it is important to examine alternative minerals that may provide a more complete record of the geological history.

The Rb-Sr isotopic system is particularly valuable for geochronology, as Rb is sufficiently abundant in common K-bearing minerals like biotite, muscovite and K-feldspar that are abundant in a wide variety of rocks, and are readily mobilized during fluid–rock interactions (Attendorn and Bowen, 1997; Riley and Compston, 1962). ^{87}Sr decays to ^{87}Rb with a recently revised decay constant of $1.3972 \pm 0.0045 \times 10^{-11}$ a (equivalent to half-life of ~49.6 Ga; Villa et al., 2015). However, the most significant disadvantage of traditional Rb-Sr geochronology is the inability to perform *in situ* dating via secondary ion mass spectrometry (SIMS) or laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS; Nebel, 2013). Although several studies have dated mineral separates on a small scale (Glodny et al., 2003; Glodny et al., 2002), some even texturally-constrained by micromilling (Charlier et al., 2006; Chen et al., 1996; Müller et al., 2000), the Rb-Sr technique could not compete with the <100 μm diameter resolution of the U-Pb method.

The major obstacle with *in situ* Rb-Sr geochronology is the isobaric interference of different isotopes, most notably that of ^{87}Rb and ^{87}Sr (Zack and Hogmalm, 2016). Pioneering work from Moens et al. (2001) and Vanhaecke et al. (2003) showed that it was possible to achieve chemical separation of interfering ^{87}Rb from ^{87}Sr inside a conventional ICP-MS by directing the ion beam through a dynamic reaction cell with CH_3F gas to produce SrF^+ ($m/v \approx 106$) but leave Rb unaffected ($m/v \approx 87$). However, this technique was relatively imprecise ($\pm$ ~10%; Vanhaecke et al., 2003), particularly when compared to *in situ* U-Pb methods ($< \pm 2\%$) and still required dissolution of the sample.

With the recent advent of 'triple quadrupole' LA-ICP-MS, it is now possible to perform *in situ* Rb-Sr dating at precision that that rivals *in situ* U-Pb geochronology (Hogmalm et al., 2017; Zack and Hogmalm, 2016). A reaction cell located between two quadrupoles is filled with a selected gas (e.g., N_2O, SF_6, O_2) that reacts with Sr^+ ions but leaves Rb^+ unaffected. Thus, the first quadrupole is used to filter ions of a specific mass (e.g., ^{87}Rb and ^{87}Sr) to enter the reaction cell and the second quadrupole

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separates the ^{87}Rb from the reacted (mass-shifted) Sr (e.g., ^{87}Sr^{16}O; now *m/v* 103, see supplementary Fig. A for graphic illustration of this process).

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Following the work of Zack and Hogmalm (2016) and Hogmalm et al. (2017) for assessing the most suitable reaction cell gases, several publications have attempted to solve geological problems using the *in situ* Rb-Sr technique (Şengün et al., 2019; Tillberg et al., 2017; Tillberg et al., 2020). All these studies, except the one from Tillberg et al. (2020), identified only a single age population within individual samples, which could have been resolved (at higher precision) with solution Rb–Sr or

70 ^{40}Ar/^{39}Ar. Tillberg et al. (2020) observed multiple age populations in their samples, but these were from mineral separates and the textural context was not preserved. To date, no published study has taken full advantage of the spatial resolving power of the *in situ* Rb-Sr technique whilst retaining textural context.

Here, we analyzed in thin sections, the *in situ* Rb-Sr ages of two mineral assemblages developed in distinctly different

75 deformation microstructures in the Tropicana Zone of the Albany–Fraser Orogen, southwestern Australia. For Rb-Sr purposes, we date (i) biotite from both assemblages, (ii) apatite from both generations, (iii) phengite from assemblage 2, and (iv) muscovite from assemblage 2. Ultimately, this work demonstrates the use of coupled *in situ* Rb-Sr geochronology and microstructural analysis for identifying and resolving multiple geological events in individual samples.

2.0 Geological Background

80 ### 2.1 Geological history of the Albany–Fraser Orogen

The Albany-Fraser Orogen is a Proterozoic orogenic belt that girdles ~1200 km of the south and southeastern margins of the Archean Yilgarn Craton in Western Australia. This belt had a protracted Proterozoic history that included a series of extensional and compressional events at ca. 2720–2530 Ma, 1810–1650 Ma and 1330–1140 Ma (Spaggiari et al., 2015). The Albany-Fraser Orogen comprises several lithotectonic domains including the Northern Foreland, Tropicana Zone, Biranup

85 Zone, Nornalup Zone and Fraser Zone (Fig. 1Fig. 1), and principally represents the reworked margin of the Archean Yilgarn Craton (Kirkland et al., 2011). Each zone comprises minor to dominant components of Archean heritage variably reworked by Paleoproterozoic and Mesoproterozoic tectonomagmatic events.

The earliest event in the belt at ca. 2720–2530 Ma was restricted to the Tropicana Zone (see section 2.2) and was followed by

90 magmatism from 1.81 Ga to 1.65 Ga in the Tropicana, Biranup and Nornalup zones (Smithies et al., 2015). This earlier Paleoproterozoic magmatism is divided into three pulses: Salmon Gums Event (1.81–1.80 Ga), Ngadju Event (1.77–1.75 Ga) and Biranup Orogeny (1.70–1.65 Ga; Kirkland et al., 2011; Smithies et al., 2015; Spaggiari et al., 2015). The tectonic setting in which this significant Paleoproterozoic magmatism occurred is not well constrained, however, it is generally interpreted to

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represent an extensional event (Hartnady et al., 2019; Smits et al., 2014; Spaggiari et al., 2015), with short-lived pulses of compression (i.e. Zanthus Event; Kirkland et al., 2011; Smithies et al., 2015).

The majority of the magmatism in the Albany-Fraser Orogen occurred during arc-accretion and subsequent reworking at 1330 Ma and 1200 Ma, respectively (Spaggiari et al., 2015). The Albany-Fraser Orogen shares a heritage with Wilkes Land in East Antarctica, and these two orogenic belts were contiguous during the late Mesoproterozoic as a result of Rodinia assembly (Clark et al., 2000; Morrissey et al., 2017). Stage I of the Albany-Fraser Orogeny (1330–1260 Ma) was a widespread high-temperature, moderate- to high-pressure event accompanied by felsic and mafic magmatism (Clark et al., 2014). Stage I is generally interpreted as the collision between the Western Australian and Mawson Craton (Bodorkos and Clark, 2004; Clark et al., 2000). Stage II of the Albany-Fraser Orogeny is considered to reflect intracratonic orogenesis (Spaggiari et al., 2009; Spaggiari et al., 2014; Spaggiari et al., 2015). This stage is associated with craton-verging thrusting, high-temperature and moderate-pressure metamorphism, and mainly felsic magmatism at ca. 1225–1140 Ma (Dawson et al., 2003; Nelson et al., 1995). Mafic intrusions associated with Stage II are not known in the eastern Albany-Fraser Orogen but have recently been documented at 1134 ± 9 (U-Pb zircon) and 1131 ± 16 Ma (U-Pb baddeleyite) in the Bunger Hills, Wilkes Land (Stark et al., 2018).

