

**CONSTRAINTS ON THE GENESIS OF GOLD IN THE TATI GREENSTONE BELT OF
NORTHEASTERN BOTSWANA: INSIGHTS FROM INTEGRATIVE
GEOCHRONOLOGY AND Pb ISOTOPE COMPOSITIONS**

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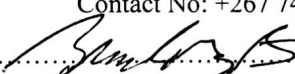
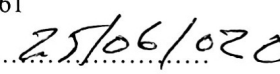
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Date...*25/06/2020*.....

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ABSTRACT

The NW trending Archean Tati Greenstone Belt is located in the southwestern part of the Zimbabwe Craton, in northeastern Botswana and consists of mafic to felsic volcanic rocks and metasediments. All rocks in the TGB have undergone greenschist facies metamorphism at $2630 \pm 70 - 2570 \pm 70$ Ma and intrusion of granitoids that comprises of granodiorite, tonalites, quartz diorite and monzonite occurred at 2.65- 2.73 Ga. The TGB is host to numerous Au deposits including from NW to SE: Map Nora, Golden Eagle, Mupane and Signal Hill. In order to unravel the genetic relationships between the different Au mineralization areas and to track the sources of gold, Ar/Ar geochronology, U/Pb geochronology, Pb/Pb geochronology and Pb isotope analyses were carried out.

The Pb/Pb dating of sulfides from the Mupane Au deposit yielded a Pb/Pb errorchron age of 2873 ± 140 Ma, pointing to a pre-metamorphic mineralization event, whereas Shashe sulfides (Map Nora and Golden Eagle), all sulfides and all arsenopyrite from both Mupane and Shashe deposits yielded overlapping and post-metamorphic Pb/Pb errorchron dates of 2250 ± 110 Ma, 2226 ± 66 Ma and 2220 ± 73 Ma, respectively. The U/Pb dating of hydrothermal almandine garnet that is spatially associated with the Mupane Au mineralization yielded overlapping concordia ages and a Tera-wasserburg lower intercept $^{206}\text{Pb}/^{238}\text{U}$ age of 2105 ± 24 Ma and 2119 ± 18 Ma, respectively. The ages also correspond to a post-metamorphic type of Au mineralization. Furthermore, phengite spatially associated with the Signal Hill Au mineralization yielded an Ar/Ar plateau age of 1987 ± 24 Ma and a weighted mean Ar/Ar ages of 1976 ± 31 Ma and 1987 ± 13 Ma, also suggesting a post-metamorphic ($2630 \pm 70 - 2570 \pm 70$ Ma) mineralization event. The 2873 ± 140 Ma Pb/Pb age of Mupane Au mineralization coincides within error with the age of BIF deposition (2.73 ± 0.15 Ga), intrusion of granitoids (2.65 - 2.73 Ga) in the TGB and also correlates within error with the ca 2.7 Ga first Limpopo-Orogeny (Limpopo-Liberian tectogenetic cycle). The phengite Ar/Ar ages coincide within error with the 1.95 - 2.05 Ga second Limpopo-Liberian tectogenetic cycle, which is here considered to have possibly triggered the Au mineralization in the Signal Hill Au deposit. The garnet ages do not correspond to any geotectonic event known both locally and regionally. The results clearly indicate that the Au mineralization across the TGB is of various ages and corresponds to at least three temporally distinct gold mineralization events, with two of them triggered by regional geotectonic events.

Lead isotope compositions of both sulfides and whole rocks are heterogeneous. Sulfides show, $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of 14.274 - 29.711, $^{207}\text{Pb}/^{204}\text{Pb}$ of 14.957 - 17.179 and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios ranging from 33.962 - 65.243, whereas the whole rocks have $^{206}\text{Pb}/^{204}\text{Pb}$ ratios range from 13.491 - 17.739, $^{207}\text{Pb}/^{204}\text{Pb}$ from 14.550 - 15.538 and $^{208}\text{Pb}/^{204}\text{Pb}$ from 33.744 - 38.261. Lead isotope compositions of both whole rocks and sulfides from Golden Eagle, Mupane and Signal Hill Au deposits overlap and the possible sources of Pb are granodiorite from Signal Hill, schist from Mupane and Map Nora Au deposits. At Map Nora however, arsenopyrite has a wide range of Pb isotopic compositions, $^{206}\text{Pb}/^{204}\text{Pb}$ range from 29.011 - 29.711, $^{207}\text{Pb}/^{204}\text{Pb}$ from 17.118 - 17.179 and the $^{208}\text{Pb}/^{204}\text{Pb}$ range from 59.921 - 65.243, suggesting that the Au source rock is likely the black shale because is the more radiogenic lithology that is known to occur in the Map Nora area.

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LIST OF ABBREVIATIONS

Act - Actinolite

Ar – Argon

Aspy – Arsenopyrite

Au - Gold

BIF- Banded Iron Formation

Bn – Bornite

Bt-Sc – Biotite schist

Cpy - Chalcopyrite

Cu - Copper

Dol – Dolerite

GIF – Graphitic Iron Formation

Grano – Granodiorite

LC – Lower Crust

M – Mantle

MSWD – Mean square of the weighted deviation

OR – Orogen

Pb – Lead

PbSL- Pb-stepwise leaching

Po - Pyrrhotite

Py – Pyrite

Qtz-Cal vein – Quartz- calcite vein

Sc – Schist

Sph - Sphalerite

TGB – Tati Greenstone Belt

TTG- Tonalite-Trondhjemite-granodiorite

UC – Upper Crust

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CHAPTER 1: GENERAL INTRODUCTION

This chapter covers the background of the study, aims and objectives, problem statement, methodology, output of the current study, as well as the outline of the thesis.

1.1. BACKGROUND

The Archean Tati Greenstone Belt (TGB) is located in the southwestern part of the Zimbabwe Craton, in northeast Botswana. The TGB is comprised of basic metavolcanics and less abundant intermediate or acid metavolcanics and minor clastic and chemical metasediments including marble and banded iron-formation (Dossing et al., 2009). The TGB has been intruded by granitoids consisting of mildly deformed tonalite, trondjemite, granodiorite and minor quartz monzonite, monzonite and quartz diorite (Aldiss, 1991), as well as Karoo dolerite dykes (Elburg and Goldberg, 2000; Hastie et al., 2014). The TGB is host to (i) the Tati Ni-Cu Mine associated with basic/ultrabasic meta-igneous rocks (Aldiss, 1991; Maier et al., 2008), as well as (ii) numerous gold and minor silver deposits / mineral occurrences in veins and shear zones (Aldiss, 1991). According to Tombale (1992), gold mineralization in the TGB occurred in three stages that comprises of Au related to volcanism, gold that coincided with deformation and Au related to D₃ shearing of the volcanic rocks and granitoids magmatism.

The TGB hosts numerous Au deposits, and the ones under investigation in this study include from NW to SE: Map Nora, Golden Eagle, Mupane and Signal Hill (Fig. 2.2). The Golden Eagle and Map Nora Au deposits are grouped together to form Shashe group of mines. These Au deposits are all owned by the Galane Gold Ltd.

The gold mineralization in the TGB is hosted by various formations. Map Nora and Golden Eagle Au deposits are hosted by the Lady Mary Formation (see chapter 2) and the Au mineralization in these deposits is hosted by schist (Tombale, 1992). The Penhalonga Formation (see chapter 2) is host to Mupane Au deposits that consists of four sub-zones (see deposits geology section in chapter 2). The Signal Hill Au deposit is hosted by Sb-Au bearing quartz veins in metasedimentary rocks (Tombale, 1992).

The gold mineralization occurring in these deposits mainly includes pyrite, pyrrhotite, arsenopyrite, chalcopyrite, bornite, galena and sphalerite. Gold occurs as an inclusion in arsenopyrite and pyrite (Tombale, 1992).

1.2. PROBLEM STATEMENT

Several studies including geochronology, geochemistry, geological and mineral paragenesis that were carried out previously in the TGB (Tombale, 1992; Bagai et al., 2002; Kampunzu et al., 2003; McCourt et al., 2004 and Døssing et al., 2009) did not investigate the source(s) of gold and epoch of its emplacement. Likewise, the genetic relationship between the Au deposits / mineral occurrences within the TGB has not been established. The age of the Au mineralization in the TGB remain poorly constrained. Therefore, it was important to carry out this investigation in order to further constrain the genesis of Au mineralization occurring in the TGB and then contribute in designing mineral exploration models, which are likely to assist in the discovery of mineral resources in the TGB.

1.3. AIM AND OBJECTIVES

The aim of this investigation is to further constrain the genesis of Au mineralization occurring within the Tati Greenstone Belt. This will be achieved by:

- 1) Tracking the source(s) of Pb and by inference Au;
- 2) Investigating the age(s) of the Au mineralization events through the TGB;
- 3) Assessing the temporal and by inference the genetic relation between Au mineral occurrences within the TGB.

1.4. METHODOLOGY

Field work and laboratory works were carried out in order to achieve the objectives of the research study.

1.4.1. Field work

Field work involved field observations and sample collection across the Tati Greenstone Belt. Ore samples were collected in the open pits of Mupane (Tau pit), Golden Eagle, Signal Hill and Map Nora. Additional samples were collected from the stockpiles from these pits and from the drill cores from Tau pit. Samples of rocks spatially associated with mineralization were also collected

from these areas and these included amphibolite, granodiorite, dolerite, sandstone and biotite schist.

1. 4.2. Laboratory methods

Selected samples collected from the field were sent for thin section preparations at the University of Johannesburg, South Africa. Thin section assessment was done at Botswana International University of Science and Technology (BIUST) using transmitted and reflected light microscope to identify the ore and gangue minerals and also to assess textural relationships of ore and gangue minerals, which were later be subjected to Pb isotope analysis and sulfides Pb/Pb, garnet U/Pb and phengite Ar/Ar geochronology techniques.

Sulfide Pb isotope laboratory work involves crushing of samples followed by handpicking under a stereo-microscope then treated in ultrasonic cleaner using ethanol. Samples of 9 whole rocks that are spatially associated with the Au mineralization in the TGB were also pulverized and sent together with 9 pure sulfide concentrate samples (including 3 pyrrhotite, 5 arsenopyrite and 1 pyrite) for Lead isotope analysis. The Pb isotope analysis was performed at the Department of Mineralogy of the University of Geneva, Switzerland in order to determine the source of lead in whole rocks and in sulfides, and by inference the source of gold. The Pb isotope measurements obtained were also used to assess the age(s) of Au mineralization across TGB. Lead isotope ratios for both sulfides and whole rocks were measured using the Thermo Finnigan TRITON mass spectrometer on Faraday cups in static mode, following the method described by Bineli Betsi et al. (2013, 2017 and 2018). All measurements were corrected for internal fractionation using $^{203}\text{Tl}/^{205}\text{Tl} = 0.418922$ 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.4.15 Excel macro of Ludwig (2003).

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 (see appendix A2).

The in situ U/Pb LA-ICP-MS age determination of garnet that is genetically associated to the Au mineralization was carried out at the Department of Earth Sciences of the University of New Brunswick, Canada using a Wavelength Resonetics M-50-LR 193-nm Excimer laser ablation system coupled to an Agilent 7700× ICP-MS. The NIST612 was used as primary standard. Operating conditions of the ablation system included 30 seconds ablations and 30 seconds backgrounds with crater size of 210 μm diameter and 4 Hz rep rate with 4 J/cm^2 fluence. Grandite garnet from the 386 Ma MacKenzie Gulch Cu-skarn was used to derive an empirical correction that was then applied to the unknowns. The U/Pb data that was obtained was used to calculate the age of garnets using Isoplot v.4.15 Excel macro of Ludwig (2003).

X-ray diffraction (XRD) was performed on samples consisting of alteration minerals, which were very fine grained and difficult to determine using optical microscope. As an example, the XRD helped in confidently identifying phengite, which was identified as sericite at the field. The XRD analysis was carried out at the Department of Physics and Astronomy, Botswana International University of Science and Technology, using a Bruker D8 Advanced power diffractometer with a 3.0 Kw generator, a copper (Cu) tube X-Ray source and also a Lynx-eye XE energy dispersive strip detector. The radiation used was $\text{K}\alpha$ with a wavelength of 1.54056 within the values of 2 θ between (5 and 90) degrees and steps of 0.029 degrees with a time of 0.45 sec/step. The machine was run at 40 Ma and 40 Kv. Data obtained was analyzed using MATCH3! Software, which compares each diffraction pattern in the reference pattern database to the pattern of the unknown sample (see appendix A1).

Phengite (as determined by XRD) associated with Au mineralization at the Signal Hill Au deposit was collected for Ar/Ar dating that was carried out at the University of Manitoba, Canada. Sample analysis followed the same method used by Bineli Betsi et al. (2017). The Phengite 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 CO_2 laser (Bineli Betsi et al., 2017). The Faraday detectors with low noise of $1 \times 10^{12} \Omega$ resistors were used to measure Ar isotopes from mass of 40 to 37, and mass 36 was measured using a compact dynode (CDD) detector (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.4.15 Excel macro of Ludwig (2003).

1.5. OUTPUT OF THE CURRENT STUDY

The economic benefit of unraveling the source of gold and the genetic relationships between the Au mineralization and the spatially associated host rocks is that it will contribute in designing mineral exploration models and guidelines, which are likely to lead to further discovery of mineral resources in the TGB.

1.6. THESIS ORGANIZATION

The thesis contains 6 chapters.

Chapter 1 is the introductory chapter and it covers the background of study, problem statement, aims and objectives, analytical techniques used as well as the output of the thesis.

Chapter 2 presents the geological setting; it covers the regional, local geology, the metallogeny of TGB, as well as the investigated deposits geology.

Chapter 3 is an outline of mineralogy and style of mineralization of the TGB deposits that are investigated in this study. This includes the presentation of the gangue and ore mineralogy found in each Au deposit, accompanied by both field photos and microphotographs. The chapter also outlines the similarities and differences across deposits based on the mineralization style.

Chapter 4 presents the Pb isotope and geochronology results. The presentation of results is divided into four sections, the first section deals with the Pb isotope results that revealed the sources of Au mineralization. The Pb isotope compositions for both whole rocks and sulfides are well plotted and presented in both the uranogenic and thorogenic diagrams. The second section presents the Pb/Pb geochronology that was performed on sulfides in order to obtain the age of the Au mineralization across the TGB. The third section focusses on the U/Pb geochronology of hydrothermal almandine garnets that are closely associated to the Au mineralization, whereas the fourth section focusses on the phengite Ar/Ar geochronology results.

Chapter 5 discusses the genesis of Au mineralization in the TGB, as well as the temporal relationships between the different Au deposits within the TGB. Several geotectonic events that are believed to have triggered the TGB Au mineralization are detailed and the ages are plotted to

show how they correlate. The chapter also outlines examples of similar cases to that of the TGB Au mineralization elsewhere across the world, based on ages obtained.

Chapter 6 outlines the conclusions drawn from the study and also addresses the potential for future work.

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CHAPTER 2: GEOLOGICAL SETTINGS

This chapter presents the geological setting of the study area and includes the regional geology, local geology and metallogeny of the TGB, as well as the investigated gold deposits.

2.1. REGIONAL GEOLOGY

The TGB is located in the southwestern edge of the Zimbabwe Craton. The Zimbabwe Craton is exposed in Zimbabwe and extends to the southwestern part into Botswana (Bagai et al., 2002). The Zimbabwe Craton is separated from the Kaapvaal Craton by the ENE-WSW trending Limpopo Belt (Fig 2.1).

