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Age of the Archaean Murchison Belt and mineralisation, South Africa

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Abstract

The ENE-trending Murchison-Thabazimbi Lineament in northern South Africa is one of the world's most important structures for its control on world-class mineral deposits, Proterozoic sedimentary basins and giant igneous intrusions. The deepest exposed Archaean parts of the lineament are the Murchison Belt. Bounded by granitoids, the belt comprises greenschist to amphibolite facies volcano-sedimentary strata with isoclinal folds and the 7 km thick meta-igneous Rooiwater Complex. The Rooiwater Complex is intruded by a northern regional granitoid dated at 2929 ± 7 Ma by SHRIMP U-Pb on zircons. Using field relationships, published isotopic age data and new SHRIMP zircon dates we confirm the age Rooiwater Complex at 2965 Ma, showing it to be contemporaneous with the Archaean volcanic and

sedimentary formations, the meta-igneous Complex being the lower sequence in a ~2980 to 2960 Ma island arc.

Despite being implicated as a source of gold for the world's largest natural accumulation of gold in the Witwatersrand Basin, the absolute age of Sb-Au mineralisation in the Murchison Belt is poorly constrained. We have utilised SHRIMP U-Pb geochronology to date monazites from a Sb-Au ore sample from the granitoid-hosted Malati Pump orebody and determine ages for two different generations of monazite, both associated with ore minerals. The older age of 2832 ± 23 Ma is from a minority of grains and is interpreted to date the primary Sb-Au mineralisation, about 120 Ma after belt formation. This age predates, or is possibly synchronous with, sedimentation of the upper-Witwatersrand Central Rand Group. The younger age of 1968 ± 17 Ma from a majority of monazite grains is unrelated in time to known events and interpreted here as a cryptic hydrothermal reworking of the Sb-Au ores in this deposit.

Keywords U-Pb dating - Zircon - Monazite - Rutile - Lineament - Antimony - Gold – Mineralisation - Igneous Complex - Kaapvaal Craton - Murchison Belt – Witwatersrand - Archaean tectonics

Introduction

The Murchison-Thabazimbi Lineament in northern South Africa is up to 20 km wide, with polyphase deformation traced for more than 500 km, in a punctuated history of more than 2500 Ma (McCourt, 1995; Good & de Wit, 1997). The ENE-trending lineament is one of the world's most important structures for its Archaean structure, control on Proterozoic sedimentary basins,

igneous intrusions and world-class mineral deposits (Figure 1). The lineament penetrates the Archaean granitoid-greenstone terrain and Proterozoic strata of the Transvaal Basin with significant periods of re-activation, including the 2200 to 2400 Ma Mhlapitsi extensional fold belt prior to deposition of the overlying Pretoria Group (Potgieter, 1992). The lineament separates the northern and southern limbs of the world-class PGE-Ni-Cu, V-Ti and Sn-bearing Bushveld Complex (~2056 Ma, Mungall et al., 2016). In the west, the lineament extends into Botswana where it is a major control, being a possible feeder for the (buried) Molopo Farms Complex, the Botswana extension of the Bushveld Complex (Key & Mapeo, 2018), and the Murchison-Thabazimbi Lineament is proximal to the Thabazimbi iron deposits in the west (van Deventer, 1986). In the east the lineament is adjacent to the world-class Cu-P mineral deposit in the alkaline complex of Phalaborwa (~2060 Ma, Heaman, 2009).

Figure 1 *The crustal geology of southern Africa (including the Murchison-Thabazimbi Lineament), the Archaean Cratons, Limpopo Belt, overlying sedimentary basins including the Witwatersrand and the Bushveld Complex. Modified after McCourt (1995) and Eglington & Armstrong (2004).*

The eastern Murchison-Thabazimbi Lineament is the deepest exposed segment, being the Archaean Murchison Schist Belt (Figure 2). Bounded by granitoids, the belt comprises greenschist to amphibolite facies volcano-sedimentary strata and the meta-igneous Rooiwater Complex. The Murchison Belt was for many years the western-world's largest producer of antimony, which occurs with gold in carbonate-altered ultramafic and mafic volcanic rocks. There are also emerald mines on the southern margin, in biotite-altered ultramafic rocks intruded by beryl pegmatites (Lum et al., 2016), volcanogenic Cu-Zn massive sulphides in felsic volcanic rocks of the central Rubbervale Formation (Schwarz-Schampera et al., 2010), and Ti-V magnetites in anorthosite-gabbro of the northern Rooiwater Complex.

Figure 2 *The Murchison Belt and surrounding granitoids. The belt geology is highly simplified from maps in Vearncombe et al. (1992) and the surrounding granitoids are from Jaguin et al. (2012a, 2013).*

This paper is foremost a critical review of isotopic age data, most of which have been published since the last overview of the geology of the belt (Vearncombe, 1988). We here present a coherent view of the geochronology data constrained by field relationships. We add some new SHRIMP isotopic age data related to the northern granitoid adjacent to the Rooiwater Complex and mineralisation in the Murchison Belt. For the Murchison Belt specific points of controversy are:

1 Is the northern meta-igneous Rooiwater Complex of similar age to the greenstones, being the lowest part of the sequence (van Eeden et al., 1939; Vearncombe et al., 1987; Zeh et al., 2013), or a younger Neoarchaeon intrusion (Poujol et al., 1996; Poujol, 2001; Anhaeusser, 2006; Jaguin et al., 2012a; Gumsley et al., 2020)? Specifically, is the northern Rooiwater (Novengilla) gabbro-anorthosite contact with the northern granitoid (a) gabbro into granitoid, (b) intrusive granitoid into gabbro, or (c) a major fault/shear zone?

2 The tectonic setting of the Murchison Belt, with suggestions that are not mutually exclusive being: (a) equivalence to the Barberton Greenstone Belt (Viljoen et al., 1978; Anhaeusser & Wilson, 1981) (b) a suture (de Wit et al., 1992; Brandl & Kroner, 1993; Eglington & Armstrong, 2004; Zeh et al., 2013), (c) an island arc (Vearncombe, 1991), or (d) the southern extent of nappe-like Limpopo deformation (McCourt & Vearncombe, 1992).

3 The Murchison Belt has been implicated in the origin of the giant gold deposits of the Witwatersrand Basin to the south, but without a critical analysis of the style of Witwatersrand mineralisation (Vearncombe, 1992; Poujol et al., 1996). Despite being implicated in the origin of the Witwatersrand, the age and relationship of Sb-Au mineralisation is poorly constrained.

94 **Geology of the Murchison Belt**

95 The deep Archaean sector of the Murchison-Thabazimbi Lineament (Figure 2) is extensively
 96 deformed with isoclinal folding, north to south thrusting, and sinistral shear zones. The belt is
 97 described in terms of five tectono-lithological domains, each juxtaposed along major faults and
 98 shear zones (Vearncombe et al., 1992; Block et al., 2012). Metamorphism is domainal lower-
 99 greenschist to amphibolite facies, some along warm $\sim 30^{\circ}\text{C}/\text{km}$ apparent geothermal gradients,
 100 but the north-eastern Silwana's Amphibolite and southern kyanite-staurolite-bearing La France
 101 Formation experienced a cooler apparent geothermal gradient of $\sim 20^{\circ}\text{C}/\text{km}$ analogous to
 102 Phanerozoic collisional belts (Block et al., 2012).

103 ***Silwana's Amphibolite***

104 The Silwana's Amphibolite in the northeast is of highly deformed amphibolite in the sinistral
 105 Letaba shear zone. The origin of the amphibolite is not known but could be deformed
 106 equivalents of the Rooiwater Complex.

107 ***Rooiwater Complex***

108 The meta-igneous Rooiwater Complex is up to 7 km thick, near-vertical and the least deformed
 109 of the Murchison domains. The Rooiwater Complex is at amphibolite facies, comprising
 110 layered Novengilla anorthosite-gabbro, the Quagga quartz-garnet-amphibolites and the albitic
 111 Free State Hornblende Granite (Vearncombe et al., 1987). A southward younging is deduced
 112 from the general disposition and from magnetitite layers with south directed increases in TiO_2
 113 in successive layers. Excepting one locality where it appears to intrude its own roof rocks (van
 114 Eeden et al., 1939; Vearncombe et al., 1987), the Rooiwater Complex lacks intrusive contacts.

115 ***Rubbervale Formation felsic volcanic rocks***

116 The Rubbervale Formation comprises quartz-porphyroclastic schists after porphyry and
117 volcanic tuffs and lavas. The Rubbervale Formation appears to be genetically related to the
118 Rooiwater Complex (Vearncombe, 1991), although isotopic age data have been used to
119 challenge this (Poujol et al., 1996; Poujol, 2001; Jaguin et al., 2012a). The domain appears to
120 be southward younging with at least twelve small Cu-Zn-Fe volcanogenic massive sulphide
121 deposits along the Copper-Zinc line, being the southern margin of the south-younging domain
122 (Figure 2; Schwarz-Schampera et al., 2010).

123 ***Central Murchison Belt ultramafic-mafic and sedimentary rocks, and antimony-gold***
124 ***mineralisation***

125 By far the largest of the domains, the central Murchison Belt comprises ultramafic and mafic
126 volcanic rocks including pillow lavas with extensive and locally complete ankerite-dolomite
127 alteration, tremolite-actinolite schists, chlorite-carbonate schists, chert and ferruginous chert,
128 quartzites and locally conglomerate. The central domain includes regional-scale isoclinal folds
129 of quartzites, and steep reverse to the south shear zones, in what may be Archaean nappe-like
130 tectonics. Younging directions vary to the north and south around folds and include downward-
131 facing structures (*sensu* Shackleton, 1957). The Antimony Line, central to the Murchison Belt
132 is a broad zone, 250 m wide, of schists, with antimony-gold mineralisation, including stibnite,
133 berthierite, arsenopyrite and locally cinnabar. Antimony-gold mineralisation is epigenetic and
134 associated with quartz-carbonate veins in chlorite-carbonate schists with fuchsite and talc
135 alteration. The Antimony Line is discordant to quartzites, quartz-conglomerates and
136 ferruginous cherts on the regional-scale (Nutt et al., 1988); at the mine-scale mineralisation is
137 oblique to quartz-carbonate alteration (Boocock et al., 1988) and oblique to primary
138 ferruginous chert (Vearncombe et al., 1988). Mineralisation is proximal to albitised granitoid

plugs that may be interconnected at depth (Figure 3). These plugs appear to have been emplaced after the main deformation, but before deformation and mineralisation had ceased. A late hydrothermal/metamorphic source has been assumed, in a relationship similar to those recognised on Archaean gold systems globally (Vearncombe et al., 1988; Vearncombe and Holyland, 1995).