2.2 Geological and mineralization history of the Tropicana Zone

The Tropicana Zone is located along the northeastern margin of the Yilgarn Craton (Fig. 1Fig. 1). Seismic sections across the Tropicana Zone reveal a northwest directed, imbricate thrust stack formed in a foreland setting by thrusting of the Tropicana Zone up along a major thrust surface known as the Plumridge Detachment (Occhipinti et al., 2014; Occhipinti et al., 2018). This thrust transported the Tropicana Zone onto the Yamarna Terrane of the Yilgarn Craton (Occhipinti et al., 2018).

The Tropicana Zone includes the Tropicana gold mine and several prospects to the northeast and southwest (Fig. 1; Occhipinti et al., 2018; Spaggiari et al., 2014). A moderately foliated metagranite (Hercules Gneiss) sampled close to the Tropicana gold mine yielded a U-Pb age of 2722 ± 15 Ma on oscillatory-zoned zircon cores interpreted to represent the magmatic crystallization age of the granite (Kirkland et al., 2015). A younger age of 2640 ± 10 Ma on zircon rims from the same sample was interpreted as the age of a high-grade metamorphic overprint in the zone. In the Tropicana gold mine itself, a similar minimum age of crystallization (2638 ± 4 Ma) was acquired from the syenitic lithofacies of the Tropicana Gneiss (Doyle et al., 2015). The Hercules Gneiss has broadly dioritic compositions and a very narrow range of low SiO_2 (58.1–63.6 wt%), and is classified as a sanukitoid (Kirkland et al., 2015). Sanukitoid magmas, usually are produced from metasomatized mantle in an arc setting (Martin et al., 2005), are known for gold fertility and are interpreted as a likely source of gold in the Tropicana Zone, although the gold may have been remobilised on several occasions (Kirkland et al., 2015). Sanukitoid intrusions commenced at 2692 ± 16 Ma near the start of a prolonged mid-amphibolite to lower granulite facies metamorphism in the Tropicana Zone that persisted until ca. 2530 Ma (Doyle et al., 2015; Kirkland et al., 2015). Kirkland et al. (2015) interpreted the characteristic high-grade metamorphic textures and grain shapes of zircon as evidence of a prolonged period of granulite

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facies metamorphism (Atlantis Event) that formed many of the gneisses in the Tropicana Zone. Structural and isotopic data imply that the Tropicana Zone was held at a deep-crustal level during much of the Neoarchean (Occhipinti et al., 2018; Tyler et al., 2015).

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Exhumation and retrogression to greenschist facies metamorphic conditions associated with folding and development of thrust shear zones occurred at ca. 2530 Ma (Blenkinsop and Doyle, 2014; Doyle et al.; Doyle et al., 2015). Thrusting onto the Yilgarn Craton is thought to have led to ingress of fluids and Au mineralization at ca. 2530 Ma (Doyle et al., 2015; Occhipinti et al., 2018). The age of ca. 2530 Ma from the Tropicana gold mine is constrained from a biotite $^{40}Ar/^{39}Ar$ age of 2531 ± 14 Ma,

135 recalculated using the decay constant of Renne et al. (2011), and an imprecise pyrite Re-Os age of ca. 2505 ± 50 Ma. Additionally, a tungsten-rich rutile population exsolved from a coarse-grained biotite yielded dates between 2539 ± 22 Ma and 2479 ± 10 Ma, overdispersed for a single population (Doyle et al., 2015). There is evidence from the work of Doyle et al. (2015) for subsequent resetting of geochronometers. Although Doyle et al. (2015) advocates for a 2521 ± 5 Ma age for rutile formation, it is more likely this represents partial resetting. Similarly, pyrite Pb/Pb results show scatter between ca. 2500 Ma

140 and 1800 Ma, disturbed $^{40}Ar/^{39}Ar$ spectra show a range of individual steps between ca. 2.0 and 1.8 Ga and U-Pb zircon and monazite ages show partial loss of Pb towards Mesoproterozoic ages but with poorly constrained lower intercepts (ca. 1.3–1.1 Ga). Whether these dates represent distinct events at ca. 2.4, 1.8 Ga and/or 1.3–1.1 Ga or are a continuum of dates towards younger ages remains unknown.

3.0 Sample selection

145 The sampling strategy for the Tropicana gold mine followed that of Blenkinsop and Doyle (2014), focusing on the Au-mineralized D3 shear zone. There is a natural strain gradient from undeformed syenitic gneiss host rock to transient low-strain, up to high-strain zones. A total of ten samples were selected from diamond drill cores (photos in Supplementary Fig. B) from three main pits in the Tropicana gold mine (Table 1, Figs. 1–2). All samples are perthitic K-feldspar dominated rocks with minor biotite and quartz, deformed at low strains to a brittle-ductile microstructure at greenschist facies conditions. Additional

150 phases include albitized plagioclase, biotite, phengite, quartz, calcite/dolomite, pyrite, zircon and monazite (Supplementary Fig. B).

Three samples were selected from satellite prospects proximal to the Tropicana gold mine and within the Tropicana Zone, one each from the New Zebra, Iceberg and Angel Eyes prospects (Table 1, Figs. 1–2). The sample from the New Zebra prospect

155 displays parasitic folding defined by muscovite and quartz (Table 1, Supplementary Fig. B). The Iceberg and Angel Eyes samples are both strongly foliated, with foliation defined by quartz, phengite ± altered plagioclase (Table 1, Supplementary Fig. B).

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A subset of four of the ten samples from the Tropicana gold mine were selected for *in situ* Rb-Sr geochronology (Table 1, Figs. 1–2). From the satellite prospects, the sample from the New Zebra prospect was selected.

4.0 Methods

4.1 Thin section preparation and imaging

Standard polished thin sections prepared at Minerex Services, Esperance, Western Australia, were imaged in plane- and cross-polarized, transmitted light on an Axio II optical microscope at the School of Earth and Planetary Sciences, Curtin University.