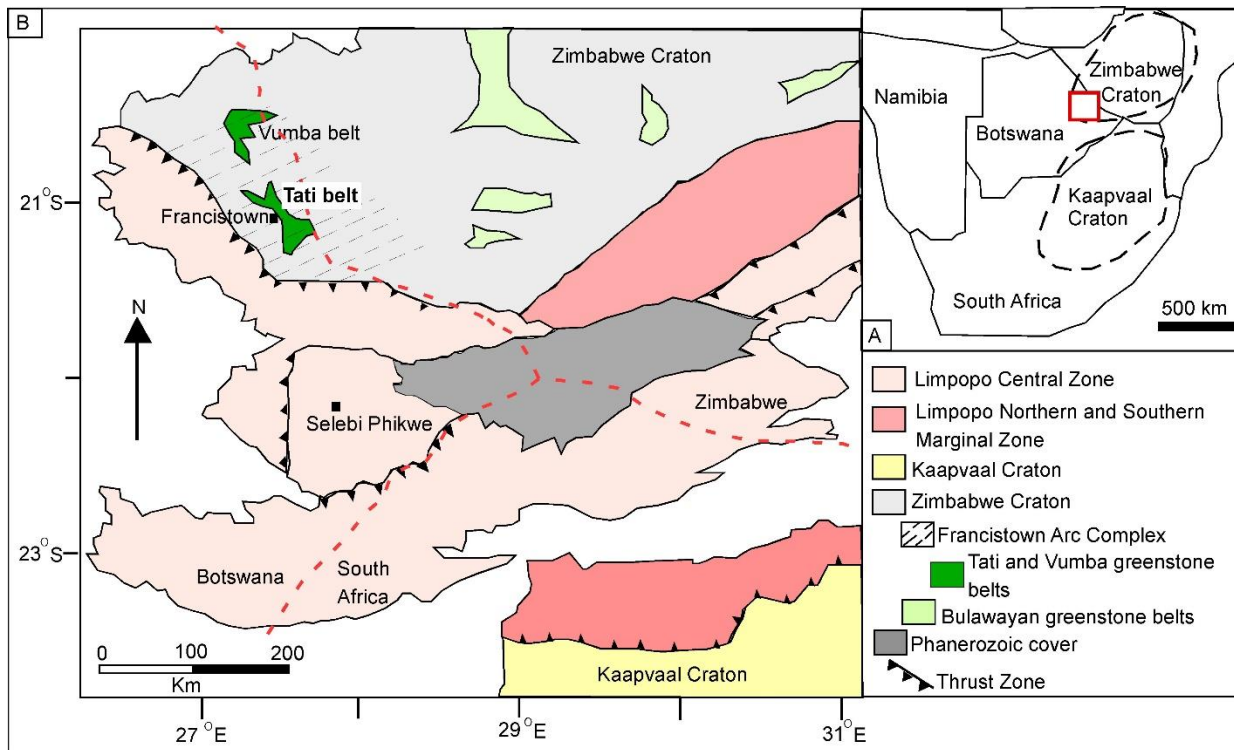


Figure 2.1: Geological map of the TGB in the Zimbabwe Craton and the adjacent Limpopo belt and Kaapvaal craton. Modified from Maier (2008).

The Limpopo Belt is divided into three zones being: (i) the Northern Marginal Zone, which shares the border with Zimbabwe Craton; (ii) the Central Zone, and; (iii) the Southern Marginal Zone, which shares a border with the Kaapvaal Craton (Tombale, 1992; Holzer et al., 1995; Holzer et al., 1998; Buick et al., 2006; Millonig et al., 2008). The Limpopo Belt experienced three high grade events including the first Paleoproterozoic event which occurred at 3.2 - 3.1 Ga, the Neoproterozoic

Limpopo-Liberian tectogenetic cycle occurring at 2.70 - 2.65 Ga and the Paleoproterozoic Limpopo-Liberian tectogenetic cycle which occurred at 1.95 - 2.05 Ga (Tombale, 1992; Holzer et al., 1995; Holzer et al., 1998; Buick et al., 2006; Chudy et al., 2008; Millonig et al., 2008). The deformation and metamorphism that occurred at the Limpopo Belt have affected adjacent parts of the Zimbabwe Craton and the boundary between the Northern Marginal Zone and the Zimbabwe Craton is not well defined (Aldiss, 1991; Key, 1976).

The Zimbabwe Craton contains twenty-three greenstone belts that include the Matsitama, Maitengwe, Tati and Vumba, which are the four greenstone belts that occur in the part of the craton exposed in the northeastern part of Botswana (Fig. 2.1) (Litherland, 1975; Key, 1976; Bagai et al., 2002; Kampunzu et al., 2003). According to Aldiss (1991), the part of the craton exposed in Botswana is further divided into three lithostratigraphic complexes including: (i) the Francistown Granite Greenstone Complex, (ii) the Motloutse Complex and (iii) the Mosetse Complex.

2.1.1. Francistown Granite Greenstone Complex (FGGC)

The FGGC consists of three greenstone belts that include the Tati, Vumba and Maitengwe greenstone belts and some foliated granitoids and orthogneisses (Carney et al., 1994).

2.1.1.1. Tati and Vumba greenstone belts

The Tati and Vumba greenstone belts (Fig 2.1) host similar lithologies that consist of mafic-ultramafic lavas occurring in the lower stratigraphic units, intermediate and felsic lavas occurring in the upper units and are both intruded by Tonalite-Trondhjemite Granodiorite (TTGs) (Bagai et al., 2002). The age of both Vumba and Tati greenstone belts ranges from 2696 ± 4 Ma to 2647 ± 4 Ma (Bagai et al., 2002). Bagai et al. (2002), dated granitoids in the Vumba Granite Greenstone Belt and they yielded an age of 2.70-2.65 Ga, which he inferred to also represent the age of TGB granitoids because the granitoids bodies between the two greenstone belts are continuous (Key et al., 1976). According to Carney et al. (1994) the Vumba Greenstone Belt sequence is subdivided into the Sebina Ultramafic Formation, Vumba Mixed Volcanic Formation, Vumba Lower Mafic Formation, Vumba Upper Felsic Formation and the Vumba Upper Mafic Formation. Gold mineralization in the Vumba Greenstone Belt occurs in quartz veins.

The Tati Greenstone Belt, which is host of the study area will be described in detail in the local geology section.

2.1.1.2. Maitengwe Greenstone Belt

The Maitengwe Greenstone Belt is divided into two formations consisting of (i) the Lower Maitengwe Banded Iron-Formation and (ii) the Maitengwe Ultramafic Formation (Litherland, 1975). The Lower Maitengwe Banded Iron-Formation consists of thick iron-rich layers alternating with chert beds, whereas the Maitengwe Ultramafic Formation consists of amphibolite that occurs in association with serpentinite and meta-peridotite (Litherland, 1975). According to Carney et al. (1994) the TTG's that intruded the Maitengwe Group are similar to those that intruded the Tati and the Vumba greenstone belts.

2.1.2. Mosetse Complex

The Mosetse Complex consists of Matsitama Greenstone Belt and some granitic to granodioritic gneisses (Carney et al., 1994).

2.1.2.1. Matsitama Greenstone Belt

The Matsitama Greenstone Belt consists of metasedimentary rocks and minor mafic-ultramafic metavolcanic rocks (Kampunzu et al., 2003). According to McCourt et al. (2004) the Matsitama Greenstone Belt does not contain intermediate and felsic lavas when compared to Tati and Vumba greenstone Belts. Granitoids that intruded the Matsitama Granite Greenstone Belt range in age from 2646 ± 3 Ma to 2710 ± 19 Ma (Bagai et al., 2002), similar to that of Vumba and Tati greenstone belts. Cu sulfides with minor Pb-Zn-Ag are the main type of mineralization in the Matsitama Greenstone Belt and occurs in calcareous quartzite and siliceous marble (Aldiss, 1991).

2.1.3. Motloutse Complex

The Motloutse Complex consists of paragneisses, Shashe metasedimentary rocks and tonalitic to granitic orthogneisses that are similar to those occurring at the FGGC (Carney et al., 1994).

2.2. LOCAL GEOLOGY

The study areas (Fig 2.2) are within the TGB that is exposed in northeast Botswana along the southern margin of the Archean Zimbabwe Craton. The TGB is dated at ca 2.7 Ga, (Wilson et al.,

1978; Wilson, 1979) and have been metamorphosed between 2630 ± 70 and 2570 ± 70 Ma (Van Breemen and Dodson, 1972). Metamorphism in the TGB is greenschist facies with a mineral assemblage consisting of chlorite + zoisite + actinolite/tremolite $\pm$ quartz (Tombale, 1992). The TGB is composed of basic metavolcanics, minor clastic and chemical metasediments that include marble and banded iron-formation (BIF) (Døssing et al., 2009). The TGB has been intruded by the 2.70 - 2.65 Ga granitoids as well as the 177.5 - 180.3 Ma Karoo dolerite dykes (Elburg and Goldberg, 2000; Hastie et al., 2014). The age of deposition of BIF in TGB was constrained to be 2.73 ± 0.15 Ma (Døssing et al., 2009).

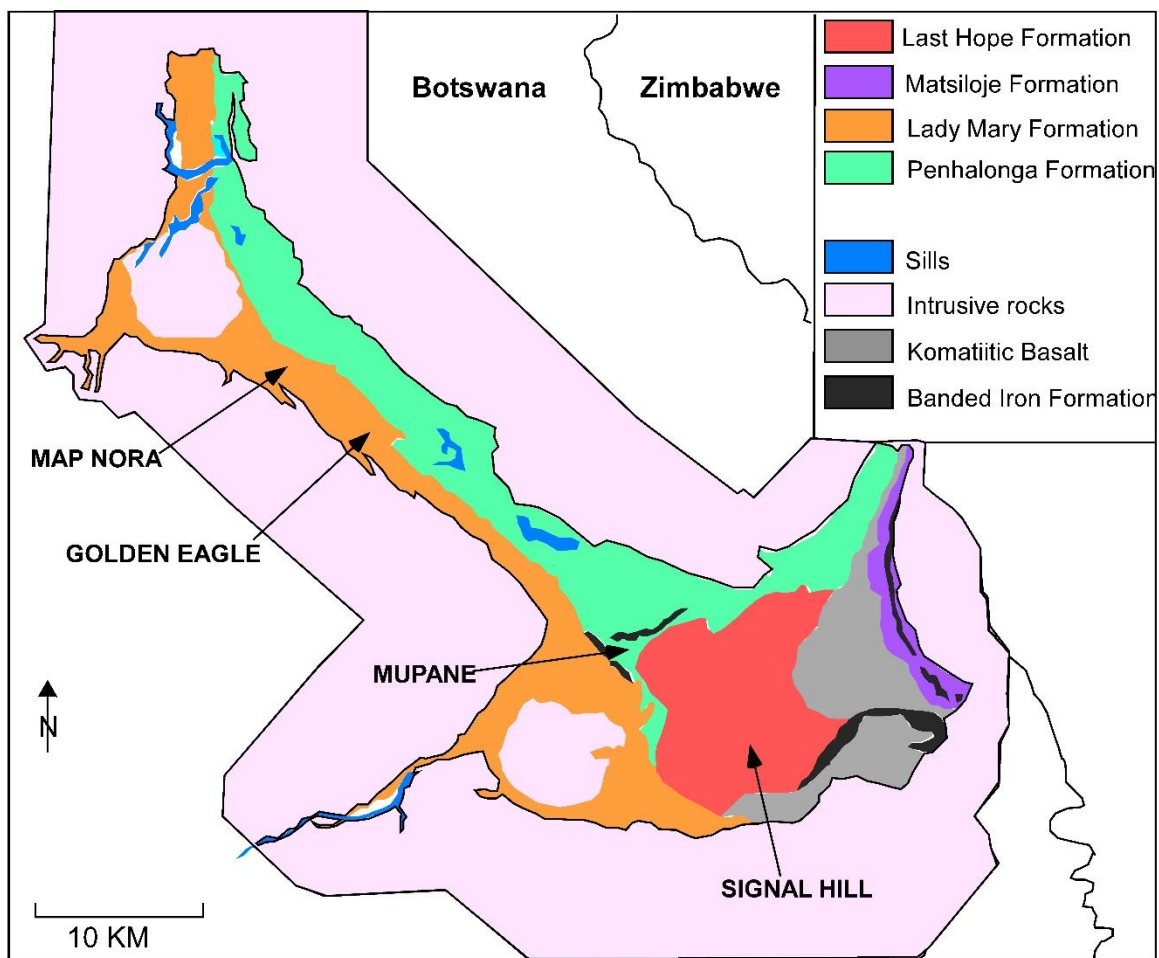


Fig 2.2: Simplified geological map of the Tati Greenstone Belt, north-eastern Botswana and the associated intrusive rocks. Also shown is the location of the investigated gold deposits. Modified from Døssing et al. (2009).

2.2.1. Stratigraphy of the TGB

The TGB was previously divided into six formations by Mason (1970), which include from bottom

to top Old Tati Formation, Matsiloje Metasedimentary Formation, Lady Mary Formation, Penhalonga Formation, Selkirk Formation and the Last Hope Formation. This stratigraphy was later modified by Key (1976), who came up with three formations that consist of the Lady Mary Formation, Penhalonga Formation and Selkirk Formation (Fig. 2.3). The Lady Mary Formation is a combination of Old Tati, Matsiloje and Lady Mary formations, whereas the Penhalonga Formation consists of Penhalonga and Last Hope formations that were proposed by Mason (1970). The Selkirk Formation remained unchanged.

2.2.1.1. Lady Mary Formation

The Lay Mary Formation forms the base of volcanic and sedimentary rocks and it consists of mafic and felsic schist, limestone, BIF, altered komatiite and komatiitic basalt (Døssing et al., 2009). According to Tombale (1992) the Lady Mary Formation consists of three magmatic suites, which include light rare earth elements (LREE)-depleted rocks, LREE-enriched rocks and komatiite. The LREE-enriched rocks occur in the margins of a basinal structure, whereas the LREE-depleted rocks and komatiite form the core of the structure (Tombale, 1992). The Lady Mary Formation is host to the Au deposits of Map Nora and Golden Eagle Deposits (Tombale, 1992).

2.2.1.2. Penhalonga Formation

The Penhalonga Formation overlies the Lady Mary Formation and comprises of basaltic, andesitic and rhyolitic volcanics, volcanoclastics and phyllitic black shale (Døssing et al., 2009). The Penhalonga Formation host the Mupane Au deposit.

2.2.1.3. Selkirk Formation

It is comprised of dacitic and rhyolitic volcanoclastic rocks and quartz sericite schist (Døssing et al., 2009). The Selkirk Formation host the Phoenix, Selkirk and Tekwane metagabbroic intrusions and Sikukwe meta-peridotite intrusions (Maier, 2008).

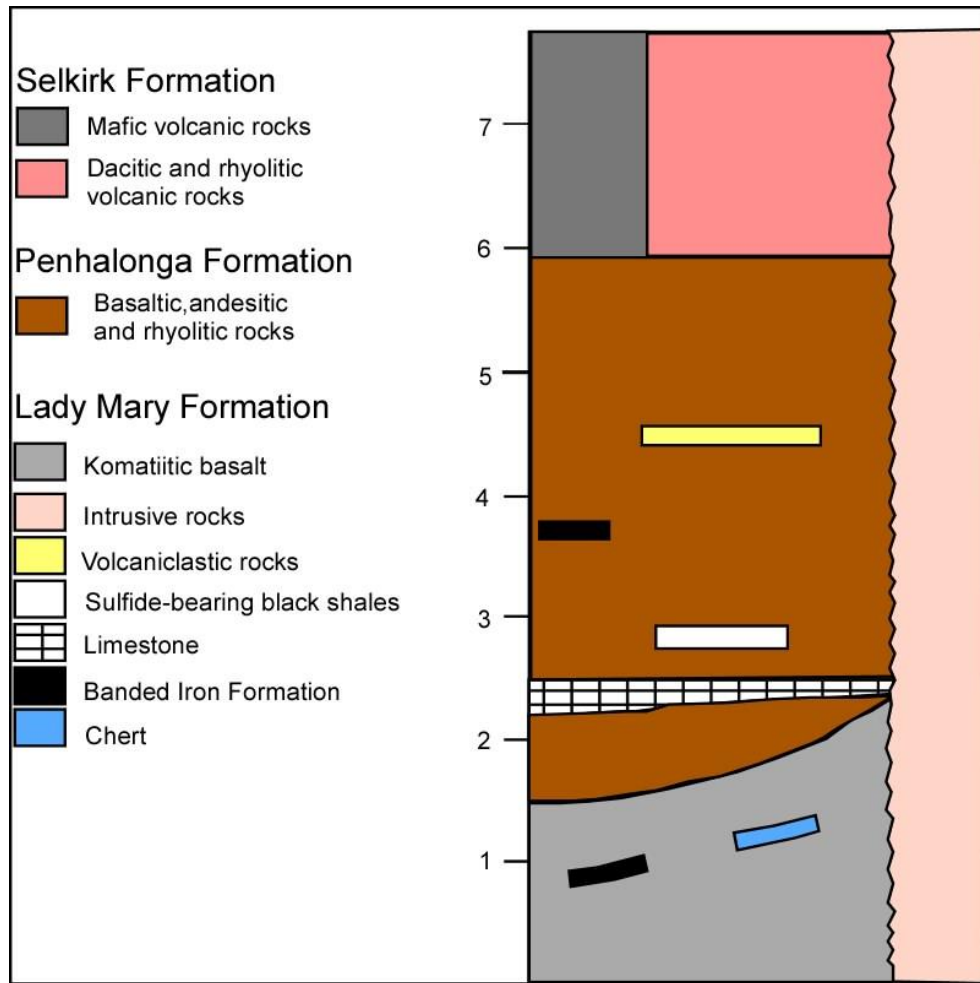


Fig 2.3. Stratigraphic section of the Tati Greenstone Belt. Modified from Døssing et al. (2009).

