



Multistage gold mineralization events in the Archean Tati greenstone Belt, northeast Botswana: Constraints from integrative white mica Ar/Ar, garnet U-Pb and sulfides Pb/Pb geochronology

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ABSTRACT

The Tati Greenstone Belt (TGB) in northeastern Botswana hosts numerous Au deposits (Shashe, Mupane and Signal Hill) associated with sulfides, garnet and white mica. In this study, integrative white mica Ar/Ar, garnet U-Pb and sulfides Pb/Pb dating techniques were combined with whole rock and sulfide Pb isotope characteristics to track the source(s) of gold and constrain the timeframes of gold mineralization events. All sulfides and arsenopyrite samples from the TGB yielded overlapping Pb/Pb errorchron ages of 2227 ± 66 Ma and 2220 ± 73 Ma, respectively, which coincide with the Shashe sulfides Pb/Pb errorchron age of 2250 ± 110 Ma. These relatively imprecise Pb/Pb dates suggest heterogeneity in the initial Pb isotope ratios of sulfides. At Mupane, whereas Au mineralization-associated hydrothermal almandine garnet yielded overlapping Tera-Wasserburg lower intercept $^{206}\text{Pb}/^{238}\text{U}$ age and a concordia age of 2119 ± 18 Ma (MSWD = 1.03) and of 2105 ± 24 Ma (MSWD of concordance = 1.10), respectively, sulfides produced an errorchron Pb/Pb age of 2873 ± 140 Ma, which despite the large error remains geologically meaningful as it coincides within error with the first Neoproterozoic Limpopo-Liberian Orogeny (2.70–2.65 Ga), granitoids intrusion emplacement (2.65–2.73 Ga) and deposition of banded iron formation (2.73 ± 0.15 Ga). Ore-related white mica from Signal Hill yielded an overlapping Ar/Ar plateau age of 1987 ± 24 Ma and a weighted mean Ar/Ar age of 1987 ± 13 Ma ($n = 15$, MSWD = 4.3), which coincide within error with the 2.05–1.95 Ga second Limpopo-Liberian tectonic cycle, herein considered to have possibly triggered the Au mineralization in this area. The obtained radiometric dates point to at least three well constrained gold mineralization events, with two of them possibly triggered by two different regional tectonic events. Lead isotope compositions of most of the sulfides overlap with those of spatially associated schists and granitoids, thus suggesting these units possibly represent Pb and by inference Au rock sources. The genetic model of the TGB Au deposits is consistent with many greenstone-hosted gold deposits worldwide, suggesting our results are not solely of local/regional interest, but can be used to characterize greenstone-hosted gold deposits worldwide.

1. Introduction

The NW trending Archean Tati Greenstone Belt (TGB) in north-eastern Botswana and in the southwestern of the Zimbabwe Craton (Fig. 1) is host to numerous types of ore deposits/mineral occurrences, including mostly: (i) magmatic Ni-Cu-(PGE) ore deposits (consisting of Phoenix, Selkirk and Tekwane deposits, Maier et al., 2008) associated with basic/ultrabasic meta-igneous rocks (Aldiss, 1991); and (ii) shear zones and veins-hosted Au $\pm$ Ag deposits/occurrences (Aldiss, 1991). The Au deposits/mineral occurrences found within the TGB are owned

by Galane Gold Ltd. and include (from NW to SE) Map Nora, Golden Eagle, Mupane and Signal Hill. The style of Au mineralization (see deposit geology and style of mineralization section) within the TGB was reported to be consistent with Archean orogenic gold found in the Archean greenstone belts of Canada, South America and Australia (see Glanville et al., 2011).

Orogenic gold deposits that span in age from Archean to Phanerozoic (Goldfarb et al., 2005) are the most important source of gold, as they have accounted for about 75% of the gold extracted by humans (Phillips, 2013). Orogenic gold deposits are broadly

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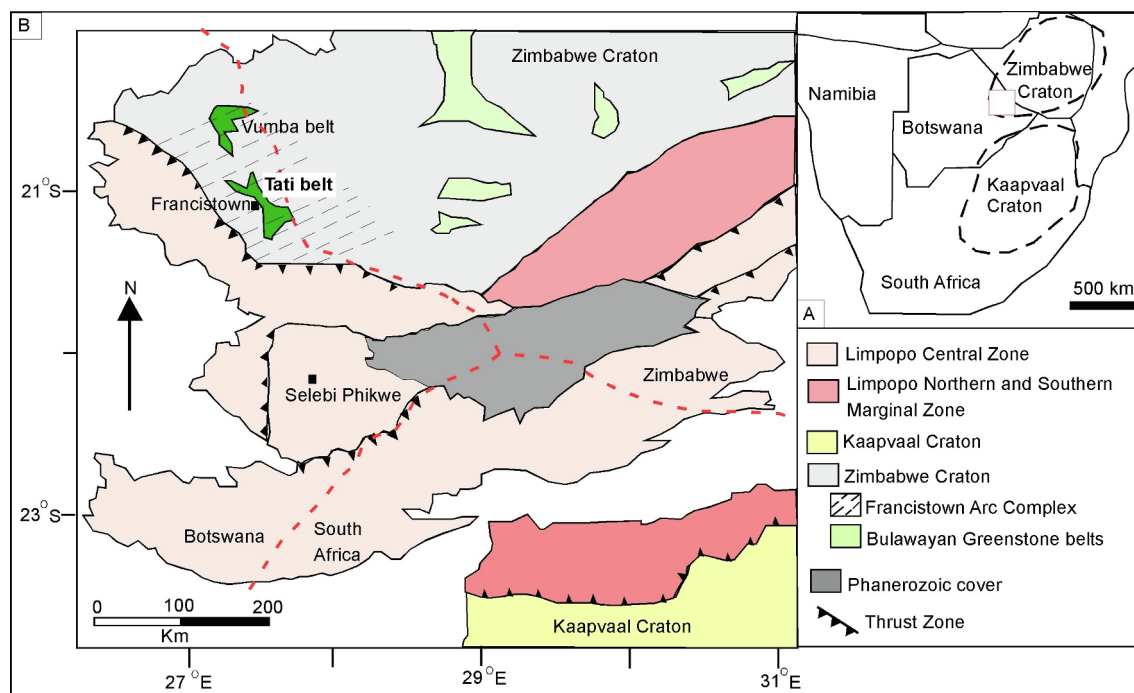


Fig. 1. (A) The location of the study area in northeastern Botswana and southwestern edge of the Zimbabwe Craton. Modified after Johnson (1986). (B) Schematic map showing the TGB (study area), the nearby Vumba Greenstone Belt, as well as the adjacent Limpopo Belt and the Kaapvaal Craton. Modified after Johnson (1986).

discriminated into sediment-hosted and altered mafic volcanics-hosted gold deposits (Steadman et al., 2014). Orogenic gold deposits form at depth > 4 km (Goldfarb et al., 2005) and were initially modeled to form under a wide range of crustal and physiochemical conditions that extend from sub-greenschist to granulite metamorphic facies (Continuum Model of Groves, 1993; Groves et al., 1998, 2003); but these pressure and temperature conditions were later restricted to the greenschist metamorphic facies (e.g., Metamorphic Model of Phillips and Powell, 2009, 2010), though upper greenschist to amphibolite conditions are still reported worldwide (e.g., Dziggel et al., 2010; Steadman et al., 2014). The genesis of the sediment-hosted subclass, including the banded-iron-formation (BIF)-hosted orogenic gold deposit type (e.g., the over 40 million ounces (Moz) gold South Dakota gold deposit, Caddey et al., 1991) is still a subject of intense debates opposing syngenetic models (e.g., Fripp, 1976; Anhaeusser, 1976; Large et al., 2007, 2009, 2011; Thomas et al., 2011) against epigenetic ones (e.g., Phillips et al., 1984; Groves et al., 1987).

With the exception of Shashe deposits (Golden Eagle and Map Nora), there is no definite style of gold mineralization within the TGB. Each deposit/mineral occurrence has a distinct style of mineralization (see outline of style of mineralization section) and is also hosted in distinct geological formations (see geological setting section). Although numerous studies (e.g., Aldiss, 1991; Tombale, 1992; Kampunzu et al., 2003; McCourt et al., 2004; Døssing et al., 2009; Tadesse et al., 2011) have been conducted in the TGB, none has produced the key data needed to come out with a robust genetic model for the orogenic Au deposits within the TGB. For example, the source(s) of gold and epoch of its emplacement in the zone are unknown. Likewise, the genetic and temporal relationships between Au deposits/mineral occurrences in the TGB are poorly understood. Therefore, it becomes important to carry out the current investigation in order to constrain the genesis of Au mineralization in the TGB.

In this paper we combine geochronological (white mica Ar/Ar, hydrothermal almandine garnet U/Pb and sulfide P/Pb) and whole rock and sulfide Pb isotope data in order to track the source(s) of Pb, and by inference Au, and investigate the ages of the Au mineralization event(s) in the TGB. The results obtained point to multiple gold mineralization

events coincident with two major tectonic cycles during which gold was sourced from various lithologies. These research findings may be useful in designing mineral exploration models and guidelines, which may lead to the discovery of significant gold resources in the TGB.

2. Geological setting

The study area, TGB, is located in the southwestern edge of the Zimbabwe Craton, which extends in a southwestern direction into Botswana (Fig. 1A, Zhai et al., 2006). The Zimbabwe Craton is separated from the Kaapvaal Craton by the Limpopo Belt and it contains 23 greenstone belts, of which four (including Maitengwe, Tati, Vumba and Matsitama) are exposed in northeastern Botswana (Fig. 1B; Litherland, 1975; Key, 1976; Bagai et al., 2002; Kampunzu et al., 2003). The part of the Zimbabwe Craton exposed in Botswana is further subdivided into three lithostratigraphic complexes: (i) the Francistown Granite Greenstone Complex (FGGC), (ii) the Motloutse Complex, and (iii) the Mosetse Complex. The FGGC Complex is made up of the Tati, Vumba and Maitengwe greenstone belts surrounded by foliated granitoids and orthogneiss (Aldiss, 1991). The Motloutse Complex is composed of tonalitic to granitic orthogneiss, similar to those that occur at the FGGC (Carney et al., 1994), as well as of para-gneiss and the Shashe meta-sedimentary rocks (Carney et al., 1994). The Mosetse Complex consists of Matsitama Greenstone Belt that hosts granitic to granodioritic gneiss (Carney et al., 1994).

The Maitengwe Greenstone Belt consists of two formations, namely (i) the Lower Maitengwe Banded Ironstone Formation consisting of thick iron-rich layers alternating with thin chert beds, and (ii) Maitengwe Ultramafic Formation consisting of amphibolite that occurs in association with serpentinite and meta-peridotite (Litherland, 1975). The Vumba and Tati Greenstone belts (Fig. 1B) host similar lithologies and consist of mafic-ultramafic lavas occurring in the lower stratigraphic units, intermediate and felsic lavas occurring in the upper units and the two units are crosscut by granitoids. The Matsitama Greenstone Belt consists of metasedimentary rocks with minor mafic-ultramafic metavolcanic rocks (Kampunzu et al., 2003) and metamorphism ranges from greenschist to amphibolite facies with local partial melting

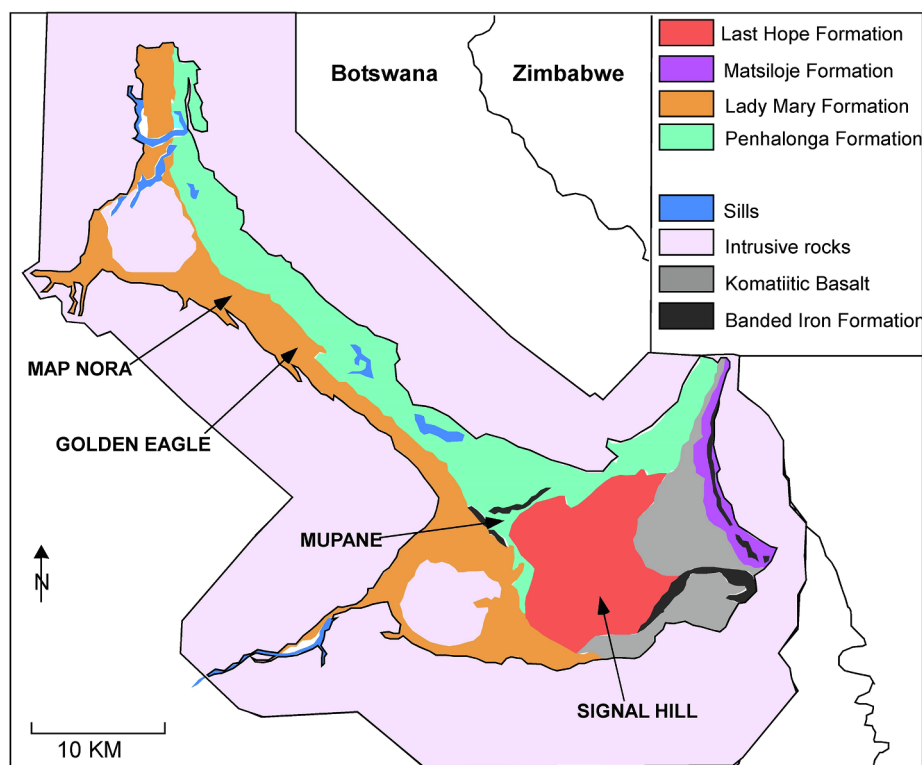


Fig. 2. Simplified geological map of the Tati Greenstone Belt, northeastern Botswana showing the location of the investigated Au deposits, as well the associated geological context. Modified from Døssing et al. (2009).

(McCourt et al. 2004).

The TGB, which is the focus of the current investigation was deposited ca 2.7 Ga, (Wilson et al., 1978; Wilson, 1979) and was greenschist-amphibolite metamorphosed from 2630 ± 70 to 2570 ± 70 Ma (Van Breemen and Dodson, 1972). The TGB is composed mainly of basic metavolcanics with some magnesium-rich, intermediate or acid metavolcanics and minor clastic and chemical metasediments including marbles and banded iron formations (Døssing et al., 2009). The TGB has been intruded by: (i) granitoids consisting of mildly deformed tonalite-trondhjemite-granodiorite (TTG) and minor quartz monzonite, monzonite and quartz diorite (Litherland, 1973, 1975; Key, 1976; Aldiss, 1991; Bagai et al., 2002) and (ii) Karoo dolerite dykes that range in age from ca 177–180 Ma (Elburg and Goldberg, 2000; Hastie et al., 2014). Based on radiometric data from both the nearby Vumba Greenstone Belt tonalite-trondhjemite gneisses (Bagai et al., 2002) and Phoenix Mine Gabbro (Van Geffen, 2004), the TTG from the TGB are believed to be ca 2.7 Ga old. The TGB is sub divided into three formations (Fig. 2) including the Lady Mary Formation, the Penhalonga Formation and the Selkirk Formation (Døssing et al., 2009). The Lady Mary Formation forms the base of volcanic and sedimentary rocks and it consists of mafic and felsic schist, limestone, banded iron-formation (BIF), altered komatiite and komatiitic basalt (Døssing et al., 2009). The Lady Mary Formation is host to the Au deposits of Map Nora and Golden Eagle (Tombale, 1992). The Penhalonga Formation that hosts the Mupane Au deposits overlies the Lady Mary Formation and consists of basaltic, andesitic, rhyolitic volcanics, volcanoclastics and phyllitic black shale (Døssing et al., 2009). The Selkirk Formation comprises of dacitic and rhyolitic volcanoclastic rocks and quartz sericite schist. The Selkirk Formation is crosscut by Phoenix, Selkirk and Tekwane metagabbro intrusions and Sikukwe meta-peridotite intrusions (Maier et al., 2008).

3. Deposits geology and style of mineralization

Gold mineralization within the TGB is spatially associated with

sulfides, which are essentially composed of arsenopyrite, pyrrhotite, pyrite, sphalerite, chalcopyrite and accessory bornite and galena. Gold found as native gold and electrum, is essentially invisible and mostly occurs as either microscopic inclusions mainly in arsenopyrite and accessory in pyrite and sphalerite or rarely as microscopic free gold. The mineralization style varies across the TGB, with Golden Eagle and Map Nora showing similar style of mineralization, whereas Mupane and Signal Hill Au deposits are characterized by distinct styles of mineralization, which in turn differs from Golden Eagle and Map Nora.