Thin sections were subsequently carbon coated and analyzed using a Tescan Integrated Mineral Analyser (TIMA) at the John de Laeter Centre (JdLC) at Curtin University to aid in mineral identification. TIMA (a is a field emission gun scanning electron microscopy) is equipped with four electron dispersive X-ray spectrometers (EDS), capable of recording 420k X-ray counts per second. Thin sections were analyzed in 'dot-mapping' mode with a rectangular mesh at a step-size of 3 µm for backscattered electron (BSE) imaging. One thousand EDS counts are collected every 9th step (i.e., 27 µm) or when the BSE contrast changes (i.e., a change in mineral phase). For a given mineral grain, EDS counts are integrated across the entire grain. TIMA analyses used an accelerating voltage of 25 kV, a beam intensity of 19, a probe current of 6.74–7.01 nA, a spot size of 67–90 nm and a nominal working distance of 15 mm. After imaging and EDS collection, BSE signals and EDS peaks are referenced to a mineral library for automatic mineral classification.

After *in situ* Rb-Sr analysis, selected regions were imaged via backscattered electron (BSE) using a Tescan Vega3 and Mira3 FEG-SEM, both in the JdLC, using working distances of 11–15 mm, a beam intensity of 12–14 and an accelerating voltage of 20 kV. Selected spot analyses were made on these BSE images using EDS to evaluate the chemistry of mineral phases.

Full thin section photomicrographs and TIMA images of each sample are in Supplementary Fig. B.

4.2 *In situ* Rb-Sr geochronology

In situ Rb-Sr data were collected on sample thin sections in the GeoHistory Facility, JdLC, Curtin University, across three sessions. For all sessions, a RESOlution LR 193 nm ArF excimer laser with Laurin Technic S155 sample cell was used. Laser settings comprised a beam diameter of 87 µm (session 1) or 64 µm (sessions 2–3), on-sample energy of 2.5 J cm^{-2}, a repetition rate of 5 Hz, 60s of analysis time and 30s of on-peak background acquisition with the laser off. All analyses were preceded by two cleaning pulses. Laser fluence was calibrated each day using a hand held energy meter, and subsequent analyses were performed in constant fluence mode. The Laurin Technic S155 sample cell was flushed with ultrahigh purity He (320 mL min$^-$

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190 ^{1}) with added N_2 (1.2 mL min^{-1}), both of which were passed through an inline Hg trap. High purity Ar was used as the ICP-MS carrier gas (flow rate ~1 L min^{-1}).

Rb-Sr data were collected on an Agilent 8900 triple quadrupole mass spectrometer in MS/MS mode (see Supplementary Table A for all relevant tuning and acquisition parameters) using N_2O reaction gas following the pioneering work of Cheng et al.
195 (2008) and Hogmalm et al. (2017). Each analytical session consisted of first tuning gas flows and ICP-MS ion lenses in single quad mode for sensitivity and a flat mass response curve, followed by adjustment for robust plasma conditions, including $^{238}U/^{232}Th$ ~ 1, $^{206}Pb/^{238}U$ ~ 0.2 and $^{238}UO/^{238}U$ <0.004 on NIST610 glass (Kent et al., 2004). The mass spectrometer was then set to MS/MS mode, and N_2O was added (~0.25 mL min; not calibrated^{-1}) to the reaction cell. The reaction cell was flushed with N_2O for several hours before sample analysis to ensure signal stability. NIST610 was used to tune N_2O to maximise
200 intensity at mass 104 ($^{88}Sr^{16}O$), while maintaining ~~zero~~ <7 cps~~counts~~ at mass 101 ($^{85}Rb^{16}O$). Finally, pulse-analog (P/A) conversion factors for $^{88}Sr^{16}O$ (as ^{104}Pd) and $^{87,85}Rb$ were determined in single quad mode on NIST610 reference glass and pressed powder tablets of phlogopite Mica-Mg, respectively (Govindaraju, 1979; Hogmalm et al., 2017; Kröner et al., 1996; Morteani et al., 2013), by varying laser spot sizes and/or laser repetition rate to yield ~2 Mcps per analyte.

205 We designed the analytical protocol to stay below the P/A conversion thresholds for Rb and Sr by reducing ablation spot size, laser repetition rate, and /or laser energy. Maximizing count rates for $^{87,86}Sr$ implied that ^{88}Sr was not available for mass bias correction. We thus followed the approach of Hogmalm et al. (2017) to calibrate $^{87}Sr/^{86}Sr$ directly against NIST610 ($^{87}Sr/^{86}Sr$ = 0.709699 ± 0.000018; Woodhead and Hergt, 2001) to calculate $^{87}Rb/^{86}Sr$ from certified values at 2.390 ± 0.005 (Woodhead and Hergt, 2001). In order to check for matrix sensitivity of measured Sr isotopic compositions using this approach, we
210 interspersed a megacrystic plagioclase and a modern shark tooth (apatite) with the samples as external standards. The measured results for plagioclase ($^{87}Sr/^{86}Sr$ = 0.7037 ± 0.0013; 2SE; n = 15) and shark tooth apatite ($^{87}Sr/^{86}Sr$ = 0.7106 ± 0.0013; 2SE; n = 15) are in excellent agreement with the published Sr isotopic compositions of 0.70310 ± 0.00007 (plagioclase Mir a; Rankenburg et al., 2004), and modern marine seawater $^{87}Sr/^{86}Sr$ of 0.709174 ± 0.000003 (McArthur et al., 2006), respectively, and attest to the validity of our analytical protocol. Our measured $^{87}Sr/^{86}Sr$ for mica-Mg calibrated against NIST610 over the
215 course of this study was 1.8692 ± 0.0022 (2SE, n = 28), and we used this value along with a crystallization age of 519.4 ± 6.5 Ma (2σ) and initial $^{87}Sr/^{86}Sr$ of 0.72607 ± 0.00070 (Hogmalm et al., 2017) to calculate a mean $^{87}Rb/^{86}Sr$ for mica-Mg of 156.9 ± 2.3, with all errors propagated in quadrature.

Whereas all Rb-Sr isotopic analyses were initially normalized and drift-corrected with factors determined from NIST610, an
220 additional matrix correction to $^{87}Rb/^{86}Sr$ was only applied to biotite analyses, with uncertainties on Mica-Mg and the unknown analyses propagated in quadrature. These corrections were also applied to phengite and muscovite, but with the caveat that Mica-Mg may not be a concentration-matched standard for these minerals. Because calculated ages from sample biotite mainly depend on accurate determination of the Rb/Sr fractionation factor, a secondary mica standard of known age is highly desirable.