Figure 3 *Photograph taken underground of discordant and intrusive albitic plug into chlorite-carbonate schist in a small abandoned adit near the Gravelotte quarry and shaft. This albitic plug is not exposed at surface.*

La France Formation

The La France Formation of clastic sedimentary origin comprises highly deformed fuchsite quartzites and quartz-mica schists with locally kyanite, staurolite and cordierite.

Geochronology of the Murchison Belt

Following original mapping of the western part of the Archaean belt by van Eeden et al., (1939), the Murchison was mapped in detail in the mid-1980s and published as 1:50,000 map sheets (Vearncombe et al., 1992). This field work was accompanied by belt-scale geophysical surveys (de Beer and Stettler in Vearncombe et al., 1992) and whole rock isotopic age studies, interpreted mostly as mixing or re-equilibration events (Vearncombe et al., 1987). In an overview of the geology of the Murchison Belt, Vearncombe (1988) wrote “despite a large dataset much of the isotope age data are ambiguous”. Since then most academic geology research on the belt has focused on isotopic dating with multiple authors (Table 1). These studies fall into two types, (1) those that are a solid detailed addition focussing on an aspect of the geology (e.g. the Rubbervale felsic volcanic rocks by Schwarz-Schampera et al., 2010; La

France Formation metamorphism by Block et al., 2012) or (2) radiogenic isotope studies on samples from road-side outcrop where the data are integrated into broad studies of crust-mantle interaction, craton-evolution and mineralisation (e.g. Poujol et al., 1996; Zeh et al., 2009, 2013). These age data provide useful insights to the timing of geologic events but include results and interpretations that are mutually incompatible and some that contradict published field relations.

Age dates from more than twenty-five publications are given with location, sample identification, method, results and interpretation in Table 1. All whole-rock Rb-Sr, U-Pb and Pb-Pb dates, and analyses with large errors are here categorised as unreliable, although some of the dates are remarkably close to those obtained more recently by modern methods. Hence, they are detailed and presented graphically (Table 1 and Figure 4).

Table 1. *Compilation of isotopic age data of granitoids and gneiss north of the Murchison Belt, the Rooiwater Complex, the felsic volcanic Rubbervale Formation, rocks of the central and southern Murchison domains, granitoids intrusive into the central Murchison Belt near or along the Antimony Line, ages on the La France Formation, and granitoids to the south of the Murchison Belt. Dates on sediments including the age of detrital components. Based on original descriptions (and photographs) of mineral morphology, relative age relationships and consistency of the results, we here categorise the dates as being xenocryst, primary, detrital, mineralisation, recrystallised or unreliable. Note S2 to S21 are of samples that lack identification numbers in their original publications and are given here identifiers to link with Figure 4.*

Figure 4 *Graphic plot of the age with error ranges of published age data for the Murchison Belt and surrounding granitoids. This is a visual simplification of data compiled and detailed in Table 1.*

186

187 **Geochronology Methods**

188 **Zircon:** Zircons from sample M03 from a granitoid dyke intruding the Rooiwater (Novengilla)
189 gabbro at Thiergarten were physically separated from the rock using routine crushing and
190 heavy liquid methods. All other samples from the dykes intrusive to the Rooiwater Complex
191 lacked zircon of a size and suitable for SHRIMP analysis. Zircons from M03 were hand-picked
192 under a binocular microscope and cast in a 25 mm epoxy mount with zircon standards. The
193 mount (N18-13) was polished to expose central zones in the zircons, and carbon coated for
194 scanning electron microscope (SEM) imaging in backscattered electron, secondary electron
195 and cathodoluminescence (CL) modes.

196 Isotopic analyses were performed on SHRIMP (Sensitive High-Resolution Ion Micro-Probe)
197 at Curtin University, following procedures described by de Laeter & Kennedy (1998) and
198 Kennedy & de Laeter (1994). A ~20 µm diameter spot from a mass-filtered O₂⁻ primary ion
199 beam of ~2.0-2.2 nA was used. The primary ²⁰⁶Pb/²³⁸U reference standard was M257 (561.3
200 Ma, 840 ppm U; Nasdala et al., 2008), whereas the ²⁰⁷Pb/²⁰⁶Pb monitor for Pb mass
201 fractionation was OGC zircon (3465.4±0.4 Ma; aka OG1 of Stern et al., 2009). No fractionation
202 was observed, and no fractionation correction was made. The common Pb correction was based
203 on the measured ²⁰⁴Pb (Compston et al., 1984). The U/Pb calibration formulae is: ²⁰⁶Pb⁺/²³⁸U⁺
204 = a(²⁵⁴UO⁺/²³⁸U⁺)^b (Claoue-Long et al., 1995) using parameter values of Black et al., (2003).
205 Constants “a” and “b” are determined empirically from the analyses of the standard during the
206 analytical session. Data processing used the SQUID II and Isoplot programs of Ludwig (2009,
207 2011) and results are detailed in Table 2, and Figure 5. For all dated minerals, ages for combined
208 data are ²⁰⁷Pb/²⁰⁶Pb ages with 95% confidence level (c.l.) errors, whereas single spot analyses in tables
209 and text are 68% c.l. errors.

Monazite: Monazite grains were identified from SEM (scanning electron microscope) images of polished thin-sections, drilled out as plugs and cast in a 25mm diameter epoxy mount suitable for SHRIMP and reimaged prior to analysis. U–Th–Pb analyses were performed using the high spatial-resolution capability of the SHRIMP II at the John de Later Centre, Curtin University. Monazite was analysed in a single analytical session. Grains were selected from SEM images from the same polished thin-sections and analysed using a 30 μm Köhler aperture, ~ 0.5 nA primary ion beam (O_2^-) and a ~ 10 μm analysis spot. Energy filtering was not applied, and the retardation lens was activated to reduce stray ion arrivals. The mass resolution ($M/\Delta M$ at 1% peak height) was >5000 . French ($^{206}\text{Pb}/^{238}\text{U}$ age 514 Ma) was used as the primary Pb/U reference material, and Z2908 and Z2234 were the secondary reference materials used to monitor matrix effects (Fletcher et al., 2010). Z2908 ($^{207}\text{Pb}/^{206}\text{Pb}$ age 1796 Ma) was also used to monitor and correct for instrumental mass fractionation of ^{207}Pb versus ^{206}Pb . Squid-2 software (Ludwig, 2009) was used for initial data reduction including ^{204}Pb correction. Matrix effects in $^{206}\text{Pb}/^{238}\text{U}$ were corrected following established protocol detailed by Fletcher et al., (2010). During the session, five analyses of Z2908 allowed the measured $^{207}\text{Pb}/^{206}\text{Pb}$ age to be compared with the true age (1796 ± 2 Ma; Fletcher et al., 2010) and a small correction and error propagation was applied to sample data. $^{207}\text{Pb}/^{206}\text{Pb}$ dates from individual analyses are presented with 1σ internal precisions, whereas weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ dates are reported with 95% confidence limits.

Rutile: As with monazite, grains were selected from SEM images from the same polished thin sections, and similarly drilled out and cast in 25 mm diameter epoxy mounts. Rutile analytical procedures used were similar to those described by Taylor et al. (2012). SHRIMP analyses used a 100 μm Köhler aperture, ~ 3.3 – 4.3 nA primary ion beam (O^-) and a ~ 20 μm analysis area. Energy filtering and the post-collector retardation lens were not used. The mass resolution ($M/\Delta M$ at 1% peak height) was >5000 . Windmill Hill rutile ($^{206}\text{Pb}/^{238}\text{U}$ age 2625 Ma; Clark et

al., 2000) was used as the primary Pb/U reference material, and the $^{207}\text{Pb}/^{206}\text{Pb}$ age was monitored for precision. The common Pb correction normally uses ^{208}Pb due to the general absence of Th in rutile, but as discussed in the text, significant levels of Th and high common Pb in all analyses invalidated the use of the ^{208}Pb correction. Instead, the ^{204}Pb correction was used for common Pb, as normally performed on zircon data. For both monazite and rutile, the reference materials were in separate mounts (N14-14 for monazite; 08-03 for rutile) and were cleaned and Au-coated together with the sample mounts before each analytical session.

Rooiwater Complex age relationship with northern granitoid

The contentious northern Rooiwater contact has been described (Poujol & Robb, 1999; Anhaeusser, 2006) as a fault or shear on the basis of now superseded age dates, not field relationships. The Rooiwater Complex is also described as an intrusion (Zeh et al. 2013) despite lacking any field evidence of intrusive contacts excepting the auto-intrusion of its own roof rocks (van Eeden et al. 1939; Vearncombe et al. 1987). Assertions that the meta-igneous Rooiwater Complex is an intrusion younger than the Murchison Belt are rejected because of the total lack of intrusive evidence such as xenoliths, dykes or metamorphic aureole. Poujol et al. (1996) and Zeh et al. (2009) dated a component of the Rooiwater Complex as being younger (2710 to 2690 Ma) than the Rubbervale Formation at 2960 Ma. Described by Poujol et al. (1996) as a tonalite, the unit they dated is the Free State Hornblende Granite. The Free State Hornblende Granite is both metamorphosed and altered, it is sodic with albitisation not confined to the Antimony Line (cf. Jaguin et al., 2013). Superficially, the younger 2710 to 2690 Ma age is supported by the Rooiwater Complex being mostly undeformed and contrasting with the rest of the highly schistose Murchison Belt. Importantly, Zeh et al. (2013), using the same

sample, were able to revise earlier incorrect ages and reliably dated the Rooiwater Complex at 2965 Ma with recrystallisation of fractured zircons at ~2795 Ma.

For this study, localities where northern granitoid dykes intrude the gabbro of the Rooiwater Complex were re-visited and sampled (see 1:50,000 maps in Vearncombe et al. 1992). The locality on the farm Thiergarten is a kopje near a game lodge and at the second locality, near Letsitele, an informal quarry opened since the 1980s mapping. At both localities the relationship is unambiguous with a younger (northern) granitoid intruding the older Rooiwater (Novengilla) gabbro (Figure 6). Both gabbro and intrusive granitoid dykes carry a modest schistosity. Published field relationships of the granitoid dykes intruding the Rooiwater are here re-iterated. Seven samples of granitoid dyke were collected. However only one sample from Thiergarten was suitable for zircon U-Pb dating.