3.1. Mupane Au deposits

The Mupane Au deposits consist of several mineralized sub zones (including Tau, Tholo, Kwena and Tawana) with the Tau mineralization sub zone (focus of the present study) being the most important in terms of size and Au production. Mupane Mines from 2005 to date have extracted over 700,000 oz of gold (<http://www.galanegold.com/operations/mupane/>). The Mupane deposits are within the Mupanipani Hills, which crop out as iron formations comprised of banded siliceous and graphitic iron formation (GIF), hosted by a sequence of variably schistose metasediments that include conglomerate, para-amphibolite, marble, metapelite and minor orthoamphibolite (Tomkinson and Putland, 2006). The geology and the style of mineralization vary across the different mineralized sub zones. Gold mineralization at Tholo and Kwena deposits is hosted by BIFs; and whereas Kwena's Au-bearing BIF is encased in amphibolite schist, at Tholo, the Au-bearing BIF is within mainly quartz-muscovite schist and occasionally occasionally in quartz biotite schist. At Tawana deposit, Au mineralization is associated with dolerite dykes (Glanvill et al., 2011), whereas at Tau deposit, the Au-bearing GIF is encased essentially within quartz-biotite/amphibolite-schist, and rarely in garnet schist and a conglomerate.

At the investigated Tau mineralized sub zone, the gold-bearing GIF units are, in most cases, hardly identifiable because of the total obliteration of the original texture by quartz-carbonate alteration. Where

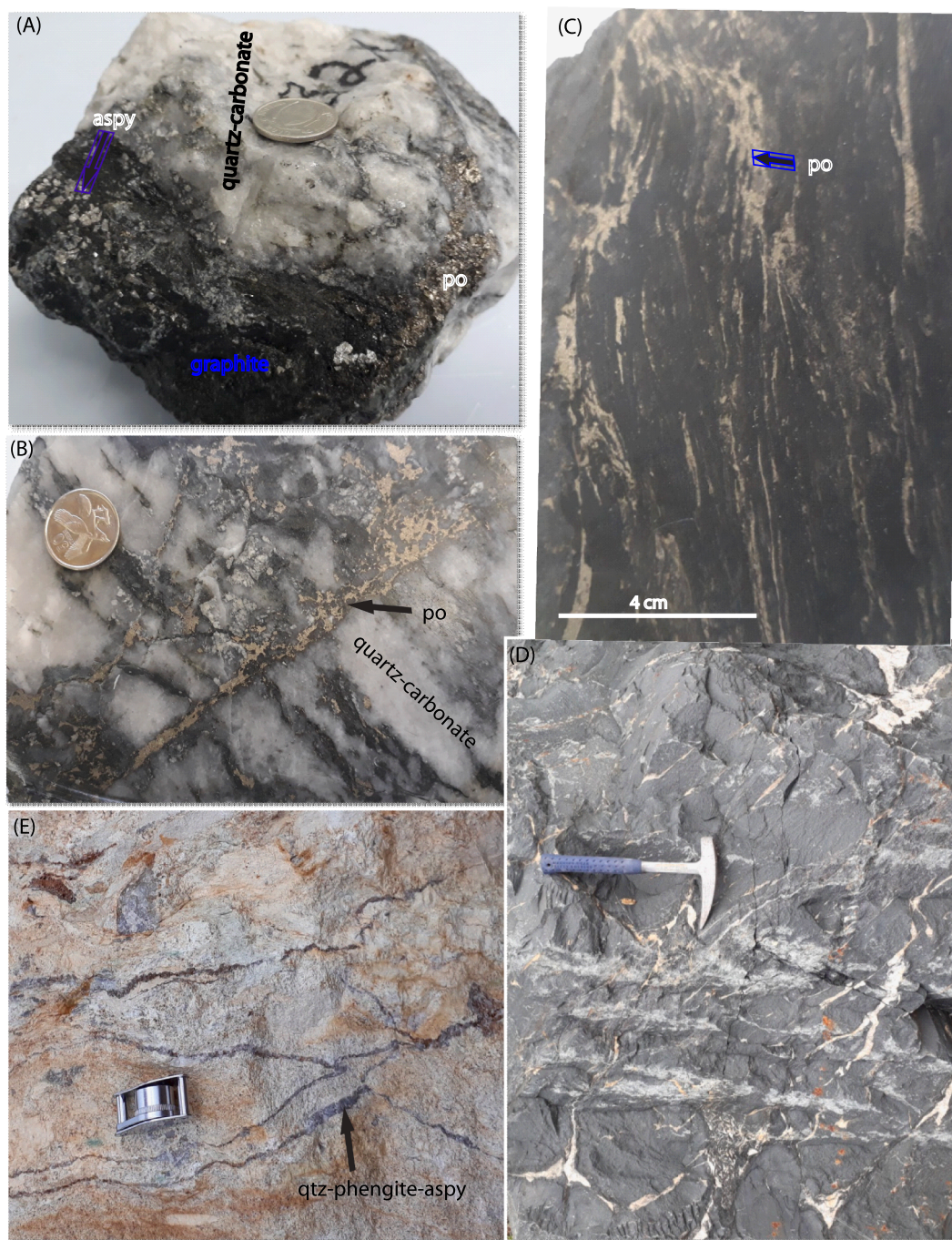


Fig. 3. Photographs (A–E) and microphotographs (F–J) showing the styles of mineralization of the investigated TGB Au deposits. (A–B) Mupane Au style of mineralization showing arsenopyrite (aspy) and pyrrhotite (po) in quartz-carbonate-altered graphitic unit. (C–D) At Shashe, mineralization is essentially concordant, with po aligned following the schistosity fabric (C), but local mineralized and discordant quartz-carbonate en echelon veins (D) are also observed. (E) Mineralization at signal Hill occurring as quartz-white mica (phengite)-arsenopyrite stockworks overprinting a pervasively white mica-altered sandstone. (F) Reflected light (PPL) microphotograph from Mupane showing sphalerite (sl)-arsenopyrite (aspy) intergrowth. (G) Back scattered electron (BSE) image from Mupane showing arsenopyrite porphyroclasts/porphyroblasts aligned following the schistosity fabric. (H–L) Reflected (H, J, K) and transmitted (I, L) light microphotographs of Shashe gold deposits showing Pyrrhotite (po) and sphalerite (sl) hosted in a biotite (bt)-rich schist. Note the presence of a second generation of po (po₂) that crosscuts the first and concordant Po event (J). H, J and K are PPL, whereas I and L are XPL. (M) Transmitted light (PPL) microphotograph from Signal Hill showing white mica (phen) and aspy intergrowth in pervasively altered sandstone.

this alteration overprint is not pervasive, graphite schist and graphite-garnet schist were identified as gold-bearing GIF units. At Tau, Au mineralization occurs essentially randomly disseminated in the ferruginous graphitic host rock, which is variably quartz-carbonate-altered (Fig. 3A), thus leading in places to gold-sulfide-bearing quartz-carbonate-rich host rocks. Locally, however, disseminated sulfide

porphyroclasts/porphyroblasts are observed aligned following the S₂ graphite-rich foliation. Locally, mineralization is also vein-controlled and within most of the cases, veins and/or stockworks are overprinting the quartz-carbonate-altered host (Fig. 3B).

The ore minerals identified are essentially arsenopyrite and pyrrhotite (Fig. 3A–D, F) with accessory, pyrite, chalcopyrite, native gold

and electrum, sphalerite, ilmenite, and bornite (probably of secondary origin) in decreasing order of abundance. Ore mineral abundance varies from mainly disseminated to locally massive content. Arsenopyrite and the other spatially associated ore minerals mentioned above rarely occur as euhedral crystals, but rather as subhedral to anhedral and deformed grains (Fig. 3G) of variable size. Arsenopyrite (and rarely pyrrhotite) in Mupane also exhibits a wide range of textures (which in places can be superposed) including vuggy, inclusions-rich (sieve texture) and highly fractured and rarely folded and boudinaged crystals. Native gold and electrum were observed to be essentially found within arsenopyrite, either as tiny inclusions or filling fractures and vugs.

3.2. Shashe Au deposits

The Map Nora and Golden Eagle Au deposits constitute the Shashe Au deposits group. In both Map Nora and Golden Eagle the mineralization is essentially hosted in a fine-grained biotite-rich schist, which accessorially also contains amphibole, talc, epidote, chlorite and garnet. Locally, the biotite-schist is overprinted by actinolite, which forms at the expense of biotite.

Map Nora deposit has a resource potential up to 200,000 oz Au (<http://www.galanegold.com/operations/mupane/exploration-and-development/>), whereas Golden Eagle deposit contains an indicated resource of 115,000 oz Au (at 0.9 g/t cut-off, Glanvill et al., 2011). In both Map Nora and Golden Eagle, mineralization is essentially stratiform and schistosity-controlled, with deformed ore minerals preferentially aligned either along the schistosity fabric (Fig. 3C, H–L) or in schistosity-parallel veins. Thus, it is consistent with the synchronicity of gold mineralization with the D₂ schistosity as evoked by Glanvill et al. (2011). In addition to the main stratiform mineralization, local discordant mineralization, including en echelon (Fig. 3D) and schistosity-oblique veins mineralization (Fig. 3J) styles were observed.

In all styles of mineralization from the two areas, native gold and electrum are chiefly associated with arsenopyrite, pyrrhotite and sphalerite (Fig. 3C, H–L) and accessorially pyrite, chalcopyrite and bornite in decreasing order of abundance. Of note however is that Golden Eagle is significantly sphalerite-rich relative to Map Nora. Like in Mupane, arsenopyrite is generally strained and elongated following the schistosity planes, whereas euhedral crystals are rarely observed. Although arsenopyrite commonly shows inclusions of pyrrhotite and chalcopyrite, intergrowth between chalcopyrite, arsenopyrite are also common observations. At Map Nora, native gold and electrum are free and appear in textural equilibrium with arsenopyrite, whereas at Golden Eagle, native gold and electrum are observed either as free grains in textural equilibrium with arsenopyrite, or as tiny inclusions within sphalerite and arsenopyrite. Worthy of note is the native gold endowment of sphalerite schistosity-parallel veins mentioned above.

3.3. Signal Hill Au deposit

The 521,000.00 t Au (measured resource at 0.9 g/t cut-off; Glanvill et al., 2011) Signal Hill deposit, is hosted in its southeast and the northeast portions by a succession of foliated metadacite to metarhyolite and siliceous iron units from the Penhalonga Formation (Glanvill et al., 2011). Mineralization at the center of Signal Hill deposit is hosted by a sequence of poorly bedded arkose sandstone, interbedded with poorly bedded conglomerates of the Last hope Formation (Glanvill et al., 2011).

In the central zone where our investigation focused, Au mineralization occurs as auriferous quartz-white mica veins and stockworks (Fig. 3E) hosted in pervasively phengite-altered sandstone and conglomerate. The white mica was identified as phengite by X-ray diffraction (XRD). But without constraints on the Si abundance (normally > 3.5 pfu for phengite), this mica phase will be simply referred to as white mica in the current investigation. White mica constitutes the main component of the sandstone matrix, which links quartz clasts. The

sulfides content in Signal Hill Au deposit is low, typically < 2% and arsenopyrite is the only ore mineral observed as either disseminated in white mica-rich matrix or hosted in quartz-white mica veins/stockworks (Fig. 3M). Apart from the observed arsenopyrite, Tombale (1992) reported other sulfides including pyrrhotite, pyrite, stibnite, gudmundite and minor chalcopyrite and sphalerite.

4. Analytical methods

Nine pure sulfide concentrates (including 1 pyrite, 5 arsenopyrite and 3 pyrrhotite) and nine rock samples (consisting of 6 schist, 2 dolerite dykes and 1 granodiorite) spatially associated with the Au mineralization in the TGB were collected. These samples were analyzed for Pb isotope compositions.

Lead isotope ratio measurements were carried out to determine the source(s) of Pb (and by inference Au) and to assess the age(s) of Au mineralization. Lead isotope ratios for both sulfides and whole rocks were measured using the Thermo Finnigan TRITON mass spectrometer housed at the Department of Earth Sciences of the University of Geneva (Switzerland), following the method described by Bineli Betsi et al. (2013, 2017, 2018). The reference material SRM981 was used as internal standard and Pb isotope ratios were corrected for instrumental fractionation by a factor of 0.07%/amu, based on > 90 measurements of the SRM981 standard and using the values of Todt et al. (1996). External reproducibility (2σ) of the standard ratios is 0.05% for ²⁰⁶Pb/²⁰⁴Pb, 0.08% for ²⁰⁷Pb/²⁰⁴Pb, and 0.10% for ²⁰⁸Pb/²⁰⁴Pb. Mass fractionation of Pb (0.08 ± 0.05%/amu) was monitored by SRM-981 standard measurements. The total procedural common lead blank was 2.07 ± 1.97 pg (average of 20 total blank measurements) and has the following isotopic composition (at 2σ uncertainty, fractionation-corrected): ²⁰⁶Pb/²⁰⁴Pb: 18.36 ± 0.34; ²⁰⁷Pb/²⁰⁴Pb: 15.59 ± 0.20; ²⁰⁸Pb/²⁰⁴Pb: 38.00 ± 0.69; the total blank isotopic composition did not vary systematically over the range of total blank common Pb amounts (0.5–7.4 pg). All measurements were corrected for internal fractionation using ²⁰³Tl/²⁰⁵Tl = 0.418922 and external fractionation using nominal values of SRM981 of Baker et al. (2004). The Pb isotope ratios that were obtained were then used to calculate the Pb/Pb ages using Isoplot v.3.31 Excel macro of Ludwig (2003). Initial Pb isotope compositions of whole rock samples were calculated using the U–Th age corrections (e.g., Sangster et al., 1998; Bouse et al., 1999). Lead, U and Th contents, which were used to calculate the initial Pb isotope ratios of whole rocks were obtained by sodium peroxide fusion (combined ICP-AES and ICP-MS package), carried out at SGS, South Africa. A maximum of 0.2 g whole rock samples were completely digested in a basic sodium peroxide oxidizing flux which renders most refractory minerals soluble.

White mica associated with Au mineralization at Signal Hill Au deposit was collected for Ar/Ar geochronology. Ar–Ar dating was carried out at the University of Manitoba, Canada. Sample analysis followed the same method used by Bineli Betsi et al. (2017). The white mica sample was loaded in a multi-collector Thermo Fisher Scientific ARGUS V1 mass spectrometer linked to a stainless steel Thermo Fisher Scientific extraction/purification line and photon machines (55 W) fusions 10.6 CO₂ laser (Bineli Betsi et al., 2017). The Faraday detectors with low noise of 1 × 10¹² Ω resistors were used to measure Ar isotopes from mass of 40 to 37, and mass 36 was measured using a compact dynode detector (CDD) (Bineli Betsi et al., 2017). All the measurements were corrected for the total system blanks, mass discrimination, radioactive decay and mass spectrometer sensitivity. The Ar/Ar plateau age and the weighted mean Ar/Ar age were calculated using Isoplot v.3.31 Excel macro of Ludwig (2003).

Garnet grains from a sheared and mineralized GIF were subjected to *in-situ* LA-ICP-MS U–Pb geochronology. The analysis was carried out at the Department of Earth Sciences of the University of New Brunswick (UNB), Canada, using a Wavelength Resonetics M-50-LR 193-nm Excimer laser ablation system coupled to an Agilent 7700x ICP-MS.