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To this end, analyses of unknowns were additionally bracketed with in-house biotite reference material CK001B (422 ± 6 Ma;

225 Daly et al., 1991; Kirkland et al., 2007). Sample CK001B was collected by Daly et al. (1991) but not dated precisely. Collected < 50 km from CK001B and having experienced equivalent Caledonian metamorphism, the age of sample CK009 was determined from amphibole, whole-rock and biotite Rb-Sr solution analyses (Kirkland et al., 2007). CK009 yielded an age of 422 ± 6 Ma ($n = 5$, MSWD = 0.57, $p = 0.68$), recalculated using the decay constant of Villa et al. (2015), and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7108 ± 0.0001 (Kirkland et al., 2007). Repeated analytical results from sessions 1–3 on adjacent spots show no

230 systematic variation in Rb-Sr age (see supplementary Fig. C). During analytical sessions 1, 2 and 3, sample CK001B yielded biotite ages of 413 ± 4 ($n = 38$, MSWD = 1.2, $p = 0.18$), 414 ± 5 ($n = 38$, MSWD = 0.99, $p = 0.49$) and 429 ± 8 ($n = 46$, MSWD = 0.28, $p = 1.00$), respectively (Supplementary Fig. C). All three sessions yielded a combined age of 416 ± 3 ($n = 122$, MSWD = 0.99, $p = 0.52$) with an initial $^{87}Sr/^{86}Sr$ of 0.714 ± 0.009 (Supplementary Fig. C). All of the ages and initial ratios overlap with the published values (Kirkland et al., 2007) within 2σ uncertainty.

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A small round robin analytical run consisting of ~20 standards preceded analytical runs to monitor long-term stability, and overall data integrity. Data were reduced in Iolite (Paton et al., 2011) and in-house Excel macros. Analyses that crosscut multiple minerals or mineral generations at depth were excluded. Rb-Sr isochrons and ages were computed using Isoplot 4.15 (Ludwig, 2012), with the decay constant after Villa et al. (2015). All uncertainties presented in the text are presented at 95%

240 confidence. Full isotopic data for the samples and reference materials are given in supplementary Table B.

5.0 Results

5.1 Microstructure and mineral paragenesis from the Tropicana gold mine

In the ten samples from the Tropicana gold mine, two mineral assemblages are identified and linked to two distinct

245 microstructures (Figs. 2, 3). Mineral assemblage 1 comprises perthitic K-feldspar, plagioclase, quartz, euhedral biotite 1 (1st generation), apatite 1 (1st generation), zircon, monazite and Au-bearing pyrite 1 (1st generation). Both Au-bearing pyrite and apatite 1 occur as inclusions in K-feldspar (Fig. 3 a, e). Very fine (<1 µm) exsolution Llamellae of rutile and/or titanite within coarse-grained biotite 1 were previously identified by Doyle et al. (2015) but were not observed in this studysamples from the Tropicana and Havana Pits (Fig. 4c–h) but these

250 were absent from biotite 1 in the Boston Shaker pit (Fig. 4a–b). The coarse-grained microstructure and associated mineral assemblage 1 is rarely preserved in the ore zone due to the low-temperature and high-strain shearing (Fig. 2Fig. 2a, b, c). However, main rock-forming minerals are preserved either in low-strain domains or as porphyroclasts within mylonites (Fig. 2Fig. 2a, b, c).

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The fine-grained microstructure and associated mineral assemblage 2 is related to localized brittle to brittle-ductile strain, overprinting assemblage 1 (Blenkinsop and Doyle, 2014). The brittle strain affects perthite to form a so-called crackle breccia (D3 of Blenkinsop and Doyle, 2014)(Blenkinsop and Doyle, 2014). The brittle–ductile strain has reworked quartz and biotite to form transitional microstructures between jigsaw puzzle breccia and core-and-mantle microstructure (Fig. 2Fig. 2c), while plagioclase broke down to a sericite mesh (Fig. 2Fig. 2a, b, c). Dynamic recrystallization was accompanied by the ingress of hydrothermal fluids that precipitated carbonates, pyrite and microcrystalline phengite (Fig. 2Fig. 2a, b, c) and breaks down perthite to albite along fractures (Fig. 2Fig. 2b). The low-strain microstructure represents the main target for our *in situ* dating of an early biotite 1 and dynamically recrystallized biotite 2 (Fig. 3a–d). In the high-strain zone, sericite forms interconnected matrix to porphyroclasts of perthite, quartz and biotite (Fig. 2d(Fig. 2d; D4 after Blenkinsop and Doyle, 2014)). A potential second generation of apatite (apatite 2) is also found interstitially together with assemblage 2 minerals (Fig. 3f).

5.2 *In situ* Rb-Sr geochronological data

5.2.1 Biotite

Biotite was analyzed from all samples from the Tropicana gold mine (Table 1). According to the mineral paragenesis, biotite was sub-divided into two texturally distinct sub-populations: (i) large, subhedral to euhedral grains associated with assemblage 1, and (ii) recrystallized, fine-grained crystals associated with assemblage 2 (Fig. 3).

The older component – texturally part of assemblage 1 – does not define a single population and has relatively low $^{87}Rb/^{86}Sr$ (8–620, mean = 171) compared to assemblage 2 biotite (Fig. 5Fig. 5). Assuming initial $^{87}Sr/^{86}Sr$ ratios of 0.7045–0.7058 (as defined by apatite, see below), the variable Rb-Sr ratios yield broadly linear trends with dates between ca. 2400 and 1500 Ma for the four samples (Fig. 5Fig. 5). However, significant variation is observed in all samples. The analyses with the oldest dates (on average) are from samples with limited presence of recrystallized biotite 2 and where biotite 1 did not any exsolution lamellae (Fig. 4a–b). Conversely, samples with younger dates have a more significant proportion of biotite 2 and biotite 1 shows exsolution lamellae of rutile and/or titanite (Fig. 4c–h). Sample HDD077-422-C, with the youngest apparent biotite 1 dates (Fig. 5c), also has the highest proportion of exsolved Ti-bearing minerals in biotite 1 (Fig. 4e–f).

Spot profiles across two large biotite 1 grains were performed to ascertain if there was systematic age variation from core to rim (Fig. 6Fig. 6). The transects show that there is no significant variation in model ages observed across the large grains, with the exception of some younger dates towards the very edges (e.g., analysis 19 in BSD114-541C or analyses 1–2 in TPD542-371-C) or where fractures were intersected with minor recrystallized biotite 2 (Fig. 6Fig. 6h,i).

Analyses from the second phase of biotite (biotite 2) yielded statistically valid isochrons in every sample and shows a wider range of $^{87}Rb/^{86}Sr$ ratios (up to 950, mean = 210, Fig. 5Fig. 5). Ages computed from Rb/Sr isochrons are 1165 ± 140 Ma, 1227

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± 100 Ma, 1211 ± 19 Ma, to 1208 ± 36 Ma for the four samples from the Tropicana gold mine ($p > 0.05$ in all cases, Fig. 5Fig. 5). For three of the samples where a putative second generation of apatite may be coeval with biotite 2 (see section 5.1), it is possible to compute an isochron with both apatite and biotite 2. Combined apatite and biotite 2 yields isochrons of 1222 ± 37, 1241 ± 33 Ma and 1205 ± 15 Ma ($p > 0.05$ in all cases, Fig. 5Fig. 5) but with ages that overlap in uncertainty if apatite is not used in the calculation. There is no systematic variation in ages between samples or between Tropicana gold mine pits.