2.3. METALLOGENY OF THE TGB

The TGB hosts copper / nickel deposits that include Tekwane, Selkirk and Phoenix deposits (Maier et al., 2008) that were owned by Tati nickel mining company. Selkirk, Tekwane and Phoenix mines are no longer operating. According to Bagai et al. (2002) most of the ore deposits in the TGB are hosted by spatially associated ultramafic to mafic and granitic rocks. The TGB also hosts numerous gold deposits that include Map Nora Au deposit, Golden Eagle Au deposit, Mupane Au mine, Signal Hill Au deposit and Jim's Luck Au deposit. These gold deposits are all owned by Galane Gold Ltd.

2.3.1. Copper-Ni deposit

2.3.1.1. Tekwane deposit

The Tekwane deposit is a massive sulfide deposit occurring in the northern part of the Tekwane troctolite (Tombale, 1992). The mineralization at the Tekwane deposit occurs in quartz rubble bed within the soil profile close to the surface (Tombale, 1992). The underlying lithology is porphyritic felsic volcanic suite of unknown origin (Tombale, 1992). The mineralization occurs as semi-massive layers, discontinuous lenses and disseminated sulfides (Maier et al., 2008). Pyrrhotite, pentlandite, and chalcopyrite are the main sulfides occurring in this deposit.

2.3.1.2. Selkirk deposit

The Selkirk deposit is located in the centre of TGB at the contact between Penhalonga and Selkirk formations. The sulfide mineralization at the Selkirk deposit is hosted by gabbroic body that intrudes the Selkirk feldspar porphyry (Tombale, 1992). It consists of massive sulfide body with disseminated sulfides at the top and stringer sulfide veins below a massive sulfide zone (Tombale, 1992). The mineralization occurring at the Selkirk deposit includes mainly pyrrhotite, pentlandite, chalcopyrite and pyrite (Maier et al., 2008).

2.3.1.3. Phoenix deposit

The Phoenix deposit is located in the northern part of the TGB. The mineralization occurs as disseminated, massive and vein-like in the gabbronorite (Maier et al., 2008). It is hosted by numerous trondhjemitic stocks and includes nickeliferous pyrrhotite, pentlandite, chalcopyrite and minor pyrite (Maier et al., 2008). The Phoenix deposit has high Ni / Cu ratio as compared to other massive sulfide deposits.

2.3.2. Gold deposits

2.3.2.1. Jim's Luck Au deposit

The Jim's Luck Au deposit is located in the southeastern part of the TGB and is hosted by the Matsiloje Formation. The gold mineralization occurs in BIF that are hosted by meta-volcanic and metasedimentary rocks similar to those that occur at the Lady Mary Formation (Tombale, 1992).

The present study is more focused on the four gold deposits, which from NW to SE include; Map

Nora, Golden Eagle, Mupane and Signal Hill Au deposits. The Au mineralization in the TGB is associated with arsenopyrite, pyrrhotite, pyrite, sphalerite, chalcopyrite, and minor bornite and galena. Native gold and/or electrum is rare and locally occurs as inclusions in arsenopyrite and pyrite or sphalerite. These four deposits are further described in the deposit geology section below

2.3.3. Deposits geology

2.3.3.1. Shashe Au deposits

Shashe deposits include Map Nora and Golden Eagle Au deposits. Mining activities within the Shashe area started in 1980s by Phelps Dodge, who recommended underground mining at the Map Nora Au deposit (Tombale, 1992). The project was later taken up by Francis Prospecting who re-opened the Monarch Au mine and established an open pit mine at the Golden Eagle area (Glanvill et al., 2011). Mining operations in the Shashe Au deposits ceased in 1994 because they were no longer profitable.

The Shashe Au deposits are hosted by the Lady Mary Formation, with Golden Eagle deposit forming the sedimentary cap of the Lady Mary Formation (Tombale, 1992). The Golden Eagle deposits consists of interbedded laminated limestone, BIF, greywacke and arkosic sandstone (Tombale, 1992). The Map Nora deposit lies beneath the Golden Eagle deposit and consists of volcano-plutonic rocks of the Lady Mary Formation which are mainly the basaltic rocks (Tombale, 1992). The host rocks for the Au mineralization in both Map Nora and Golden Eagle Au deposits are schists that comprises of amphibole, biotite, chlorite, sericite, talc and garnet. The alteration minerals that are spatially associated to the Au mineralization include muscovite, carbonate, actinolite and phengite.

2.3.3.2. Mupane Au deposit

The Mupane Gold deposits are located in the Mupanipani Hills and are hosted by the Penhalonga Formation, which consists of mafic lavas intercalated with metasedimentary rocks (Døssing et al., 2009). The Mupane deposits consist of four subzones that include, (1) Tau deposit (focus of the present study), which is the most important one in terms of size and Au production. It consists of GIF- hosted lenses of Au mineralization, (2) Tholo deposit which is hosted by BIFs, (3) Kwena deposit hosted by BIF unit with amphibolite schist and lastly, (4) Tawana deposit where the Au mineralization is related to dolerite dykes (Glanvill et al., 2011). The Mupane ore body consists of

sulfides (arsenopyrite, pyrite, pyrrhotite, galena, sphalerite, and covellite), carbonaceous black shales and interbanded siderite facies and carbonate facies, limonite and goethite facies (Tadesse et al., 2011). A non-negligible amount of Au mineralization is also-hosted in garnet-graphite schist (Glanvill et al., 2011). The Au bearing ore is mined from quartz veins, silicified rocks and stockworks. The gold production started in 2005, and from 2005 to date over 700,000 ounces of gold were produced (<http://www.galanegold.com/operations/mupane/>).

The Tau sub-zone consists of banded siliceous and graphitic iron-formation (GIF), hosted by a sequence of metasediments that include conglomerate, para-amphibolite, marble, metapelite and minor orthoamphibolite (Tomkinson and Putland 2006).

2.3.3.3 Signal Hill Au deposit

The Signal Hill Au deposit is located in the southern zone of the Last Hope Basin and consists of rocks of the Penhalonga Formation overlaid by the Last Hope Formation (Tombale, 1992). The Penhalonga Formation, which occurs in both the northeast and southeast of the Signal Hill deposit comprises of siliceous iron-formation, andesite, diorite, dacite and rhyolite (Tombale, 1992). The Last Hope Formation occurs in the central part of the Signal Hill deposit, and it consists of poorly bedded sequence of meta-arkose sandstone inter-bedded with conglomerate (Tombale, 1992). Conglomerate is matrix-supported with the quartz-mica schist forming the matrix and the sedimentary cap consists of dark brown ferruginous conglomerate unit of BIF and quartz-mica schist clasts (Tombale, 1992).

The sedimentary-hosted Au-Sb mineralization was the main interest in this area and the concentration of antimony was high as compared to that of gold, therefore the ore was mainly mined for antimony (Tombale, 1992). Antimony was mined in the 1920s -1930s and gold mineralization was first recognized by the Seltrust / Falconbridge Joint venture in 1982 (Glanvill et al., 2011). Gold mineralization occurs in number of zones and the mining activities within these zones ceased from 2009-2010. These zones are the F- zone, West- zone, B- zone and A-zone (Glanvill et al., 2011) A-zone is the focus of the current study.

Mineralization within Signal Hill occurs as massive, disseminated and bleb textures within boudinaged quartz veins, as well as in a stockwork veins system hosted by sericitized and kaolinitized arkosic sandstone (Tombale, 1992). The sulfide mineralization at Signal Hill mainly consists of pyrrhotite, pyrite, arsenopyrite, stibnite, gudmundite and minor chalcopyrite and

sphalerite (Tombale, 1992).

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***CHAPTER 3: MINERALOGY AND OUTLINE OF THE STYLES OF MINERALIZATION**

This chapter presents the mineralogy and the style of mineralization of the four investigated deposits within the TGB. The mineralization style varies across the TGB, with Golden Eagle and Map Nora Au deposits showing some similarities, whereas Mupane Au deposit and Signal Hill Au deposit are different.

3.1. SHASHE Au DEPOSITS

3.1.1. Map Nora Au deposit

The mineralization at the Map Nora Au deposit is hosted by veins, which locally occur as enechelon, and are composed of quartz calcite - epidote $\pm$ chlorite $\pm$ actinolite (Fig. 3.1A and 3.1B). The mineralization also occurs as disseminated (Fig. 3.1C-E) and schistosity - controlled (Fig. 3.1F-G). Arsenopyrite, pyrrhotite, pyrite, chalcopyrite, sphalerite and bornite are the main ore minerals found in the area and are hosted by the fine-grained schist. Arsenopyrite is the most abundant (~45 vol. % of the ore minerals), and is of at least two different morphologies including the elongated and deformed crystals (Fig. 3.1F), and euhedral cubic crystals (Fig. 3.1E), suggesting mineralization at the Map Nora deposit is pre-syn to post-tectonic. The arsenopyrite occurs bounded to biotite (Fig. 3.1G) and has inclusions of pyrrhotite and chalcopyrite. Pyrrhotite (Fig. 3.1C-E) occurs intergrowths with chalcopyrite (Fig. 3.1D), inclusion in arsenopyrite and as disseminated free anhedral grains. Pyrite is less abundant and it occurs either as euhedral grains that are closely associated with actinolite (Fig. 3.1H) or associated with pyrite, pyrrhotite and chalcopyrite along quartz-calcite vein. Chalcopyrite occurs as anhedral grains intergrown with pyrrhotite (Fig. 3.1D). In places, chalcopyrite also occurs either intergrown with arsenopyrite or included in the arsenopyrite. Actinolite is the main alteration mineral in the deposit and intergrows with sulfides.

*The latest version of this chapter has been published in the Precambrian Research (2020), PII: S0301-9268(19)30670-9, DOI: <https://doi.org/10.1016/j.precamres.2020.105623>, Reference: PRECAM 105623, co-authored by Thierry Bineli Betsi, Christopher McFarlane, Kelebogile Phili and Tebogo Kelepile.

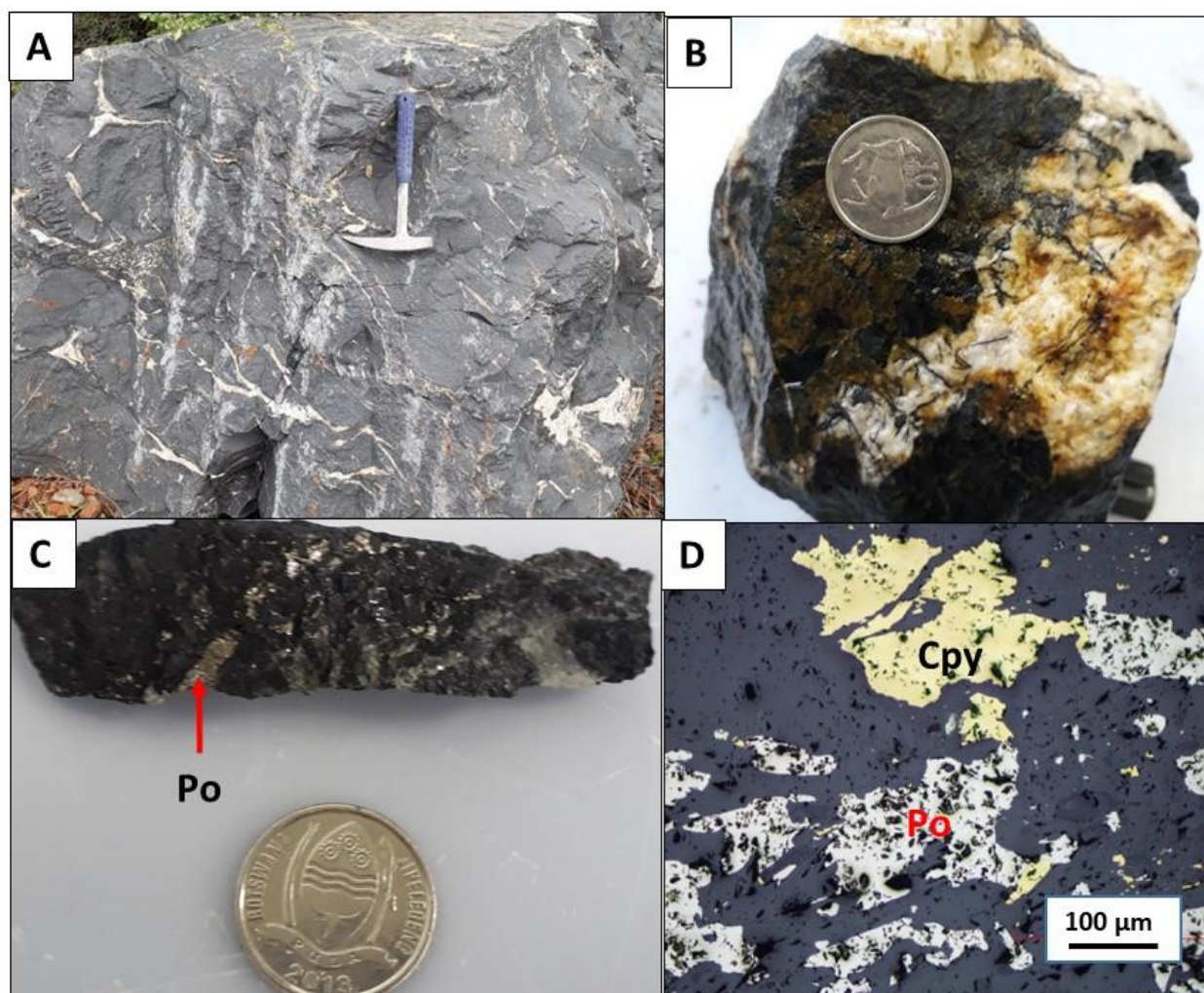


Figure 3.1: Style of the mineralization from the Map Nora Au deposit. (A) Photograph of fine-grained schist with mineralized quartz-calcite en-echelon veins. (B) Quartz-calcite vein sample with acicular actinolite and disseminated sulfides. (C) Disseminated pyrrhotite (Po) in the schist. (D) Reflected light (PPL) microphotograph showing the disseminated anhedral Po and chalcopyrite (Cpy).