Geochronological data were acquired from 210 μm size spots during a 30 s ablation time and a 30 s washout time between each ablation. Care was taken to select only areas free of fractures and inclusions. The repetition rate of the laser (pulses per second) was 4 Hz, with an on-sample fluence (energy) of 4 J/cm². Carrier gases were run at a rate of 930 ml/min for argon, 300 ml/min for ultra-pure helium, and 2 ml/min for ultra-pure nitrogen. Primary standard used was NIST612, and empirical correction was applied to the unknowns using an in-house and matrix-matched Mackenzie Gulch Cu-skarn deposit grandite garnet standard that has a known age of 385 ± 3 Ma (Chris McFarlane, personal communication). A total of 14 spot analyses were acquired from the primary standard NIST 612, whereas 20 spot analyses were collected from the Mackenzie Gulch grandite garnet standard. 71 unknowns were acquired and there was a standard at least every three unknowns. During standard and sample analyses, ⁴⁴Ca, ²⁰⁴Pb, ²⁰⁶Pb, ²⁰⁷Pb, ²⁰⁸Pb, ²³²Th, ²³⁸U, Approx U, Approx Th and Approx Pb contents were measured from each spot analysis.

During tuning, only the heavy elements were monitored (Pb, Th, U) and tuning was adjusted to maximize sensitivity on the heavy isotopes only. Oxide production was kept below 0.3%. As the grains were large in each sub sample, each array of spots was run in a linear orientation across the grains. Detection limits were calculated using the backgrounds before and after each ablation. The Concordia and lower intercept ages were calculated using Isoplot ver.3.31 (Ludwig, 2003). Errors are quoted at the 2-sigma (95% confidence) level and are propagated from all sources except mass spectrometer sensitivity and age of the flux monitor. First order characterization of garnet prior to U-Pb dating was done using a JEOL JSM 6400 scanning electron microscope (SEM), a superprobe JEOL JXA-8230 electron microprobe and a M4 Tornado Bruker micro X-ray fluorescence (μ -XRF) mapping, housed at the Department of Biology of UNB, the Department of Earth and Environmental Sciences of Botswana University of Sciences and Technology (BIUST) and at the Department of Earth Sciences of UNB, respectively.

5. Results

5.1. Pb isotope systematics

The measured and initial Pb isotope compositions of sulfides and

whole rocks are reported in Table 1 and plotted in Fig. 4. Lead isotope compositions of sulfides from the TGB Au deposits are heterogeneous and show a wide range of Pb isotope ratios. ²⁰⁶Pb/²⁰⁴Pb range from 14.274 to 29.711, whereas ²⁰⁷Pb/²⁰⁴Pb and ²⁰⁸Pb/²⁰⁴Pb are between 14.957 and 17.179 and 33.962–65.243, respectively. Of note is the highly radiogenic character of arsenopyrite from Map Nora, which clearly distinguishes it from the other TGB sulfides (Table 1, Fig. 4).

The whole rocks also show heterogeneity and a wide range of measured Pb isotope compositions (Pb_i), which span from 13.491 to 17.739 for ²⁰⁶Pb/²⁰⁴Pb_i, 14.549–15.538 for ²⁰⁷Pb/²⁰⁴Pb_i and 33.743–38.261 for ²⁰⁸Pb/²⁰⁴Pb_i. The initial Pb isotope compositions (Pb_i) of whole rocks were calculated at 2.7 Ga for schists and granodiorite and 179 Ma for dolerite dykes (based on the ages provided in the geological setting section) using Th, U and Pb data reported in Appendix 1. The calculated Pb_i isotope compositions are similarly characterized by a wide range (Table 1). For example, ²⁰⁶Pb/²⁰⁴Pb_i are between 12.133 and 17.806, ²⁰⁷Pb/²⁰⁴Pb_i spanning from 14.550 to 15.498 and ²⁰⁸Pb/²⁰⁴Pb_i ranging from 33.744 to 38.322. In all cases, dolerite dykes show the most radiogenic end member.

5.2. Pb/Pb geochronology

Lead isotope compositions of sulfides presented in the Section 5.1 above were used to produce Pb/Pb ages (Fig. 5) using Isoplot v.3.31 Excel macro of Ludwig (2003). Sulfides from TGB, when plotted together, yielded an errorchron Pb/Pb age of 2227 ± 66 Ma ($n = 9$, MSWD = 2.7E + 7, Fig. 5A), whereas an errorchron of 2220 ± 74 Ma ($n = 5$, MSWD = 3E + 5, Fig. 5B) was obtained when only arsenopyrite from the TGB was considered. Mupane sulfides yielded an errorchron Pb/Pb age of 2873 ± 140 Ma ($n = 4$, MSWD = 1E + 5, Fig. 5C), whereas Shashe deposit sulfides also yielded an errorchron Pb/Pb age of 2250 ± 110 Ma ($n = 5$, MSWD = 1.3E + 7, Fig. 5D).

5.3. Ar/Ar geochronology

A white mica sample obtained from pervasively altered sandstone from Signal Hill Au deposit was dated using Ar/Ar technique in order to investigate the age of the alteration and by inference the age of associated Au mineralization in the area. Two aliquots were analyzed and results are reported in Table 2 and Fig. 6. Aliquot 1 is characterized by a

Table 1
Initial ($t = 270$ and 179 Ma) and measured ($t = 0$ Ma) Pb isotope compositions of TGB sulfides and spatially associated rocks.

Samples ID/species	$t = 0$ Ma			$t = 2700$ Ma			$t = 179$ Ma		
	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁷ Pb/ ²⁰⁴ Pb	²⁰⁸ Pb/ ²⁰⁴ Pb
Mupane Au deposit									
LBC-4 (dolerite dyke)	17.814	15.515	38.077				17.806	15.544	38.322
LB10 (schist)	16.087	15.338	35.290	14.494	15.043	35.140			
LB7 (arsenopyrite)	14.274	15.037	33.962						
LB8 (pyrrhotite)	14.546	15.089	34.182						
LB2B (pyrrhotite)	14.882	15.162	34.591						
LB2B (arsenopyrite)	14.983	15.181	34.674						
Map Nora Au deposit									
SH8 (schist)	16.981	15.448	36.604	12.1328	14.550	33.744			
SH5 (schist)	17.044	15.385	36.655	15.279	15.058	35.493			
SH10 (arsenopyrite)	29.011	17.118	65.243						
SH2 (arsenopyrite)	29.711	17.179	59.921						
Golden Eagle Au deposit									
GEP1 (schist)	14.732	15.109	34.391	13.491	14.879	33.943			
GEP31 (schist)	17.813	15.500	37.676	17.576	15.456	37.568			
GEP25V (dolerite dyke)	17.818	15.544	38.333				17.465	15.498	37.870
GEP29D (pyrrhotite)	14.282	14.957	34.023						
GEP29C (arsenopyrite)	14.558	15.060	34.486						
GEP14 (pyrite)	15.498	15.235	35.722						
Signal Hill Au deposit									
SG5 (granodiorite)	16.399	15.427	35.757	14.631	15.099	34.882			

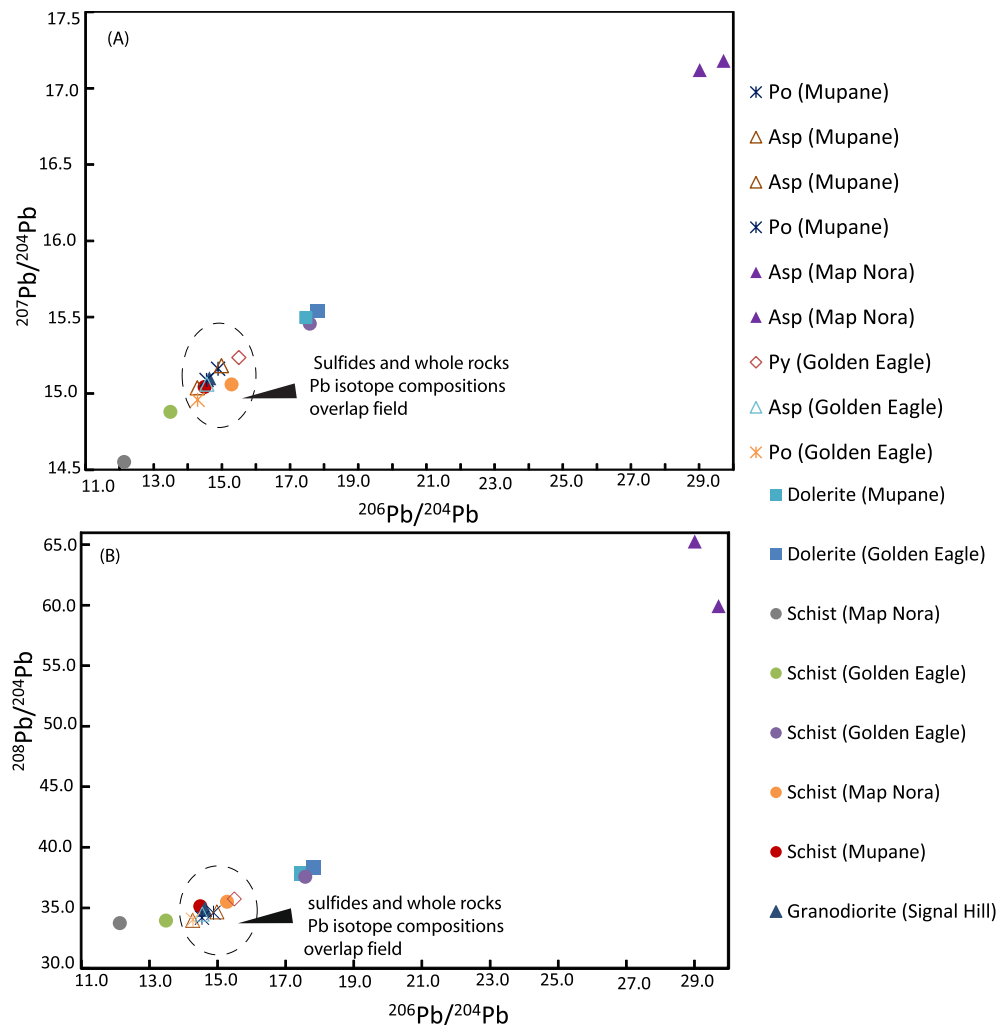


Fig. 4. Uranogenic (A) and thorogenic (B) plots of TGB sulfides and spatially associated rocks. Note the overlap in Pb isotope compositions between sulfides (excepted Map Nora arsenopyrite) and granodiorite and some schists.

systematic and uniform Ar degassing as shown in Fig. 6A. After the two first fragments of ^{39}Ar release, which may have been contaminated by trapped argon (either atmospheric argon, or excess argon, or both), the apparent ages declined at 1876.5 Ma, rising to a plateau age of 1987 ± 24 Ma (MSWD = 0.27, Fig. 6A) of 5 consecutive segments between 35% and 100% total ^{39}Ar release. Aliquot 1 also produced a weighted mean Ar/Ar age of 1976 ± 31 Ma ($n = 7$, MSWD = 3.9), which is rigorously similar within error to the 1987 ± 24 Ma plateau age.

Aliquot 2 age spectrum (Fig. 6B) is characterized by a saddle-shaped pattern, whereby after the first step of ^{39}Ar release, the apparent ages increased, without, however, giving a plateau age (Fig. 6B). Aliquot 2 also yielded a weighted mean Ar/Ar age of 1987 ± 13 Ma ($n = 15$, MSWD = 4.3, Fig. 6C), which is similar to the plateau age of aliquot 1. Of note also is that our white Ar/Ar dates overlap the Mupane (Tau sub zone) 1976 ± 88 Ma (MSWD = 48) garnet Pb step wise leaching age obtained by Døssing et al. (2009).

5.4. LA-ICP-MS hydrothermal almandine garnet U-Pb geochronology

Garnet (Fig. 7) from a highly sheared and mineralized GIF (Fig. 7A), was dated using *in-situ* LA-ICP-MS U-Pb technique. The sheared and mineralized GIF sample (LBC-3), collected from Mupane drill core is composed of mainly garnet porphyroblasts/porphyroclasts (Fig. 7A) and accessory carbonate set in a Fe-rich and fined-grained matrix

composed essentially of carbonate and graphite and various sulfides and accessory of quartz, biotite, chlorite, ilmenite and muscovite. Two sub samples/aliqots (LBC-3(1) and LBC-3(2), Fig. 7B-C) were generated from LBC-3 and then analyzed. Garnet (Fig. 7) is coarse grained (up to 1 cm in diameter), euhedral to anhedral, Fe-rich (ave. 32.09–33.93 wt% FeO_7), typically of almandine composition (see Table 3) and highly anisotropic, with the latter feature symptomatic of hydrothermal garnet. Likewise, the age yielded by the Mupane almandine garnet (see the last paragraph of this section) significantly contrasts with the age of metamorphism within the TGB, thus, once again supporting its hydrothermal origin. The investigated hydrothermal almandine garnet is essentially homogenous as shown in EPMA maps (Fig. 8C–G), but detailed μ -XRF elemental mapping revealed subtle Mn zoning (Fig. 8B) in some grains.

Forty six spot analyses from 3 garnet grains were collected from LBC-3(1) whereas 25 spots analyses from 3 garnet grains were collected from LBC(3)-2. Of the 71 spot analyses collected, only 60 returned reliable results. The summary results obtained are presented in Table 4, while the full data set is contained in the supplementary electronic material (ESM). The U and Th contents of Mupane garnet are low, ranging between 0.03 and 0.27 ppm and 0.001–0.077 ppm, respectively with resulting higher U/Th ratios up to 46.43 (Table 4). Mupane garnet ^{204}Pb contents are low and range from 375 to 907 ppb, suggesting common Pb (Pb_c) in Mupane garnet is lower, similar to most garnet worldwide known to contain negligible common Pb (Mezger et al.,

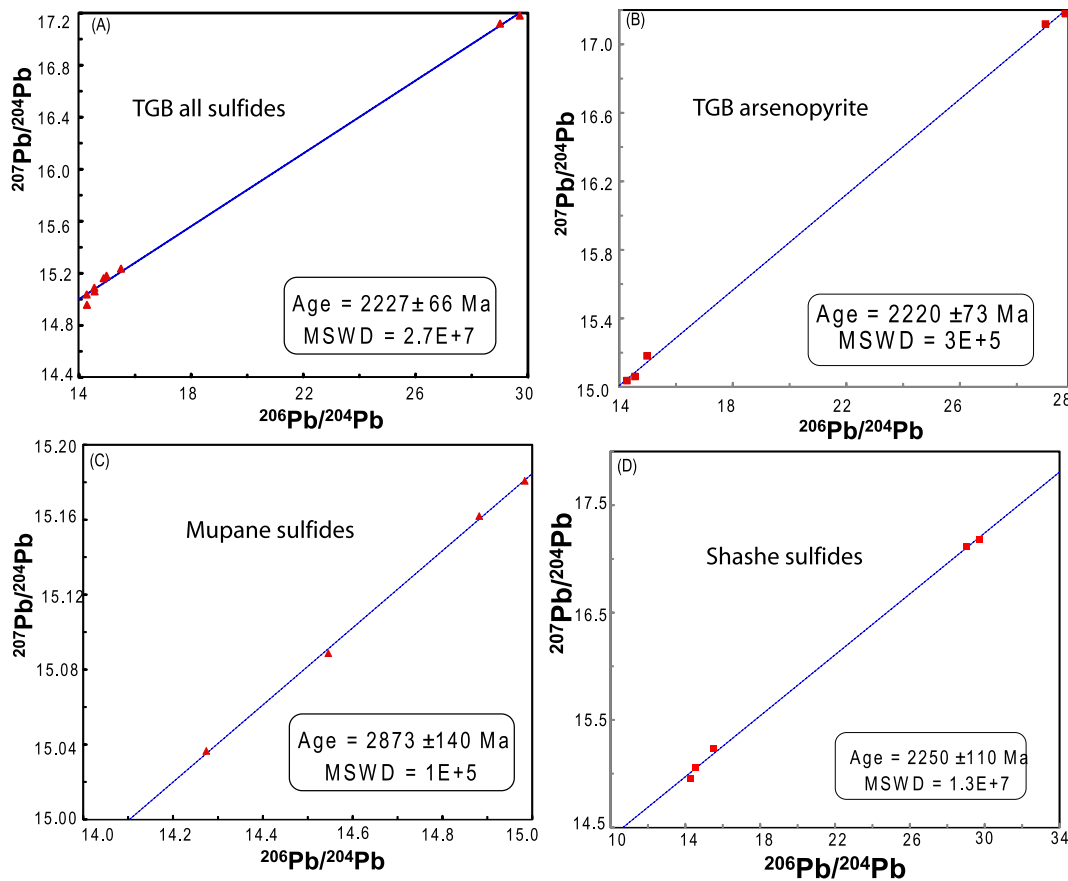


Fig. 5. Pb/Pb isochron plots of TGB all sulfide (A), TGB arsenopyrite (B), Mupane sulfides (C) and Shashe sulfides (D). Note that all the plots display errorchron.