5.2.2 Phengite

Microcrystalline Pphengite was analyzed from three of the four samples from the Tropicana gold mine. Phengite, associated with assemblage 2 in the Tropicana gold mine, yielded single, linear Rb/Sr trends with low to moderate $^{87}Rb/^{86}Sr$ values (0.2–32, mean = 13; Fig. 7Fig. 7). Sample TPD542-371-C yielded a statistically-reliable but imprecise age of 1212 ± 98 Ma ($n = 6$, MSWD = 1.3, $p = 0.28$, Fig. 7Fig. 7b). The two other samples, both from the Havana Pit, yielded broadly linear trends with age estimates of ca. 1220 and 1280 Ma but with overdispersion for a single population (MSWD = 3.5–3.7, $p < 0.05$; Fig. 7Fig. 7c, d). Notwithstanding the data scatter, on a given sample, the phengite age estimates are similar to those obtained via biotite Rb/Sr (cf. Fig. 5Fig. 5).

5.2.3 Muscovite

Euhedral Mmuscovite was present as euhedral crystals in the New Zebra satellite deposit. Muscovite showed only minor spread in $^{87}Rb/^{86}Sr$ (2.0–3.4, **Fig. 7**Fig. 7a). Consequently, it yielded a statistically-valid but imprecise isochron of 1255 ± 170 Ma ($n = 37$, MSWD = 1.14, $p = 0.26$) with an initial $^{87}Sr/^{86}Sr$ intercept of 0.7116 ± 0.0062 (**Fig. 7**Fig. 7a).

5.2.4 Apatite

As apatite has negligible Rb, there is no modification of initial $^{87}Sr/^{86}Sr$ from any radiogenic decay of ^{87}Rb. Thus, the measured $^{87}Sr/^{86}Sr$ is equivalent to the initial $^{87}Sr/^{86}Sr$ ratio at the time of (re)crystallization. Apatite 1 was analyzed in three samples, yielding $^{87}Sr/^{86}Sr_{(i)}$ ratios between 0.7045 ± 0.0012 to 0.7058 ± 0.0039 ($p > 0.05$ in all samples; Fig. 8Fig. 8a, c, d). Apatite 2 was analyzed in three samples, yielding $^{87}Sr/^{86}Sr_{(i)}$ ratios between 0.7053 ± 0.0012 to 0.7092 ± 0.0033 ($p > 0.05$ in all samples, Table 1, Fig. 8Fig. 8a, b, d). In the two samples where both assemblages of apatite were analyzed, BSD114-514-C yielded initial $^{87}Sr/^{86}Sr$ that overlapped within 2σ error but HDD254-711-C yielded more radiogenic values for apatite 2 compared to apatite 1 (Fig. 8Fig. 8a, d).

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6.0 Discussion

6.1 Ages recorded by the Rb-Sr geochronometers in the Tropicana Zone

Two distinct temporal patterns are identified in the Rb-Sr results (Figs. 4–7). We examine below the two isotopic patterns to evaluate their significance and assess the formation mechanisms.

6.1.1 Assemblage 1: ca. 2530 Ma

The first generation of biotite grains consistently shows a scatter of data and a variation in mean isochron ages, with a strong textural control on these age estimates. Samples with dominantly euhedral, exsolution-free biotite grains and minimal recrystallized biotite 2 (e.g., BSD114–541-C) yielded a mean age estimate of ca. 2500 Ma (Fig. 4a). Conversely, where the majority of biotite 1 has been recrystallized to biotite 2 (e.g., HDD077-422-C) and where exsolution lamellae were abundant (Fig. 4c–h), the age estimates from biotite 1 are as young as ca. 1500 Ma (Fig. 5Fig. 5c). If this exsolution occurred during the formation of biotite 2 with the incomplete transformation of biotite 1 to 2, it would also explain why biotite 2 appears more bleached (i.e., depleted in Fe-Ti) than biotite 1 (Fig. 3a–d). Thus, any laser spots in biotite 1 in samples from the Tropicana and Havana pits would have hit physical mixtures of biotite 1 and 2, thereby providing a meaningless age. The relative consistency of dates for a single sample (albeit still overdispersed) is attributed to the consistency of exsolution lamellae. For example, the 'age' of biotite 1–2 mixtures in HDD077-422-C (ca. 1.5 Ga; Fig. 5c) is younger than HDD254-711-C (ca. 1.7 Ga; Fig. 5d) because the former has, on average, a higher proportion of lamellae (Fig. 4f & h). These exsolution lamellae could also have facilitated

~~The most likely explanation for this data scatter is~~ variable loss of Rb and Sr (especially radiogenic ^{87}Sr) during (partial) resetting of the Rb-Sr isotopic system (Eberlei et al., 2015; Evans et al., 1995; Kalt et al., 1994; Matheney et al., 1990). ~~The mechanism for this phenomenon is related to the crystallographic position and relative stability of ^{87}Rb and ^{86}Sr vs ^{87}Sr. In trioctahedral micas (e.g., biotite and phlogopite), both ^{87}Rb (1.72 Å) and ^{86}Sr (1.44 Å) are situated within a large 12 fold coordinated X-site (Shannon, 1976), where Rb can readily exchange for K and Na, and Sr can exchange with Ca (Zussman, 1979). However, once ^{87}Rb has decayed to ^{87}Sr in a K or Na site, there is a significant decrease in ionic radius from 1.72 to 1.44 Å (16%; Shannon, 1976), which makes ^{87}Sr prone to mobility. Therefore, in fluid-mediated recrystallization during hydrothermal or metamorphic events, ^{87}Sr can escape more readily from the crystal lattice than ^{87}Rb or ^{86}Sr into the percolating fluid.~~

Considering that the excess scatter in the first assemblage biotite grains is due to partial resetting linked to dynamic recrystallization (and thereby mixing biotite 1 and 2 components), it follows that the oldest biotite grains can yield a minimum age for the first event. In the samples where the crystals are freshest, coarsest and least overprinted by shearing and assemblage 2, the oldest biotite grains provide a minimum age of 2535 ± 18 Ma for assemblage 1 (Fig. 5Fig. 5a). This is consistent within error with biotite ^{40}Ar/^{39}Ar (2531 ± 14 Ma) and pyrite Re-Os ages (2505 ± 50 Ma), and broadly compatible with the oldest W-

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rich rutile U-Pb dates of ca. 2539–2479 Ma obtained from similar samples in the Tropicana gold mine (Fig. 9; Doyle et al., 2015).

