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Geometallurgical characterisation of cassiterite at the groenfontein and zaaiplaats deposits in the Northern limb of the bushveld complex, South Africa

Nethononda, Tshilisanani Simon

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GEOMETALLURGICAL CHARACTERISATION OF CASSITERITE AT THE GROENFONTEIN AND ZAAIPLAATS DEPOSITS IN THE NORTHERN LIMB OF THE BUSHVELD COMPLEX, SOUTH AFRICA

Tshilisanani Simon Nethononda

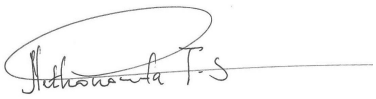
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A research report submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of MSc.

Johannesburg, 2019

Declaration

I declare that this research report is my own, unaided work. It is being submitted for degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any other degree or examination at any other university.



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(Signature of Candidate)

January 2019

ABSTRACT

Properties of the Groenfontein 227 KR and Zaaiplaats 223 KR farms are located within the Zaaiplaats tin mining district about 30 km north-west of Mokopane in Polokwane, South Africa. The present study evaluate the geometallurgical characteristics of the Groenfontein 227 KR and Zaaiplaats 223 KR farms, with the view of understanding the mineralogical constituent, grading analysis, grain size distribution, element deportment, and recovery of tin occurring within cassiterite ore. Within the properties of the Groenfontein and Zaaiplaats farms, the Renetype (Pty) Ltd obtained a prospecting licence in 2010, to explore for tin within cassiterite. The geometallurgical characteristics of the ore are the key to value realisation when applied to the optimisation of mining and plant processing, and the variability in the orebody enables optimum operational design and extraction methods that maximise value recovery. This has been accomplished by obtaining quantitative mineralogical information coupled with chemical assay, laboratory scale milling, and pilot-scale test-work by gravity spirals and shaking tables. The bulk samples and drilled core were collected from cassiterite ore on surface (old workings) at Groenfontein farm. The collected bulk samples were further coarsely crushed and estimated for mineral modal abundances, and then analysed for tin (Sn) concentrate. However, within the Zaaiplaats farm, samples were also collected from bulk samples, and further from tailings dump. The results from the studied samples indicate that impurities such quartz, feldspars, chlorite are the dominant mineralogical constituent within the bulk samples, drilled core and tailings. The calculated head grade of samples from drilled core, bulk samples within Groenfontein farm, and bulk samples and tailings from Zaaiplaats farm were 0.44 %, 0.12 %, 0.1 %, 0.13 %, and 0.13 % respectively. Shaking table results of the tailings at the upper-stream within the Zaaiplaats farm indicate that 50 % of Sn reported to the concentrate of 8 % and gravity tests at 0.2 % of Sn. In sample ZTD02, 40 % of Sn was recovered in the concentrate consisting of about 5 % mass and a final gravity tails of 0.22 % of Sn. In the drilling core sample within the Groenfontein farm, it was possible to upgrade the Sn concentrate to as high as 15 % into the concentrate, indicating that the drilling core sample was controlled by gravity concentration. Furthermore, in bulk samples from Groenfontein and Zaaiplaats farms, and drilled core from Groenfontein farm tin grade have a decreasing trend towards the coarse grained size fractions, while most of the tin mass is in the coarse fractions. Nonetheless, in bulk samples from Zaaiplaats farm the highest tin grade was 4887 ppm in the -425/+212 µm to -212/+106 µm size fraction. Based on core sample and ore dump, the study recommends a thorough evaluation based on the suitability of density medium separation prior to shaking table or spirals, by doing heavy liquid separation test-work at two different top sizes (8 mm and 5 mm) and two different densities (2.8 and 3).

Keywords: *Geometallurgy; Cassiterite; grading analysis; recovery*

DEDICATION

I dedicate this research report to my late grandmother

Mrs Muofhe Madzanga Mugwagwa-Nengwenkhulu

My thoughts are always with you and may your soul rest in peace

My lovely uncle

Mr Gumani Nengwenkhulu

Thank you for always supporting me in everything I do, no words can ever explain how grateful I am to have you in my life

And my parents

Mr and Mrs Nethononda

With love and thanks.

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The VM Investment Exploration division staff is especially thanked for treating me as part of their team. To the Technical Directors (Prof Richard Viljoen and Prof Morris Viljoen), as well as my co-supervisor, Dr Luke Longridge, thank you for all your input and assistance concerning my studies.

I also would like to thank SGS laboratory for conducting the mineralogical characterisation test work on GHT2016/2017 and ZP2016/2017 tin ore samples respectively, and also as well Maelwyn Mineral Services Africa for analysis of size by assay products through XRF as well as performing Shaking Table Scouting tests on half core from GHT011, and tailings from ZTU01 and ZTD02 respectively.

Lastly, I'd like to thank my family, friends and everyone who has supported me throughout the research journey. To my parents (Mr Ndifelani Nelson Nethononda and Mrs Margret Nengwenkhulu-Nethononda), brothers, sisters, without you I would not be where I am today; my late grandmother (Mrs Muofhe Madzanga Mugwagwa-Nengwenkhulu) my thoughts are always with you and may your soul rest in peace. My uncle Mr Gumani Nengwenkhulu, thank you for everything and for being there for me. Above all, I thank God for His mercy and wisdom to complete this work.