1989, 1991). ^{206}Pb abundances are relatively higher, ranging from 523 to 3680 ppb, thus leading to moderately high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios (1.18–18.1, ave. = 5.11 ppm, Table 4)

The 60 analyses yielded a Tera-Wasserburg concordia age of 2105 ± 24 Ma (MSWD of concordance = 1.10, Fig. 9A) and a Tera-Wasserburg lower intercept $^{206}\text{Pb}/^{238}\text{U}$ age of 2119 ± 18 Ma (MSWD = 1.03, Fig. 9B).

6. Discussion and interpretation

6.1. Sources of metals

As shown in both Table 1 and Fig. 4, Pb isotope compositions of sulfides from the TGB Au deposits are heterogeneous and display a wide range of Pb isotope ratios. Sulfides from the TGB can also be discriminated into least radiogenic and highly radiogenic sulfides, with the latter being represented by the 2 Map Nora arsenopyrite samples. The

causes of such a huge variability in sulfide Pb isotope compositions from the TGB, as well as the significances of the elevated $^{206}\text{Pb}/^{204}\text{Pb}$ (up to 17.179) and $^{208}\text{Pb}/^{204}\text{Pb}$ (up to 65) ratios of Map Nora arsenopyrite are not clear. Arsenopyrite from the world class Homestake BIF-hosted gold deposit also recorded similar high radiogenic character (Frei et al., 2009) and the authors attributed the elevated $^{208}\text{Pb}/^{204}\text{Pb}$ ratios to the presence of inclusions of old and radiogenic monazite and allanite within arsenopyrite. Whether or not the assessed Map Nora arsenopyrite contains similar inclusions of radiogenic minerals is uncertain, as systematic identification of sulfide inclusions was beyond the scope of the current investigation. But, as outlined in the deposits geology and style of mineralization section, the sieve-textured arsenopyrite contains so many inclusions and the possibility of radiogenic inclusions cannot be totally ruled out and this may therefore explain the observed higher Pb isotope compositions variability. In the absence of irrefutable evidences of radiogenic inclusions, likely to have affected arsenopyrite Pb compositions, we prefer to argue that the observed

Table 2a

Ar/Ar results of aliquot 1 phengite sample spatially associated with Au mineralization at Signal Hill.

Aliquot 1															
Power (%)	Ar40	± (1σ)	Ar39	± (1σ)	Ar38	± (1σ)	Ar37	± 1σ	Ar36	± (1σ)	⁴⁰ Ar*/ ³⁹ Ar	± (1σ)	⁴⁰ Ar* (%)	Age (Ma)	± (1σ)
0.1	10292.820	0.4304	29.0650	0.0321	0.3678	0.0158	0.0358	0.0123	0.0128	0.0013	353.820	0.527	99.96	1912.6	1.8
0.2	Background														
0.4	16.741	0.0626	0.0127	0.0267	0.0218	0.0159	−0.0262	0.0134	−0.0009	0.0010	1331.535	2775.704	101.62	3774.0	3296.5
0.6	449.761	0.1079	1.3093	0.0282	0.0416	0.0153	−0.0150	0.0127	0.0010	0.0010	343.103	7.380	99.94	1876.5	25.1
0.8	4452.049	0.2701	12.3935	0.0267	0.1798	0.0147	0.0026	0.0140	−0.0005	0.0010	359.053	0.852	100.00	1929.9	2.8
1.0	11133.650	0.4835	29.4590	0.0309	0.3600	0.0139	0.0312	0.0135	−0.0018	0.0011	377.761	0.547	100.00	1990.7	1.7
1.2	15258.200	0.5214	39.8484	0.0325	0.4602	0.0145	0.0272	0.0130	0.0025	0.0012	382.691	0.493	100.00	2006.3	1.6
1.5	25141.430	0.7741	66.4574	0.0429	0.7850	0.0144	0.0172	0.0129	0.0029	0.0013	378.101	0.449	100.00	1991.7	1.4
2.0	37117.930	0.9855	98.8690	0.0418	1.1797	0.0142	−0.0033	0.0133	0.0033	0.0014	375.221	0.406	100.00	1982.5	1.3

Table 2b

Ar/Ar results of aliquot 2 phengite sample spatially associated with Au mineralization at Signal Hill.

Aliquot 2															
Power (%)	Ar40	± (1σ)	Ar39	± (1σ)	Ar38	± (1σ)	Ar37	± 1σ	Ar36	± (1σ)	⁴⁰ Ar*/ ³⁹ Ar	± (1σ)	⁴⁰ Ar* (%)	Age (Ma)	± (1σ)
0.1	Background														
0.5	282.455	0.0937	0.8300	0.0247	−0.0078	0.0150	−0.0126	0.0128	−0.0002	0.0010	340.175	10.117	100.00	1867.0	35.0
0.8	8883.527	0.3881	27.0705	0.0323	0.3239	0.0144	−0.0152	0.0120	0.0050	0.0010	327.918	0.390	100.00	1824.0	1.0
0.9	11045.170	0.4399	30.6573	0.0308	0.3893	0.0142	0.0158	0.0124	−0.0004	0.0012	360.076	0.362	100.00	1933.0	1.0
1.0	12817.540	0.4366	33.8345	0.0337	0.3849	0.0144	0.0186	0.0128	−0.0020	0.0011	378.630	0.377	100.00	1993.0	1.0
1.1	14121.970	0.5217	36.5588	0.0287	0.4566	0.0157	−0.0311	0.0129	0.0065	0.0013	386.005	0.303	100.00	2017.0	1.0
1.2	16822.320	0.6303	43.5957	0.0350	0.4812	0.0139	0.0112	0.0141	−0.0016	0.0012	385.660	0.310	100.00	2016.0	1.0
1.3	18567.080	0.6342	48.5076	0.0335	0.5629	0.0151	0.0212	0.0123	0.0001	0.0012	382.546	0.265	100.00	2006.0	1.0
1.4	21945.160	0.7141	57.9471	0.0328	0.6919	0.0148	0.0301	0.0129	−0.0004	0.0012	378.495	0.215	100.00	1993.0	1.0
1.5	17523.000	0.5643	46.5678	0.0349	0.5190	0.0141	0.0285	0.0136	−0.0030	0.0013	376.093	0.282	100.00	1985.0	1.0
1.6	16165.130	0.6301	43.1609	0.0348	0.5060	0.0154	0.0160	0.0117	−0.0013	0.0012	374.324	0.302	100.00	1980.0	1.0
1.7	10055.980	0.4538	26.7963	0.0318	0.3041	0.0146	0.0328	0.0140	−0.0003	0.0012	375.063	0.446	100.00	1982.0	1.0
1.8	4147.417	0.2881	11.0946	0.0288	0.1250	0.0148	0.0406	0.0132	−0.0018	0.0011	373.661	1.971	100.00	1978.0	3.0
1.9	3964.521	0.2690	10.6150	0.0290	0.1282	0.0145	−0.0096	0.0134	−0.0020	0.0011	373.323	1.021	100.00	1976.0	3.0
2.0	4152.001	0.2619	11.1179	0.0274	0.1603	0.0144	0.0459	0.0132	−0.0026	0.0010	373.313	0.992	100.00	1976.0	3.0
2.5	18941.150	0.6605	51.4453	0.0334	0.6493	0.0146	0.0049	0.0137	0.0001	0.0013	367.966	0.240	100.00	1959.0	1.0
3.0	3114.838	0.2598	8.1891	0.0272	0.1294	0.0152	0.0285	0.0136	0.0000	0.0010	380.148	1.262	100.00	1998.0	4.0

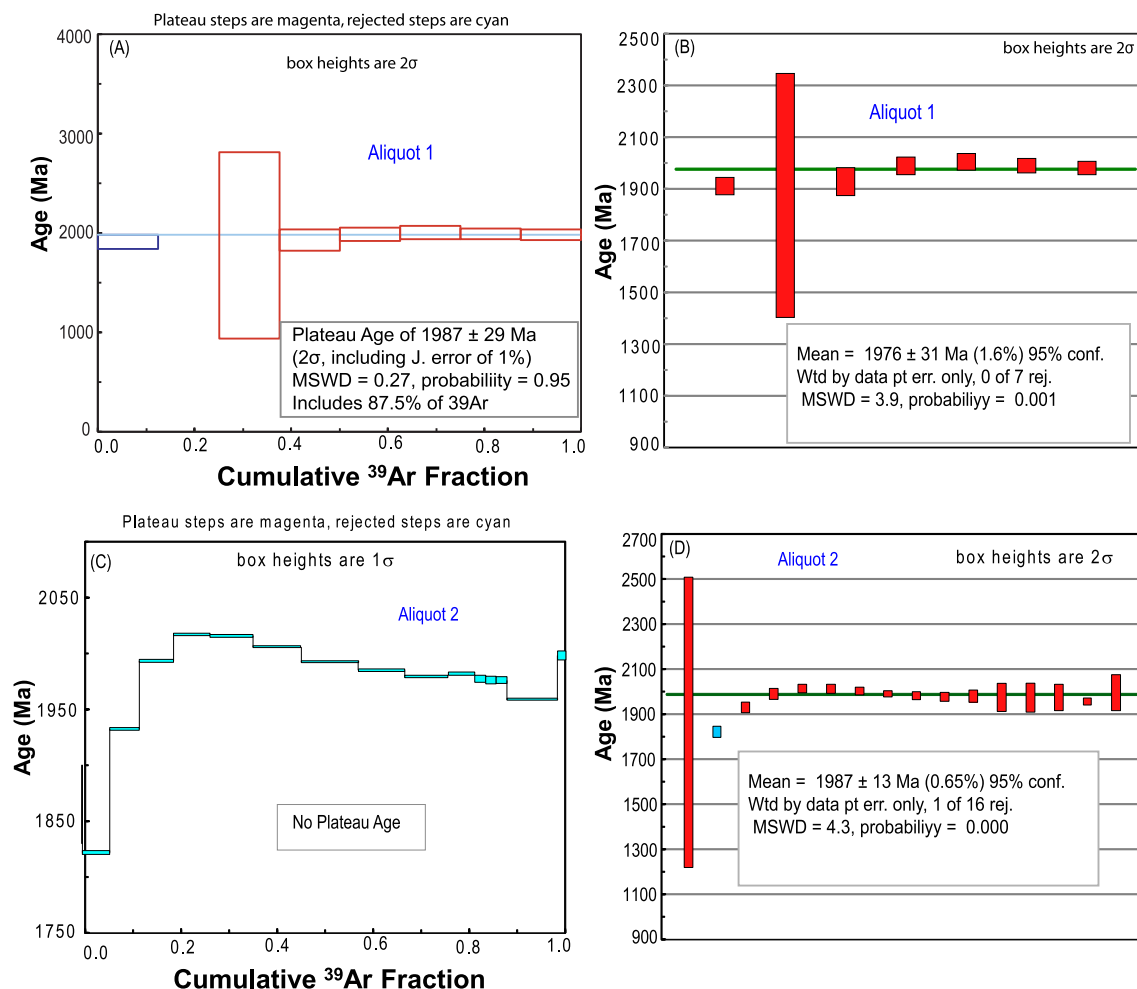


Fig. 6. (A) Ar-Ar spectrum from white mica aliquot 1. After the two first steps of ³⁹Ar release, which may have been contaminated by trapped argon, the apparent ages declined at 1876.5 Ma, rising to a plateau age of 1887 ± 24 Ma (MSWD = 0.27) of 5 consecutive segments between 35% and 100% total ³⁹Ar release. (B) Aliquot 1 also produced a weighted mean Ar/Ar age of 1976 ± 31 Ma (n = 7, MSWD = 3.9), which is rigorously similar within error to the 1887 ± 24 Ma plateau age. (C) Ar-Ar spectrum from white mica aliquot 2, which is characterized by a saddle-shaped pattern, whereby after the first step of ³⁹Ar release, the apparent ages increased, without, however, giving a plateau age. (D) Aliquot 2 also yielded a weighted mean Ar/Ar age of 1987 ± 13 Ma (n = 15, MSWD = 4.3), which is similar to the plateau age of aliquot 1.

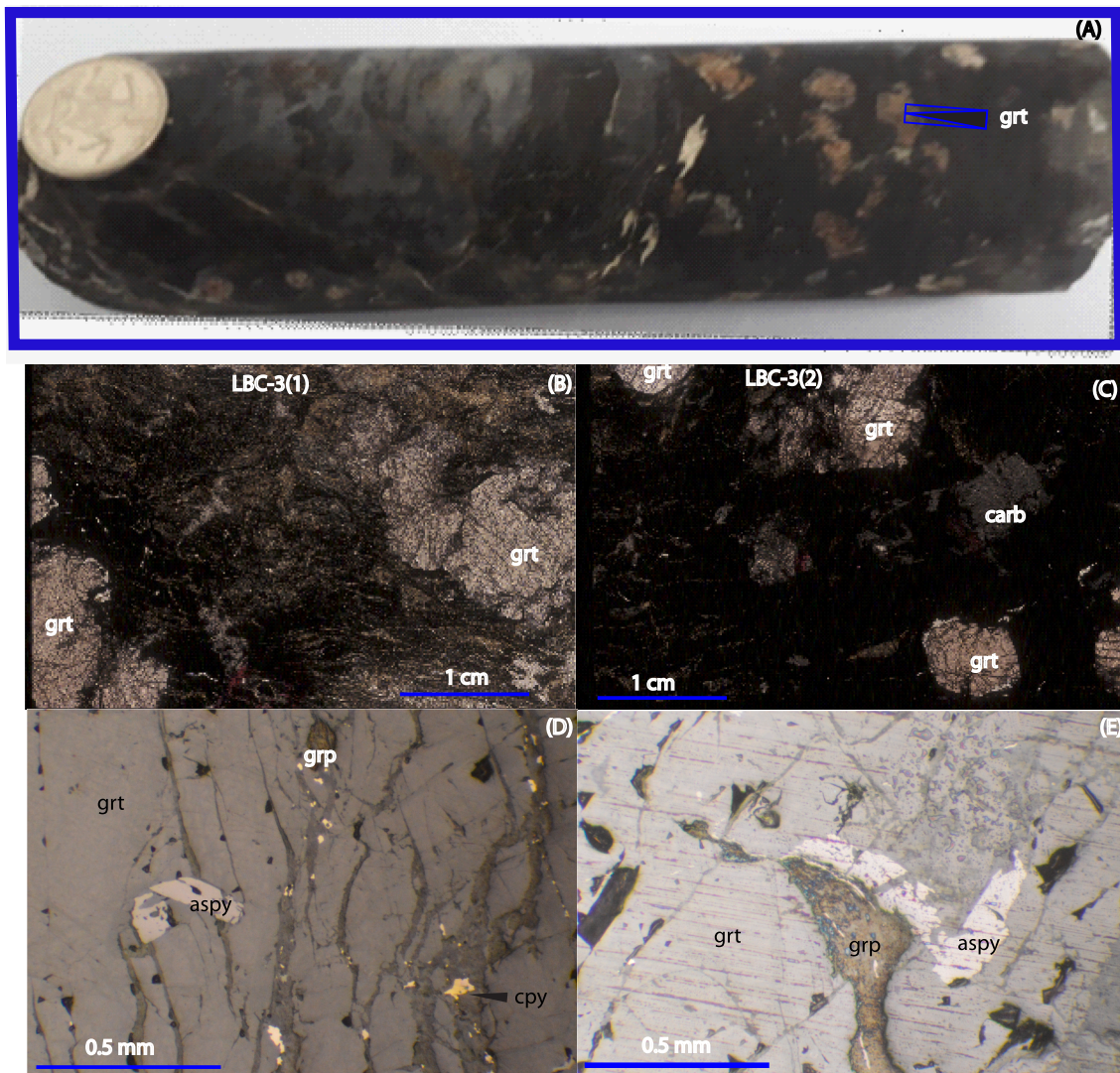


Fig. 7. (A) Photograph of Mupane sheared and mineralized GIF showing the garnet (grt) assessed for *in-situ* LA-ICP-MS U/Pb dating. (B-C) Scanned images of the two polished thin section samples (LBC-3 (1) and LBC-3 (2)) prepared from sample in (A) and showing that the dated grt is coarse grained (up to 1 cm wide) and of various shapes. (D-E) Reflected light (LLP) microphotographs showing that dated grt contains arsenopyrite (aspy), chalcopyrite (cpy) and graphite (grp) inclusions and its fractures are also filled with the same ore minerals.

elevated radiogenic composition of Map Nora arsenopyrite is typically inherent to these sulfides and the variability in Pb isotope compositions of sulfides from TGB is therefore an indication of multiple Pb sources for sulfides. Leaching of Pb from different lithologies (with different Pb isotopic compositions) by mineralizing hydrothermal fluids is likely to explain this multiple Pb sources signature.