6.1.2 Assemblage 2: ca. 1210 Ma

Ages of the recrystallized biotite grains from assemblage 2 are within uncertainty of one another for all samples from the Tropicana gold mine. Considering the relative proximity of all samples within the Tropicana gold mine, it is unlikely that the duration of a hydrothermal event associated with dynamic recrystallization of biotite would have exceeded the uncertainty of the Rb-Sr geochronometer. We therefore calculate a single weighted mean age of 1207 ± 12 Ma ($n = 62$, MSWD = 0.91, $p =$ 0.68) for all available analysis of this fabric (Fig. 9Fig. 9), and consider this age to record a synchronous event across the Tropicana gold mine. Assuming biotite 2 grains were coeval with apatite 2, a better initial $^{87}Sr/^{86}$ intercept can be defined, relative to one generated from a free-regressed biotite 2 isochron. Hence, we have also computed a weighted mean age with apatite 2 and biotite 2 at 1212 ± 9 Ma ($n = 102$, MSWD = 1.3, $p = 0.05$), overlapping within uncertainty with the biotite-only regressed age (Fig. 9Fig. 9).

The phengite ages consistently yield similar ages within 2σ of the biotite 2 ages, albeit with excess scatter, implying that biotite 2 and phengite are coeval (Figs. 6, 8). This is consistent with the mineral paragenetic sequence (Fig. 2Fig. 2). The overdispersion in the phengite data could be a consequence of heterogeneous minerals or differences in the matrix between the phengite and the phlogopite primary standard Mica-Mg (see section 4.2). Alternatively, the overdispersion may be a real geological phenomenon, implying that phengite formed over a protracted period.

The only sample that contained euhedral muscovite, from the New Zebra deposit, yielded an age of 1255 ± 170 Ma that, although imprecise, also overlaps with the second phase of biotite (biotite 2) and the phengite ages (Figs. 4, 6). Thus, all samples point towards a single event at ca. 1210 Ma.

The ca. 1210 Ma event could either represent a distinct, fluid-flow episode that recrystallized biotite, formed phengite and yielded muscovite, or it may record an exhumation event that cooled the Rb-Sr geochronometers to below their closure temperatures. The implication with the latter is that the fluid flow event occurred prior to exhumation.

6.2 Implications for metamorphic, hydrothermal and mineralization events in the Albany–Fraser Orogen

Two ages at ca. 2530 Ma and 1210 Ma have been previously linked to events in the Albany–Fraser Orogen, although the latter had not been previously identified in the Tropicana Zone. The discovery of the Mesoproterozoic age at Tropicana needs to be explored in terms of implications for structural and hydrothermal evolution, and metallogenesis.

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The ca. 2530 Ma age is only known from the Tropicana Zone of the Albany–Fraser Orogen (Doyle et al., 2015; Kirkland et al., 2015). Previous workers have interpreted the ca. 2530 Ma age as a distinct hydrothermal event at greenschist facies conditions during D3 shearing, which was also associated with Au mineralization (Blenkinsop and Doyle, 2014; Doyle et al., 2015; Occhipinti et al., 2018). This ca. 2530 Ma event is postulated to have followed a protracted period of granulite-facies
380 metamorphism from ca. 2640 to 2530 Ma as part of the Atlantis event (Doyle et al., 2015; Kirkland et al., 2015).

Here, we propose an alternative plausible scenario, namely that the ca. 2530 Ma age represents the timing of cooling below the closure temperatures of the various geochronometers, including U-Pb rutile ≈ ca. 2539–2479 Ma, Re-Os pyrite = 2505 ± 50 Ma, Rb-Sr biotite 1 ≥ 2535 ± 18 Ma and $^{40}Ar/^{39}Ar$ biotite = 2531 ± 14 Ma (Doyle et al., 2015 and this study). The closure
385 temperatures for these minerals are low to moderate, in decreasing order: (i) Pb diffusion in rutile = 550–650 °C (Ewing et al., 2015; Kooijman et al., 2010), (ii) ^{187}Os in pyrite closure = ~500 °C (Brenan et al., 2000), (iii) ^{87}Sr diffusion in biotite = 300–400 °C (Del Moro et al., 1982), and (iv) ^{40}Ar diffusion in biotite = 280–350 °C (Harrison et al., 1985). Given that all the geochronometers are all broadly within error of ca. 2530 Ma (this study and Doyle et al., 2015), exhumation at ca. 2530 Ma would have been relatively faster than the preceding ~120 m.y. of the Atlantis Event. Such prolonged slow cooling followed
390 by a relatively faster period of cooling is also observed in the core of the Yilgarn Craton (Goscombe et al., 2019). The rate of cooling and exhumation in Tropicana Zone is difficult to ascertain as the uncertainty on the various geochronometers is insufficiently precise to develop a cooling curve. If the ca. 2530 Ma age recorded in the Tropicana Zone represents a cooling age rather than a distinct tectonic event, an important implication is that D3 shearing occurred post-2530 Ma.

395 We propose that D3 shearing instead occurred at ca. 1210 Ma. There are several lines of evidence to support this interpretation:

(1) Mineral assemblage 2 associated with the brittle-ductile microstructure is stable from low- to high-strain zones across the Tropicana gold mine. Blenkinsop and Doyle (2014) attributed the crackle breccia with dominantly biotite-pyrite assemblage to the D3 event, and a muscovite-chlorite bearing assemblage only recorded in the high-strain zones to the D4 event. However, they have attributed the same kinematics of NE–SW shortening to both D3 and D4 events.
400 We see a possibility that a variable amount of muscovite/phengite might be a function of variable plagioclase content of the host syenitic gneiss. Breakdown of plagioclase to micas localises strain within anastomosing and simple shear-dominated D4 ductile shears, while K-feldspar dominated domains show a more brittle response within an apparent low-strain and pure shear-dominated domain (Fig. 2). A presence of carbonate and euhedral pyrite in both microstructures support the coincident development of the D3 and D4 microstructures (Fig. 2, Supplementary Fig.
405 B). If only a single shearing event is implicated (i.e., D3–D4), this would have to occur during the formation of mineral assemblage 2 (i.e., 1210 Ma). Although, the question of a possible reactivation is not the primary goal of this paper, it is likely that some reactivation of D3–D4 fabric might have occurred during a localised D5 event (Blenkinsop and Doyle, 2014).

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(2) Rb-Sr profiles across coarse-grained biotite 1 show limited resetting at grain edges, linked to dynamic recrystallization (Fig. 6Fig. 6), and also consistent with a single shearing event (i.e., 1210 Ma).