Figure 5 *Concordia plot of zircon isotopic data from sample MO3 (mount N18-13A) with the interpreted ages of a xenocryst population and granitoid magmatism. Error ellipses are 1σ . The most discordant analysis is not shown. Open ellipse is grain #20, not included in the age calculations (see text).*

Figure 6 *Photographs showing granitoid dykes on the northern Rooiwater contact intrusive into the Rooiwater (Novengilla) meta-gabbro. (a) At 23°51'29.699" S 30°30'48.6" E granitoid dyke in gabbro on farm Thiergarten. (b) At 23°53'43.699" S 30°20'30.6" E granitoid dykes and quartz veins intrude gabbro at Letsitele quarry.*

Table 2 *Zircon U-Pb isotopic data for sample MO3 (mount N18-13A).*

Geochronology Results

Geochronology results are detailed in Table 2 and Figure 5. Cathodoluminescence images of zircons revealed distinct cores as euhedral overgrowths on a minority of grains. Both the

internal and external morphology of the grains were euhedral to subhedral, typical of magmatic growth. In-situ analyses identified two age populations amongst the most concordant data, and some intermediate ages. Duplicate analyses on the cores of two grains (#5 and #12) provided identical ages of 3148 ± 6 Ma ($n=4$; MSWD=0.4). These two grains are also distinct by having the highest U-contents. Another grain is slightly younger (#20; 3111 Ma), but significantly older than the main population. These three grains are all considered to be xenocrysts, with the main population from both zircon rim and core zones representing the magmatic age of the granitoid. The age for grain #20 could reflect either a separate pre-magmatic event or a mixed analysis of 3148 Ma and younger zircon.

The main population of <10% discordant data comes from zircon cores and rims. However, there is no reliable way to distinguish xenocrystic from magmatic cores, apart from their age. The main group has excess scatter for a single age population (i.e. MSWD=2.8 for $n=10$). The presence of xenocryst cores to some zircon grains may produce some mixed ages, slightly older than the magmatic age. Omission of the two oldest analyses reduces the scatter to approach that for a single age population and yields an age of 2931 ± 12 Ma (MSWD=1.2; $n=8$). Increasing the discordance cut-off from <10% to <20% adds four more analyses to the main population and further reduces the MSWD to yield an age of 2929 ± 7 Ma (MSWD=1.1, $n=12$). Including these additional data assumes that the discordance is due to modern day Pb-loss only. This is statistically acceptable as all of the 10-20% discordant data have an indistinguishable age compared to the more concordant data. Accordingly, we interpret the main population to yield the magmatic age of the dyke and the minimum age of the Rooiwater (Novengilla) gabbro: 2929 ± 7 Ma. We conclude that the younger published (2710 to 2690 Ma) Rooiwater isotope ages date resetting or recrystallisation, and the most reliable age for the Rooiwater Complex is that of 2965 Ma (Zeh et al., 2013), identical to the age, albeit with a much larger error margin, of Burger and Walraven (1979).

306 **Age of antimony-gold mineralisation**

307 Ore samples from the Antimony Line collected in 2018 were examined by scanning electron
308 microscope (SEM) to identify datable minerals associated with mineralisation. Only one
309 sample of veined and mineralised microgranitoid from Malati Pump (sample M10) was
310 selected: location 23°51'53.2"S, 30°46'34.5"E. This is believed to be the same location as the
311 Jaguin et al. (2013) samples, and the old Malati Pump working is now in the early stages of a
312 modern open-cut operation. Five polished thin-sections of this sample were prepared and were
313 examined in detail using the Thermo-Fisher Tescan Integrated Mineral Analyser (TIMA) and
314 Mira3 SEM to identify datable minerals. Suitable monazite and rutile grains were identified
315 for SHRIMP U-Pb geochronology. The most suitable grains identified in polished thin-sections
316 were large enough for ion microprobe analysis (i.e., $\geq 10 \mu\text{m}$) and were drilled out, in $\sim 3 \text{ mm}$
317 plugs, and cast in a 25 mm epoxy mount (mount M10A for monazite, and mounts N19-02 and
318 N19-03 for rutile).

319 Sample M10 consists primarily of massive, porous albite ($> 60\%$) and quartz ($> 20\%$).
320 Accessory minerals are Fe-oxides, including possible hematite after pyrite or magnetite, an Fe-
321 rich mica, rutile, zircon, monazite, xenotime and baryte (Figure 7). The Fe-oxide minerals
322 contain variable amounts of As, Sb, S and Br, and are large (up to 1 cm), porous, botryoidal
323 masses suggestive of goethite infill of vugs (e.g. Figure 7D). Baryte occurs as $\sim 1\text{--}5 \mu\text{m}$,
324 tabular, clusters on the vug walls of the Fe-oxide. Also, within the Fe-oxides are cinnabar
325 crystals ($\sim 1 \mu\text{m}$) (Figure 7D). Monazite is found as euhedral to anhedral grains up to $50 \mu\text{m}$
326 in size within the albite matrix and as inclusions within the Fe-oxide masses and has a close
327 association with xenotime.

328 **Figure 7** BSE (backscattered electron) images of representative SHRIMP-analysed monazite
329 grains from sample M10. Red circle and number indicate the location of the analysis and age
330 (Ma) from Table 3. Drilled plugs on the SHRIMP mount M10A were, Figure 7A M10A.D; Fig 7B

M10A.F; Figure 7C M10A.B; Figure 7D M10A.I). Abbreviations: monazite (mz, white in BSE), albite (ab), quartz (qtz), Fe-oxide/oxyhydroxide (FeO, goethite?), xenotime (xt), cinnabar (cbr) and baryte (ba).

Geochronology Results

Monazite: A total of 22 spot analyses were conducted on 19 individual grains (Table 3). Of these, two analyses had unacceptably high discordance (>7%) and were not considered further. The U-contents of the remaining 21 analyses were low for monazite (~40-350 ppm) but the common Pb corrections were all below 1.0%, and mostly below 0.2% (f206; Table 3). There is a spread of near-concordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages from 2845 to 1896 Ma (Figure 8; Table 3). However, an age probability plot (Figure 9) shows two age clusters, around 1970 and 2830 Ma. The dominant peak contains 11 analyses within error of each other (MSWD = 1.07) and has an age of 1968 ± 17 Ma. These analyses are also characterised by generally lower Th/U. The age probability and concordia plots (Figs 8, 9) show the strong clustering of data comprising the 1968 Ma population and the general spread of near-concordant ages towards the older ~2830 Ma age.

Table 3. Monazite U-Th-Pb isotopic data for sample M10, ranked in order of decreasing age. Two discordant analyses were not considered in age discussion. All data corrected for common Pb: f206 is the % of ^{206}Pb attributed to common Pb; * radiogenic Pb; Disc – discordance.

Figure 8 Concordia plot for near-concordant monazites from ore sample M10, Malati Pump.

Figure 9 Age probability plot and histogram for near-concordant monazites (Table 3) from ore sample M10, Malati Pump.

The older ages are near-concordant and probably not affected by Pb-loss due to radiation damage from these low-U grains (see Rasmussen and Muhling, 2007; Rasmussen et al., 2010). Instead, given the tendency for monazite to dissolve and reprecipitate as overgrowths on

existing grains during low temperature hydrothermal events, we interpret the spread in ages as probably mixtures between pre-existing older monazite grain cores, overgrown by new monazite growth during the ~ 1970 Ma event. The SEM images and ~10 μm resolution of the SHRIMP spot did not permit detection or resolve cores-rims on individual grains of such “mixtures”. The younger end-member age is well defined at ~ 1970 Ma, and the older endmember is calculated from the oldest analyses. The five oldest analyses gave an MSWD of 2.0, which is too large to represent a single age. The three oldest analyses are within analytical uncertainty of each other (MSWD = 0.86) and their weighted average 2832 ± 23 Ma age is taken as the best estimate of the older end-member age. The intermediate seven analyses show no age grouping and are interpreted as variable mixtures of the two end-member ages. Six of these seven “mixed” analyses are >2400 Ma (Figure 10) and the area of each analysis appears to be dominantly on the older part of the grains.

Figure 10 Age versus Th/U plot for near concordant monazites (Table 1) from ore sample M10, Malati Pump.

Rutile: Thirty-four analyses on 24 rutile grains from sample M10 are presented in Table 4. All analyses showed very low U-contents (<1-13 ppm U) and consequently low levels of radiogenic Pb. With a small amount of common Pb as measured by ^{204}Pb , the proportion of common ^{206}Pb to total ^{206}Pb was unacceptably high in all analyses (i.e. 9-50%), resulting in none of the analyses providing acceptable age data. By comparison, for typical zircon analyses, common ^{206}Pb proportions of >1 % are often omitted as less reliable data for age calculations. Nonetheless, in light of the monazite ages, the analyses with the lowest proportion of common ^{206}Pb , >5 ppm U and <25 % discordance are shown in Figure 11. The nine analyses with the lowest % common ^{206}Pb (<30%; Fig 11) show considerable age uncertainty and scatter and do not group around a common value. However, the best nine of 17 analyses shown in Figure 11 are all between the bimodal monazite ages of 2832 and 1968 Ma. Accordingly, although we do

not interpret any numeric age data from the low-U rutile data, we consider the rutile grains had a similar genesis to the monazites in the same sample (i.e., formed at ~2832 Ma and overprinted at ~1970 Ma.) The rutile grains thus provide weak support for the monazite interpretation herein.

Table 4.: U-Th-Pb isotopic data for rutile from sample M10, ranked in order of increasing common Pb correction. All data corrected for common Pb using ^{204}Pb . Com – common; Disc – discordance.

Figure 11 Plot of common Pb-corrected rutile $^{207}\text{Pb}/^{206}\text{Pb}$ age versus the % of common ^{206}Pb (Table 3), excluding data >25% discordant and <5 ppm U. Error bars are 1σ .