The least radiogenic sulfides plot in a narrow Pb isotope compositional range and cluster in both the thorogenic and uranium diagrams (Fig. 4), thus suggesting a unique source of Pb for those sulfides. In both the radiogenic and thorogenic plots, the Pb isotope compositions of least radiogenic sulfides ($^{206}\text{Pb}/^{204}\text{Pb}$ ranging from 14.274 to 15.498.711, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ between 14.957 and 15.235 and 33.962–35.722, respectively) and granodiorite (from Signal Hill) and schist (from Mupane and Map Nora) overlap (Fig. 4), thus suggesting schist and granodiorite are the possible sources of Pb and by inference Au.

On the other hand, the highly radiogenic Map Nora arsenopyrite ($^{206}\text{Pb}/^{204}\text{Pb}$ ranging from 29.011 to 29.711, whereas $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ are between 17.118 and 17.179 and 59.921–65.243, respectively) plots beyond the Pb isotope compositions field of other sulfides and whole rocks, thus suggesting a totally different Pb source,

other than the assessed schist, granodiorite and dolerite dykes. The possible source of Pb and by inference Au in Map Nora mineralization may be black shale that was observed to occur in Map Nora (Tombale, 1992; Døssing et al., 2009). The shale is known to be of a more radiogenic lithology, as it is enriched in Th, U and K (Bottoms and Potra, 2017). Likewise, Map Nora black shale is 2.7 Ga old, thus providing time needed for radiogenic Pb ingrowth. Black shales were also reported to be Au-rock sources in many orogenic gold deposits worldwide (e.g., Large et al., 2007, 2009, 2011; Thomas et al., 2011; Steadman et al., 2013, 2014). The Pb isotope compositions of dolerite dykes do not coincide with any of the investigated sulfide, ruling out their possibility as Au-rock sources within the TGB.

6.2. Significance of the obtained radiometric dates and implications for the age of TGB Au mineralization event (s)

Alteration minerals in hydrothermal systems are footprints of mineralizing fluid pathways. The alteration minerals and the spatially associated elements of economic interest (in this case gold) are also believed to have precipitated from the same mineralizing hydrothermal fluids and are thus genetically related. Therefore, dating alteration

Table 3

Chemical composition of the Mupane garnet associated with Au mineralization.

Samples ID	LBC-3 (1)				LBC-3 (2)			
	3		4		3		4	
	n analyses/ grain		n analyses/ grain		n analyses/ grain		n analyses/ grain	
	Av	1 σ	Av	1 σ	Av	1 σ	Av	1 σ
SiO ₂	35.39	0.41	35.73	0.45	36.03	0.25	35.45	0.81
TiO ₂	0.08	0.03	0.08	0.02	0.07	0.01	0.08	0.02
Al ₂ O ₃	20.09	0.18	20.38	0.15	20.42	0.12	20.16	0.44
Cr ₂ O ₃	0.01	0.01	0.02	0.01	0.01	0.01	0.03	0.02
FeOT	32.09	1.05	33.93	0.56	33.41	0.87	33.38	1.02
MnO	4.38	0.38	3.43	0.23	3.74	0.54	3.60	0.61
MgO	0.63	0.10	0.88	0.14	0.77	0.11	0.76	0.11
CaO	6.05	0.75	5.26	0.51	5.58	0.41	5.16	0.54
Total	98.73		99.69		100.03		98.60	
Atoms (O = 24)								
Si	5.831		5.830		5.858		5.852	
Al ^{IV}	0.169		0.170		0.142		0.148	
Al	3.732		3.751		3.773		3.775	
Ti	0.010		0.009		0.008		0.010	
Cr	0.001		0.002		0.001		0.004	
Fe ³⁺	0.417		0.397		0.350		0.351	
Fe ²⁺	4.005		4.234		4.193		4.258	
Mn	0.612		0.474		0.515		0.503	
Mg	0.155		0.213		0.186		0.188	
Ca	1.069		0.919		0.973		0.913	
Total	16.000		16.000		16.000		16.000	
Almandine	70.661		74.250		73.075		74.183	
Spessartine	9.777		7.598		8.282		8.100	
Pyrope	2.484		3.416		2.994		3.022	
Grossular	17.079		14.736		15.650		14.694	
Andradite	0.000		0.000		0.000		0.000	
Uvarovite	0.000		0.000		0.000		0.000	

minerals can be an efficient and indirect way of constraining the age of the Au mineralization (see Bineli Betsi et al., 2007, Chiaradia et al., 2013, Bineli Betsi et al., 2017). The close spatial association between arsenopyrite (that hosts the Au mineralization as mentioned above) and white mica (Fig. 3M), suggests the two minerals may have precipitated at the same time and are co-genetic. Likewise, the Mupane hydrothermal almandine garnet includes ore minerals (arsenopyrite, pyrrhotite and chalcopyrite, Fig. 7D-E) and its numerous fractures are also filled with the same sulfides (Fig. 7D-E). This relationship clearly indicates an inter mineralization garnet, coeval with sulfides that host native gold and electrum. Numerous researchers (DeWolf et al. 1996, Meinert et al. 2001, Seman et al., 2017; Deng et al., 2017; Fu et al., 2018; Wafforn et al., 2018; Gevedon et al., 2018, Zhang et al., 2019) were able to tightly constrain the ages of various skarn deposits worldwide, dating the spatially associated hydrothermal garnet of grandite composition using U-Pb radiometric technique. Therefore, white mica and almandine garnet dates obtained in the present study can be confidently used and associated to sulfides Pb/Pb dates to discuss and infer the age(s) of the Au mineralization in their respective mineralization zone and within the TGB.

All sulfides and arsenopyrite only from across the TGB yielded Pb/Pb errorchron ages of 2227 ± 66 Ma and 2220 ± 73 Ma, respectively, whereas sulfides from Shashe yielded a Pb/Pb errorchron age of 2250 ± 110 Ma. These relatively imprecise Pb/Pb dates may indicate post-sulfides open system behavior. As indicated by Døssing et al. (2009), the TGB was overprinted by a later ca. 2.0 Ga Limpopo tectono-metamorphic event and this thermal activity could have reset the sulfides Pb/Pb chronometer, thus leading to the obtained errorchron ages. However, the sulfides Pb/Pb geochronological data also yielded closely corresponding and overlapping dates, suggesting the large uncertainties

may have arisen from non-uniform initial Pb isotope compositions, rather than open system behavior post-sulfides deposition. Heterogeneity in initial Pb isotope compositions will arise upon leaching of Pb from different sources, with different Pb isotopic compositions that were not perfectly homogenized. Based on the set of closely corresponding and overlapping dates obtained, as well as the similarity in age with the relatively precise 2.12 Ga hydrothermal almandine garnet U-Pb dates, the sulfide Pb/Pb dates are likely to indicate the maximum age of one Au mineralization event in Shashe and within the TGB.

At Mupane, two sets of radiometric data were obtained and these include the sulfides Pb/Pb 2873 ± 140 Ma errorchron age and the hydrothermal almandine garnet dates (Tera-Wasserburg lower intercept $^{206}\text{Pb}/^{238}\text{U}$ age of 2119 ± 18 Ma (MSWD = 1.03) and a concordia age of 2105 ± 24 Ma (MSWD (of concordance) = 1.10). Though the 2873 ± 140 Ma sulfides Pb/Pb date appears imprecise and that the sulfides Pb/Pb chronometer is likely to undergo thermal resetting (as argued above), it is geologically meaningful as discussed in the Section 6.3 below and its contrast with the hydrothermal almandine garnet suggests gold deposition in this area cannot represent a single mineralization event. Unlike the U-rich (up to 200 ppm, Wafforn et al., 2018) hydrothermal grandite garnet routinely assessed to date skarn deposits, the TGB hydrothermal almandine garnet that was dated is relatively U-poor (up to ca. 0.3 ppm). Despite its lower U content, we obtained robust and reliable ages probably because of the large crater size (210 μm used in this study), which affords greater accuracy and precision (see Wafforn et al., 2018). The two hydrothermal almandine garnet U-Pb radiometric dates are relatively precise and overlap within errors. In addition, the garnet U-Pb closing temperature is > 750 °C (Mezger et al., 1989, Chiaradia et al., 2014 and references therein), suggesting this chronometer is likely to have withstood the ca. 2.0 Ga Limpopo tectono-metamorphic event, as well as other thermal events that may have taken place in the TGB. Therefore, the Mupane hydrothermal almandine garnet U-Pb dates are reliable and are used to confidently time frame at least one mineralization event within the Mupane Au deposit. The 2119 ± 18 Ma lower intercept $^{206}\text{Pb}/^{238}\text{U}$ date is more precise and represents the best date obtained from Mupane almandine hydrothermal garnet. We then interpret the 2119 ± 18 Ma lower intercept $^{206}\text{Pb}/^{238}\text{U}$ date as the age of one of the gold mineralization events in Mupane and within the TGB. The closeness between the 2.12 Ga hydrothermal almandine garnet dates and the 2.2 Ga sulfide Pb/Pb dates, may suggest the two date sets correspond to the same Au mineralization event, which we ascribe to the more precise 2.12 Ga age. Such an inter mineralization hydrothermal almandine garnet was also successfully dated (though by Sm-Nd technique) to constrain the age of gold mineralization in the world-class greenstone BIF-hosted Au Musselwhite deposit (Biczok et al., 2012). Given that both sulfides Pb/Pb and hydrothermal almandine garnet U/Pb dates are reliable and deemed to represent the age of gold mineralization as discussed above, it is therefore, reasonable to postulate that more than one Au mineralization event took place in the Mupane mineralized area. In addition to radiometric dates, textural features, such as, the coexistence and superposition of both pre-to-syn tectonic (folded, boudinaged and fractured) and post-tectonic (euhedral and lacking deformation textures) sulfides (arsenopyrite chiefly) further indicate sulfides from Mupane mineralized zone clearly formed at different epochs, thus consistent with multiple mineralization events across the TGB.

At Signal Hills, aliquot 1 white mica yielded plateau and weighted mean ages of 1987 ± 24 Ma (MSWD = 0.27) and 1976 ± 31 Ma ($n = 7$, MSWD = 3.9) respectively, whereas aliquot 2 white mica yielded a weighted mean age of 1987 ± 13 Ma ($n = 15$, MSWD = 4.3). The 3 dates obtained from white mica spatially associated with Au mineralization overlap, are relatively precise and in addition, the plateau age of aliquot 1 is rigorously similar to the

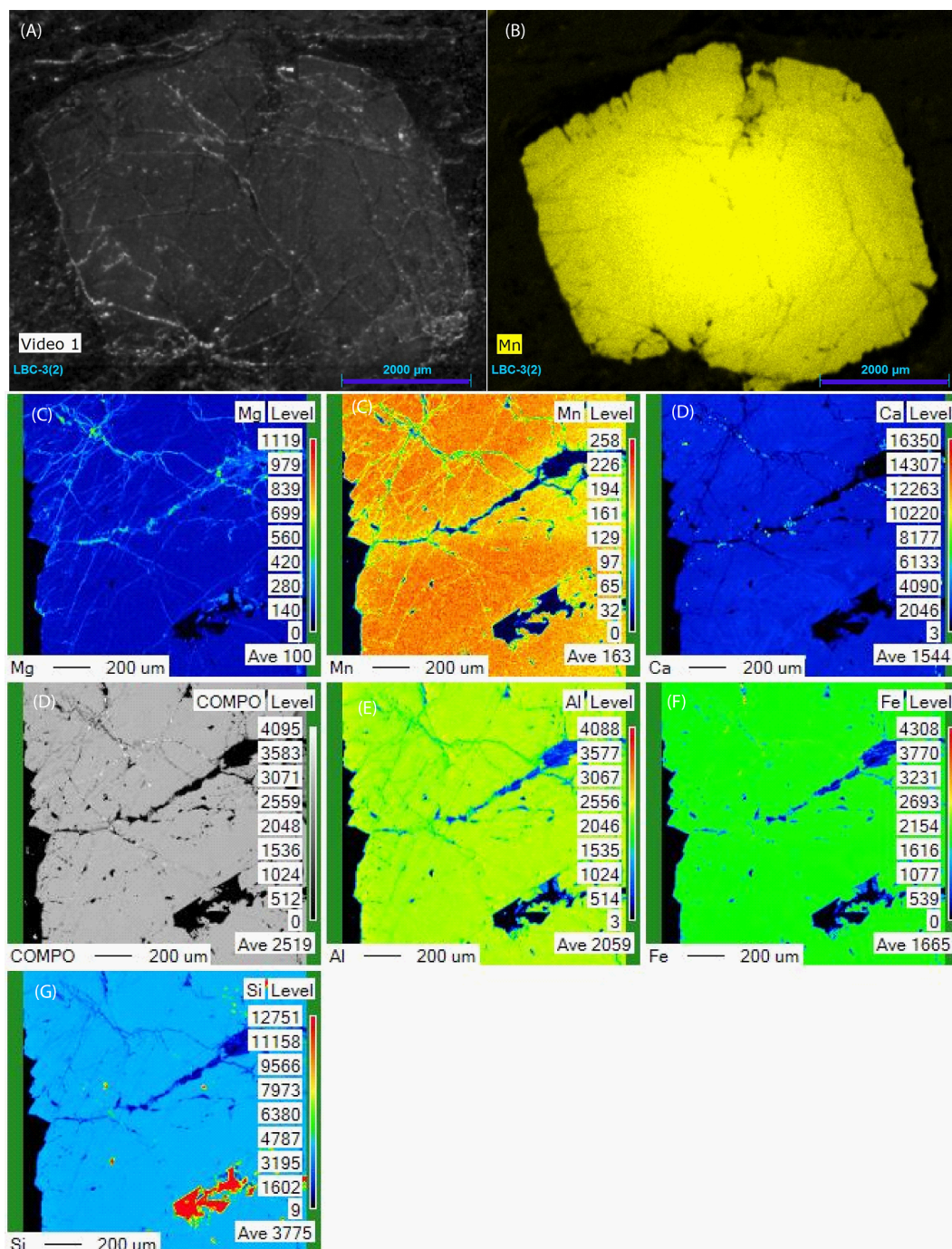


Fig. 8. Micro XRF (A-B) and EPMA maps of the Mupane hydrothermal almandine garnet showing that the investigated garnet is consistently homogeneous, with exception of local Mn zoning (B).

weighted mean age of aliquot 2, thus suggesting the white mica Ar/Ar dates obtained are reliable. The white mica Ar/Ar dates also overlap the Mupane 1976 ± 88 Ma (MSWD = 48, Døssing et al., 2009) garnet Pb stepwise leaching age, further supporting the reliability of our white mica dates. The mean weighted age of aliquot 2 is more precise and statistically more reliable (when considering the number of data acquired) and the 1987 ± 13 Ma ($n = 15$, MSWD = 4.3) and is then here considered as the best crystallization age of white mica and by

inference the age of the Au mineralization event at Signal Hill. If the Mupane 1976 ± 88 Ma (MSWD = 48, Døssing et al., 2009) garnet Pb stepwise leaching age was simply interpreted as overprint of the Limpopo tectono-metamorphic event within the TGB (see Section 6.3), we emphasize that, our 1987 ± 13 Ma ($n = 15$, MSWD = 4.3) Ar/Ar age, based on textural features (as discussed above), is the age of Au mineralization at Signal Hill. Whether there is more than one mineralization event at Signal Hill remains unconstrained. Also, the closure

Table 4a
Summary garnet LA-ICPMS U-Pb geochronology data for aliquot LBC-3 (1).