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(3) If D3 shearing occurred at ca. 2530 Ma and it was reset at ca. 1210 Ma, one would expect a range of Proterozoic ages from biotite 2, which is clearly not the case (Fig. 9Fig. 9). One could argue that previous geochronological studies in the Tropicana gold mine pointed towards a potential mineralizing event at ca. 2000–1800 Ma on the basis of disturbed ^{40}Ar/^{39}Ar spectra and Pb-Pb dates (Doyle et al., 2015). Additionally, quartz vein-related Au mineralization is implicated at ca. 2100 Ma for the Hercules and Atlantic gold prospects in the Tropicana Zone based on Re-Os pyrite model ages (Kirkland et al., 2015). However, it is equally likely that the Pb-Pb and Re-Os pyrite dates (Doyle et al., 2015) represent mixed assemblage 1 and 2 populations, and do not represent distinct events. Disturbed ^{40}Ar/^{39}Ar spectra are also notoriously unreliable (Baksi, 2007).

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(4) Finally, there is no unequivocal geological evidence for a distinct shearing event at ca. 2530 Ma (Doyle et al., 2015).

Our support for D3 shearing at ca. 1210 Ma does not necessarily mean that assemblage 2 was linked to the primary Au mineralization in the Tropicana deposit (Fig. 9). Mesoproterozoic orogens are typically poor in orogenic Au deposits across the world (e.g., Goldfarb et al., 2001), and the Albany–Fraser Orogen is no exception. Since the discovery of Tropicana in 2005 (Doyle et al., 2007; Kendall et al., 2007), it remains the only deposit with economic Au mineralization in the Albany-Fraser Orogen. Although Tropicana is unlike typical Archean lode gold deposits in the Yilgarn Craton (e.g., gold not directly associated with quartz and carbonate veining; Cassidy et al., 1998; Kent et al., 1996), the Tropicana Zone experienced long-lived granulite facies metamorphism from ca. 2640 to 2530 Ma (Atlantis Event; Doyle et al., 2015; Kirkland et al., 2015). Such long-lived metamorphism might have efficiently reworked all textural indicators of primary mineralization. Indeed, a detailed microscale study of the gold compartment in the Tropicana gold mine has demonstrated gold and telluride inclusions within granulite facies coarse-grained material from assemblage 1 (Hardwick, 2020). Following these observations, it seems that D3 shearing and alteration minerals of assemblage 2 masks the controls on primary gold mineralization.

There are certainly Proterozoic occurrences of sub-economic Au mineralization in the rest of the Tropicana Zone and possibly the wider Albany–Fraser Orogen (Figs. 1b, 6a, 9). Gold prospects such as New Zebra, Iceberg or Angel Eyes lack obvious Archean events (Fig. 6a) but still show elevated Au. Therefore, it is probable that subordinate, secondary Au mineralization in the Tropicana Zone is associated with the D3–D4 shearing event and mineral assemblage 2 formation at ca. 1210 Ma (Fig. 9), but it is uncertain whether the Au is remobilized from an Archean source or was only introduced into the Mesoproterozoic crust at ca. 1210 Ma.

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The ca. 1210 Ma event in the Albany–Fraser Orogen is known from both the early stages of the Albany–Fraser Orogeny Stage II (Clark et al., 2000; Kirkland et al., 2011; Spaggiari et al., 2014) and the widespread intrusions of the Marnda Moorn dyke swarm (Dawson et al., 2003; Wang et al., 2014; Wingate and Pidgeon, 2005). We favour the association of the D3 shearing with Stage II of the Albany–Fraser Orogeny given the macro- and microstructural characteristics of the Tropicana gold mine.

7.0 Conclusions

In situ Rb-Sr geochronology from two assemblages of biotite in the Tropicana gold mine yielded ages of 2535 ± 18 Ma and 1212 ± 9 Ma. The former overlaps with ^{40}Ar/^{39}Ar biotite, Re-Os pyrite and U-Pb rutile ages obtained in a previous study, whilst the latter is the first record of a Mesoproterozoic age in the Tropicana Zone. We propose that the ca 2530 Ma represents cooling of the Yilgarn Craton after granulite facies metamorphism and that the ca. 1210 Ma represent a distinct shearing event (D3–D4 of Blenkinsop and Doyle, 2014), potentially associated with Au mineralization. Considering the likely association of the ca. 1210 Ma event with major shearing, we consider the most likely cause of this Mesoproterozoic event to be Stage II of the Albany–Fraser Orogeny. At present, the *in situ* Rb-Sr method is the only technique that could have revealed these two age populations without foregoing textural context.

8.0 Code/Data availability

All data related to this contribution may be found as part of the supplementary material.

9.0   Author contributions

HKHO, SU, BIAM and MD conceptualized the project. KR and BM designed the methodology and investigated the experiments. CLK, NJE and AP carried out formal analysis. SU, SB and MD provided resources, data curation and funding to the project. BIAM and MD provided project administration. HKHO prepared the original draft of the manuscript with reviewing and editing from all co-authors.

10.0 Competing interests

The authors declare that they have no conflict of interest.

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9.012.0   References

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Figures, tables and captions

Fig. 1: **(a) Simplified, pre-Mesozoic interpreted bedrock geology of the Albany–Fraser Orogen, modified from Spaggiari et al. (2015),**
660 **Doyle et al. (2015) and Scibiorski et al. (2016). Abbreviations: GCG—Gwynne Creek Gneiss; MBG—Mount Barren Group; MM—**
Malcolm Metamorphics; MRF—Mount Ragged Formation; WF—Woodline Formation. (b) Interpreted basement map of the
Tropicana Zone/Plumridge Terrane, modified from Kirkland et al. (2015). Gold deposits and prospects are shown from the
Geological Survey of Western Australia MINEDEX database, with studied locations labelled. (c) Interpreted basement map of the
Tropicana gold mine from internal AngloGold Ashanti maps, showing locations of drill holes analyzed in this study. Note the
665 **Tropicana and Havana pits have now joined. (d) Interpreted cross-section across the ore-bearing and F3 shear zone of the Tropicana**
gold mine from AngloGold Ashanti, showing locations of drill holes (pale grey lines). All maps use GDA 1994 geodetic datum with
(c) using MGA zone 51 projection.

Fig. 2: **Dual transmitted and reflected light, cross-polarized photomicrographs showing characteristic low-strain (a–c) and high-**
670 **strain (d) microstructures and mineral relationships of studied samples. (a) Sample BSD132-316-C shows fractured perthitic**
feldspar from Assemblage 1 in the centre with carbonate, pyrite and quartz from Assemblage 2 filling the fracture. Quartz and
biotite 1 show formation of sub-grains (Biotite 2). (b) Sample HDD254A-711-C, a carbonate from Assemblage 2 fills shear fractures
that crosscut perthitic feldspar from Assemblage 1. Reaction rims along fractures show breakdown of perthite to albite. (c) Sample
BSD132-316-C shows brittle–ductile deformation of large quartz and biotite 1 (bottom right) grains and precipitation of pyrite in
675 **strain shadows. (d) Sample HDD077-431-F shows porphyroclasts of perthitic feldspar within a mylonitic matrix consisting of biotite**
2, quartz, carbonate, pyrite and sericite.