Petrography-age relationship: This study has identified two different generations of monazite growth in a single ore sample from the Malati Pump Sb-Au orebody. Monazite is robust to isotopic resetting and has a known ability to preserve multiple stages of growth during low temperature overprint events via dissolution-precipitation processes (Rasmussen & Muhling, 2007). New monazite growth requires fluid movement to distribute monazite solutes, and these characteristics underpin the following interpretation that preserved monazite grains formed both during the initial Sb-Au mineralisation at Malati Pump at ~2832 Ma, and monazite formed during a later hydrothermal alteration at ~1968 Ma. Figures 7A and 7B are BSE images showing examples of the oldest dated grains. In Figure 7A, the monazites are anhedral in the albite and quartz matrix with Fe-oxide/oxyhydroxide (probably goethite). Red circles indicate where age data were taken. Although these are old grains, there is some evidence of age mixtures as the ages vary from 2845 to 2645 Ma. The youngest age in this image is coincident with a euhedral crystal with strong cleavage traces. Figure 7B shows an example of old, subhedral monazite grains within an Fe-oxide mass. Here, all ages are consistently old, between 2726 and 2839 Ma suggesting no or minimal overgrowths from younger monazite. Figures 7C

and 7D are examples of monazite grains that belong to the young age population. Figure 7C shows subhedral grains with a range of U-Pb ages from 1965 to 2476 Ma. The older ages of 2078 and 2476 Ma are examples of age mixtures. There is no apparent textural difference between areas in the monazite that give differing ages. Figure 7D shows a similar pattern of ages within the monazite grains, with generally young ages, 1913 to 1976 Ma, but with one slightly older age at 2003 Ma. This also suggests this analysis may contain a small contribution from a relict older grain in addition to monazite from the later hydrothermal event. Also associated with these monazite grains are cinnabar and baryte as void-filling clusters in the Fe-oxide/oxyhydroxide. All monazites are associated with Fe oxides/oxyhydroxide considered to be goethite from its texture and composition comprising Fe-O as the major elements from SEM-EDS analyses. Goethite is unlikely to be a primary ore mineral and probably replaced a primary Fe-mineral such as pyrite (cf epizonal Wiluna Sb-Au ores; Hagemann et al., 1992). Jaguin et al., (2013) observed pyrite in their samples from Malati Pump and only found the older generation of monazites. We therefore speculate that the goethite precursor mineral was probably pyrite formed during the ~2830 Ma event, and goethite subsequently replaced this, possibly during Recent weathering.

Archaean tectonic setting of the Murchison Belt

The Murchison Belt (South Africa) is more deformed than the Barberton Belt, the history of which, from first eruption of volcanic rocks to marginal granitoids and mineralisation, is 3550 to 3200 Ma, and thus considerably older than the Murchison Belt (Drabon et al., 2017; Peng et al., 2019). In the Murchison, the Rooiwater Complex and related Rubbervale Formation were formed between 2980 and 2960 Ma. Whilst there are no primary age dates on the Central Murchison, detrital zircons are in the range 3530 to 3074 Ma with one sample at 2979 Ma thereby providing a maximum age of this domain. Detrital zircons in the range 3480 to 2986

429 Ma similarly provide a maximum age for the La France Formation (Table 1 and Figure 4).
430 Granitoid plugs intrusive into the Central Murchison are dated at ~ 2970 Ma, albeit a small
431 data set, with many younger ages interpreted as recrystallisation. The Murchison Belt formed,
432 deformed and was intruded by granitoids in a short time span between 2980 and 2960 Ma, with
433 mineralisation later at 2830 Ma.

434 The Murchison Belt sits between the southern Kaapvaal Craton, which was stabilised by ~
435 3100 Ma (de Wit et al., 1992), and the northern Himalayan-style Limpopo Belt, which was
436 active at 2672 to 2620 Ma (McCourt & Vearncombe, 1992; Barton & van Reenen, 1992;
437 Kramers et al., 2014; Smit et al., 2019). The early-stabilised southern Barberton-Witwatersrand
438 domain witnessed intra-cratonic inversion and basin development with the Dominion Group at
439 3120 to 3070 Ma, Witwatersrand basin 3074 to 2714 Ma, the Pongola 2985 to 2870 Ma and
440 Ventersdorp basins ~2710 Ma (Armstrong et al., 1991; Hegner et al., 1994; Kositcin et al.,
441 2003). The Witwatersrand may be slightly older, possibly 3074 to 2790 Ma based on the recent
442 baddeleyite date of intrusive mafic sills in the lower West Rand Group if those sills relate to
443 and are feeders for the overlying Ventersdorp Supergroup volcanic rocks (Gumsley et al.,
444 2020). The period after southern cratonisation witnessed formation of the Murchison Belt
445 (2980 to 2960 Ma) and younger phases of granitoid intrusion, tectonism, and mineralisation on
446 its northern margin. Clearly, the Murchison-Thabazimbi Lineament represents a structure
447 along which younger northern terrains accreted onto the small southern early Archaean cratonic
448 domain.

449 The Murchison Belt separates two granitoid terrains accreted in the Meso-Archaean. The
450 southern terrain appears to have fed detritus on to the belt and the accretion was complete by
451 the timing of the within-belt granitoids at or before 2960 Ma (Jaguin et al., 2012a; Zeh et al.,
452 2013). The Rooiwater Complex and the overlying Rubbervale Formation are of the same age,

and have overlapping geochemical trends that encompass Fe-rich tholeiite and calc-alkaline fields. The Rubbervale Formation REE patterns are generally flat and coherent, and mirror the gabbro-anorthosite patterns which display low REE contents and a positive Eu anomaly (Vearncombe, 1991). The belt shows remarkable similarities to Tertiary and Mesozoic island arcs, including sub-volcanic magma chambers, related calc-alkaline volcanic rocks and VMS deposits. Rocks of the Rooiwater Complex and Rubbervale Formation have common parental magmas, and ascent occurred without significant assimilation of older crust (Zeh et al., 2013). The Rooiwater Complex and Rubbervale Formation appear to have been part of a primitive island arc.

There is now a substantial dataset of ages for granitoids surrounding the Murchison Belt. However, the maps showing the outline and relationships of these granitoids are based on cursory studies only. There has been no detailed geology mapping of the surroundings comparable to the 1:50,000 mapping within the Murchison Belt. Future studies to better define differences north and south of the Murchison Belt will require detailed mapping of the granitoids with an underlay of regional aeromagnetic imagery.

The Murchison Belt has been described as a suture by some (Poujol et al., 1996; Brandl & Kroner, 1993; Zeh et al., 2013), and by others as a major cratonic sub-terrain boundary (Good & de Wit 1997). Clearly, amalgamation of the Murchison Belt onto the proto-Kaapvaal Craton occurred prior to the Limpopo orogeny at 2672 to 2620 Ma. Based on the complete absence of any ophiolitic rocks (that could be interpreted as remnants of Archaean ocean crust) Vearncombe (1988) concluded that the Murchison Belt and Murchison-Thabazimbi Lineament are not a suture. Whether the belt is a suture or not appears to depend on the user's precise definition of the word "suture".

The timing of Murchison Belt Sb-Au mineralisation

Previous geochronology of deposits along the Antimony Line by Jaguin et al. (2013) also included monazite age data on the Malati Pump deposit. Their calculated age for ore-related monazites from Malati Pump was 2793 ± 24 Ma. However, the geochronology technique used by Jaguin et al. (2013) was LA-ICPMS (laser ablation inductively coupled plasma mass spectrometry), which did not allow a correction for common Pb due to the high isobaric interference on the ^{204}Pb measurement from ^{204}Hg for this technique. Thus, all their ages should be reinterpreted as maximum ages, as any correction for common Pb would produce younger corrected ages. Notwithstanding this technical limitation, the Malati Pump monazites analysed by SHRIMP (which does not introduce Hg during analysis) showed relatively small corrections for common Pb. If applicable to the Malati Pump monazite ages determined by LA-ICPMS, then their age data for monazite formation can be considered reliable.

The petrography of the dated monazites and ore minerals indicates a spatial link at a sub-mm scale. The SHRIMP age of 2832 ± 23 Ma is not precise, due to the low amount of data and the low signal measured on SHRIMP for the analysis area of 10 microns in diameter on generally low-U monazites. These features combine to yield a relatively large age uncertainty. However, the result is real and requires an explanation. Three near-concordant analyses with identical age and coherence with the Jaguin et al. (2013) age suggests the age is accurate, although not particularly precise. Reassessing the Jaguin et al. (2013) LA-ICPMS age of 2793 ± 24 Ma we note the age distribution is slightly bimodal and skewed with a young tail, with an MSWD of 1.4 for 14 analyses. This indicates real age scatter about a common value. Given the evidence for a ~ 1970 Ma overprint of the orebody and the possibility of younger monazite overgrowths at this time, it is possible that a small number of analyses may represent mixtures of the two monazite growth events, as observed in the SHRIMP data. Omitting the youngest analyses from the Jaguin et al. (2013) dataset yields 2805 ± 16 Ma (MSWD = 0.73; n = 11). Marginally

502 older and more precise than the Jaguin et al. (2013) result this age is more compatible with the
503 M10 monazite age by SHRIMP.

504 Jaguin et al. (2013) also recorded a titanite age (with poor precision; MSWD = 6) of 1936 ± 41
505 Ma from the Baderoukwe Granite, which intrudes the Murchison Belt and intersects the
506 extrapolated Antimony line (Figure 2). The emplacement age of this granitoid is 2966 Ma
507 (zircon U-Pb age; see Jaguin et al., 2013) which indicates the titanite grains were secondary.
508 However, no titanite Th/U (or $^{208}\text{Pb}/^{206}\text{Pb}$ from which Th/U can be calculated) or Fe/Al data
509 for the titanites were presented by Jaguin et al. to support a secondary origin (cf Aleinikoff et
510 al., 2002). Nonetheless, selecting only the most concordant titanite data (i.e. <10% discordant)
511 yields a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1923 ± 33 Ma ($n = 4$; MSWD = 1.14). This approach avoids the
512 influence from the more discordant data (ie. 30-73% discordant), shows less scatter (lower
513 MSWD) and is considered a more reliable age estimate of the secondary overprint recorded by
514 titanite in the Baderoukwe Granite. Whether using this result or that proposed by Jaguin et al.
515 (2013), these calculated ages are (just) still within error of the 1968 ± 17 Ma monazite age from
516 M10 and probably reflects the same event.

517 Although the Baderoukwe Granite is ~50 kms from the Malati Pump deposit (Figure 2), both
518 record a hydrothermal event at ~1970 Ma within the Antimony Line and its extension, which
519 hitherto has not been recognised in the Murchison Belt, apart from the Baderoukwe Granite.
520 Known major events in the craton, such as the Bushveld and Phalaborwa intrusions, are
521 distinctly older at ~2055–2060 Ma (Bushveld - Mungall et al., 2016; Phalaborwa - Heaman,
522 2009). Possible known events around ~1970 Ma in the region have not been recognised,
523 although younger mafic dyke emplacement (Letts et al., 2005) and mafic igneous complex
524 emplacement (Tisane et al., 2019) may have older, undiscovered counterparts. Although such
525 magmatic activity could have been accompanied by reactivation of existing lineaments, such
526 as the Antimony Line, further geochronology of potential igneous rocks from this time interval

are necessary to progress a more detailed understanding of the “cryptic” ~1970 Ma event discussed herein.