Analysis spots	U ²³⁸			Aprox U			Th ²³²			Approx Th			Final U/ Th			Pb ²⁰⁶			Pb ²⁰⁷			Pb ²⁰⁸		
	ppm			ppm			ppm			ppm			Ratio			ppb			ppb			ppm		
	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE			
LBC-3(1) - 1	0.1021	0.0051	0.1021	0.0051	0.0111	0.0015	0.0015	0.0111	0.0015	0.0111	0.0015	0.0015	9.20	568	39	1503	81	269	21	324	54			
LBC-3(1) - 4	0.0849	0.0016	0.0849	0.0016	0.0092	0.0012	0.0012	0.0092	0.0012	0.0092	0.0012	0.0012	9.23	595	30	1226	31	194.7	9.8	123	27			
LBC-3(1) - 6	0.0891	0.0029	0.0891	0.0029	0.00561	0.00077	0.00077	0.00561	0.00077	0.00561	0.00077	0.00077	15.88	542	29	1300	50	205	12	148	29			
LBC-3(1) - 7	0.0802	0.0018	0.0802	0.0018	0.00342	0.00072	0.00072	0.00342	0.00072	0.00342	0.00072	0.00072	23.45	592	25	1247	34	273	14	322	43			
LBC-3(1) - 8	0.079	0.0017	0.079	0.0017	0.00344	0.00071	0.00071	0.00344	0.00071	0.00344	0.00071	0.00071	22.97	548	27	1125	32	189	12	100	21			
LBC-3(1) - 9	0.0906	0.0023	0.0906	0.0023	0.0051	0.0013	0.0013	0.0051	0.0013	0.0051	0.0013	0.0013	17.76	585	38	1331	45	233	11	222	50			
LBC-3(1) - 10	0.079	0.0017	0.079	0.0017	0.00382	0.00087	0.00087	0.00382	0.00087	0.00382	0.00087	0.00087	20.68	573	33	1153	37	190	13	103	25			
LBC-3(1) - 11	0.0764	0.0015	0.0764	0.0015	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD		517	27	1119	32	183.1	9.9	148	25			
LBC-3(1) - 12	0.0785	0.0027	0.0785	0.0027	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD		557	49	1165	54	212	17	182	38			
LBC-3(1) - 13	0.089	0.0023	0.089	0.0023	0.0059	0.0012	0.0012	0.0059	0.0012	0.0059	0.0012	0.0012	15.08	574	40	1510	51	419	18	713	69			
LBC-3(1) - 14	0.0757	0.0015	0.0757	0.0015	0.00602	0.00083	0.00083	0.00602	0.00083	0.00602	0.00083	0.00083	12.57	527	27	1052	34	148	10	55	15			
LBC-3(1) - 15	0.0565	0.0013	0.0565	0.0013	0.00346	0.0007	0.0007	0.00346	0.0007	0.00346	0.0007	0.0007	16.33	539	27	858	30	171	11	148	30			
LBC-3(1) - 16	0.079	0.0016	0.079	0.0016	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD		486	30	1256	33	291	16	431	55			
LBC-3(1) - 17	0.0933	0.002	0.0933	0.002	0.0086	0.0012	0.0012	0.0086	0.0012	0.0086	0.0012	0.0012	10.85	532	33	1603	50	458	22	681	75			
LBC-3(1) - 18	0.0981	0.0016	0.0981	0.0016	0.0103	0.0012	0.0012	0.0103	0.0012	0.0103	0.0012	0.0012	9.52	510	28	1562	42	429	27	603	66			
LBC-3(1) - 19	0.079	0.0016	0.079	0.0016	0.00462	0.00089	0.00089	0.00462	0.00089	0.00462	0.00089	0.00089	17.10	581	27	1705	48	668	33	1268	99			
LBC-3(1) - 20	0.1116	0.002	0.1116	0.002	0.00628	0.00096	0.00096	0.00628	0.00096	0.00628	0.00096	0.00096	17.77	510	26	1692	36	357	19	470	55			
LBC-3(1) - 21	0.0765	0.0014	0.0765	0.0014	0.0067	0.001	0.001	0.0067	0.001	0.0067	0.001	0.001	11.42	456	24	1080	36	204	14	182	31			
LBC-3(1) - 22	0.0891	0.0019	0.0891	0.0019	0.00438	0.00084	0.00084	0.00438	0.00084	0.00438	0.00084	0.00084	20.34	463	25	1212	34	185	11	114	27			
LBC-3(1) - 23	0.0868	0.002	0.0868	0.002	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD		536	33	1716	52	567	32	1190	110			
LBC-3(1) - 24	0.0543	0.0025	0.0543	0.0025	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD		464	45	1241	48	540	29	1250	110			
LBC-3(1) - 25	0.077	0.0028	0.077	0.0028	0.0043	0.001	0.001	0.0043	0.001	0.0043	0.001	0.001	17.91	494	31	1323	50	361	21	604	89			
LBC-3(1) - 31	0.27	0.011	0.27	0.011	0.077	0.0076	0.0076	0.077	0.0076	0.077	0.0076	0.0076	3.51	472	40	3680	200	758	47	911	78			
LBC-3(1) - 32	0.102	0.0021	0.102	0.0021	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD		469	37	1289	51	213	17	178	49			
LBC-3(1) - 33	0.0719	0.0017	0.0719	0.0017	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD		426	22	936	31	166	11	146	30			
LBC-3(1) - 34	0.1134	0.0031	0.1134	0.0031	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD		476	33	1365	42	179	19	36	19			
LBC-3(1) - 35	0.2636	0.0044	0.2636	0.0044	0.0103	0.0013	0.0013	0.0103	0.0013	0.0103	0.0013	0.0013	25.59	432	25	3191	73	422	16	85	20			
LBC-3(1) - 36	0.1173	0.0021	0.1173	0.0021	0.00492	0.00096	0.00096	0.00492	0.00096	0.00492	0.00096	0.00096	23.84	431	24	1453	43	214	16	88	25			
LBC-3(1) - 38	0.13	0.0022	0.13	0.0022	0.0028	0.00067	0.00067	0.0028	0.00067	0.0028	0.00067	0.00067	46.43	426	23	1578	37	218	13	87	21			
LBC-3(1) - 39	0.065	0.0014	0.065	0.0014	0.00219	0.00061	0.00061	0.00219	0.00061	0.00219	0.00061	0.00061	29.68	418	26	821	28	142.3	9	139	27			
LBC-3(1) - 40	0.0651	0.0016	0.0651	0.0016	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD	< LLD		440	24	1038	26	284	15	447	54			
LBC-3(1) - 41	0.0349	0.001	0.0349	0.001	0.00325	0.00071	0.00071	0.00325	0.00071	0.00325	0.00071	0.00071	10.74	460	24	523	29	108	13	153	33			
LBC-3(1) - 42	0.1512	0.0031	0.1512	0.0031	0.0066	0.0012	0.0012	0.0066	0.0012	0.0066	0.0012	0.0012	22.91	421	24	2018	65	302	18	176	45			
LBC-3(1) - 43	0.0732	0.0016	0.0732	0.0016	0.00255	0.00064	0.00064	0.00255	0.00064	0.00255	0.00064	0.00064	28.71	423	24	906	28	120.2	9.7	15.9	8.1			
LBC-3(1) - 44	0.0441	0.0011	0.0441	0.0011	0.00244	0.00057	0.00057	0.00244	0.00057	0.00244	0.00057	0.00057	18.07	388	20	597	23	135	11	175	30			
LBC-3(1) - 45	0.0426	0.0011	0.0426	0.0011	0.00271	0.00068	0.00068	0.00271	0.00068	0.00271	0.00068	0.00068	15.72	398	21	690	27	212	15	298	43			
LBC-3(1) - 46	0.0557	0.0012	0.0557	0.0012	0.00187	0.0005	0.0005	0.00187	0.0005	0.00187	0.0005	0.0005	29.79	375	24	672	24	95.9	8.5	23.7	8.7			

Analysis spots	Approx Pb			Pb ²⁰⁷ /U ²³⁵			Pb ²⁰⁶ /U ²³⁸			Pb ²⁰⁶ /Pb ²⁰⁴			Pb ²⁰⁷ /Pb ²⁰⁴			Pb ²⁰⁸ /Pb ²⁰⁴			FinalAgePb ²⁰⁷ /U ²³⁵			FinalAgePb ²⁰⁶ /U ²³⁸		
	ppm			Ratio			Ratio			Ratio			Ratio			Ratio			Age (Ma)			Age (Ma)		
	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Int2SE	Prop2SE	Prop2SE	Prop2SE	Age	Pro-p2SE	Pro-p2SE
LBC-3(1) - 1	0.0184	0.0031	0.0184	0.0031	2.8	0.460	0.019	5.46	0.97	0.95	0.16	1.3	0.33	3566	83	2433	86							
LBC-3(1) - 4	0.0069	0.0016	0.0069	0.0016	1.7	0.465	0.018	4.17	0.63	0.69	0.12	0.51	0.17	3502	60	2474	81							
LBC-3(1) - 6	0.0083	0.0017	0.0083	0.0017	1.9	0.469	0.019	5.06	0.6	0.789	0.097	0.57	0.15	3478	66	2471	85							
LBC-3(1) - 7	0.0188	0.0026	0.0188	0.0026	2.9	0.488	0.017	4.25	0.58	1.01	0.18	1.04	0.22	3861	64	2574	71							
LBC-3(1) - 8	0.006	0.0013	0.006	0.0013	32	0.466	0.018	4.74	0.66	0.82	0.16	0.5	0.14	3537	73	2465	79							
LBC-3(1) - 9	0.0131	0.003	0.0131	0.003	2.3	0.479	0.022	4.26	0.51	0.753	0.097	0.71	0.21	3616	65	2518	98							
LBC-3(1) - 10	0.0057	0.0015	0.0057	0.0015	2.3	0.456	0.02	4.28	0.68	0.643	0.096	0.37	0.12	3470	81	2414	89							

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Table 4a (continued)

Analysis spots	Approx Pb		Pb^{207}/U^{235}		Pb^{206}/U^{238}		Pb^{206}/Pb^{204}		Pb^{207}/Pb^{204}		Pb^{208}/Pb^{204}		FinalAge Pb^{207}/U^{235}		FinalAge Pb^{206}/U^{238}	
	ppm	Int2SE	Ratio	Prop2SE	Ratio	Prop2SE	Ratio	Int2SE	Ratio	Int2SE	Ratio	Int2SE	Age (Ma)	Prop2SE	Age (Ma)	Pro-p2SE
LBC-3(1) – 11	0.0084	0.0015	32	2.2	0.474	0.018	3.9	1.30	0.64	0.21	0.57	0.26	3530	67	2494	80
LBC-3(1) – 12	0.0108	0.0023	35.7	3.5	0.467	0.031	4.37	0.82	0.82	0.18	0.63	0.21	3634	95	2460	130
LBC-3(1) – 13	0.0427	0.0042	60.7	3.0	0.543	0.026	5.4	1.10	1.66	0.49	2.88	0.78	4177	50	2788	110
LBC-3(1) – 14	0.00274	0.0009	26.2	2.1	0.453	0.02	4.5	1.40	0.6	0.17	0.21	0.15	3323	77	2397	90
LBC-3(1) – 15	0.0084	0.0018	40.4	2.9	0.496	0.024	3.72	0.53	0.72	0.11	0.69	0.2	3777	70	2596	100
LBC-3(1) – 16	0.0263	0.0034	48.3	3.0	0.505	0.02	6.80	1.50	1.64	0.4	2.22	0.53	3969	63	2652	83
LBC-3(1) – 17	0.0419	0.0046	66.8	4.3	0.549	0.025	6.03	0.87	1.78	0.29	2.55	0.44	4283	65	2821	100
LBC-3(1) – 18	0.0372	0.0041	61.9	5.1	0.530	0.023	6.50	1.00	2.01	0.37	3.1	1.1	4117	82	2739	95
LBC-3(1) – 19	0.0781	0.0061	114.2	7.0	0.697	0.03	5.57	0.54	2.15	0.22	4.32	0.5	4820	64	3396	110
LBC-3(1) – 20	0.0293	0.0034	42.7	2.7	0.485	0.018	6.16	0.57	1.33	0.14	1.79	0.28	3806	63	2550	78
LBC-3(1) – 21	0.0109	0.0019	35.8	2.8	0.470	0.02	5.70	1.20	1.14	0.27	1.03	0.29	3631	86	2474	86
LBC-3(1) – 22	0.0073	0.0017	27.8	2.0	0.436	0.017	6.10	1.50	0.84	0.3	0.62	0.17	3399	72	2334	76
LBC-3(1) – 23	0.0744	0.0072	89.4	5.6	0.646	0.03	7.20	1.20	2.5	0.49	5.03	0.86	4579	61	3200	120
LBC-3(1) – 24	0.0789	0.007	142	12.0	0.775	0.047	6.80	1.60	3.03	0.76	6.7	1.6	5024	79	3680	170
LBC-3(1) – 25	0.0381	0.0056	64.1	4.7	0.563	0.034	5.25	0.55	1.45	0.17	2.46	0.45	4232	75	2880	140
LBC-3(1) – 31	0.0591	0.0051	40.8	2.1	0.473	0.018	17.9	5.70	4.09	0.89	4.8	1.7	3793	50	2504	83
LBC-3(1) – 32	0.0116	0.0032	30.7	2.7	0.448	0.023	5.69	0.92	0.98	0.19	0.77	0.25	3509	86	2380	100
LBC-3(1) – 33	0.0096	0.0019	34.1	2.7	0.467	0.02	5.84	0.96	0.99	0.18	0.75	0.24	3624	77	2459	87
LBC-3(1) – 34	0.0018	0.0012	23.1	2.4	0.432	0.02	7.5	1.90	0.93	0.25	0.11	0.11	3174	100	2319	91
LBC-3(1) – 35	0.0049	0.0013	24.1	1.2	0.4316	0.014	18.1	2.90	2.92	0.66	0.66	0.29	3254	47	2315	63
LBC-3(1) – 36	0.0049	0.0017	25.7	2.1	0.429	0.017	7.90	1.30	1.09	0.29	0.42	0.19	3314	79	2296	77
LBC-3(1) – 38	0.0053	0.0014	24.1	1.6	0.426	0.015	8.90	2.20	1.1	0.45	0.33	0.13	3286	62	2286	68
LBC-3(1) – 39	0.0091	0.0018	31.6	2.3	0.440	0.021	5.00	1.30	0.95	0.29	0.95	0.42	3527	75	2347	94
LBC-3(1) – 40	0.0301	0.0036	61.2	3.7	0.557	0.024	5.50	1.80	1.66	0.54	2.46	0.64	4206	62	2850	100
LBC-3(1) – 41	0.01	0.0022	40.7	5.1	0.504	0.034	2.87	0.43	0.51	0.11	0.81	0.26	3780	130	2600	140
LBC-3(1) – 42	0.0115	0.003	28.3	1.9	0.458	0.02	11.5	1.90	1.68	0.28	0.87	0.3	3420	68	2427	88
LBC-3(1) – 43	0.00096	0.0006	21.6	1.9	0.406	0.017	5.10	1.30	0.72	0.2	0.041	0.053	3165	88	2190	76
LBC-3(1) – 44	0.012	0.002	43.4	3.6	0.484	0.025	5.40	1.70	1.12	0.33	0.99	0.36	3874	84	2536	110
LBC-3(1) – 45	0.0204	0.0029	70.5	5.3	0.569	0.028	4.80	1.40	1.4	0.47	2.01	0.67	4326	74	2909	110
LBC-3(1) – 46	0.00164	0.0006	24	2.3	0.417	0.021	4.57	0.97	0.54	0.13	0.134	0.07	3220	95	2236	93

temperature of mica-Ar/Ar chronometers is between 300 and 350 °C (Harrison et al., 1985; Lovera et al., 1997; Love et al., 1998). This suggests that isotopic disturbances of younger thermal events are susceptible to affect mica-Ar/Ar chronometers. The youngest recorded thermal event within the TGB is the intrusion of the ca 177–180 Ma (Elburg and Goldberg, 2000; Hastie et al., 2014) Karroo dolerite dykes. The obtained white mica ages well coincide with a major regional tectonic event (see Section 6.3 below), suggesting the white mica Ar/Ar chronometer withstood isotopic disturbance of the youngest Karroo thermal event, thus once again supporting the reliability and robustness of the obtained 1987 ± 13 Ma age.