Fig. 3: **Thin section photomicrographs in transmitted light showing detailed mineral. (a) Biotite 2 recrystallized sub-parallel to axial**
plane of folded biotite 1, situated in association with phengite and interstitial to K-feldspar phenocrysts, from HDD254A-711-C. (b)
680 **Biotite 1 variably recrystallized to biotite 2, and associated with pyrite and apatite, all interstitial to K-feldspar phenocrysts from**
HDD077-422-C. (c) Recrystallized biotite 2 corridor between biotite 1 in TPD542-371-C. (d) Biotite in various stages of
recrystallization, from euhedral biotite 1 to partly recrystallized biotite 1/2 to fully recrystallized biotite 2, from BSD114-541-C. Note
association of unstrained quartz with recrystallization. (e) Apatite (magmatic?; 1?) fully enclosed in K-feldspar phenocryst from
HDD077-422-C. (f) Apatite (2) porphyroclast with rare strain shadow of biotite 2 and phengite, implying locally biotite 2 > apatite
685 **> phengite, from TPD542-371-C. Also note close association of pyrite. (g) Carbonate ingress with recrystallization of biotite 1 to**
biotite, interstitial to K-feldspar from HDD077-422-C. (h) euhedral muscovite in association with quartz, from NZD021-159-F. apa
= apatite, bio1 = euhedral, first generation biotite, bio1/2 = partly recrystallized biotite 1, bio2 = recrystallized biotite 1, cal = calcite,
Kspar = K-feldspar, msc = muscovite, phg = phengite, py = pyrite, qtz = quartz, ppl = plane-polarized, xpl = cross-polarized. Circular
holes are laser ablation pits of 87 or 60 µm diameters.
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Fig. 4: BSE images of zoomed-in regions from Fig. 3 showing first and second generations of biotite. Circular holes are laser ablation analyses. (a & b) In BSD114-541-C from the Boston Shaker pit, biotite 1 is free of micro-scale inclusions, whereas biotite 2 shows mixtures of biotite and quartz. (c & d) In TPD542-371-C from the Tropicana pit, biotite 1 shows thin exsolution lamellae of titanite (ttn). Biotite 2 contains larger (2–5 μm) inclusions of titanite. (e & f) In HDD077-422-C from the Havana pit, biotite 1 has titanite ± ruitle exsolution lamellae and biotite 2 contains larger grains of titanite (up to 50 μm). (g & h) In HDD254-711-C from the Havana pit, both biotite 1 and 2 show thin rutile exsolution lamellae, with biotite 2 occasionally showing slightly larger (up to 2μm) rutile grains.

Fig. 5: Biotite Rb–Sr isochrons for individual samples, with red data corresponding to assemblage 1 and green data corresponding to assemblage 2 biotite. Grey data is considered to be part of assemblage 1 but with loss of radiogenic Sr. In samples where only disturbed biotite 1 exists, only a minimum age can be estimated based on a broad isochron through the oldest analyses. All error ellipses are plotted at 2σ. The 2530 Ma model age is based off Fig. 4a, assuming an initial $^{87}Sr/^{86}Sr$ of 0.7045. Note that for assemblage 2, ages are calculated both solely with biotite 2 and with biotite 2 and apatite combined (see section 3 and discussion).

Fig. 6: Transects across two large, euhedral biotite grains. (a, b) Transmitted, plane-polarized photomicrographs of part of the euhedral grains, showing 87 μm (run 1) and 64 μm (run 3) laser ablation pits along the grains. (c, d) Rb-Sr model ages for each spot in the transect across two runs. Model ages were computed using $^{87}Sr/^{86}Sr$ of apatite 1 in corresponding sample (see Fig. 78). (e & f) BSE images of the same regions as a & b. (g) Zoomed-in region showing inclusion-free biotite 1 in the BSD114-541-C, similar to Fig. 4a & b. (h–i) Zoomed-in regions showing exsolution lamellae and fractures (commonly titanite-filled), with these fracture zones contributing to yielding younger Rb-Sr model ages. Spot numbers and colours refer back to panels c & d.

Fig. 7: Phengite and muscovite Rb-Sr isochrons for individual samples, with green data corresponding to assemblage 2 phengite or muscovite. All error ellipses are plotted at 2σ. Ages in italics are estimates only due to overdispersion for a single population.

Fig. 8: Apatite weighted mean $^{87}Sr/^{86}Sr$. Due to the lack of Rb in apatite, measured $^{87}Sr/^{86}Sr$ values can be considered as initial ratios.

Fig. 9: Combined isochron of biotite 2 analyses from all four samples in the Tropicana gold mine, computed with and without apatite 2.

Fig. 10: Synthetic time–space plot showing geological history of the Tropicana Zone, modified from Spaggiari et al. (2015) and Kirkland et al. (2015). The timing of mineralization in the Tropicana Zone is uncertain (see discussion).

Table 1: List of samples dated in this study. TGM = Tropicana gold mine. C = Coarse-grained. F = Fine-grained. Rb/Sr phases indicates the minerals that were dated in each sample, with 1 and 2 corresponding to assemblage 1 and 2, respectively. Eastings, Northings and Reduced Level (RL = Z) are in GDA 1994, MGA zone 51 projection for the drill hole collar.Supplementary Table A: Rb-Sr geochronology parameters during the three analytical sessions.

Supplementary Table B: Compendium of Rb-Sr data, including unknowns and reference materials.

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730 **Supplementary Fig. A: Graphic illustration of how a reaction cell sandwiched between two quadrupoles separates Rb from Sr isotopes, as well as deals with interfering ions.**

Supplementary Fig. B: Compilation of (i) core photos, (ii) transmitted, plane-polarized light image of full thin section, (iii) transmitted, cross-polarized light image of full thin section, and (iv) automated mineral analysis image of full thin sections,
735 **accompanied by legend. Yellow line in core photos indicates approximate position of thin section billet. All thin sections are 46 × 27 mm.**

Supplementary Fig. C: Rb-Sr isochron showing identical ages within uncertainty between sessions 1, 2 and 3 for biotite 2 from HDD254-711-C (Tropicana, WA) and biotite from CK001B (Finnmark, Norway). Spots for these analyses were collected adjacent
740 **to each other (see Fig. 2 for examples). Ages for CK001B overlap with ages obtained by Rb-Sr solution ages (Kirkland et al., 2007).**

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