The nature of the ~1970 Ma event is currently poorly characterised. The petrography of the titanite in the Baderoukwe Granite indicates low temperature hydrothermal alteration producing saussuritisation in plagioclase, and a biotite-muscovite-chlorite-epidote-titanite alteration assemblage (Jaguin et al., 2013). At Malati Pump, the two generations of monazite occur in the same thin sections of one hand sample, and their mineral association at this scale is the same. The ~1970 Ma event observed at Malati Pump and the Baderoukwe Granite were probably focussed along the Antimony Line, with reworking of the pre-existing Sb-Au ore and accompanied by new monazite growth. The Jaguin et al. (2013) ore sample from Malati Pump did not contain any ~1970 Ma monazites, at least at the scale of analysis, whereas sample M10 contained monazites of this age as the dominant population, and pyrite. This suggests the ~1970 Ma hydrothermal activity and overprint was probably localised and will require a more detailed study at the orebody scale to understand the significance of this overprint, including whether it enhanced or reduced the ore grade.

A potential source of Witwatersrand gold?

Our data suggest that Murchison antimony-gold mineralisation was at ~ 2832 Ma, before the well-established global Neo-Archaean gold event (Bierlein et al., 2006). This makes the Murchison Belt rare as one of the world’s goldfields with gold known to be introduced prior to the Neo-Archaean event at 2650 ± 50 Ma.

Both Vearncombe (1992) and Poujol et al. (1996, 1997) have suggested the Murchison Belt as a possible source of gold for the Witwatersrand Basin. Kositcin & Krapez (2004) suggest that the Murchison lies outside the palaeo-current reconstructed source area but may be a model of

the source terrain of Witwatersrand detritus in an arc around the northwest of the Witwatersrand basin. This remains a possibility based on the age data presented here. However, an interpretation of gold source in the Witwatersrand is entirely dependent on the conceptual model for controls on Witwatersrand mineralisation as a modified syngenetic placer (Frimmel & Minter, 2002; Frimmel et al., 2005; McCarthy, 2006) or as later structure- and rheology-controlled hydrothermal deposits (Jolley et al. 2004; Phillips & Powell 2015). The Witwatersrand has produced about 30% of the world's gold, from strata-parallel reefs. The Witwatersrand includes more gold than all the world's combined greenstone belts. Economic factors in favour of the Witwatersrand are their high-tonnage, high gold-grade and the remarkable lateral continuity of the ores over hundreds to thousands of metres. This lateral continuity is absent in all recent placers globally where meso-scale variations in grade in placers are controlled by subtle meanders in river systems or marine processes in coastal environments (Becker & Batt, 2016; Phillips & Sumpter, 1990; Stanaway, 2012). In the Witwatersrand grade continuity is such that major mines have been opened on less than ten drill holes.

The Witwatersrand Basin is dated between 3074 and 2714, possibly 2790 Ma and the upper gold-bearing Central Rand Group 2910 to 2780 Ma (Armstrong et al., 1991; Gumsley et al., 2019; Kositsin et al., 2003; Kositsin & Krapez, 2004). The detrital and post-depositional age constraints for the Central Rand Group are summarised in Figure 12. In the central part of the Group (Booyens-Krugersdorp-Luipaardsvlei Formations), the age is best constrained as between the youngest detrital xenotime grains (2815 ± 6 Ma; $n=5$; $MSWD=0.54$: calculated from data in Kositsin & Krapez, 2004) and the post-depositional xenotime age of 2778 ± 3 Ma ($n=8$: Kositsin et al., 2003). This 2815-2778 Ma age bracket for sediment deposition for this part of the Central Rand Group overlaps, the 2832 ± 23 Ma age for Malati Pump mineralisation. This age window is further reduced to ~ 2790 to 2815 Ma if the recent baddeleyite ages for

mafic sills into the Witwatersrand Supergroup below the Central Rand Group are accepted to be feeders to the lower Ventersdorp Supergroup, immediately above the Central Rand Group (Gumsley et al., 2020). The age constraints are compatible with both a modified syngenetic placer model with gold derived from the Murchison Belt, or later hydrothermal gold mineralisation in the Central Rand Group, from an undefined source. The Murchison Belt remains a theoretic possibility as a source of detrital gold. However, known mineralisation in the Murchison Belt, whilst atypical for its antimony-mercury association, is at grades and tonnages no different to most Archaean belts globally. The Murchison Belt itself is trivial in gold content compared to the Witwatersrand. On the data available, the eroded material from the Murchison Belt post-Sb-Au mineralisation is age-compatible, but unlikely to contain enough gold to be a detrital source for Witwatersrand gold.

Figure 12 *Central Rand Group stratigraphic column with available age constraints for the maximum sediment deposition imposed from the ages of detrital zircon (circle plus error bar) and xenotime (open square plus error bar), and post-depositional xenotime growth (filled square plus error bar). Data from Kositcin et al., 2003; Kositcin & Krapez, 2004.*

Conclusions

The 2980 to 2960 Ma Murchison Belt is an exhumed Archaean island arc sequence with a basal layered meta-igneous complex with Ti-V-bearing magnetites, overlying calc-alkaline volcanic rocks with VMS, and a mafic-ultramafic volcanic sequence and clastic sediments with orogenic gold-antimony. It lies along a cratonic sub-terrain boundary but is not a suture with ophiolites, ocean crust being absent in the belt. Formation, deformation, granitoid intrusion and mineralisation all occurred prior to Limpopo Orogeny to the north at 2672 to 2620 Ma.

Geochronology of the Malati Pump Sb-Au deposit suggests that Murchison Sb-Au mineralisation formed at ~2832 Ma. This makes the Murchison Belt rare as one of the world's few goldfields with gold known to be introduced prior to the global event at ~2650 Ma. Murchison antimony-gold mineralisation is hydrothermal, structurally controlled and post-dates belt formation by >100 Ma. Gold mineralisation in the Murchison Belt remains a theoretical possibility as a source conduit of gold for the younger Witwatersrand Basin (Central Rand Group), whether transported as detrital gold or by an undefined hydrothermal process.

A cryptic thermal event at ~1970 Ma is recorded at Malati Pump and in the Baderoukwe Granite along an extension of the Antimony Line. Hydrothermal alteration includes new monazite growth in the Sb-Au ore sample and probable goethite replacement of pyrite in the same sample, indicating localised hydrothermal fluid activity.

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Table 1

Formation	Locality	Location easting	Location northing	Sample ID	Age Ma	Error Ma 2σ	Category	Method	Comment(s)	Abbreviated Reference
Northern Granitoids										
Eden Granitoid	Eden Farmstead			S2	2646	+/-80	unreliable	Rb-Sr whole rock isochron	Original: hydrothermal alteration. Here: probably un-reliable	Vearncombe (1987)
Duiwelskloof Batholith	Locality >10km north of Murchison on map in publication			DWK 06	2776	+/- 10	primary	LA-ICPMS U-Pb zircon	Crystallisation age	Laurent (2013)
Groot Letaba gneiss	South of Giyani	30°42'95.8"E	23°29'11.7"S	GB1	2784	+/-8	primary	LA-ICPMS U-Pb zircon	Crystallisation age	Zeh (2009)
Groot Letaba gneiss	c. 10km E Tzaneen	30°14'20.0"E	23°48'18.3"S	MB4	2839	+/-8	primary	LA-ICPMS U-Pb zircon	Crystallisation age	Zeh et al., 2009
Duiwelskloof Batholith	Locality north of Murchison on map in publication			DWK 01	2841	+/- 10	primary	LA-ICPMS U-Pb zircon	Crystallisation age	Laurent (2013)
Duiwelskloof Batholith	Locality >10km north of Murchison on map in publication			DWK 04	2866	+/- 31	metamorphism	LA-ICPMS U-Pb zircon	Re-setting during younger magmatic events	Laurent (2013)
Granitoid dyke	Thiergarten, near game lodge	23°51'30.4"S	23°51'30.4"S	MO3	2929	+/- 7	primary	U-Pb SHRIMP zircon	Magmatic age of granitoid that is an intrusion into Rooiwater hence a minimum age for Rooiwater	this paper
Duiwelskloof Batholith	Locality north of Murchison on map in publication			DWK 01	2936	+/- 21	xenocryst	LA-ICPMS U-Pb zircon	Inherited age	Laurent (2013)
Duiwelskloof Batholith	Locality >10km north of Murchison on map in publication			DWK 04	2941	+/- 13	primary	LA-ICPMS U-Pb zircon	Crystallisation age	Laurent (2013)
Granitoid dyke Intrusive into Silwana's amphibolite	Letaba Shear zone; multiple whole rock samples across the mapped unit, see reference			0982	2964	+/-5	primary	LA-ICPMS U-Pb zircon	Syn-tectonic granitoid emplacement, provides minimum age for the Silwana's amphibolite	Block (2013)
Duiwelskloof Batholith	Locality >10km north of Murchison on map in publication			DWK 06	2983	+/- 44	xenocryst	LA-ICPMS U-Pb zircon	Inherited age	Laurent (2013)

* samples with precursor MUR or MURCH identifier omitted

Formation	Locality	Location easting	Location northing	Sample ID	Age Ma	Error Ma	Category	Method	Comment(s)	Reference
Duiwelskloof Batholith	Locality north of Murchison on map in publication			DWK 01	3119	+/- 44	xenocryst	LA-ICPMS U-Pb zircon	Inherited age	Laurent (2013)
Duiwelskloof Batholith	Locality north of Murchison on map in publication			DWK 01	3124	+/- 45	xenocryst	LA-ICPMS U-Pb zircon	Inherited age	Laurent (2013)
Duiwelskloof Batholith	Locality >10km north of Murchison on map in publication			DWK 06	3126	+/- 41	xenocryst	LA-ICPMS U-Pb zircon	Inherited age	Laurent (2013)
Granitoid dyke (post Rooiwater)	Thiergarten, near game lodge	23°51'30.4"S	23°51'30.4"S	MO3	3148	+/- 6	xenocryst	SHRIMP U-Pb zircon	Xenocryst in syn-tectonic granitoid	this paper
Groot Letaba gneiss	Half-way between Giyani and Murchison belts			T9	3171	+/- 6	primary	Single zircon Pb/Pb evaporation	Interpreted by Brandl and Kroner to show gneiss as younger than the Murchison belt; this interpretation is equivocal	Brandl, Kroner (1993)
Xenocryst in above Granitoid dyke intrusive into Silwana's amphibolite	Letaba Shear zone; multiple whole rock samples across the mapped unit, see reference			0982	3251	+/-18	xenocryst	LA-ICPMS U-Pb zircon	Xenocryst in above	Block (2013)