From the discussion elaborated above, it is therefore reasonable to postulate that at least 3 well constrained epochs of Au mineralization are recorded within the TGB. These include the 2119 ± 18 Ma and the 1987 ± 13 Ma mineralization events as revealed by the hydrothermal almandine garnet and white mica, respectively. The third Au mineralization event is related to the 2873 ± 140 Ma age, which despite its relative imprecision remains geologically meaningful as it will be discussed in the following section below.

6.3. Regional implications of the TGB dates and mineralization ages

The recorded geological events that occurred within the TGB include: deposition of the TGB (~2.7 Ga, Wilson et al., 1978; Wilson, 1979), intrusion of TTG (2.65–2.75 Ga, Bagai et al., 2002; Van Geffen, 2004), metamorphism (2630 ± 70 – 2570 ± 70 Ma, Van Breemen and Dodson, 1972) and the 177–180 Ma (Elburg and Goldberg, 2000; Hastie et al., 2014) Karroo dolerite dykes intrusion. Other geological events regionally recorded include the first and second Limpopo tectonic events. The first Neoproterozoic Limpopo Orogeny (2.70–2.65 Ga, Carney et al., 1994; Holzer et al., 1998; Tombale, 1992; Millonig et al., 2008; McCourt et al., 2004 and references therein) also referred to as Limpopo-Liberian tectonic cycle (Kröner, 1977) involved the continent-continent collision between the Zimbabwe and the Kapvaal cratons and is coeval with igneous rocks intrusion within the TGB (Tombale, 1992). The second Paleoproterozoic Limpopo-Liberian tectonic cycle (1.95–2.05 Ga, Barton et al., 1994; Kamber et al., 1995a, b; Jaekel et al., 1997; Holzer et al., 1998 and references therein) took place at the Limpopo Belt in the Central zone. This second Limpopo tectonic event is described as the shear zone-bounded metamorphic overprinting (Carney et al., 1994; Holzer et al., 1998; Tombale, 1992; Millonig et al., 2008; McCourt et al., 2004 and references therein) and characterized by prograde amphibolite facies metamorphism, which reached peak metamorphic temperatures and pressures of ~8–12 kbar, 800–850 °C (Watkeys, 1984; Holzer et al., 1998; Buick et al., 2006 and references therein), followed by retrograde P-T of 600 °C/4 kbar (Zeh et al., 2004, 2009).

The Signal Hill Au deposit 1987 ± 13 Ma white mica weighted mean Ar/Ar age coincides within error with the second Paleoproterozoic Limpopo-Liberian tectonic cycle (1.95–2.05 Ga). Therefore, this orogenic event is the likely possible event that had triggered the Au mineralization in the Signal Hill Au deposit. The Mupane 1976 ± 88 Ma (MSWD = 48) garnet Pb step wise leaching age obtained by Døssing et al. (2009) was also interpreted by the authors as an overprint of the Limpopo tectono metamorphic event in the TGB. Likewise, the 2873 ± 140 Ma Mupane sulfides Pb/Pb date coincides within error with both the early stage of the first Neoproterozoic Limpopo Orogeny (2.70–2.65 Ga) and the early stage of TTG intrusions (2.65–2.73 Ga) within the TGB. The 2873 ± 140 Ma Mupane sulfides Pb/Pb date also overlaps the mesoband BIF Pb/Pb age of 2.73 ± 0.15 Ga (Døssing et al., 2009), which was interpreted by the authors as the age of BIF deposition within the TGB. This shows the

Mupane sulfides Pb/Pb date, despite its imprecision remains geologically meaningful as it overlaps well-known regional and local geological events, as well as the time of BIF deposition with the TGB.

On the other hand, the overlapping Shashe sulfides (2250 ± 110 Ma), TGB sulfides (2227 ± 66 Ma) and TGB arsenopyrite (2220 ± 73 Ma) dates do not correlate with any known geological event both in the TGB and within the region and their significance with respect to the geological context remains undetermined. Similarly, the precise and well constrained 2119 ± 18 Ma Mupane hydrothermal almandine garnet U-Pb age does not correspond to any geological event recorded both in the TGB and in the Limpopo Belt. As indicated in Section 6.2, partial resetting of the sulfide Pb/Pb chronometer during the ca. 2.0 Ga Limpopo tectono-metamorphic event is unlikely to produce the nearly corresponding ages obtained and will therefore not fully explain the lack of coincidence with recorded geological events. Likewise, partial resetting of the 2630 ± 70 – 2570 ± 70 Ma (Van Breemen and Dodson, 1972) metamorphic garnet by the younger 1.95–2.05 Ga second Limpopo-Liberian tectono-metamorphic event is susceptible to produce the obtained 2119 ± 18 Ma age. However, the garnet U-Pb chronometer is robust and its closure temperature typically > 750 °C (Mezger et al., 1989), suggesting the garnet U-Pb chronometer is likely to have withstood isotopic disturbance related to the Limpopo Paleoproterozoic tectonic event. Therefore, based on textural evidences extensively outlined in Sections 5.4 and 6.2, the 2119 ± 18 Ma ore-related hydrothermal almandine garnet corresponds to a sulfide (and by inference gold) mineralization event. Therefore, the 2.12 Ga hydrothermal almandine garnet and the 2.2 Ga sulfide Pb/Pb ages can be related to a concealed magmatic event. This was also observed in mantle sulfides with respect to Os isotopes, which, due to initial Os isotopic heterogeneity, yielded an imprecise age that has no surface expression, but correlates with far-field tectonic events that caused intralithospheric Os remobilization (Aulbach et al., 2018).

From the discussion elaborated above, it is evident that the Au mineralization at TGB is consistent with multiple mineralization events, with two of them possibly triggered by major geotectonic events. One of the Au mineralization events at Mupane may correspond to the beginning of the first Limpopo-Liberian tectonic cycle and associated TTG emplacement, while Signal Hill Au deposit is coincident with the second Limpopo-Liberian tectonic cycle (see Fig. 10).

6.4. Implications for the TGB genetic model

The TGB is an Archean greenstone belt that hosts numerous gold deposits/mineral occurrences of various styles. Based on their association with greenschist-amphibolite facies metamorphic rocks, the nature of the gold mineralization host rocks, the ore mineral assemblages, the spatial association with structures such as shear zones and the mode of occurrences of gold, the style of gold mineralization within the TGB is therefore consistent with orogenic gold found in the greenstone belts worldwide.

Deciphering the timing of gold mineralization with respect to metamorphism and deformation is a critical step when aiming at fully understanding the genesis of gold deposits in greenstone belts. It is in this regard that greenstone-hosted Au deposits are classified into post, syn and pre-metamorphic greenstone-hosted Au deposits. With regard to the timing of metamorphism within the TGB (2630 ± 70 – 2570 ± 70 Ma, Van Breemen and Dodson, 1972), the well constrained Signal Hill (1987 ± 13 Ma) and Mupane (2119 ± 18 Ma) Au mineralization events are all post-metamorphic, thus similar to the nearby South African Kalahari Goldridge (Hammond and Moore, 2006) and New Consort (Dziggel et al., 2010) Au deposits

Table 4b
Summary garnet LA-ICPMS U-Pb geochronology data for aliquot LBC-3 (2).

Analysis spots	U ²³⁸			Aprox U			Th ²³²			Approx Th			Final U/ Th			Pb ²⁰⁶			Pb ²⁰⁷			Pb ²⁰⁸		
	ppb	Int2SE	ppm	Int2SE	ppm	Int2SE	ppm	Int2SE	Ratio	ppb	Int2SE	Ratio	ppb	Int2SE	ppb	Int2SE	ppm	Int2SE	ppb	Int2SE	ppm	Int2SE		
LBC-3(2) - 1	0.0503	0.0016	0.0503	0.0016	< LLD	< LLD	0.0016	< LLD	< LLD	< LLD	< LLD	< LLD	881	46	779	42	122	13	36	20				
LBC-3(2) - 2	0.0655	0.0021	0.0655	0.0021	< LLD	< LLD	0.0021	< LLD	< LLD	< LLD	< LLD	< LLD	825	62	1050	45	152	12	80	31				
LBC-3(2) - 3	0.0758	0.0019	0.0758	0.0019	0.0045	0.0012	0.0019	0.0045	16.84	907	48	1270	49	204	17	173	53							
LBC-3(2) - 4	0.0994	0.0024	0.0994	0.0024	< LLD	< LLD	0.0024	< LLD	< LLD	842	60	1782	55	384	35	510	100							
LBC-3(2) - 5	0.0829	0.0032	0.0829	0.0032	< LLD	< LLD	0.0032	< LLD	< LLD	707	49	1476	44	343	35	391	79							
LBC-3(2) - 6	0.0804	0.0024	0.0804	0.0024	< LLD	< LLD	0.0024	< LLD	< LLD	757	42	1547	69	381	30	517	84							
LBC-3(2) - 7	0.0971	0.0029	0.0971	0.0029	< LLD	< LLD	0.0029	< LLD	< LLD	763	65	1802	77	500	43	650	130							
LBC-3(2) - 8	0.0546	0.0022	0.0546	0.0022	< LLD	< LLD	0.0022	< LLD	< LLD	782	71	1140	57	329	37	600	110							
LBC-3(2) - 9	0.0881	0.0018	0.0881	0.0018	0.0050	0.0008	0.0018	0.0050	17.66	793	35	1470	36	279	16	293	45							
LBC-3(2) - 10	0.0962	0.0019	0.0962	0.0019	0.0036	0.0006	0.0019	0.0036	26.57	763	39	1477	35	209	13	114	24							
LBC-3(2) - 11	0.1086	0.0019	0.1086	0.0019	0.0044	0.0007	0.0019	0.0044	26.43	732	33	1665	37	240	13	134	31							
LBC-3(2) - 12	0.1042	0.002	0.1042	0.002	0.0050	0.0008	0.002	0.0050	20.67	728	36	1537	39	213	11	88	20							
LBC-3(2) - 13	0.088	0.0023	0.088	0.0023	0.0043	0.0008	0.0023	0.0043	20.47	749	35	1257	37	180	13	64	18							
LBC-3(2) - 14	0.0978	0.0018	0.0978	0.0018	0.0038	0.0007	0.0018	0.0038	25.94	742	33	1435	34	207	9.7	84	20							
LBC-3(2) - 15	0.194	0.022	0.194	0.022	0.0161	0.0046	0.022	0.0161	12.05	722	31	3040	340	414	40	205	35							
LBC-3(2) - 16	0.0717	0.0016	0.0717	0.0016	0.0045	0.0008	0.0016	0.0045	15.90	610	26	1074	33	199	12	163	28							
LBC-3(2) - 17	0.0635	0.0015	0.0635	0.0015	0.0037	0.0007	0.0015	0.0037	17.02	643	27	1052	33	182	14	138	26							
LBC-3(2) - 18	0.0629	0.0014	0.0629	0.0014	< LLD	< LLD	0.0014	< LLD	< LLD	674	30	950	32	137	9.4	78	21							
LBC-3(2) - 19	0.0603	0.0012	0.0603	0.0012	0.0030	0.0007	0.0012	0.0030	20.17	602	31	919	29	135	11	83	25							
LBC-3(2) - 20	0.0405	0.0013	0.0405	0.0013	< LLD	< LLD	0.0013	< LLD	< LLD	601	35	791	39	251	17	377	73							
LBC-3(2) - 21	0.0806	0.0016	0.0806	0.0016	0.0032	0.0007	0.0016	0.0032	25.35	606	27	1164	36	175	11	99	23							
LBC-3(2) - 22	0.0928	0.0018	0.0928	0.0018	0.0039	0.0008	0.0018	0.0039	24.10	621	28	1398	31	213	14	118	26							
LBC-3(2) - 23	0.0687	0.0017	0.0687	0.0017	0.0025	0.0005	0.0017	0.0025	28.04	537	30	1006	26	173	15	138	34							

Analysis spots	Approx Pb			Pb ²⁰⁷ /U ²³⁵			Pb ²⁰⁶ /U ²³⁸			Pb ²⁰⁶ /Pb ²⁰⁴			Pb ²⁰⁷ /Pb ²⁰⁴			Pb ²⁰⁸ /Pb ²⁰⁴			FinalAgePb ²⁰⁷ /U ²³⁵			FinalAgePb ²⁰⁶ /U ²³⁸		
	ppm	Int2SE	Ratio	Prop2SE	Ratio	Prop2SE	Ratio	Int2SE	Ratio	ppm	Int2SE	Ratio	Int2SE	Ratio	ppb	Int2SE	Ratio	Age (Ma)	Prop2SE	Age (Ma)	Pro- p2SE			
LBC-3(2) - 1	0.002	0.001	25.7	2.9	0.41	0.03	1.18	0.11	0.178	0.022	0.04	0.028	0.178	0.022	0.04	0.028	0.178	0.022	3340	110	2240	130		
LBC-3(2) - 2	0.004	0.002	26.6	2.4	0.44	0.025	1.87	0.24	0.268	0.032	0.12	0.053	0.268	0.032	0.12	0.053	0.268	0.032	3356	100	2360	120		
LBC-3(2) - 3	0.009	0.003	31.1	3.2	0.47	0.024	1.94	0.17	0.306	0.037	0.3	0.096	0.306	0.037	0.3	0.096	0.306	0.037	3492	98	2517	96		
LBC-3(2) - 4	0.027	0.006	44.3	4.2	0.51	0.023	3.79	0.58	0.77	0.130	0.99	0.230	0.77	0.130	0.99	0.230	0.77	0.130	3860	97	2661	99		
LBC-3(2) - 5	0.021	0.004	47.3	5.4	0.5	0.029	3.33	0.37	0.775	0.095	0.79	0.160	0.775	0.095	0.79	0.160	0.775	0.095	3970	110	2620	120		
LBC-3(2) - 6	0.027	0.005	53.0	4.5	0.54	0.03	3.08	0.34	0.763	0.095	1.06	0.210	0.763	0.095	1.06	0.210	0.763	0.095	4061	89	2770	130		
LBC-3(2) - 7	0.034	0.007	59.8	5.5	0.53	0.029	3.74	0.5	0.96	0.14	1.26	0.250	0.96	0.14	1.26	0.250	0.96	0.14	4180	94	2770	130		
LBC-3(2) - 8	0.032	0.006	72.0	8	0.59	0.042	2.33	0.34	0.71	0.13	1.19	0.240	0.71	0.13	1.19	0.240	0.71	0.13	4370	120	2970	170		
LBC-3(2) - 9	0.016	0.002	37.7	2.8	0.48	0.019	2.76	0.19	0.543	0.061	0.64	0.110	0.543	0.061	0.64	0.110	0.543	0.061	3712	76	2525	80		
LBC-3(2) - 10	0.005	0.001	26.1	2	0.45	0.016	3.69	0.62	0.48	0.15	0.27	0.081	0.48	0.15	0.27	0.081	0.48	0.15	3319	72	2400	71		
LBC-3(2) - 11	0.007	0.002	26.2	1.9	0.44	0.017	3.95	0.35	0.574	0.064	0.33	0.094	0.574	0.064	0.33	0.094	0.574	0.064	3357	68	2338	75		
LBC-3(2) - 12	0.004	0.001	25.3	1.6	0.44	0.016	3.70	1.00	0.500	0.21	0.29	0.091	0.500	0.21	0.29	0.091	0.500	0.21	3322	64	2348	71		
LBC-3(2) - 13	0.003	1E-03	25.2	2.1	0.42	0.016	2.65	0.19	0.385	0.038	0.14	0.044	0.385	0.038	0.14	0.044	0.385	0.038	3302	80	2288	74		
LBC-3(2) - 14	0.005	0.001	26.1	1.4	0.44	0.015	3.26	0.87	0.522	0.061	0.24	0.065	0.522	0.061	0.24	0.065	0.522	0.061	3354	54	2363	65		
LBC-3(2) - 15	0.011	0.002	28.3	1.9	0.46	0.017	7.42	0.93	1.070	0.18	0.56	0.140	1.070	0.18	0.56	0.140	1.070	0.18	3402	60	2435	77		
LBC-3(2) - 16	0.009	0.002	33.7	2.6	0.45	0.019	3.06	0.25	0.576	0.066	0.57	0.120	0.576	0.066	0.57	0.120	0.576	0.066	3569	80	2385	83		
LBC-3(2) - 17	0.007	0.002	35.5	3.5	0.49	0.021	3.02	0.33	0.519	0.068	0.44	0.100	0.519	0.068	0.44	0.100	0.519	0.068	3591	88	2554	92		
LBC-3(2) - 18	0.004	0.001	26.5	2.1	0.44	0.022	2.4	0.22	0.337	0.039	0.17	0.055	0.337	0.039	0.17	0.055	0.337	0.039	3333	81	2359	97		
LBC-3(2) - 19	0.001	0.001	27.2	2.4	0.44	0.019	2.79	0.32	0.420	0.055	0.24	0.076	0.420	0.055	0.24	0.076	0.420	0.055	3341	84	2350	90		
LBC-3(2) - 20	0.004	0.001	73.9	5.5	0.56	0.038	2.34	0.29	0.714	0.079	1.09	0.230	0.714	0.079	1.09	0.230	0.714	0.079	4360	76	2820	160		
LBC-3(2) - 21	0.021	0.004	27.3	1.9	0.44	0.017	4.16	0.57	0.630	0.11	0.44	0.200	0.630	0.11	0.44	0.200	0.630	0.11	3380	70	2372	79		