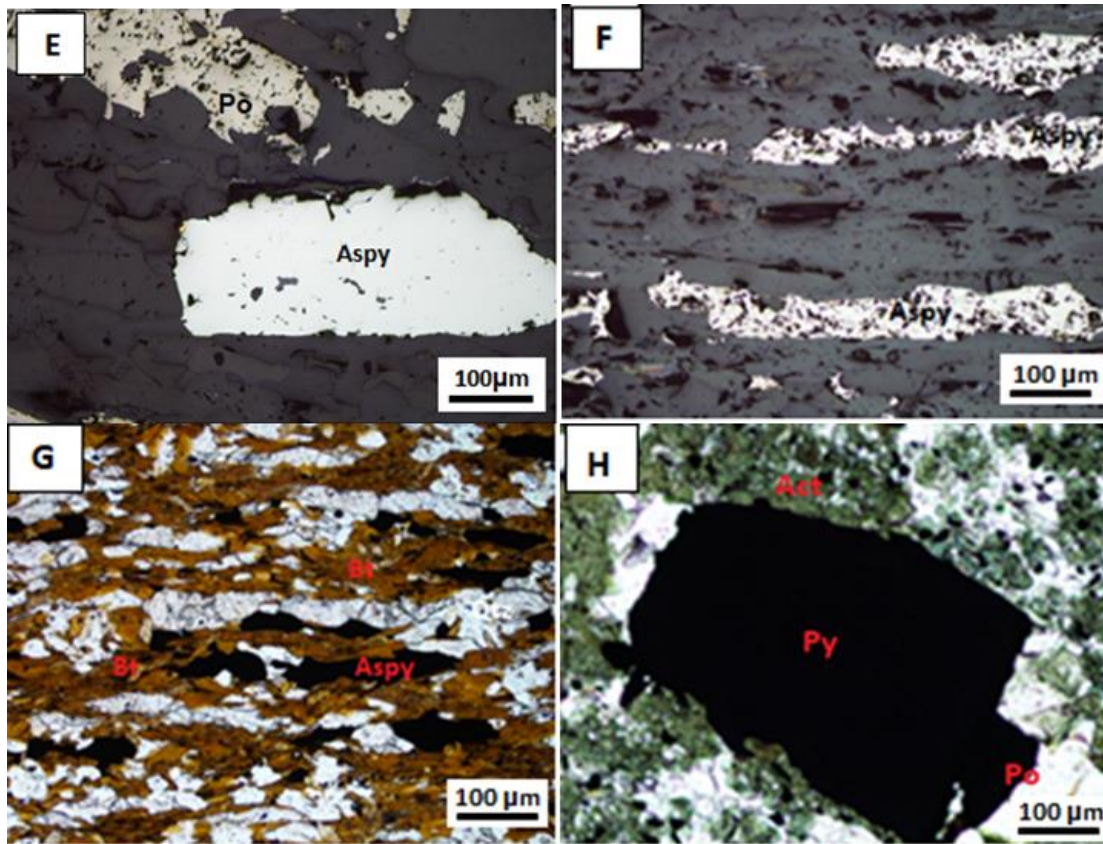


Figure 3.1 continued: (E) Reflected light (PPL) microphotograph of disseminated arsenopyrite (Aspy) and Po in the schist. (F) Elongated Aspy grains occurring along schistosity of the biotite-schist under reflected light (PPL). (G) Transmitted light microphotographs (PPL) showing the elongated Aspy and biotite (Bt) bounded together and, (H) Transmitted light microphotograph (PPL) showing pyrite (Py) and Po surrounded by the actinolite (Act).

3.1.2. Golden Eagle Au deposit

The Golden Eagle Au deposit is characterized by three styles of mineralization that include (i) schistosity-controlled (Fig. 3.2A), (ii) vein-hosted (Fig. 3.2B), (iii) disseminated (Fig. 3.2C). Ore minerals identified include pyrrhotite (60 vol. % of the ore minerals), arsenopyrite (20 vol. % of the ore minerals), sphalerite (10 vol.% of the ore minerals), chalcopyrite (4 vol. % of the ore minerals) pyrite (3.5 vol.% of the ore minerals), bornite (2 vol.% of the ore minerals) and gold (0.5 vol.% of the ore minerals). Pyrrhotite (Fig. 3.2B, D) occurs as either stringers and veinlets or intergrown with chalcopyrite and locally shows inclusions of arsenopyrite (Fig. 3.2E).

Arsenopyrite occurs mostly as subhedral to euhedral grains either with sphalerite along quartz veins (Fig. 3.2F) or included within the pyrrhotite (Fig. 3.2E). Sphalerite occurs as anhedral grains

that are either disseminated in the biotite schist or observed within quartz veins (Fig. 3.2F). Chalcopyrite, galena and bornite are subordinate, disseminated in the biotite schist (example of bornite in Fig. 3.2C). Chalcopyrite occurs either intergrown with pyrrhotite and arsenopyrite or as inclusions in the pyrrhotite (Fig. 3.2E). Alteration minerals found in the deposit mainly include actinolite (Fig. 3.2G), biotite and minor occurrences of sericite. In all the observed styles of mineralization, no free Au was observed but Au is found to occur as inclusions in arsenopyrite that is closely associated with pyrrhotite (Fig. 3.2 H).

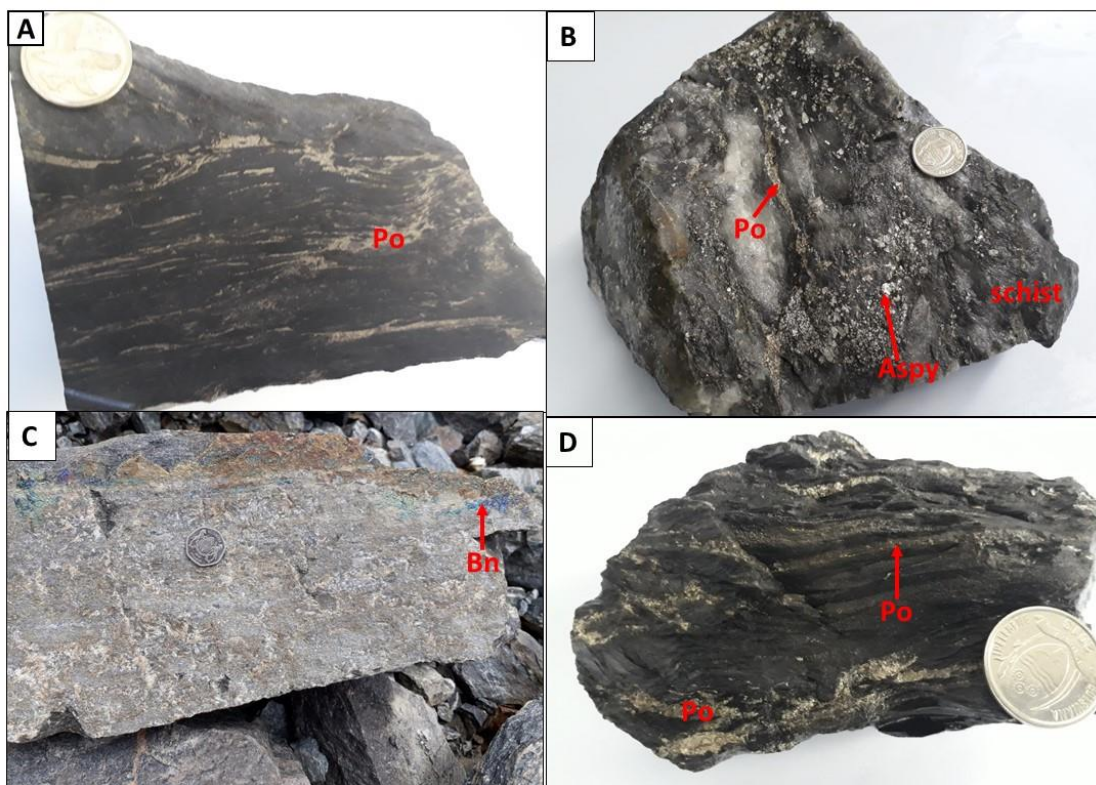


Figure 3.2: Photographs of mineralized samples from the Golden Eagle Au deposit. (A) Pyrrhotite (Po) along schistosity in the biotite schist slab. (B) Disseminated arsenopyrite (Aspy) in a biotite schist and Po bounding quartz porphyroclast. (C) Disseminated bornite (Bn) in the schist. (D) Po occurring along schistosity similar to the Po observed in A.

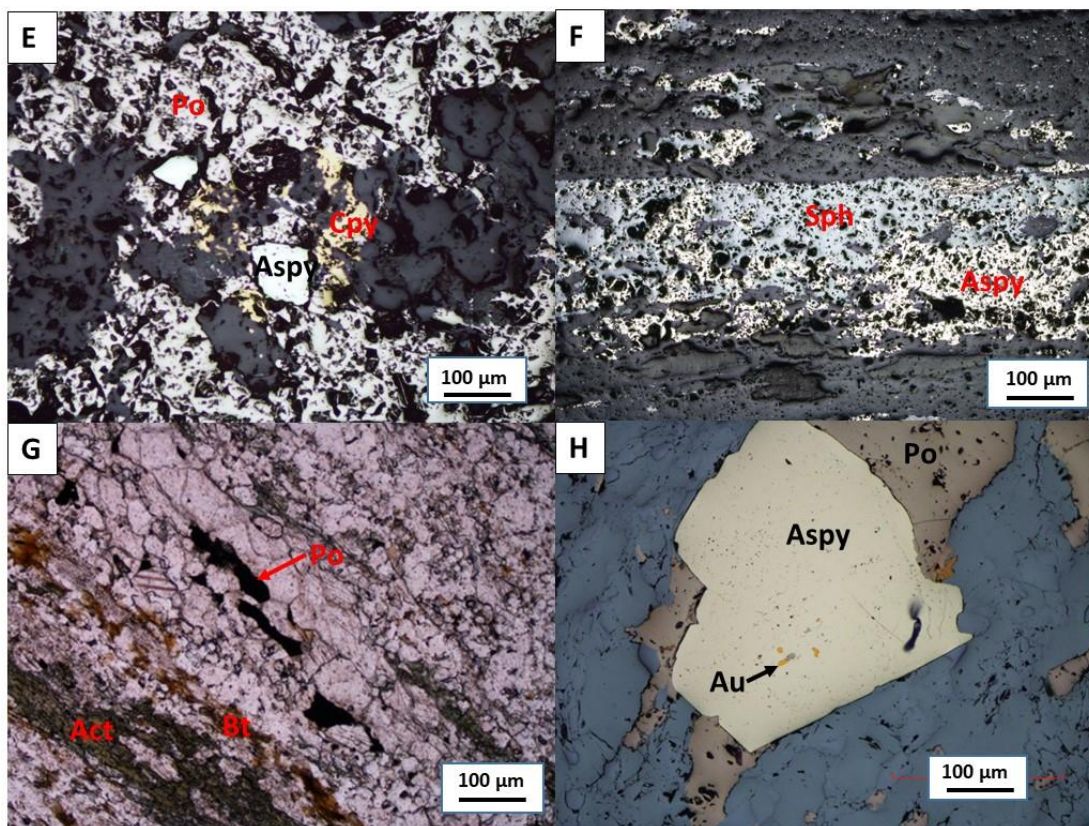


Figure 3.2 continued: (E) Reflected light microphotograph (PPL) showing the association of chalcopyrite (Cpy), Po and Aspy. (F) Reflected light microphotograph (PPL) showing Aspy and sphalerite (Sph) intergrow along schistosity. (G) Transmitted light (PPL) microphotographs showing Po occurs along a quartz-calcite vein. (H) Microphotograph (PPL) showing subhedral Aspy cuts the Po grain and showing inclusions of gold (Au).

3.2. MUPANE Au DEPOSITS

Gold mineralization at the Mupane Au deposit, i.e., the Tau sub zone is disseminated (locally in massive content, Fig. 3.3A) in the GIF (Fig. 3.3B-D), which is variably quartz-carbonate-altered, in places, with total obliteration of graphite, thus leading to gold-bearing quartz-carbonate-rich host rocks. Apart from the main quartz and carbonate gangue minerals phases, garnet (abundantly observed where graphite is still an important component of the host rock, Fig. 3.3E) biotite, chlorite and muscovite are accessorially observed. Locally, mineralization is vein-controlled (Fig. 3.3C, F), with veins commonly overprinting the quartz-altered GIF.

The ore minerals identified are arsenopyrite, pyrrhotite, sphalerite, pyrite, chalcopyrite, ilmenite and gold. Arsenopyrite is the most abundant (~50 vol. % of ore minerals) and rarely occurs as euhedral crystals, but rather as subhedral to anhedral grains of variable size. Arsenopyrite in

Mupane also exhibits a wide range of texture including porous, inclusions-rich and highly fractured crystals. Arsenopyrite from Mupane was not only subjected to intense brittle deformation as indicated by its highly fractured nature (Fig. 3.3H), but it also recorded ductile deformation as supported by folded and boudinaged arsenopyrite. Pyrrhotite is the second most abundant ore minerals (30 vol. % of ore minerals) and commonly occurs either as disseminated free anhedral grains or as inclusions and filling fractures in arsenopyrite (Fig. 3.3G-H). Like arsenopyrite, pyrrhotite also exhibits porous and non-porous specimen (Fig. 3.3G - I). Sphalerite which occupies about 10 vol. % of the ore minerals, occurs as subhedral to anhedral crystals of variable size. Pyrite and chalcopyrite occur as anhedral grains that are disseminated in quartz-carbonate-rich GIF host and represent about 5 vol. % of ore minerals each (Fig. 3.3I, J). Gold (< 1 vol. % of the ore minerals) was observed to be essentially found within arsenopyrite either as tiny inclusions or filling fractures and vugs.

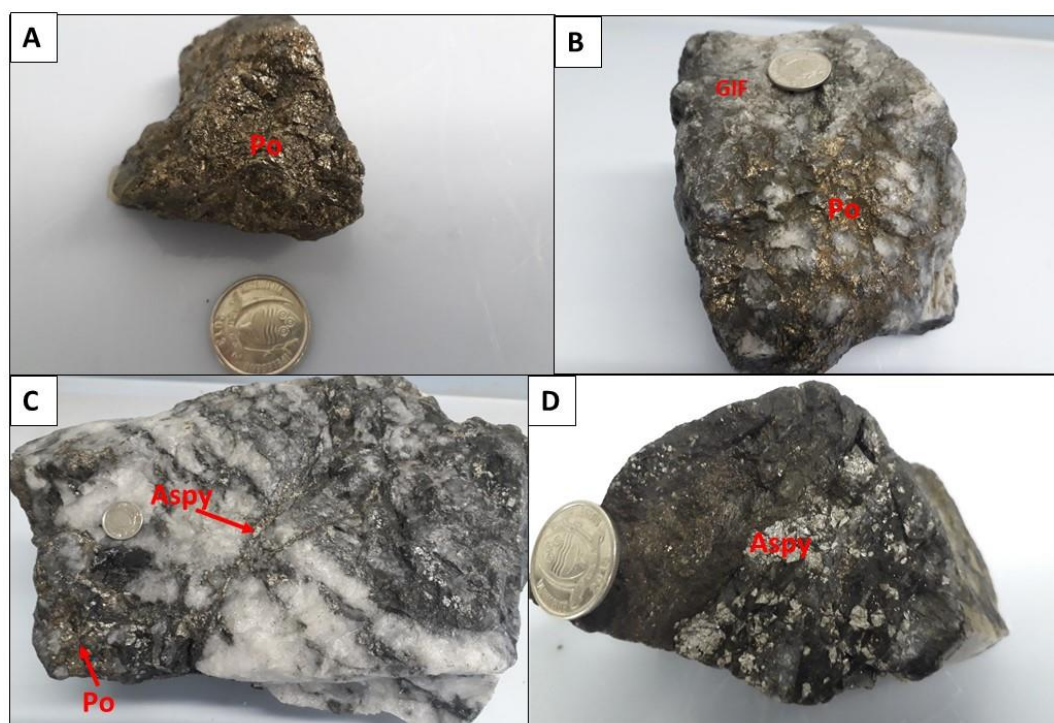


Figure 3.3: Photographs showing the style of mineralization from the Mupane Au deposit. (A) Shows Massive pyrrhotite (Po). (B) Disseminated Po in the silicified Graphitic Iron Formation (GIF). (C) Disseminated Po and arsenopyrite (Aspy) in the silicified GIF and Aspy also occur along fractures cutting across the quartz veins. (D) Disseminated Aspy in silicified GIF.