* samples with precursor MUR or MURCH identifier omitted

Formation	Locality	Location easting	Location northing	Sample ID	Age Ma	Error Ma	Category	Method	Comment(s)	Reference
Rooiwater Complex										
Gabbro and anorthosite of Novengilla series	Multiple whole rock samples across the mapped unit, see reference			S4	2490	+/- 80	unreliable	87Sr/86Sr vs 87Rb/86Sr	Original: hydrothermal alteration. Here: probably unreliable	Vearncombe (1987)
Free State Hornblende Granite	Multiple whole rock samples across the mapped unit, see reference			S5	2544	+29/-31	unreliable	U-Pb whole rock isochron	Original: hydrothermal alteration. Here: probably unreliable	Vearncombe (1987)
Gabbro and anorthosite of Novengilla series	Multiple whole rock samples across the mapped unit, see reference			S6	2610	not given	unreliable	U-Pb whole rock isochron	Original: hydrothermal alteration. Here: probably unreliable	Vearncombe (1987)
Rooiwater Complex gabbro	SE Tzaneen	30°15'21.7"E	23°59'19.5"S	MB3	2611	+/-10	unreliable	LA-ICPMS U-Pb zircon	Conflicted age see discussion	Zeh (2009)
Rooiwater Complex (Hornblende Tonalite)	Western Free State Suite	30°22'20.34"E	23°56'52.45"S	94-6	2740	+/- 4	recrystallised	ID-TIMS U-Pb zircon	? Partially re-crystallised or fractured (Zeh et al., 2013)	Poujol (1996, 1997)
Free State (Tonalite)		30°22'20.34"E	23°56'52.45"S	94-6	2795	+/-25; range between 2992 and 2200	recrystallised	LA-ICPMS U-Pb zircon	Re-crystallised and strongly fractured zircons	Zeh (2013)
Free State Hornblende Granite dykes	Locality H on map in Vearncombe et al., 1987	30°39.3E	23°52.7'S	GJ1019	2961	+/- 75	unreliable	U-Pb age, no detail	A minimum age (Vearncombe, 1988), but analytical problems described by Ed Retief reported in Vearncombe et al. 1987. Despite these caveats and large error, this age is stunningly close to that now regarded as Rooiwater emplacement.	Burger, Walraven (1979)
Free State Hornblende Granite		30°22'20.34"E	23°56'52.45"S	94-6	2965	+/-6	primary	LA-ICPMS U-Pb zircon	Pristine zircons	Zeh (2013)

* samples with precursor MUR or MURCH identifier omitted

Formation	Locality	Location easting	Location northing	Sample ID	Age Ma	Error Ma	Category	Method	Comment(s)	Reference
Rubbervale Formation										
Quartz porphyry Rubbervale Formation	Multiple whole rock samples across the mapped unit, see reference			S8	2837	+/- 25	unreliable	87Sr/86Sr vs 87Rb/86Sr	Original: hydrothermal alteration. Here: probably unreliable	Vearncombe (1987)
Quartz porphyry Rubbervale Formation	Multiple whole rock samples across the mapped unit, see reference			S9	2953	+29 / -38	unreliable	207Pb/204Pb vs 206Pb/204Pb	Within error range of subsequent reliable results	Vearncombe (1987)
Felsic volcanic rocks in vicinity of VMS mineralisation Rubbervale Formation	Ka Phokwe, Letaba, Mulati, Maranda J, Romotshidi, Mashawa, multiple whole rock samples across the mapped unit, see reference			61 zircons dates yield close cluster in range	2960 to 2977	+1.4	primary	Pb/Pb evaporation on generally prismatic zircons	Extensive study of 61 zircons from 7 sites, volcanic eruption and synchronous VMS activity	Schwarz-Schampera (2010)
Quartz porphyry, rhyolite, Rubbervale	Road cut S of Rubbervale rail station, our GPS record of this location given right	30°34'30.8"	23°57'27.1"	TR61	2966	+/- 1.6	primary	Zircon Pb/Pb evaporation; 2 grains	First precise age on felsic unit, and a maximum age for the Rooiwater Complex intrusive into the Rubbervale	Brandl (1996)
Quartz porphyry Rubbervale Formation		30°32'50.8"E	23°55'10.1"S	Rub1	2966	+/-7	primary	LA-ICPMS U-Pb zircon	Intrusion	Zeh (2013)
Dacite - Rubbervale Formation	2km north of Weigel Shaft on road to Beacon Ranch			95-18	2969	+/- 20	primary	ID-TIMS U-Pb zircon	Emplacement	Poujol (2001)
Rhyolite - Rubbervale Formation	Western Rubbervale; multiple zircons in sample, location given on map in reference			94-3	2971	+/- 10	primary	ID-TIMS U-Pb zircon	Crystallisation	Poujol (1996, 1997)
Quartz porphyry Rubbervale Formation		30°32'03.3"E	23°57'02.7"S	Rub2	2972	+/- 7	primary	LA-ICPMS U-Pb zircon	Intrusion	Zeh (2013)

* samples with precursor MUR or MURCH identifier omitted

Formation	Locality	Location easting	Location northing	Sample ID	Age Ma	Error Ma	Category	Method	Comment(s)	Reference
Central Murchison Suite										
Mulati Formation, garnet-quartz schist	Map in reference	30°57'09.69"E	23°48'53.49"S	Mur	2979	+/- 7	detrital	LA-ICPMS U-Pb zircon	Youngest igneous detrital grain; several older clusters of ages of detrital zircons	Zeh (2013)
Central Murchison Suite	Old gold working central			S10	3020	+/- 50	recrystallised	Model Pb/Pb age galena, no detail		Saager, Koppel (1976)
Mackop Conglomerate	MacKop Eastern Murchison			S11	3074		detrital	ID-TIMS U-Pb zircon	Deposition after this date	Poujol (2001)
Mackop Conglomerate	MacKop Eastern Murchison			94-9	3076	+/-4	detrital	ID-TIMS U-Pb zircon	Youngest detrital grain; several older clusters of ages of detrital zircons	Poujol (1996, 1997)
Weigel Formation felsic volcanic	Near Gravelotte, locations on map, see reference			95-15, 16, 17	3087	+/-21	detrital and/or volcanism	ID-TIMS U-Pb zircon	Mean age, best estimate of volcanism	Poujol (1996, 1997)
Mulati Formation, garnet-quartz schist	Map in reference	30°57'09.69"E	23°48'53.49"S	Mur	3090 to 3050		detrital	LA-ICPMS U-Pb zircon	Cluster of ages on detrital zircons	Zeh (2013)
Mulati Formation, garnet-quartz schist	Map in reference	30°57'09.69"E	23°48'53.49"S	Mur	3130		detrital	LA-ICPMS U-Pb zircon	Cluster of ages on detrital zircons	Zeh (2013)
Mackop Conglomerate	MacKop Eastern Murchison			94-9	3186	+/-11	detrital	ID-TIMS U-Pb zircon	Detrital zircon population; deposition younger than this age	Poujol (1996)
Weigel Formation felsic volcanic	Near Gravelotte, locations on map, see reference			95-16c	3196	+/-28	detrital	ID-TIMS U-Pb zircon	Oldest zircon grain: deposition was younger	Poujol (1996)
Mulati Formation, garnet-quartz schist	Map in reference	30°57'09.69"E	23°48'53.49"S	Mur	3290 to 3200		detrital	LA-ICPMS U-Pb zircon	Cluster of ages on detrital zircons	Zeh (2013)
Mackop Conglomerate	MacKop Eastern Murchison			94-9	3364	+/-18	detrital	ID-TIMS U-Pb zircon	Oldest detrital grains	Poujol (1996)
Mulati Formation, garnet-quartz schist	Map in reference	30°57'09.69"E	23°48'53.49"S	Mur	3370 to 3300		detrital	LA-ICPMS U-Pb zircon	Cluster of ages on detrital zircons	Zeh (2013)
Mulati Formation, garnet-quartz schist	Map in reference	30°57'09.69"E	23°48'53.49"S	Mur	3450 to 3410		detrital	LA-ICPMS U-Pb zircon	Cluster of ages on detrital zircons	Zeh (2013)
Mulati Formation, garnet-quartz schist	Map in reference	30°57'09.69"E	23°48'53.49"S	Mur	3530 to 3510		detrital	LA-ICPMS U-Pb zircon	Cluster of ages on detrital zircons	Zeh (2013)

* samples with precursor MUR or MURCH identifier omitted

Formation	Locality	Location easting	Location northing	Sample ID	Age Ma	Error Ma	Category	Method	Comment(s)	Reference
Within-belt granitoids										
Baderoukwe granite	Coarse-grained biotite granitoid	30°59'44.5"E	23°45'30.8"S	09-5a	1936	+/- 41	recrystallised	LA-ICPMS U-Pb titanite	Growth in response to circulation of a metamorphic fluid	Jaguin (2013)
Malati Pump mine Granitoid	Albitic granitoid plug being mined for gold	30°46'34.5"E	23°51'53.2"S	M10	1968	+/- 17	recrystallised	SHRIMP U-Pb on monazites with mineralisation	Only possible matching geological event is Proterozoic dykes swarm	this paper
Maranda Granitoid				S12	2617	+188 / - 216	unreliable	Rb-Sr whole rock	Intrusion into Antimony Line	Barton unpublished
Albitites	Unclear but probably Malati Pump, Monarch and Gravelotte mines			09-89	2784	+/- 21	recrystallised	LA-ICPMS U-Pb monazite	Main albitisation at ~2800Ma in response to circulating fluid, but with almost continuous record of events to <2000Ma	Jaguin (2013)
Slightly deformed albitite	Gravelotte mine drill core			09-92	2793	+/- 24	recrystallised	LA-ICPMS U-Pb monazite		Jaguin (2013)
Malati Pump mine Granitoid	Albitic granitoid plug being mined for gold	30°46'34.5"E	23°51'53.2"S	M10	2832	+/- 23	mineralisation	SHRIMP U-Pb monazites associated with mineralisation	Mineralisation	this paper
Maranda Granitoid	Map in reference			94-12	2901	+/- 20	recrystallised	ID-TIMS U-Pb zircon	Intrusion into western end of Antimony Line giving a minimum age of emplacement	Poujol (1996, 1997)
Maranda albitite	Plug	30°42'50.5"E	23°53'7.7"S	09-54	no age			LA-ICPMS U-Pb zircon	No meaningful age	Jaguin (2013)
Silicified albitite	Plug	30°36'28.7"E	23°56'23.1"S	09-41	2922	+/- 8	recrystallised	LA-ICPMS U-Pb zircon	Intrusion into Antimony Line, possibly a second magmatic event	Jaguin (2013)
Slightly deformed albitite	Gravelotte mine drill core			09-92	2944	+/- 42	recrystallised	LA-ICPMS U-Pb zircon		Jaguin (2013)
Malati Pump Granitoid	Gold mine	30°36'19.2"E	23°51'31.7"S	09-13, 111, 89A, 89B, 89C, 89D	2964	+/- 7	recrystallised	LA-ICPMS U-Pb zircon	Intrusion into Antimony Line that is, at time of writing, being mined for gold	Jaguin (2012b)