Continued on next page

Table 4b (continued)

Analysis spots	Approx Pb		Pb^{207}/U^{235}		Pb^{206}/U^{238}		Pb^{206}/Pb^{204}		Pb^{207}/Pb^{204}		Pb^{208}/Pb^{204}		FinalAge Pb^{207}/U^{235}		FinalAge Pb^{206}/U^{238}	
	ppm	Int2SE	Ratio	Prop2SE	Ratio	Prop2SE	Ratio	Int2SE	Ratio	Int2SE	Ratio	Int2SE	Age (Ma)	Prop2SE	Age (Ma)	Prop2SE
LBC-3(2) - 24	0.007	0.002	28.4	2.1	0.45	0.017	4.20	0.35	0.638	0.072	0.38	0.092	3442	72	2410	78
LBC-3(2) - 25	0.007	0.002	30.5	3.0	0.45	0.019	3.49	0.35	0.630	0.110	0.58	0.190	3450	110	2381	84

LLD: lower limit of detection.

and the Zimbabwe Renco (Kolb and Meyer, 2002) greenstone-hosted Au deposits, whereas the geologically meaningful 2873 ± 140 Ma Mupane Au mineralization event is pre-metamorphic.

The > 400 Ma age difference between metamorphism and Au mineralization events raises the question of the origin of mineralizing fluids, which is also another key question pertaining to the genesis of orogenic gold deposits, that has to be addressed. Though mineralizing fluids in greenstones belt-hosted Au deposits are well constrained to have derived from metamorphic dehydration (Groves et al., 1998; McCuaig and Kerrich, 1998; Jia et al., 2003; Goldfarb and Groves, 2015), our radiometric data show that mineralization within the TGB took place significantly before and after metamorphic devolatilization was complete, thus ruling out the involvement of metamorphic fluids in the mineralizing process (es). The synchronicity between the Mupane 2873 ± 140 Ma sulfides Pb/Pb age and the 2.65–2.75 Ga TTG, as well as, the overlap in Pb isotope compositions between sulfides and granodiorite point to a possible genetic link between the TTG intrusions and gold mineralization event (s) and consequently the involvement of magmatic fluids in the TGB mineralizing process(es).

Based on the discussion elaborated above it appears that, with respect to the orogenic events, Au mineralization within the TGB is of two main events. These include: (i) the pre-metamorphic Au mineralization event, which was likely promoted by the intrusion of the TTG (as supported by the overlap in Pb compositions between sulfides and granodiorite, as well as the synchronicity between sulfides and TTG), which triggered the 2873 ± 140 Ma Mupane Au mineralization event, and (ii) the post-metamorphic Au mineralization event, which led to the genesis of at least two gold mineralization events at 2119 ± 18 Ma and 1987 ± 13 Ma, in Mupane and Signal Hill, respectively. As there is a huge time gap between the two gold mineralization events and metamorphism and related devolatilization process, it is postulated that metamorphic fluids are not likely to have contributed to the gold mineralization processes.

6.5. Global significance and relevance of the TGB study

As outlined in Section 6.4, the TGB is consistent with orogenic gold found in the Archaean greenstones belt worldwide. In addition, mineralization at Mupane is a BIF-GIF-hosted gold deposit that shares some similarities with many Precambrian greenstone BIF-hosted Au deposits worldwide, such as, the Homestake Au deposit of South Dakota in USA (Goldfarb et al., 2005; Morelli et al., 2010), Musselwhite Au deposit in Canada (Hill et al., 2006; Kolb, 2011; McNicoll et al., 2016), Kalahari Goldridge Au deposit in South Africa (Hammond and Moore, 2006), Lamego Au deposit (Martins et al., 2016) and São Sebastião Au deposit (Brando Soares et al., 2018) in Brazil, to name a few.

From our radiometric dates, at least 3 well constrained epochs of Au mineralization are recorded within the TGB. The 2119 ± 18 Ma and the 1987 ± 13 Ma gold mineralization events as revealed by the hydrothermal almandine garnet and white mica, respectively are consistent with the 2100–1800 Ma (Goldfarb et al., 2005) major period of orogenic gold deposits formation in the Precambrian. Our radiometric data further indicate Au mineralization within the TGB is pre-to-post-metamorphic. Numerous post and pre-metamorphic greenstone-hosted Au deposits are known worldwide. Worldwide examples of post-metamorphic greenstone-hosted Au deposits include: South Dakota Homestake in USA (Caddey et al., 1991; Terry et al., 2003; Frei et al., 2009), Hemlo in Canada (Phillips and Powell, 2009), Hutti in South India (Rogers et al., 2003, 2007; Kolb et al., 2005), Big Bell in Western Australia (Phillips and Powell, 2009), Challenger in South Australia (Phillips and Powell, 2009), Tropicana in the Yilgarn Craton (Blenkinsop and Doyle, 2014), whereas Mount Olympus Au deposit in Western Australia (Sheppard et al., 2010; Fielding et al., 2018) is a classic example of pre-metamorphic greenstone-hosted Au deposit.

Furthermore, our radiometric data, in conjunction with Pb isotope characteristics rule out the involvement of metamorphic fluids in the

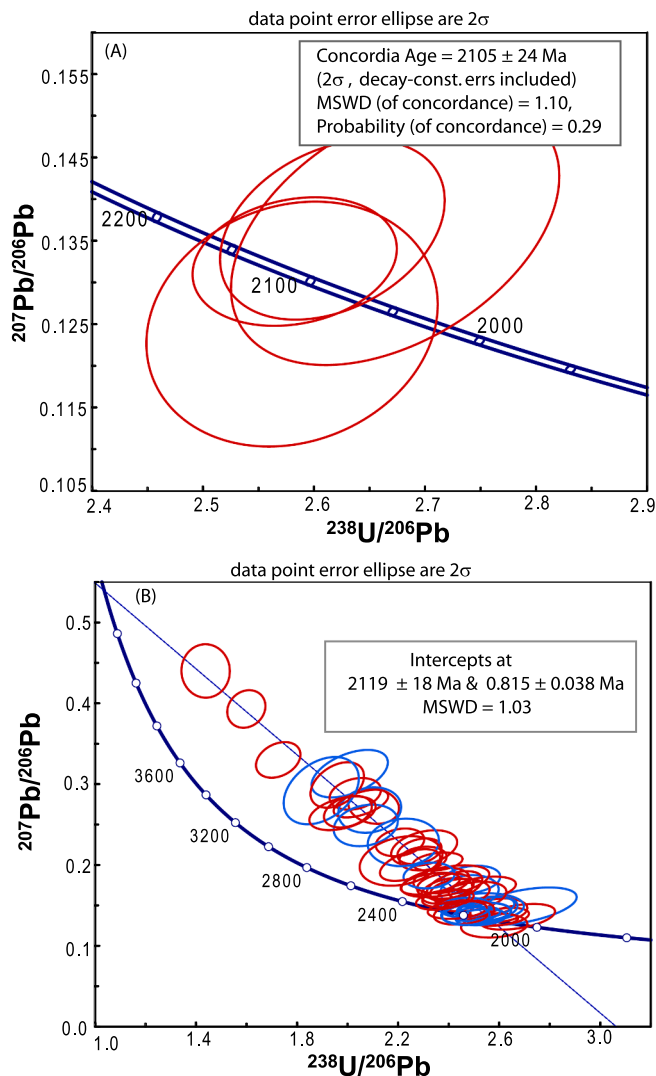


Fig. 9. Tera-Wasserburg concordia (A) and intercept (B) plots showing Mupane hydrothermal almandine garnet yielded a concordia age of 2105 ± 24 Ma (MSWD of concordance = 1.10) and lower intercept $^{206}\text{Pb}/^{238}\text{U}$ age of 2119 ± 18 Ma (MSWD = 1.03), respectively.

mineralizing process (es); but rather point to a possible genetic link between gold mineralization events and magmatism. The spatial and genetic association between orogenic intrusions and the orogenic gold systems is documented worldwide (cf. Groves et al., 1998; Goldfarb et al., 2001) and numerous works (Mueller, 1997; Mueller et al., 2004; Ciobanu et al., 2010; McFarlane et al., 2011; Ootes et al., 2011; Wyman et al., 2016) also evoked the possibility of involvement of magmatic mineralizing fluids in the genesis of orogenic gold deposits. For example, a genetic link between gold mineralization and granitic magmatism was similarly established at Homestake deposit on the basis of overlap between Pb isotope composition of galena and feldspar from a pegmatitic granite (Frei et al. 2009). This genetic link established through Pb isotope compositions was then after constrained based on geochronological evidences (Morelli et al., 2010). Likewise, granitoids in the Kalahari Goldridge Archean greenstone BIF-hosted Au deposits were reported to have been the source of the mineralizing fluids

(Hammond and Moore, 2006) and granitoids in São Sebastião Au deposit in Brazil provided the heat effect that possibly promoted mineralizing fluids flow (Brando Soares et al., 2018).

Based on the discussion elaborated above, it is clear that in terms of epoch of mineralization, time frame of mineralization with respect to metamorphism, as well as the involvement of magmatism in the genesis of Au deposits, the TGB Au deposits are consistent with many greenstone-hosted gold deposits worldwide. From the current study, it can also be highlighted that Au preconcentrated in crustal rocks, such as schists and black shales, was remobilized during regional tectono-thermal events, thus leading to the formation of the TGB Au deposits. Such a process is likely to occur in other geological environments worldwide, provided similar favorable conditions exist. Therefore, the results obtained during the current investigation are not solely of local/regional interest, but can also be efficiently used as proxy to characterize greenstone-hosted gold deposits worldwide.

7. Conclusions

This study aimed at further constraining the genesis of Au deposits/mineral occurrences found in the Tati Greenstone Belt of northeastern Botswana, by shedding light on both the genetic relationships between Au deposits/mineral occurrences and the source(s) of Au. At the end of this investigation, the following conclusions can be drawn:

1. The sulfide Pb isotope compositions within the TGB are heterogeneous, indicating multiple Pb and by inference Au rock sources, which are possibly granodiorite from Signal Hill and Mupane and Map Nora's schist;
2. The Au deposits/mineral occurrences within the TGB are not co-genetic and formed through numerous Au mineralization events, 3 of which were constrained and these include: the first Mupane 2873 ± 140 Ma Au mineralization event, the second Mupane 2119 ± 18 Ma Au mineralization event and the 1987 ± 13 Ma Signal Hill Au mineralization event;
3. The Au Mineralization events within the TGB also coincide with major regional geotectonic activities, with the first Mupane Au mineralization event coinciding with the 2.70–2.65 Ga first Neoproterozoic Limpopo-Liberian tectonic cycle, whereas the Signal Hill Au mineralization event is coincident with the 1.95–2.05 Ga Paleoproterozoic Limpopo-Liberian tectonic cycle;
4. Gold mineralization within the TTG is also of two main events comprising the pre-metamorphic Au mineralization event, which was likely promoted by the intrusion of the 2.65–2.75 Ga TTG and the post metamorphic Au mineralization event, which led to at least two gold mineralization events, associated with the 2119 ± 18 Ma and 1987 ± 13 Ma Au mineralization events at Mupane and Signal Hill, respectively;
5. As there is a huge time gap between the two gold mineralization events and metamorphism and related devolatilization process, we postulate that metamorphic fluids are not likely to have contributed to the gold mineralization processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

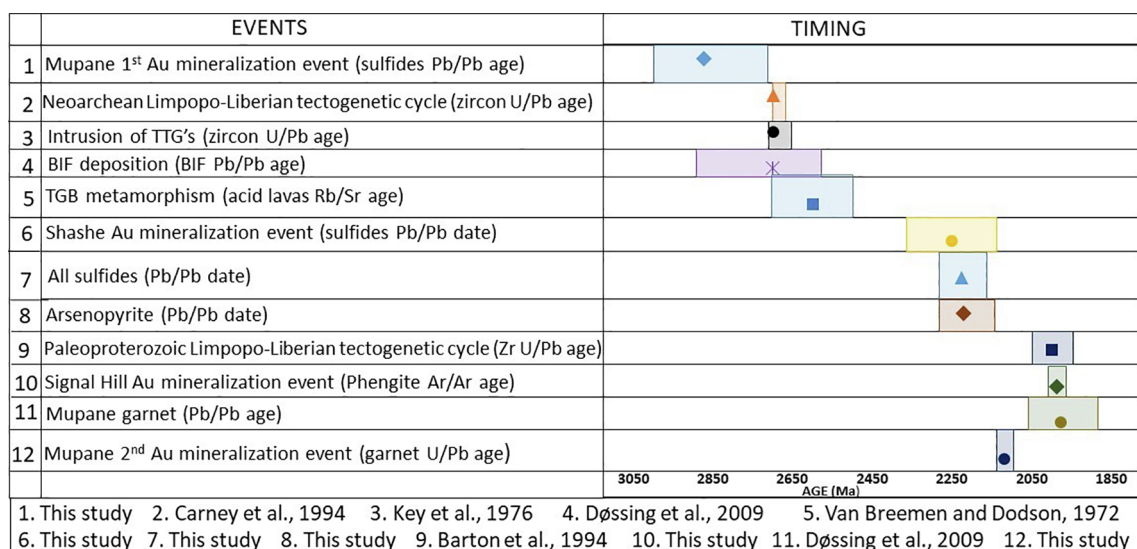


Fig. 10. Summary of the recorded geological events that occurred within the TGB and the nearby Limpopo Belt and its correlation with the TGB Au mineralization events.

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Appendix A

Appendix 1

U, Th and Pb contents used to calculate the initial Pb isotope compositions of rocks spatially associated with the TGB investigated Au deposits.

Sample ID	Pb (ppm)	Th (ppm)	U (ppm)
GEP 31	119	1.4	0.87
GEP 1	13	0.7	0.55
LBC 4	< 5	1.8	0.99
SG 5	34	3.4	1.95
SH 8	< 5	1.6	0.77
SH 5	10	1.3	0.56
LB 10	86	9.5	4.50
GEP 25 V	8	1.7	0.58

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.precamres.2020.105623>.

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