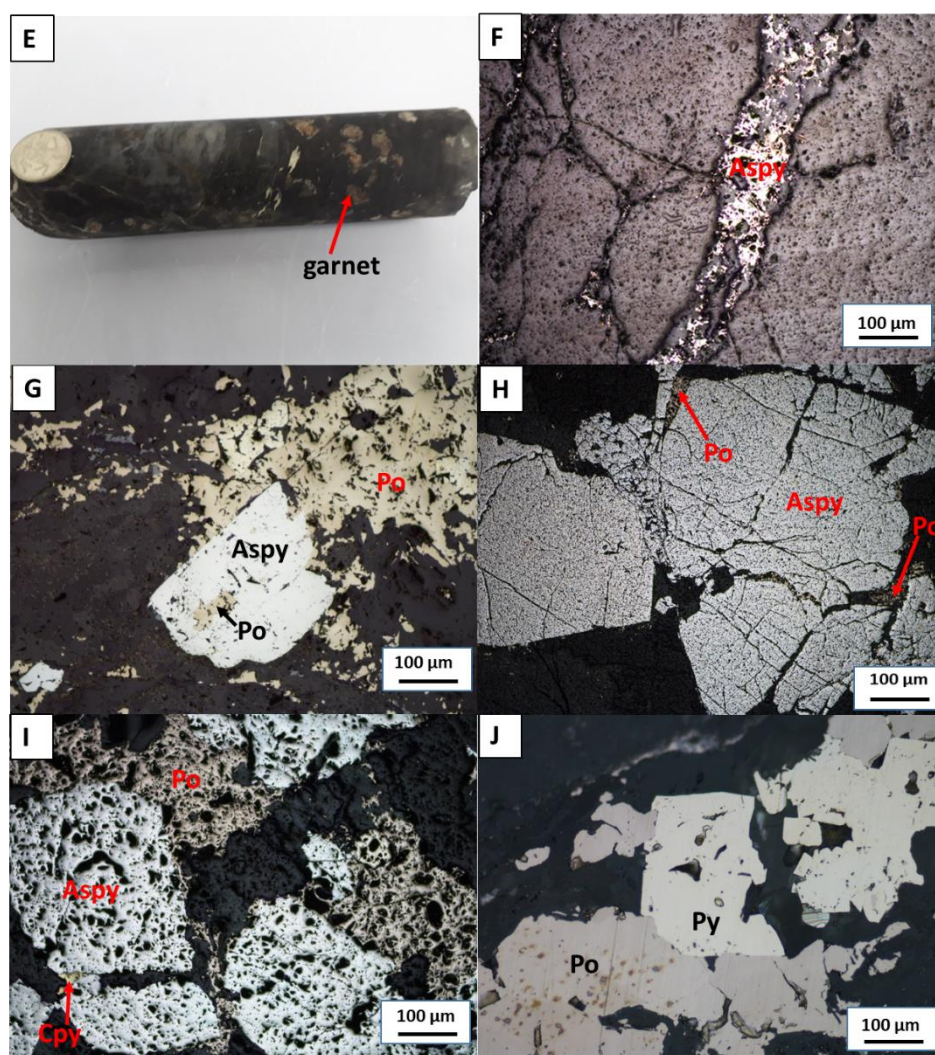


Figure 3.3 continued: (E) Photograph showing the occurrence of garnets within the graphitic iron-formation (GIF). (F) Reflected light microphotographs (PPL) showing the occurrence of Aspy in a vein. (G) Reflected light microphotograph showing disseminated Po occurring with Aspy, and inclusions of Po in the Aspy. (H) Reflected light microphotograph showing Po filling fractures in deformed Aspy. (I) Reflected light microphotograph (PPL) showing the occurrence of porous Po between Aspy grains and traces of chalcopyrite (Cpy) occur in the boundary of Aspy. (J) Reflected light (PPL) microphotograph showing Po and pyrite (Py).

3.3. SIGNAL HILL Au DEPOSITS

In the investigated A-zone, mineralization is characterized by auriferous quartz veins and stockworks (Fig. 3.4A-B), hosted in pervasively phengite-altered arkosic sandstone.

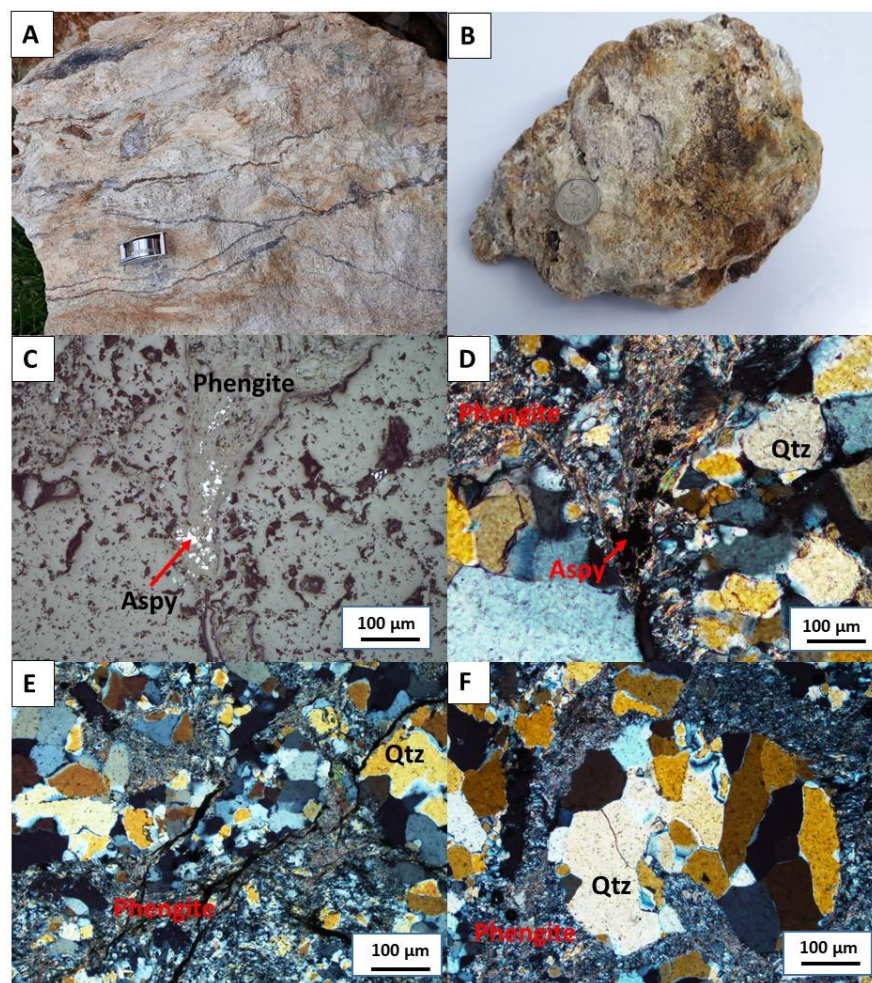


Figure 3.4: Photographs and microphotographs from the Signal Hill Au deposit. (A) Photograph showing a pervasively phengite-altered sandstone crosscut by quartz vein sets. (B) Photograph of a sandstone sample that consists of the phengite that is associated to mineralization. (C) Reflected light microphotograph (PPL) showing the occurrence of arsenopyrite (Aspy) within the phengite alteration indicating that they occurred together. (D) Transmitted light microphotograph (XPL), showing Aspy occurring within the phengite alteration, both surrounded by large quartz (Qtz) grains. (E) Transmitted light microphotograph (XPL) dominated by mostly Qtz showing the occurrence of phengite with some small veinlets cutting across the phengite, and (F) Transmitted light microphotograph showing phengite alteration occurring around large Qtz clasts.

The Au mineralization is mainly associated with arsenopyrite, which is the most abundant of the ore minerals. Arsenopyrite occurs within the phengite alteration (Fig. 3.4C-D), suggesting that they precipitated together. Phengite (as identified by X-ray diffraction (XRD) and quartz constitute the alteration mineral assemblage and phengite essentially occurs around the quartz grains (Fig. 3.4E-F).

***CHAPTER 4: LEAD ISOTOPES AND GEOCHRONOLOGY**

This chapter focusses on the Pb isotope analysis, as well as on geochronology investigations.

4.1. Pb ISOTOPE

The Pb isotope studies are widely used in base metal mineralization containing galena and in other sulfides with trace amount of Pb, such as arsenopyrite, in order to understand the genesis of ore deposits (Browning et al., 1987). In this study Pb isotope study was applied to sulfides and whole rocks in order to obtain their isotope compositions, which were then used to identify the source of Pb and by inference Au.

Nine concentrate sulfide samples and eight whole rock samples from the four Au deposits described in chapters 2 and 3 were investigated for their Pb isotopic compositions and the results for the actual Pb isotope compositions of sulfides and whole rocks are reported in Table 4.1. Table 4.2 presents both the actual and the recalculated whole rocks initial Pb isotope compositions, which are plotted in (Fig. 4.1A and 4.1B). Lead isotope compositions of sulfides from the investigated Au deposits are heterogeneous and display a wide range of Pb isotope ratios. $^{206}\text{Pb}/^{204}\text{Pb}$ range from 14.274 - 29.711, $^{207}\text{Pb}/^{204}\text{Pb}$ range from 14.957 - 17.179 and the $^{208}\text{Pb}/^{204}\text{Pb}$ range from 33.962 - 65.243. Arsenopyrite from Map Nora is more radiogenic as compared to all other sulfides, and displays a wide range of Pb isotopic compositions, with $^{206}\text{Pb}/^{204}\text{Pb}$ ranging from 29.011 - 29.711, $^{207}\text{Pb}/^{204}\text{Pb}$ from 17.118 - 17.179 and the $^{208}\text{Pb}/^{204}\text{Pb}$ ranging from 59.921 - 65.243.

*The latest version of this chapter has been published in the Precambrian Research (2020), PII: S0301-9268(19)30670-9, DOI: <https://doi.org/10.1016/j.precamres.2020.105623>, Reference: PRECAM 105623, co-authored by Thierry Bineli Betsi, Christopher McFarlane, Kelebogile Phili and Tebogo Kelepile.

Table 4.1: Pb isotope values of the whole rocks and sulfide samples from the four investigated Au deposits in the TGB.

SAMPLES	SPECIES	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
Mupane Au deposit				
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
LB10	Schist	16.087	15.338	35.290
LBC-4	Dolerite dyke	17.814	15.515	38.077
Map Nora Au deposit				
SH10	Arsenopyrite	29.011	17.118	65.243
SH2	Arsenopyrite	29.711	17.179	59.921
SH8	Schist	16.981	15.448	36.604
SH5	Schist	17.044	15.385	36.655
Golden Eagle Au deposit				
GEP29D	Pyrrhotite	14.282	14.957	34.023
GEP29C	Arsenopyrite	14.558	15.060	34.486
GEP14	Pyrite	15.498	15.235	35.722
GEP1	Schist	14.732	15.109	34.391
GEP31	Schist	17.813	15.500	37.676
GEP25V	Dolerite dyke	17.818	15.544	38.333
Signal Hill Au deposit				
SG5	Granodiorite	16.399	15.427	35.757

The whole rocks also display heterogeneous and a wide range of Pb isotope compositions, which span from 13.4912 - 17.7393 for $^{206}\text{Pb}/^{204}\text{Pb}$, from 14.5498 - 15.5383 for $^{207}\text{Pb}/^{204}\text{Pb}$ and from 33.7436 - 38.2613 for $^{208}\text{Pb}/^{204}\text{Pb}$. Both whole rocks and sulfides (excepted arsenopyrite from Map Nora) overlap (Fig. 4.2A and 4.2B) and fall between the mantle and upper crust curves of Zartman and Doe (1981).

Table 4.2: Initial and actual Pb isotope composition of the whole rocks of the four Au deposits.

SAMPLES	t = 0 Ma			t= 2700Ma			t= 179 Ma		
	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
	Mupane Au deposit								
LBC-4 (Dolerite dyke)	17.814	15.515	38.077				17.806	15.544	38.322
LB 10 (Schist)	16.087	15.338	35.290	14.494	15.043	35.140			
	Map Nora Au deposit								
SH 8 (Schist)	16.981	15.448	36.604	12.1328	14.550	33.744			
SH 5 (Schist)	17.044	15.385	36.655	15.279	15.058	35.493			
	Golden Eagle Au deposit								
GEP 1 (Schist)	14.732	15.109	34.391	13.491	14.879	33.943			
GEP 31 (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
	Signal Hill Au deposit								
SG 5 (Granodiorite)	16.399	15.427	35.757	14.631	15.099	34.882			

Age of granitoids intrusion: 2700 Ma (Bagai et al., 2002)

Age of schist: 2700 Ma (Carney et al., 1994)

Age of Karoo dolerite dykes: 179 Ma (Elburg and Goldberg, 2000; Hastie et al., 2014)

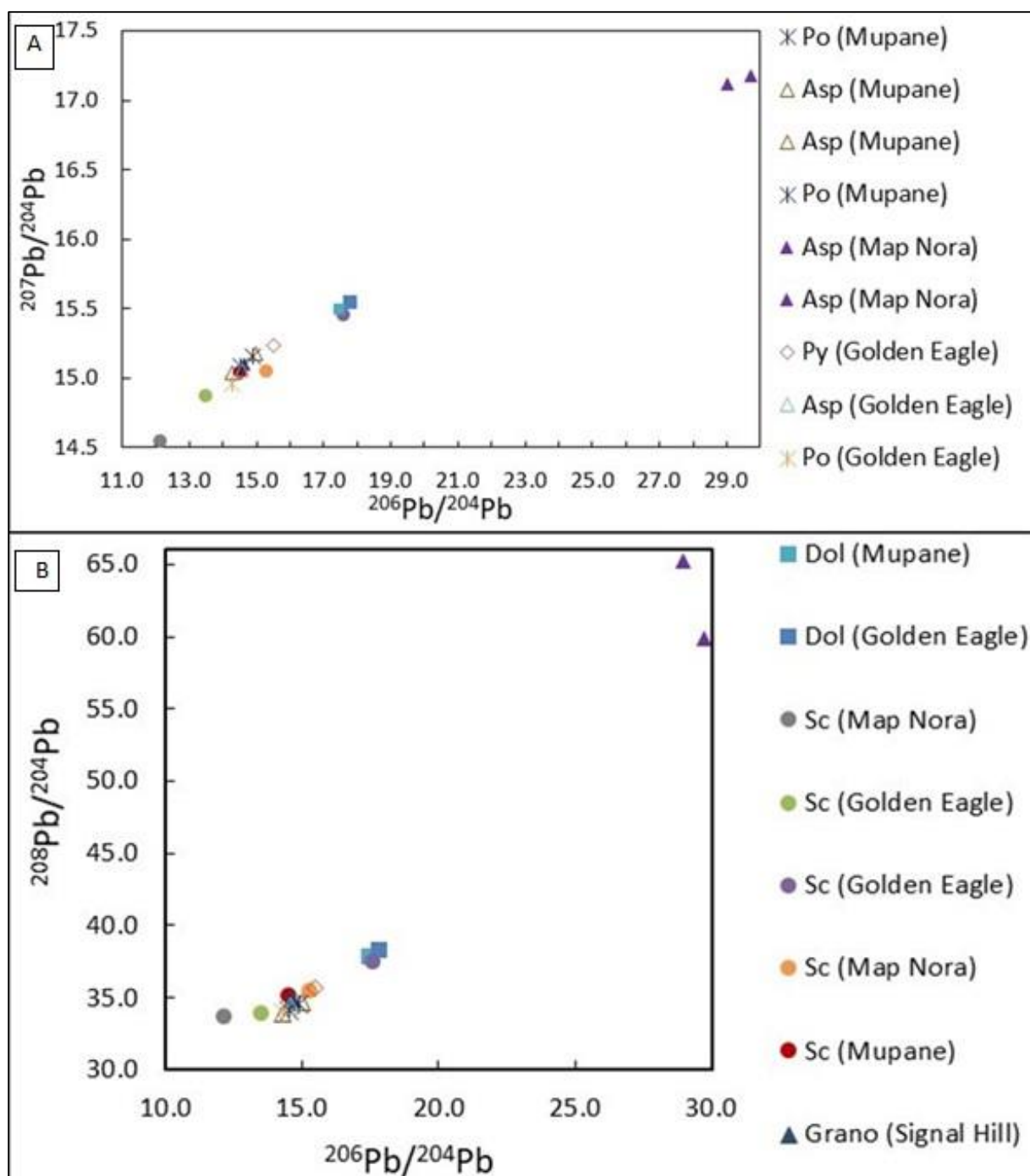


Figure 4.1: Uranogenic (A) and thorogenic (B) plots showing the distribution of Pb isotope compositions of both ore minerals and whole rocks from the four investigated Au deposits across the TGB. The legend in the uranogenic plot is for sulfides and the one on the thorogenic plot is for whole rocks. Abbreviations (Dol –Dolerite, Bt sc – Biotite schist, Sc – schist, Grano- Granodiorite, Asp- Arsenopyrite, Py- pyrite, Po- Pyrrhotite).