* samples with precursor MUR or MURCH identifier omitted

Formation	Locality	Location easting	Location northing	Sample ID	Age Ma	Error Ma	Category	Method	Comment(s)	Reference
Malati Pump mine Granitoid	Detail locations in reference	30°36'19.2"E	23°51'31.7"S	09-5 & 09-82	2967	+/- 48	mineralisation	Model Pb/Pb age pyrite	Age of mineralisation	Jaguin (2012b)
Malati Pump (Granodiorite)	Old working east of Monarch mine			94-11	2970	+/- 15	primary	ID-TIMS U-Pb zircon	Intrusion and crystallisation of granitoid	Poujol (1997)
Baderoukwe granite	Eastern belt toward Kruger Park; this is the largest within belt granitoid, see detail on locations in Jaguin et al. 2013	30°59'44.5"E	23°45'30.8"S	09-5 & 09-82	2970.4 also 2966.2	+/- 6.9, +/- 2.9	primary	LA-ICPMS U-Pb zircon	Intrusion and crystallisation of granitoid	Jaguin (2012b)
Malati Pump Granodiorite	Old working east of Monarch mine			Eleven samples	2979	+/- 25	unreliable	Pb/Pb isochron age (from pyrites)	oxidised, possible date of mineralisation	Poujol (1997)
Baderoukwe granitoid	1km north of Inyathi			94-10	3018	+/- 12	primary	ID-TIMS U-Pb zircon	Minimum estimate of emplacement	Poujol (2001)
Silicified albitite	Near Gravelotte mine	30°36'28.7"E	23°56'23.1"S	09-41	3051	+/- 25	unreliable	LA-ICPMS U-Pb zircon	Upper intercept age	Jaguin (2013)

La France Formation

La France meta-pelites	Map in reference			B	2752	+/- 7	recrystallised	LA-ICPMS U-Th-Pb monazite and xenotime	Partial alteration and resetting	Block (2013)
La France meta-pelites	Map in reference			B	2906	+/- 26	recrystallised	LA-ICPMS U-Th-Pb monazite and xenotime	Monazite inclusions in kyanite formed at 2923 Ma or before metamorphism	Block (2013)
La France meta-pelites	Map in reference			B	2923	+/- 11	metamorphism	LA-ICPMS U-Th-Pb monazite and xenotime	Minimum age of metamorphism	Block (2013)
Quartzite schist with kyanite	Map in reference	30°41'49.16"E	23°56'29.62"S	LF	2986	+/-12	detrital	LA-ICPMS U-Pb zircon	Youngest igneous detrital grain; several older clusters of ages of detrital zircons	Zeh (2013)
Quartzite schist with kyanite	Map in reference	30°41'49.16"E	23°56'29.62"S	LF	3020		detrital	LA-ICPMS U-Pb zircon	Cluster of ages on detrital zircons	Zeh (2013)
Quartzite schist with kyanite	Map in reference	30°41'49.16"E	23°56'29.62"S	LF	3140		detrital	LA-ICPMS U-Pb zircon	Cluster of ages on detrital zircons	Zeh (2013)
Quartzite schist with kyanite	Map in reference	30°41'49.16"E	23°56'29.62"S	LF	3280		detrital	LA-ICPMS U-Pb zircon	Cluster of ages on detrital zircons	Zeh (2013)
Quartzite schist with kyanite	Map in reference	30°41'49.16"E	23°56'29.62"S	LF	3480		detrital	LA-ICPMS U-Pb zircon	Cluster of ages on detrital zircons	Zeh (2013)

* samples with precursor MUR or MURCH identifier omitted

Formation	Locality	Location easting	Location northing	Sample ID	Age Ma	Error Ma	Category	Method	Comment(s)	Reference
Southern Granitoids										
Mashishimale	Mica area	30°50.7'E	24°06.1'S	GJ1012	2554	+/- 65	unreliable	U-Pb no detail given		Burger, (1979) Walraven
Mashishimale (Lily Granitoid)	Mica area	30°51.3'E	24°03.7'S	GJ1049	2622	+/- 65	unreliable	U-Pb no detail given		Burger, (1979) Walraven
Mashishimale Suite (Peraluminous granitoid)	Map in reference			94-8	2677	+/- 14	primary	ID-TIMS U-Pb zircon	Emplacement age	Poujol (1997)
Lekkersmaak peraluminous granitoid	La Parisa	30°34.5'E	23°29.5'S	GB240	2690	+/-65	unreliable	U-Pb no detail given		Burger, (1979) Walraven
Discovery Granitoid	Cobra North and Discovery (Gravelotte) emerald mines			ten samples	2690	+/- 35	unreliable	Pb/Pb isochron age (from pyrites)	No geological meaning	Poujol (1997)
Lekkersmaak peraluminous granitoid	Granitoid with xenoliths greenstone and zircon xenocrysts	30°51'68.6"E	23°55'12.5"S	MB1	2795	+/-8	primary	LA-ICPMS U-Pb zircon	Crystallisation age	Zeh (2009)
Mashishimale peraluminous granitoid	Road Gravelotte to Mica	30°48'69.0"E	24°04'10.5"S	MB2	2671	+/-8	primary	LA-ICPMS U-Pb zircon	Crystallisation age	Zeh (2009)
Willie peraluminous granitoid	Granitoid with greenstone xenoliths			94-14	2820	+/- 38	primary	ID-TIMS U-Pb zircon	Minimum age for emplacement	Poujol (1997)
Makhustwi pegmatite	8 km south of Mica township on road to Hoedspruit, same locality as 95-21			95-20	2848	+/- 58	primary	ID-TIMS U-Pb multiple zircons in sample	Minimum estimate of intrusion of pegmatite into granitoid	Poujol, Robb (1999)
Discovery Granitoid	Cobra North Gravelotte emerald mine			94-13	2960	+/- 43	primary	ID-TIMS U-Pb zircon	Intrusion and crystallisation	Poujol (1997)
Discovery Granitoid	Cobra North Gravelotte emerald mine			94-13	2969	+/- 14	primary	ID-TIMS U-Pb zircon	Intrusion and crystallisation	Poujol (2001)
Makhustwi tonalite gneiss	8 km south of Mica township on road to Hoedspruit; multiple zircons in sample, location given on map in reference			95-21	3063	+/- 12	primary	ID-TIMS U-Pb zircon	Emplacement of tonalitic gneiss protolith	Poujol, Robb (1999)
Harmony trondhjemitic gneiss	20km south of Gravelotte on Tzaneen to Lydenburg road; multiple zircons in sample, location given on map in reference			94-7	3091	+/- 5	primary	ID-TIMS U-Pb zircon	Crystallisation	Poujol, Robb (1999)

* samples with precursor MUR or MURCH identifier omitted

Formation	Locality	Location easting	Location northing	Sample ID	Age Ma	Error Ma	Category	Method	Comment(s)	Reference
Makhutswi Gneiss	South of Murchison Greenstone belt			T6, T7, T8	3112 to 3078	+/- 5 +/- 6	primary	Pb-Pb single zircon evaporation	Interpreted by Brandl and Kroner to give a minimum age for the Murchison belt; this interpretation is equivocal	Brandl, Kroner (1993)
French Bobs trondhjemite-tonalite gneiss	See reference, near French Bobs mine			94-5	3228	+/- 12	primary	ID-TIMS U-Pb zircon	Crystallisation age of older basement	Poujol (1997)

* samples with precursor MUR or MURCH identifier omitted

Table 2

Grain-spot	U (ppm)	Th (ppm)	²³² Th / ²³⁸ U	f ₂₀₆ (%)	²⁰⁷ Pb*/ ²⁰⁶ Pb*	% err	²⁰⁷ Pb*/ ²³⁵ U	% err	²⁰⁶ Pb*/ ²³⁸ U	% err	err corr	²⁰⁶ Pb / ²³⁸ U Age (Ma)	1σ err	²⁰⁷ Pb / ²⁰⁶ Pb Age (Ma)	1σ err	% Disc.
Xenocrysts																
5-1.core	209	64	0.32	0.03	0.245	0.38	21.2	1.3	0.629	1.3	0.96	3147	31	3152	6	+0
12-2.core	254	99	0.40	0.05	0.245	0.60	19.4	1.4	0.575	1.2	0.90	2930	29	3151	9	+9
12-1.core	276	133	0.50	0.10	0.244	0.35	20.2	1.3	0.601	1.2	0.96	3032	29	3149	6	+5
5-2.core	303	39	0.13	0.11	0.244	0.32	19.8	1.2	0.591	1.2	0.96	2993	28	3144	5	+6
20-1.core	92	22	0.25	0.18	0.239	0.98	20.2	1.8	0.613	1.5	0.84	3082	38	3111	16	+1
Main group																
11-1.core	122	36	0.30	0.14	0.218	0.59	16.8	1.5	0.558	1.4	0.92	2860	33	2969	10	+5
14-1.core	167	46	0.28	0.05	0.216	0.50	17.0	1.4	0.569	1.3	0.94	2906	31	2953	8	+2
10-1.rim	80	18	0.24	0.00	0.215	0.69	16.5	1.7	0.556	1.6	0.92	2852	37	2944	11	+4
21-1.core	104	33	0.33	0.07	0.215	0.60	17.3	1.6	0.584	1.5	0.92	2963	35	2941	10	-1
24-1.core	33	15	0.47	0.27	0.214	1.29	16.6	2.6	0.562	2.3	0.87	2875	53	2940	21	+3
13-2.core	96	14	0.15	0.18	0.214	0.69	15.7	1.7	0.532	1.5	0.91	2751	34	2936	11	+8
6-1.core	111	24	0.22	0.15	0.213	0.62	16.3	1.6	0.556	1.5	0.92	2851	34	2927	10	+3
8-1.core	70	8	0.12	0.26	0.213	1.38	16.7	2.2	0.569	1.7	0.77	2903	39	2925	22	+1
4-1.rim	162	57	0.37	0.00	0.212	0.82	16.2	1.5	0.554	1.3	0.85	2842	30	2919	13	+3
16-1.core	146	49	0.34	0.13	0.209	0.89	16.1	1.6	0.559	1.4	0.84	2861	32	2899	14	+2
Discordant																
15-1.rim	64	29	0.47	0.17	0.215	0.89	14.4	1.9	0.487	1.7	0.89	2556	36	2942	14	+16
9-1.rim	204	92	0.46	0.28	0.212	0.60	14.2	1.5	0.484	1.3	0.91	2545	28	2924	10	+16
1-1.rim	94	26	0.28	0.53	0.211	0.81	14.8	1.7	0.507	1.5	0.88	2642	33	2916	13	+11
2-1.core	60	19	0.32	0.53	0.211	0.98	14.9	2.0	0.510	1.7	0.87	2658	37	2914	16	+11
1-2.rim	61	15	0.25	0.85	0.206	1.15	12.7	2.0	0.448	1.7	0.83	2387	34	2873	19	+20

Footnotes

f₂₀₆ (%) = % of ²⁰⁶Pb attributed to common PbPb* = radiogenic Pb, corrected for common Pb using ²⁰⁴Pb

All errors are 1σ

err corr = error correlation

Disc. = discordance

Table 3.