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CHAPTER 1

General Background

1. Introduction

This chapter presents a brief overview on the location of the study area, local geology, regional geology, historical mining activities, and previous research work done on the study area. A brief outline is provided on the historical tin production and market in relation to other deposits in South Africa.

1.1. Location of the study area

The study area is located at the Groenfontein (678401/7339473) and Zaaiplaats (6802004/7337082) deposits in the Northern Limb of the Bushveld Complex, northwest of Mokopane area in the Limpopo Province, South Africa (Fig.1.1).

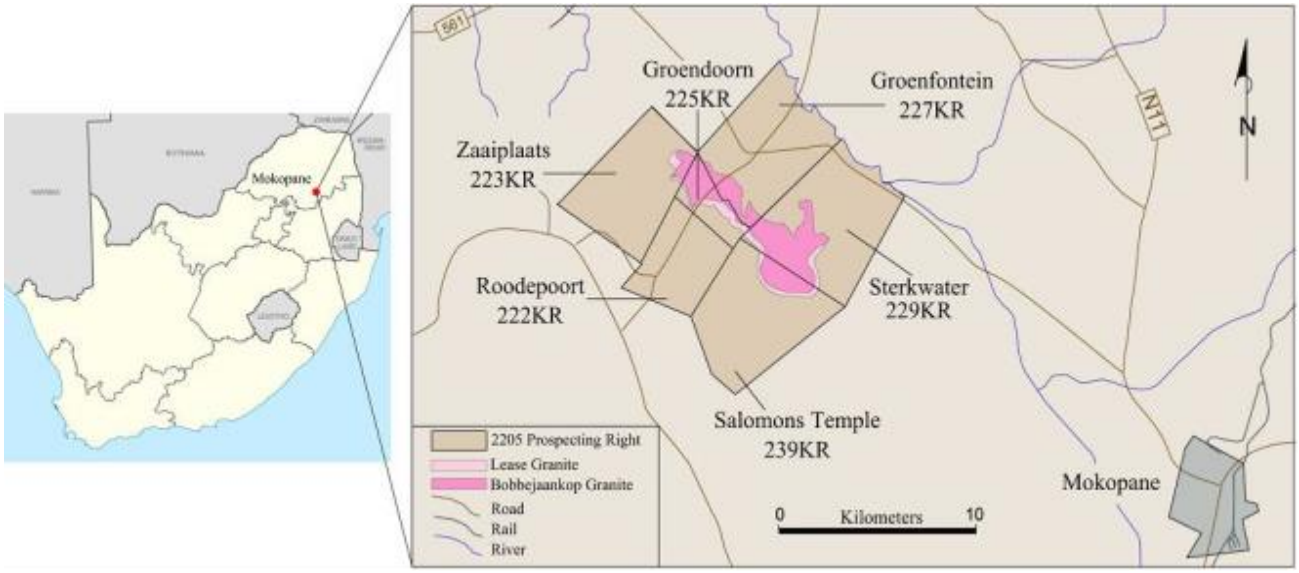


Figure 1.1 Location map of the Groenfontein and Zaaiplaats deposits in Mokopane, Limpopo Province, South Africa (Modified after SRK, 2013).

Renetype Pty (Ltd), a company owned by Bushveld Minerals Limited, was granted prospecting rights in 2010 for the property 2205PR, comprising six farms: Zaaiplaats 223KR, Roodepoort 222KR, Groenfontein 227KR, Groendoorn 225KR, Sterkwater 229KR and Salomon's Temple 230KR (SRK, 2013). Within the licence area, numerous targets for open-cast disseminated cassiterite resources have been identified and the company has explored and drilled two targets, the Groenfontein and Zaaiplaats deposits. These two deposits form the focus area for the present study.

1.2. Regional geology

The Bushveld Complex (~2.06 Ga) is the largest layered intrusion in the world (SAC, 1980; Cawthorn, 1999). The Bushveld Complex intruded into the Pretoria Group of the Transvaal Supergroup (Eriksson, 1995). It consists of four lithological subdivisions, namely; the intrusive Rustenburg

Layered Suite (RLS), Rashoop Granophyre Suite (RGS), the extrusive Rooiberg Group (RG) and the Lebowa Granite Suite (LGS) (Schweitzer *et al*., 1997). Currently, the Bushveld Complex is exposed as five lobes namely the western, far western, eastern, northern and south-eastern Bethal limb, obscured by younger sediments (Kinnaird *et al*., 2004). The tin project is situated in granite of the Lebowa Granite Suite (LGS) of the Northern Limb of the Bushveld Complex (Fig. 1.2).