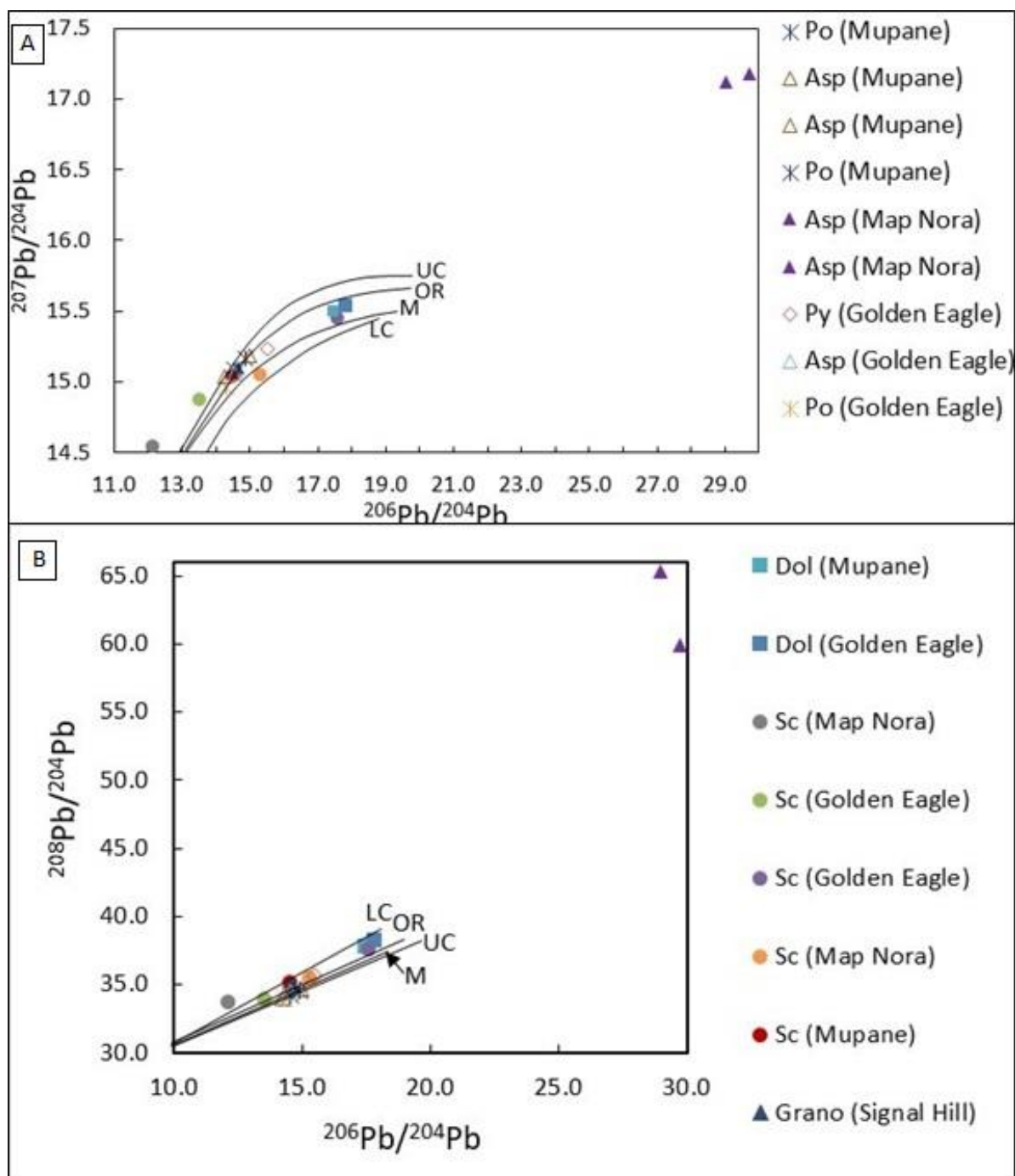


Figure 4.2: Uranogenic (A) and thorogenic (B) plots showing the Pb isotope compositions of both ore minerals and spatially associated whole rocks from the four investigated Au deposits of TGB with evolution curves inserted. The legend in the uranogenic plot is for sulfides and the one on the thorogenic plot is a continuation, it shows whole rocks. Abbreviations (Dol –Dolerite, Bt sc – Biotite schist, Sc – schist, Grano- Granodiorite, Asp- Arsenopyrite, Py- pyrite, Po- Pyrrhotite). The evolution curves of mantle (M), upper crust (UC), lower crust (LC) and orogen (OR) are from Zartman and Doe (1981).

4.2. Pb/Pb GEOCHRONOLOGY

The Pb/Pb geochronology technique is used to date igneous rocks, metamorphic rocks, sedimentary carbonate rocks and sulfides containing Pb (Faure, 1986). The Pb/Pb dating was performed on sulfides that were collected from the investigated Au deposits area. Lead isotope compositions of sulfides presented in the Pb isotopes section were used to calculate the Pb/Pb ages using Isoplot v.3.31 Excel macro of Ludwig (2003). Pb/Pb isochron plot for all sulfides yielded an errorchron age of 2227 ± 66 Ma ($n = 9$, $\text{MSWD} = 2.7\text{E} + 7$, Fig. 4.3A), whereas for all arsenopyrite, a Pb/Pb errorchron age of 2220 ± 73 Ma ($n = 5$, $\text{MSWD} = 3\text{E} + 5$, Fig. 4.3B) was obtained. The sulfides were then separated according to the mineralized areas because some differences were visible across the deposits with the Mupane Au deposit being unique in terms of mineralization style and its sulfides were plotted alone (Fig. 4.3C). Golden Eagle and Map Nora Au deposit sulfides were plotted together (Fig. 4.3D) as they share similarities in term of geological setting, mineralization styles and ore minerals (see chapters 2 and 3) and they are adjacent to each other (see Fig. 2.2). The Pb isotope compositions of sulfide samples from the Mupane Au deposit yielded an errorchron Pb/Pb age of 2873 ± 140 Ma ($n = 4$, $\text{MSWD} = 1\text{E} + 5$), whereas sulfides samples from Shashe deposits yielded the errorchron age of 2250 ± 110 Ma ($n = 5$, $\text{MSWD} = 1.3\text{E} + 7$).

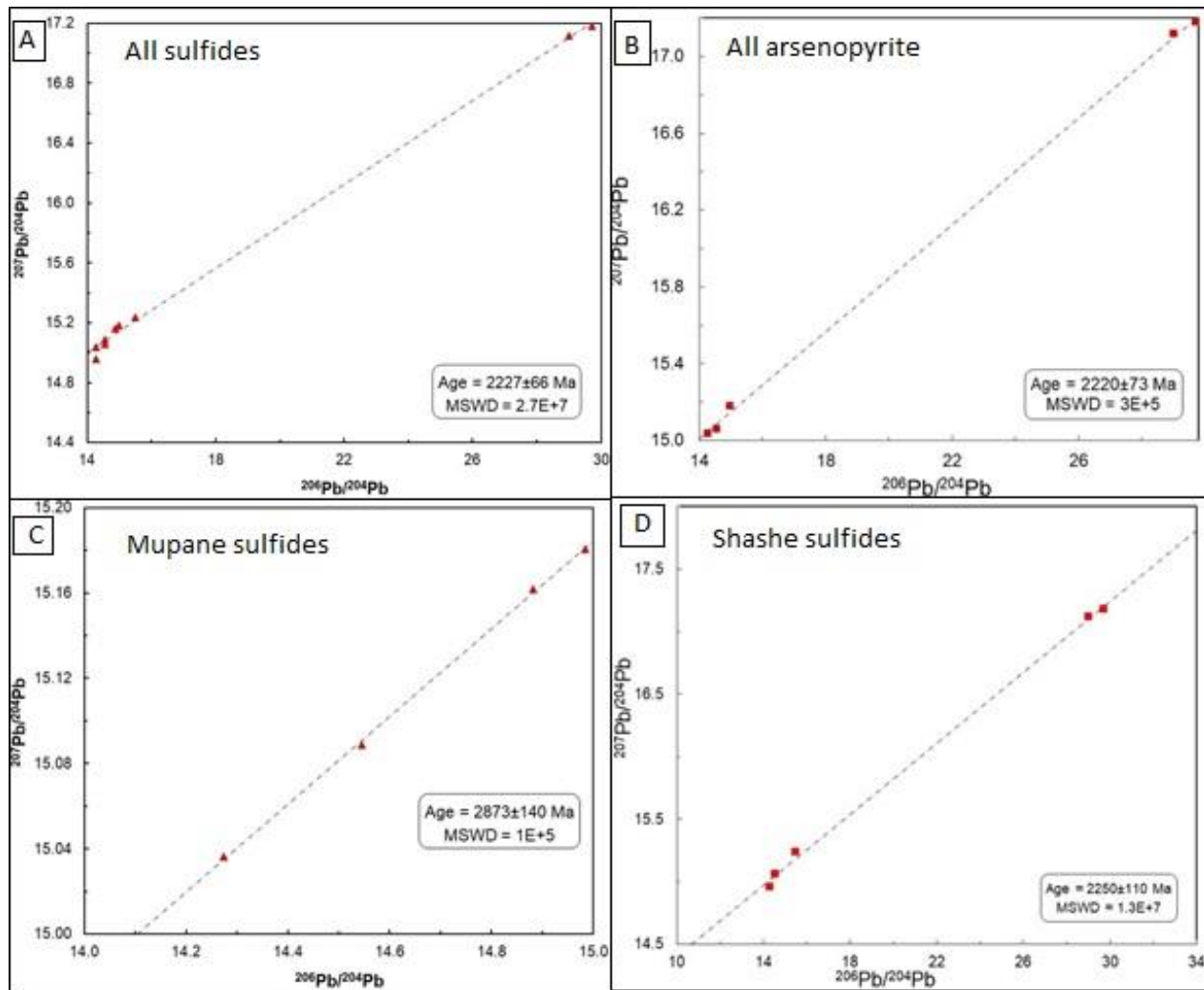


Figure 4.3: Pb/Pb isochron plots of sulfides from Mupane and Shashe Au deposits showing at least three Pb-Pb errorchron ages that overlap within errors from these deposits. (A) Pb/Pb isochron plot of sulfides from Mupane and Shashe Au deposits that yielded an errorchron Pb/Pb age of 2227 ± 66 Ma. (B) Arsenopyrite from Mupane and Shashe deposits yielded an errorchron Pb/Pb age of 2220 ± 73 Ma. (C) Pb/Pb isochron plot of sulfides from the Mupane Au deposit that yielded an errorchron Pb/Pb age of 2873 ± 140 Ma. (D) Sulfides Pb/Pb isochron plot from Shashe deposits that yielded the errorchron age of 2250 ± 110 Ma.

4.3. U/Pb GEOCHRONOLOGY

The U/Pb method is based on the radioactive decay of ^{238}U to ^{206}Pb and ^{235}U to ^{207}Pb . Radioactive decay of U to Pb gives two independent geochronometers that gives concordant ages in closed system and discordant ages with respect to concordia curve in open systems (Chelle-Michou and Schaltegger, 2018). There are two types of concordia curves that consist of the Tera-wasserburg

curve which is basically the relationship between $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{238}\text{U}/^{206}\text{Pb}$ and Wetherill curve which is based on the relation between $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ (Chelle-Michou and Schaltegger, 2018). Both Tera-wasserburg and Wetherill concordant curves give same information on age but the Tera-wasserburg (used in the present study) is more advantageous because the error correlation between $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{238}\text{U}/^{206}\text{Pb}$ is much smaller as compared to $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ (Chelle-Michou and Schaltegger, 2018).

The U/Pb dating method was mainly used to date zircons in the past because uranium and zirconium easily substitutes each other, whereas Pb is excluded in its chemical structure (Faure, 1986). The method was later used to date the growth of garnet, usually the grandite, because it is an abundant mineral that mainly occur in skarn type ore deposits, granite and low- and high grade metamorphic rocks (Fu et al., 2018; Zhang et al., 2018). Grandite is suitable for U/Pb geochronology as compared to pyrope and almandine because it contains ~100 ppb U or Th whereas pyrope and almandine contain less (Seman et al., 2017). The (LA-ICP-MS) U/Pb dating of garnet is more advantageous because it provides in-situ and rapid analyses (Fu et al., 2018).

The garnet sample collected from the Mupane Au deposit is coarse grained, Fe-rich, U-poor (up to ca. 0.03 – 0.27 ppm), Th-poor (0.001 – 0.077 ppm) and highly anisotropic clearly resembling the hydrothermal and almandine (see the compositions in appendix 3) type of garnet. The LA-ICP-MS U/Pb dating technique was used to date hydrothermal almandine garnet collected from GIF sample from the Mupane Au deposit (Fig. 4.4 A), in order to investigate the age of the garnet and by inference the age of associated Au mineralization in the TGB. The genetic relationship between the Au mineralization and the garnet is visible in (Fig 4.4B-D), whereby arsenopyrite occurs as inclusions in the garnet (Fig.4.4B – 4.4C), whereas chalcopyrite occurs in garnet fractures (Fig.4.4C). Sphalerite also occurs in the carbonate veins that cuts across the garnet grain (Fig.4.4D). The close association between the garnet and Au mineralization indicate that they both precipitated at the same time and are therefore cogenetic and coeval.

The Mupane garnet yielded overlapping concordant ages and a lower intercept $^{206}\text{Pb}/^{238}\text{U}$ age of 2105 ± 24 Ma (MSWD = 1.10; Fig 4.5A) and 2119 ± 18 Ma ($n = 58$, MSWD = 1.03; Fig 4.5B), respectively. The 2119 ± 18 Ma lower intercept $^{206}\text{Pb}/^{238}\text{U}$ age is more precise and then considered as the best age for garnet.

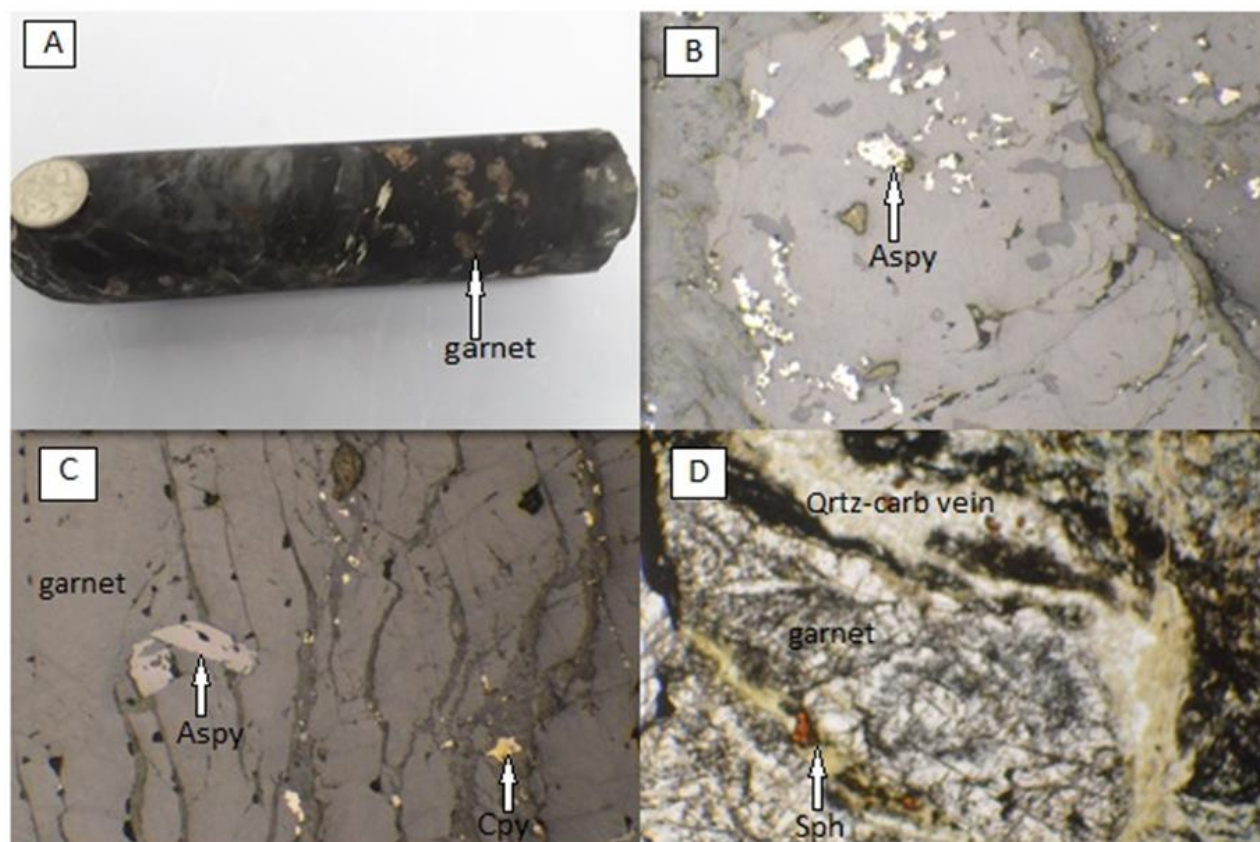


Figure 4.4: Photograph and microphotographs from the Mupane Au deposit. (A) Photograph of a GIF sample showing garnet grains, which were sampled for U/Pb dating. (B) Microphotograph showing inclusions of arsenopyrite (Aspy) within the garnet. (C) Microphotograph depicting inclusions of Aspy within the garnet and also the occurrence of chalcopyrite (Cpy) in garnet fractures. (D) Microphotograph of a garnet grain being crosscut by the quartz-carbonate vein containing sphalerite (Sph).