Mount- plug- grain- spot	U (ppm)	Th (ppm)	$\frac{\text{Th}}{\text{U}}$	f206 (%)	$\frac{^{207}\text{Pb}^*}{^{206}\text{Pb}^*}$	± 1sd	$\frac{^{206}\text{Pb}^*}{^{238}\text{U}}$	± 1sd	$\frac{^{207}\text{Pb}^*}{^{235}\text{U}}$	± 1sd	% Disc.	$\frac{^{207}\text{Pb}^*}{^{206}\text{Pb}^*}$ Age (Ma)	± 1sd	$\frac{^{206}\text{Pb}^*}{^{238}\text{U}}$ Age (Ma)	± 1sd
Near concordant															
M10A.D.2-1	173	11685	68	0.15	0.2023	0.0024	0.567	0.013	15.81	0.40	-2	2845	19	2895	52
M10A.F.3-1	115	9811	85	0.13	0.2016	0.0025	0.552	0.009	15.33	0.31	0	2839	20	2832	36
M10A.F.1-1	352	12356	35	0.53	0.1979	0.0026	0.589	0.010	16.06	0.34	-6	2809	21	2984	40
M10A.C.1-1	168	9734	58	0.18	0.1950	0.0024	0.544	0.012	14.632	0.36	-1	2785	20	2801	49
M10A.D.3-1	72	10682	149	0.19	0.1949	0.0027	0.528	0.009	14.18	0.32	2	2784	23	2731	38
M10A.F.2-1	94	11431	122	0.56	0.1900	0.0037	0.551	0.017	14.43	0.52	-3	2742	32	2828	69
M10A.F.4-1	71	13124	184	0.12	0.1882	0.0027	0.528	0.009	13.70	0.31	0	2726	24	2734	39
M10A.D.1-1	43	9131	211	0.15	0.1799	0.0030	0.504	0.013	12.50	0.38	1	2652	28	2631	55
M10A.B.2-1	84	16408	196	0.97	0.1619	0.0040	0.449	0.008	10.02	0.30	3	2476	42	2391	34
M10A.I.3-1	57	14298	249	0.89	0.1232	0.0033	0.375	0.010	6.36	0.24	-2	2003	47	2051	47
M10A.A.2-1	87	4404	51	0.00	0.1229	0.0019	0.386	0.006	6.53	0.15	-5	1998	28	2103	30
M10A.A.1-1	154	271	2	0.06	0.1224	0.0017	0.384	0.008	6.48	0.16	-5	1991	24	2096	37
M10A.B.1-1	118	2317	20	0.12	0.1218	0.0019	0.376	0.007	6.32	0.15	-4	1983	27	2058	32
M10A.B.1-2	97	815	8	0.08	0.1215	0.0019	0.379	0.006	6.34	0.14	-5	1978	28	2071	29
M10A.I.2-1	132	2756	21	0.07	0.1213	0.0018	0.382	0.006	6.39	0.14	-6	1976	26	2087	28
M10A.B.3-1	91	3500	38	0.07	0.1206	0.0019	0.380	0.009	6.32	0.18	-6	1965	29	2076	42
M10A.G.1-1	80	4739	59	0.10	0.1202	0.0020	0.382	0.008	6.33	0.18	-6	1959	30	2085	39
M10A.E.1-1	148	1271	9	0.44	0.1193	0.0020	0.382	0.008	6.29	0.16	-7	1946	30	2088	35
M10A.I.1-1	57	1161	20	0.12	0.1171	0.0022	0.366	0.009	5.92	0.18	-5	1913	34	2012	40
M10A.A.2-2	115	20009	174	0.58	0.1160	0.0023	0.349	0.006	5.58	0.14	-2	1896	35	1928	27
Discordant															
M10A.G.1-2	37	7661	210	3.03	0.1076	0.0072	0.345	0.008	5.12	0.35	-9	1759	122	1912	36
M10A.D.3-2	73	5189	71	17.99	0.1063	0.0344	0.419	0.017	6.14	1.94	-30	1737	593	2255	75

Table 4

Mount-plug-grain-spot Disc. <25%	U ppm	Th ppm	Th/U	% com ²⁰⁶ Pb	²⁰⁷ Pb* / ²⁰⁶ Pb*	1σ % error	²⁰⁷ Pb* / ²³⁵ U	1σ % error	²⁰⁶ Pb* / ²³⁸ U	1σ % error	Error correl.	²⁰⁷ Pb* / ²⁰⁶ Pb* Age (Ma)	1σ error (Ma)	% Disc
N19-03.A.4-1	5.5	1.1	0.2	8.77	0.14	11	7.2	12	0.377	4.9	0.41	2222	191	9
N19-03.A.5-1	9.2	1.7	0.19	9.46	0.174	6	10	7	0.419	2.3	0.34	2598	104	16
N19-03.A.11-2	6.2	3.9	0.64	10.31	0.18	14	10.3	15	0.415	5.7	0.38	2657	230	19
N19-03.A.11-1	3.4	2.5	0.74	11.37	0.142	22	7.5	23	0.384	4.7	0.21	2251	384	8
N19-02.9-1	4.3	2.5	0.59	12.37	0.18	13	12.2	14	0.492	4	0.29	2651	222	3
N19-03.A.8-1	5.8	2.2	0.4	14.17	0.169	15	9.4	16	0.404	3.2	0.21	2550	257	17
N19-03.A.11-3	3.6	8	2.31	14.42	0.197	16	15.5	16	0.572	3.4	0.21	2802	257	-5
N19-02.5-1	5.8	4.2	0.76	14.92	0.156	17	10.4	18	0.484	5	0.28	2408	288	-7
N19-03.B.2-1	8.2	10.6	1.33	15.94	0.21	8	14	9	0.482	4.3	0.49	2906	124	15
N19-03.A.3-1	4.3	4.9	1.17	18.5	0.222	20	14.6	21	0.475	5.1	0.25	2996	320	20
N19-03.A.5-2	2.9	2.3	0.82	18.91	0.192	27	12.4	27	0.468	4.6	0.17	2760	445	12
N19-03.A.6-1	3.3	1.2	0.37	19.6	0.156	16	10.4	19	0.483	8.9	0.47	2408	280	-7
N19-02.6-1	2.5	1.8	0.74	19.88	0.178	35	10	37	0.406	10.7	0.29	2633	584	19
N19-02.7-1	6.5	5.9	0.94	20.6	0.156	15	9	16	0.422	4.9	0.31	2408	257	7
N19-03.A.7-1	11.4	11.9	1.08	20.83	0.179	12	12.6	12	0.511	3.7	0.29	2646	197	-1
N19-03.A.1-1	3.5	1.3	0.38	23.69	0.143	45	9.4	46	0.477	6	0.13	2268	779	-13
N19-02.10-1	6.8	5.9	0.91	25.98	0.169	14	10.4	14	0.446	3.4	0.23	2549	236	8
N19-03.A.9-1	8	5.8	0.75	29.97	0.223	18	18.3	19	0.595	6.1	0.33	3005	284	0
N19-03.A.9-2	7.2	6.5	0.92	31.39	0.269	16	21.1	17	0.571	5.5	0.33	3298	247	15
N19-03.A.2-1	3.9	5	1.32	33.29	0.265	16	29.9	17	0.819	4.7	0.28	3276	252	-24
N19-03.A.12-7	5.5	6.2	1.15	33.51	0.314	13	38.7	14	0.892	4.6	0.33	3543	199	-22
N19-03.A.12-6	4.7	4.8	1.06	33.64	0.218	15	14.6	15	0.485	4.4	0.29	2962	238	17
N19-02.1-1	8.3	13.7	1.71	33.81	0.211	19	17.8	20	0.611	4.5	0.23	2915	315	-7
N19-03.A.10-1	9	7.2	0.83	35.67	0.194	12	15	13	0.56	4.9	0.37	2779	203	-4
N19-02.3-1	5.1	7.2	1.44	36.23	0.133	48	8.7	48	0.473	7	0.15	2141	832	-20
N19-03.A.12-1	6.5	5.3	0.84	38.9	0.162	19	10.1	19	0.452	4.9	0.25	2476	316	3
N19-03.A.12-4	4.7	2.6	0.58	41.72	0.19	17	12.7	18	0.485	4.3	0.24	2742	281	9
N19-03.A.12-3	12.6	14.9	1.22	44.04	0.184	24	15.2	24	0.6	4.8	0.2	2691	393	-16
N19-02.8-1	1	1.6	1.64	45.63	0.422	32	48.8	36	0.838	16.3	0.45	3991	480	2
Disc. >25%														
N19-02.2-1	2.5	2.7	1.09	19.59	0.209	11	21.9	12	0.76	5	0.4	2899	184	-34
N19-02.4-1	3.9	3.4	0.88	29.11	0.18	30	17.6	30	0.709	5.8	0.19	2654	493	-39
N19-03.B.1-1	2.1	2.7	1.34	24.04	0.316	5	77.7	9	1.782	7.4	0.8	3552	85	-142
N19-04.B.1-1	0.3	0.2	0.68	24.14	0.062	433	2.7	434	0.314	32.1	0.07	677	9261	-183
N19-03.A.12-2	7.9	5.6	0.74	49.73	0.117	60	8.8	61	0.542	7.8	0.13	1914	1083	-57

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12