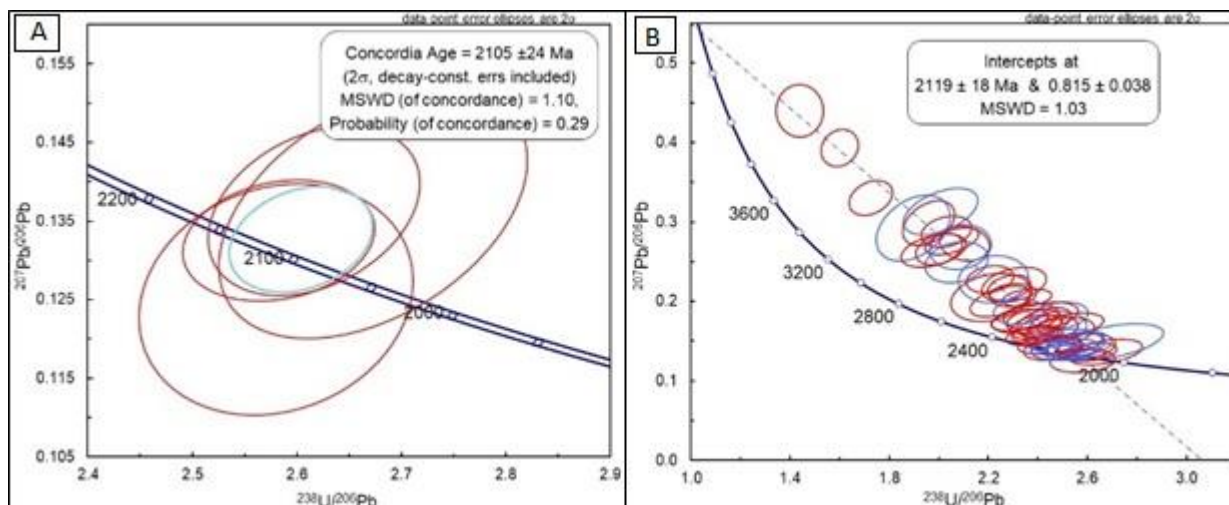


Figure 4.5. (A) Concordia plot of garnet sample that yielded a concordia age of 2105 ± 24 Ma. (B) Tera-wasserburg lower intercept plot of garnet sample that yielded a lower intercept $^{206}\text{Pb}/^{238}\text{U}$ age of 2119 ± 18 Ma.

4.4. Ar/Ar GEOCHRONOLOGY

The $^{40}\text{Ar}/^{39}\text{Ar}$ dating method is based on the irradiation of K-bearing samples with thermal and fast neutrons to form ^{39}Ar (Faure, 1986). The $^{40}\text{Ar}/^{39}\text{Ar}$ method is mainly used to date high grade metamorphic and igneous rocks that contain several K-bearing minerals, such as hornblende, K-feldspar, biotite and muscovite in order to construct the cooling histories of rocks (Faure, 1986). The method can also be used to date alteration minerals including chlorite and sericite in order to obtain their ages. The Ar/Ar method is more advantageous as compared to the K/Ar method because it does not require the need to measure the absolute K and Ar concentrations and also overcomes problems of sample inhomogeneity, which are limitations of the K/Ar method (Faure, 1986).

A phengite (as determined by XRD) sample collected from a pervasively altered sandstone from the Signal Hill Au deposit (see Fig. 4.6A and 4.6B), 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 TGB. The close association between the Au mineralization and the phengite (Fig. 3.4C, 3.4D and 4.6B) suggests a possible genetic link. Therefore, the age of the phengite is deemed to reflect the age of the Au mineralization.

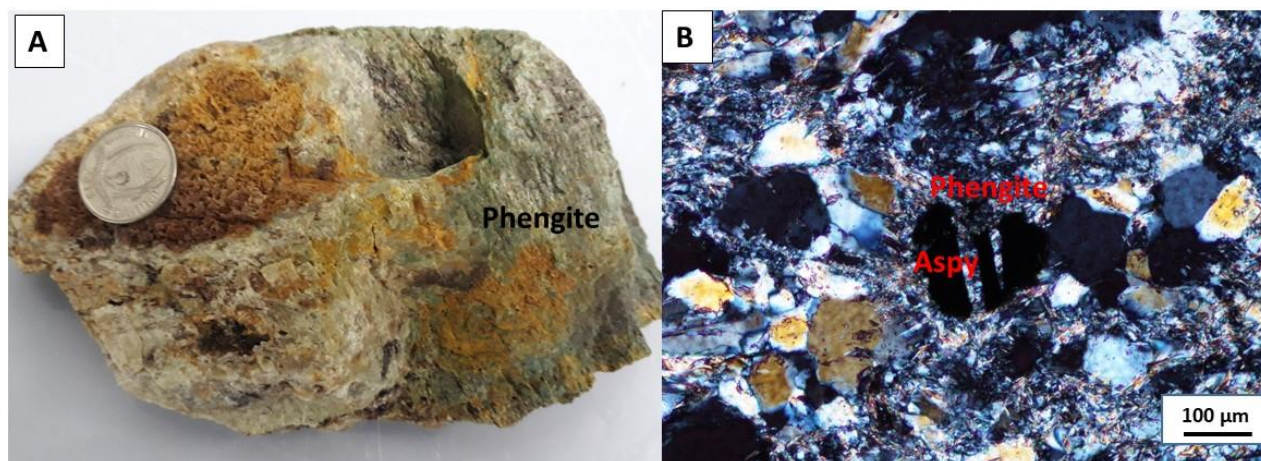


Figure 4.6: (A) Photograph of phengite (green)-altered sandstone from the Signal Hill which was investigated for Ar/Ar dating. (B) Transmitted light microphotograph (XPL) showing the occurrence of arsenopyrite (Aspy) within the phengite, thus clearly showing that Aspy and phengite are closely associated.

Two aliquots were analyzed and gave similar results (Table 4.3). Aliquot 1 is characterized by a rise in age spectra from 1876.5 Ma at low temperature steps to 2006.3 Ma, then decreasing from 2006.3 to 1982.5 Ma as the temperature increased, yielding a plateau age of 1987 ± 29 Ma ($n = 8$, MSWD = 0.27; Fig. 4.7A). The weighted mean Ar/Ar age for aliquot 1 is 1976 ± 31 Ma ($n = 7$, MSWD = 3.9; Fig. 4.7 B). Aliquot 2 age spectra form a saddle-shaped pattern, where age rises from 1867.0 Ma in relatively low temperatures steps to 2017.0 Ma when disregarding the first low temperature steps, then decreasing from 2017.0 Ma to 1998.0 Ma while temperatures increased, without giving a plateau age (Fig. 4.7C). The weighted mean Ar/Ar age obtained for phengite aliquot 2, is 1987 ± 13 Ma ($n = 15$, MSWD = 4.3) as shown in Figure 4.7D and this age overlaps with both the plateau age and the weighted mean age of aliquot 1.

Table 4.3: Ar/Ar results (aliquot 1 and 2) of phengite associated with Au mineralization from the Signal Hill Au deposit.

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	2775.70	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
Aliquot 2															
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

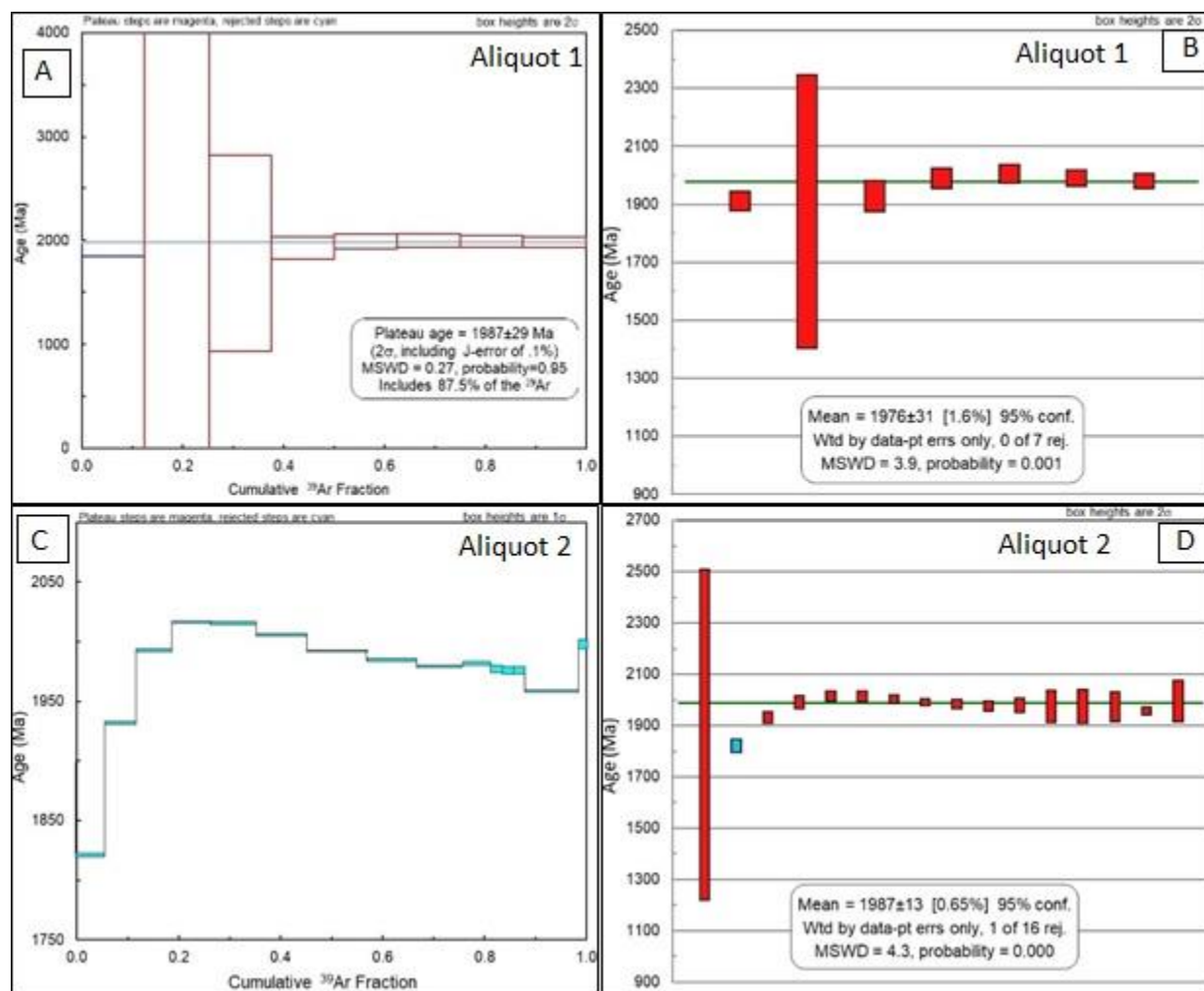


Figure 4.7: Age spectra of phengite aliquot 1 and 2, from the Signal Hill Au deposit. The two Aliquots yielded similar results. (A) Aliquot 1 yielded a plateau age of 1987 ± 24 Ma, and is characterized by rise in the age spectra from 1876.5 Ma at low temperature steps to 2006.3 Ma, then decreasing from 2006.3 to 1982.5 Ma as the temperature increases. (B) The weighted mean Ar/Ar age obtained for aliquot 1 is 1976 ± 31 Ma. (C) Aliquot 2 did not yield a plateau age and yielded scattered age spectra from 1867.0 Ma in relatively low temperatures steps to 2017.0 Ma when disregarding the first low temperature steps, then decreasing from 2017.0 Ma to 1998.0 Ma while temperatures increased. The weighted mean Ar/Ar age plot of phengite aliquot 2, is represented by figure D. The red boxes represent phengite analyses which were integrated in the calculation of the weighted mean Ar/Ar age, whereas the blue box represents the excluded analyses in the calculation of the weighted mean Ar/Ar age. The green crosscutting line corresponds to the area of final age. The weighted mean age obtained is 1987 ± 13 Ma.

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*CHAPTER 5: DISCUSSION

The age(s) and the source(s) of Au mineralization in TGB were investigated in the current study through the Pb/Pb, U/Pb and Ar/Ar geochronology and Pb isotope studies, respectively. The obtained results are discussed in detail below.

5.1. Sources of metals

In both the uranogenic and thorogenic plots (Fig. 4.2), the whole rock and sulfide signatures overlap and mostly fall between the mantle and upper crust curves of Zartman and Doe (1981), suggesting mixing of crustal and mantle-derived Pb. The Pb isotope compositions of sulfides are heterogeneous, which is an indication of mixing of multiple Pb sources for sulfides. The Pb isotope compositions of both sulfides and whole rocks (including schists and granodiorite) from Mupane, Shashe and Signal Hill overlap (Fig. 4.5), thus suggesting granodiorite from Signal Hill and schist from Mupane and Map Nora are the possible sources of Pb and by inference the other metals including Au. The sulfides from Map Nora are however more radiogenic and plot beyond the Pb isotope compositions field of other sulfides and whole rocks, thus suggesting a totally different Pb source, other than the schist, granodiorite and dolerite. The possible source of Pb and by inference Au in Map Nora Au mineralization may be the black shale that was observed to occur in the mineralization area (Tombale, 1992; Dossing et al., 2009) and which is known to be more radiogenic lithology, as it is enriched in Th, U and K (Bottoms and Potra, 2017).

5.2. Age of TGB Au mineralization and its geological significance

Sulfides from the investigated TGB Au deposits yielded an imprecise Pb/Pb errorchron age of 2227 ± 66 Ma (MSWD = 2.7E + 7). The Pb/Pb errorchron dates were also obtained when only sulfides from the same mineralized zone were considered, suggesting that different mineralization events took place within single mineralized zones / deposits. This is also supported by the petrographic studies described in chapter 3, which shows some varying textures of arsenopyrite. Some arsenopyrite grains are not strained (Fig.3.2G), indicating they have not been affected by any deformation, whereas others are highly fractured (Fig. 3.2G) and elongated indicating that they underwent both brittle and ductile deformation.

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At Mupane, sulfides yielded a Pb/Pb errorchron age of 2873 ± 140 Ma (MSWD = 1E + 5), whereas hydrothermal almandine garnet spatially associated with Au mineralization yielded a Tera Wasserburg lower intercept $^{238}\text{U}/^{206}\text{Pb}$ age of 2119 ± 18 Ma (MSWD = 1.03) and a concordia age of 2105 ± 24 Ma (MSWD = 1.10). The U/Pb method produced a more precise and robust age (MSWD of 1.03) as compared to the Pb/Pb method. The Pb/Pb errorchron age for Mupane indicates that either the isotopic system did not remain closed or the initial Pb isotope ratios were not homogenous and therefore the investigated sulfides may be of different ages. Although the Mupane 2873 ± 140 Ma Pb/Pb errorchron age is imprecise, the age is postulated to represent one event of the Mupane Au mineralization because this age is geologically meaningful, as it coincides with major events that occurred both locally and regionally.

The 2873 ± 140 Ma Pb/Pb errorchron age obtained corresponds within error to the age of the deposition of BIF (2.73 ± 0.15 Ma, Døssing et al., 2009) in the TGB, intrusion of granitoids (2.65 - 2.73 Ga, Bagai et al., 2002) in the TGB and to the beginning of the 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), which was named Limpopo-Liberian tectogenetic cycle (Kröner, 1977a). According to Tombale (1992) the relationship between the Zimbabwe Craton and the Limpopo Belt is evident through this 2.7 Ga orogenic event (Limpopo-Liberian tectogenetic cycle) which affected most parts of the African continent including the Zimbabwe Craton. This tectono metamorphic event involved the continent-continent collision between the Zimbabwe and the Kaapvaal cratons and was accompanied by granitoids intrusion (Tombale, 1992), which occurred at the same time as the intrusion of granitoids in the Zimbabwe Craton (Aldiss 1991; Tombale, 1992; Bagai et al., 2002; Kampunzu et al., 2003; Rigby et al., 2008).

The 2119 ± 18 Ma and 2105 ± 24 Ma hydrothermal almandine garnet ages overlap each other and do not match any known geotectonic event. These ages can be confidently used to represent a distinct Au mineralization event at Mupane.

The 2250 ± 110 Ma errorchron age for Shashe deposits, 2222 ± 66 Ma errorchron age for all sulfides and 2220 ± 73 Ma errorchron age for all arsenopyrite overlap but however, indicate either heterogeneous sulfides initial Pb isotope ratios and/or open system behavior.

At the Signal Hill Au deposit, the obtained 1987 ± 29 Ma phengite Ar/Ar plateau age and the 1976 ± 31 Ma and the 1987 ± 13 Ma phengite weighted mean Ar/Ar ages overlap within error. These phengite Ar/Ar ages are also consistent with the garnet Pb-stepwise leaching (PbSL) age of 1976 ± 88 Ma obtained by Døssing et al. (2009). Therefore, the phengite Ar/Ar ages obtained here are reliable. The 1987 ± 13 Ma phengite weighted mean Ar/Ar age is more precise as compared to other ages and is therefore considered as the best age to represent the Signal Hill Au mineralization event. The phengite ages are younger than ages of all geological events that occurred locally, in the TGB. The geological events that occurred in the TGB include metamorphism (2630 ± 70 – 2570 ± 70 Ma, Van Breemen and Dodson, 1972), intrusion of igneous rocks (2.65-2.75 Ga, Bagai et al., 2002), BIF deposition (Døssing et al., 2009) and deposition of TGB (~ 2.7 Ga, Wilson et al., 1978; Wilson, 1979). The phengite Ar/Ar ages corresponds within error to the age of the Paleoproterozoic Limpopo-Liberian tectogenetic cycle (1.95– 2.05 Ga, Barton et al., 1994; Kamber et al., 1995a, b; Jaeckel et al., 1997; Holzer et al., 1998 and references therein), which took place at the Limpopo Belt in the Central Zone, as Døssing et al. (2009) had already correlated their PbSL garnet age. The close relationship between the Zimbabwe Craton and the Limpopo Belt also suggests the possibility of the Paleoproterozoic Limpopo-Liberian tectogenetic cycle to have affected some parts of the Zimbabwe Craton, since the event affected the three zones of the Limpopo Belt including the Northern Marginal Zone, which is adjacent to the Zimbabwe Craton. The 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., 2004b). Therefore, this orogenic event is likely the possible event that triggered the Au mineralization in the Signal Hill Au deposit.

Gold mineralization at the TGB corresponds to at least three distinct mineralization events, triggered by different geotectonic events as summarized in Fig. 5.1 below. The Signal Hill Au mineralization event is promoted by the Paleoproterozoic Limpopo-Liberian tectogenetic cycle, whereas the Mupane Au mineralization event correspond to the Neoproterozoic Limpopo-Liberian tectogenetic cycle and granitoids intrusion.

5.3. Genetic model

Based on the style of mineralization, host rocks and mineral assemblages, the TGB Au deposits share similarities with many orogenic Au worldwide (Groves et al., 1998; Goldfarb et al., 2005). Host rocks in orogenic Au deposits are mainly mafic-ultramafic rocks, sedimentary rocks and granitoid plutons and are generally metamorphosed to greenschist facies. Mineralization occurs as disseminated, filling fractures and as vein-hosted and the common ore minerals found within the orogenic Au deposit include pyrrhotite, arsenopyrite, pyrite, sphalerite, galena and chalcopyrite. Hydrothermal alteration types include sericitization, chloritization and silicification.

Orogenic Au deposits can be classified based on the timing of Au with respect to the metamorphism and can be pre-metamorphic, syn-metamorphic and post-metamorphic. The two well constrained ages for Mupane (2119 ± 18 Ma) and Signal Hill Au deposits (1987 ± 13 Ma) are both post-metamorphic ($2630 \pm 70 - 2570 \pm 70$ Ma, Van Breemen and Dodson, 1972), whereas the 2873 ± 140 Ma Mupane Au mineralization is pre-metamorphic ($2630 \pm 70 - 2570 \pm 70$ Ma, Van Breemen and Dodson, 1972). The post-metamorphic Mupane and Signal Hill Au mineralization can be compared to many orogenic Au mineralization worldwide, where mineralization was also recognized to be post-metamorphic. The Danba orogenic Au mineralization, Yangtze Craton, is such a post-metamorphic mineralization that occurred at ca. 185 ± 9 Ma after regional amphibolite facies metamorphism at ca. 193 ± 5 Ma, (Huang et al., 2003a, b; Zhao et al., 2019). Other few examples of orogenic Au deposits that were formed post amphibolite facies metamorphism include the Hutti Orogenic Au mineralization in South India (Rogers et al., 2003, 2007; Kolb et al., 2005), the giant orogenic Au deposit at Hemlo, Canada (Phillips and Powell, 2009) and numerous orogenic Au deposits at Big Bell, Western Australia (Phillips and Powell, 2009), Renco, Zimbabwe (Kolb and Meyer, 2002), New Consort, South

Africa (Dziggel et al., 2010), Challenger orogenic Au deposit in South Australia (Phillips and Powell, 2009) and the Neoarchean Tropicana Au deposit on the edge of the Yilgarn Craton (Goldfarb and Groves, 2015).

The pre-metamorphic Neoarchean Mupane Au mineralization (2873 ± 140 Ma) is similar to the 2.5- 2.3 Ma Au mineralization events at Dongyaozhuang, Diantou, Xiaobanygu orogenic Au deposits of the Wutai greenstone belt, which are also pre-metamorphic (1.95- 1.80 Ma, Zhang et al., 2017).

The pre-metamorphic and post-metamorphic TGB Au mineralization events shows no temporal relationship with the metamorphism, suggesting that metamorphic fluids were not involved in mineralizing processes. However, the correlation between the 2873 ± 140 Ma Mupane mineralization event and the 2.65 – 2.75 Ma granitoids intrusion, as well as the overlapping Pb isotope compositions between sulfides and granitoids imply the possible genetic link between granitoids intrusion and mineralization events, therefore, indicating the possible involvement of magmatic fluids in mineralizing fluids.

The discussion above clearly indicates that with reference to metamorphism, two mineralization events occurred at TGB, with the first event (2873 ± 140 Ma) being pre-metamorphic and probably triggered by the Neoarchean Limpopo-Liberian tectogenetic cycle and granitoids intrusion. The second event represented by two mineralization events (1987 ± 13 Ma and 2119 ± 18 Ma) is post-metamorphic and the 1987 ± 13 Ma is promoted by the Paleoproterozoic Limpopo-Liberian tectogenetic cycle.

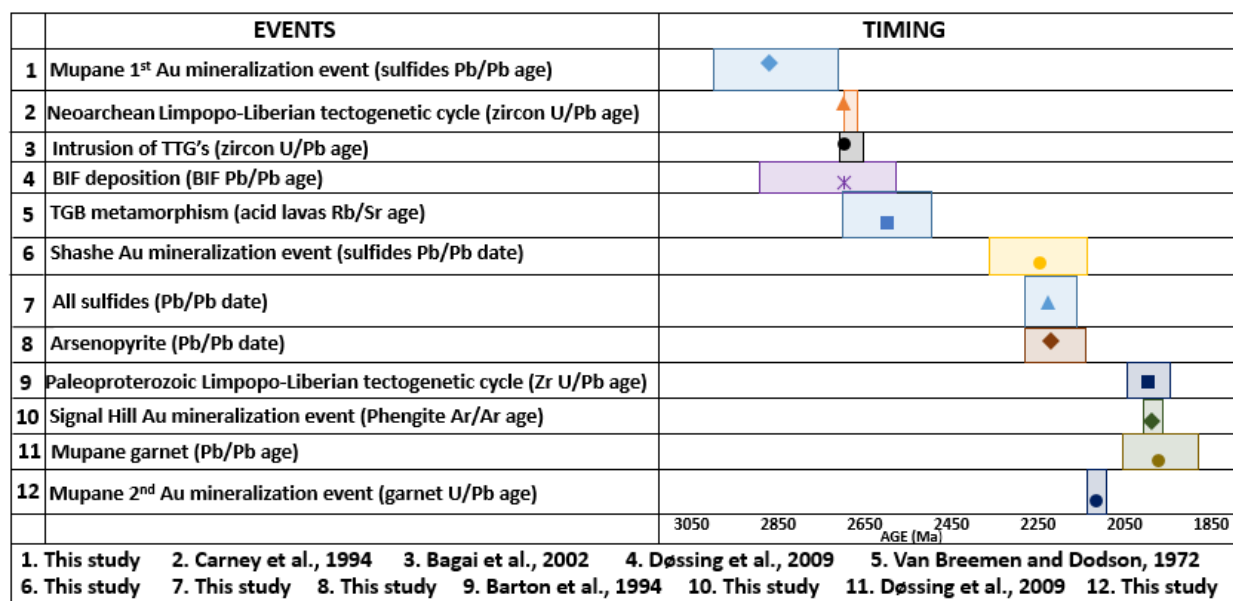


Figure 5.1: Correlation between gold mineralization events and other geologic increments in the TGB and in the Limpopo Belt.

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CHAPTER 6: CONCLUSIONS AND PERSPECTIVES

The study was aimed at constraining the genesis of Au mineralization occurring within the Tati Greenstone Belt through investigations combining Ar/Ar, Pb/Pb and U/Pb geochronology and Pb isotope analyses. The main objectives of the study were, (i) to track the source of Au (ii) to investigate the ages of the Au mineralization events through the TGB and, (iii) to assess the temporal and by inference the genetic relation between Au mineral occurrences within the TGB. The following conclusions can be drawn based on the discussion elaborated in chapter 5:

1. The TGB Au mineralization corresponds to at least 3 distinct gold mineralization events that took place at 2873 ± 140 Ma, 2119 ± 18 Ma and 1987 ± 13 Ma and were triggered by different geotectonic events.
2. The 2873 ± 140 Ma mineralization event coincides with the Neoproterozoic Limpopo-Liberian tectogenetic cycle, granitoids intrusion and the deposition of BIF within the TGB.
3. The 1987 ± 13 Ma Signal Hill Au mineralization event was triggered by the Paleoproterozoic Limpopo-Liberian tectogenetic cycle.
4. The sulfides Pb isotope compositions in the TGB are heterogeneous indicating multiple sources of Pb for sulfides; and by inference multiple Au sources.
5. Granodiorite from Signal Hill, schist from Mupane and Map Nora, and black shales are the main possible sources of Au.

The findings of this study are also likely to provide exploration guidelines that could help in further discoveries in the TGB. Information pertaining to the source of gold, the age and the possible events that triggered the mineralization across the TGB can be of significant importance in Au exploration within the TGB. The BIF and the granitoids (including granodiorite) are coeval with mineralization, suggesting that the two co-existed at the same time as the mineralization, so areas crosscut by granitoids and areas consisting of BIF could be the most targeted areas for Au exploration in the TGB. The areas overprinted by the Neoproterozoic Limpopo Orogeny and the Paleoproterozoic Limpopo Orogeny could also be the targeted areas for Au mineralization in the TGB.

The age of geological events in the Zimbabwe Craton are not well constrained. This therefore

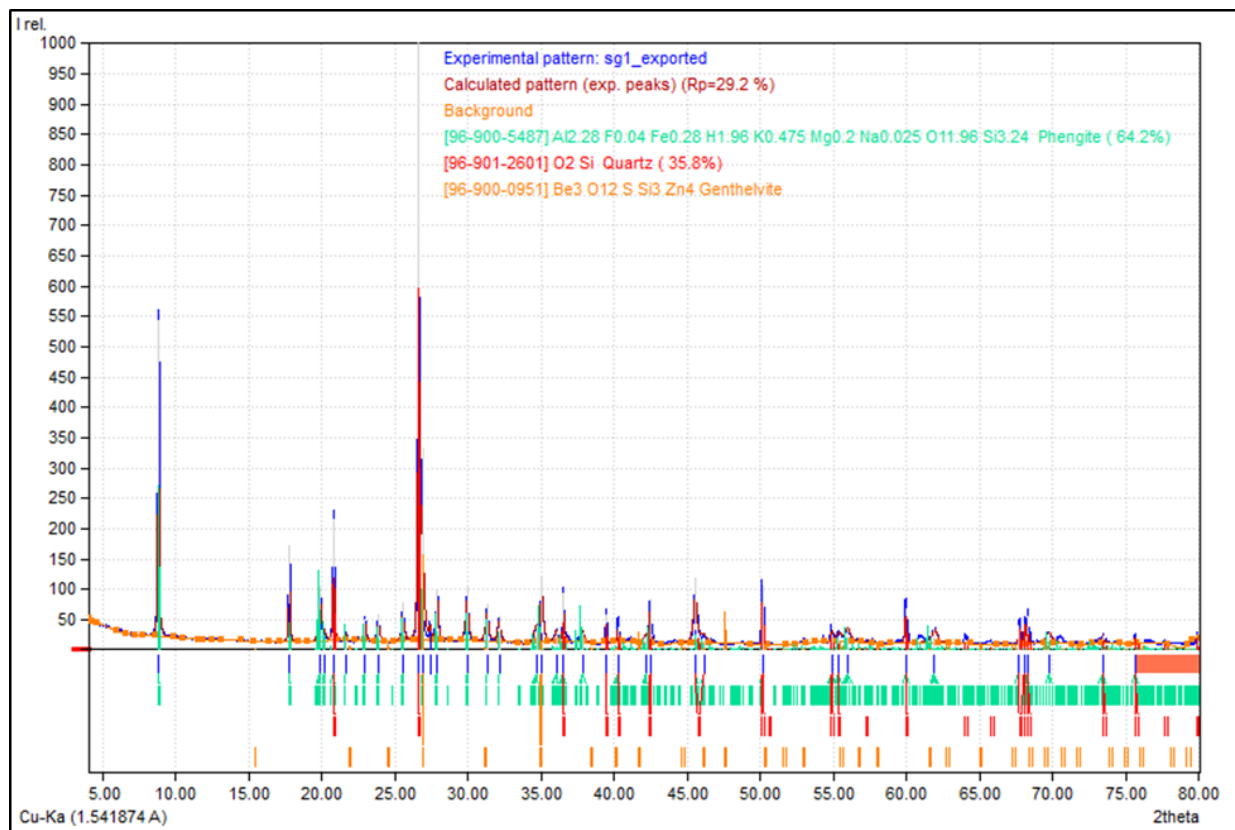
posed a problem when correlating the ages of the mineralization events to the ages of the geotectonic events that took place in the TGB. Additional geochronology studies are needed to further constrain the ages of geotectonic events in the TGB and also to constrain the ages of Au mineralization in the neighboring greenstone belts that include the Vumba Greenstone Belt.

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APPENDIX A1

XRD diffractogram for the phengite identification.



APPENDIX A2

Table A2 the contents of U, Th and Pb that were used to calculate the initial Pb isotope compositions of whole rocks spatially associated with the four investigated Au deposits.

ICM90A			
SAMPLE NUMBER	Pb 5 ppm	Th 0.1 ppm	U 0.05 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 25V	8	1.7	0.58

APPENDIX A3

Chemical compositions of garnet associated with Au mineralization from Mupane

Samples ID Grain ID n analyses/grain	LBC-3(1)				LBC-3(2)			
	3		4		3		4	
	11		15		10		15	
	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	

APPENDIX A4

The appendix presents the front page of the Precambrian Research paper in its published format by Thierry Bineli Betsi, Lebogang Mokane, Kelebogile Phili and Tebogo Kelepile (2020).

Journal Pre-proofs

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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