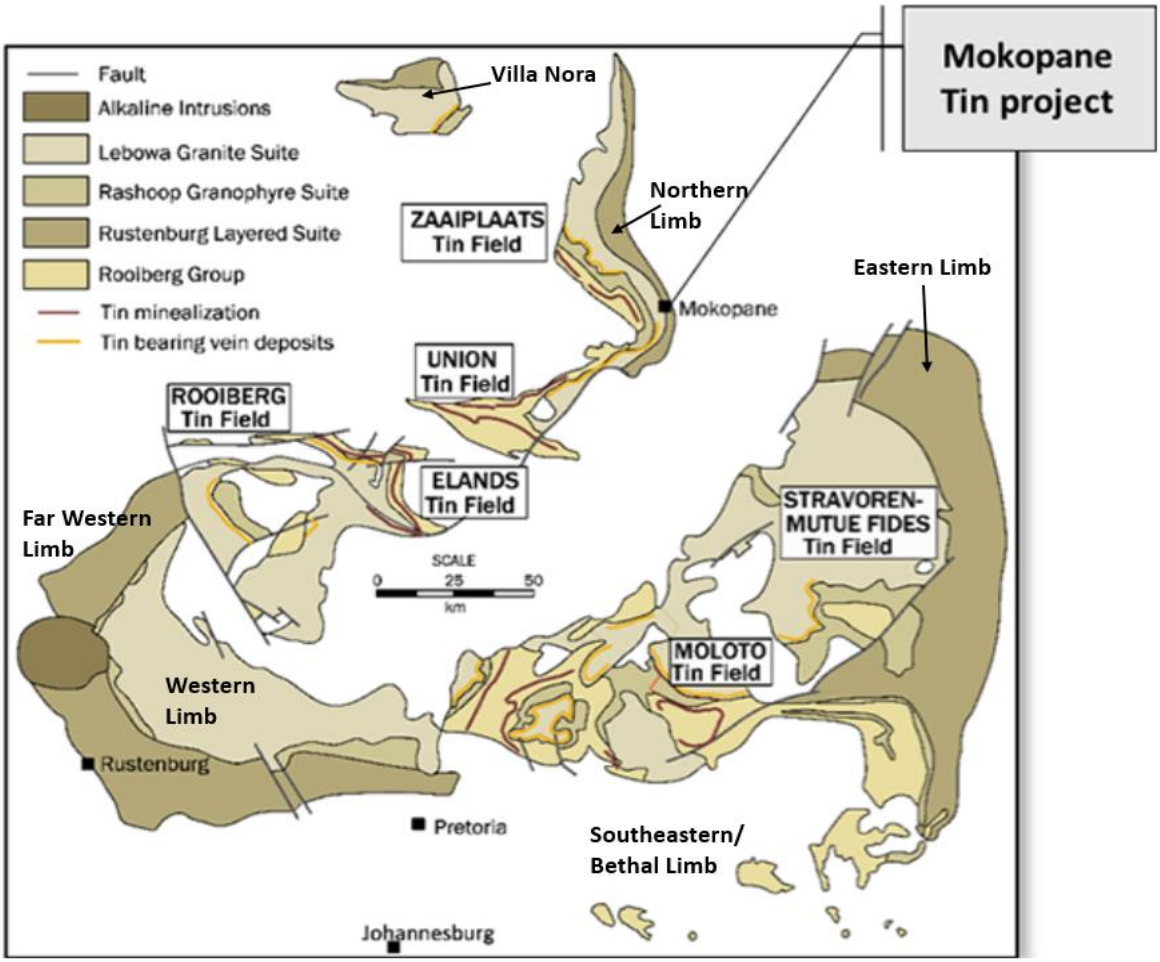


Figure 1.2 Map of the Bushveld Complex (Modified after Afritin 2017).

The Rooiberg Group, is petrographically linked to the Bushveld Complex. It is believed that intrusion of the Rustenburg Layered Suite (RLS) lifted the upper Rooiberg Group lavas, causing then to detach from the Dullstroom lavas thereby forming the roof of the Bushveld Complex (Twist, 1985). The Rooiberg Group is an approximately 3.5 km thick sequence of felsic volcanic rocks covering an area of more than 50 000 km² (Buchanan *et al*., 2002). The stratiform Rustenburg Layered Suite (RLS) is a 7-8 km thick sequence of mafic and ultramafic rocks covering an approximately area of 90 000 km² (Eales and Cawthorn, 1996).

The Rashoop Granophyre Suite (RGS) that is compositionally similar to the Rooiberg Group, and is thought to represent remobilised Rooiberg material (Lenhardt and Eriksson, 2012). The younger Lebowa Granite Suite (LGS) is a 1.5-3.5 km thick, sheet-like intrusion with an area that covers about 30 000 km² (Kinnaird, 2005). The Lebowa Granite Suite (Fig. 1.3) is considered to have been emplaced as large stratified sheets between the Transvaal Sequence below and rhyolites of the Rooiberg Group and granophyric granites of the Rashoop Granophyre Suite above (Pollard *et al*.,

1991). The Bushveld Complex is host to ore deposits such as PGE, vanadium, chromium, cassiterite, fluorite, scheelite, molybdenite, with enrichments of copper, nickel, cobalt and gold etc (Jones, 1999; Bailie and Robb, 2004).

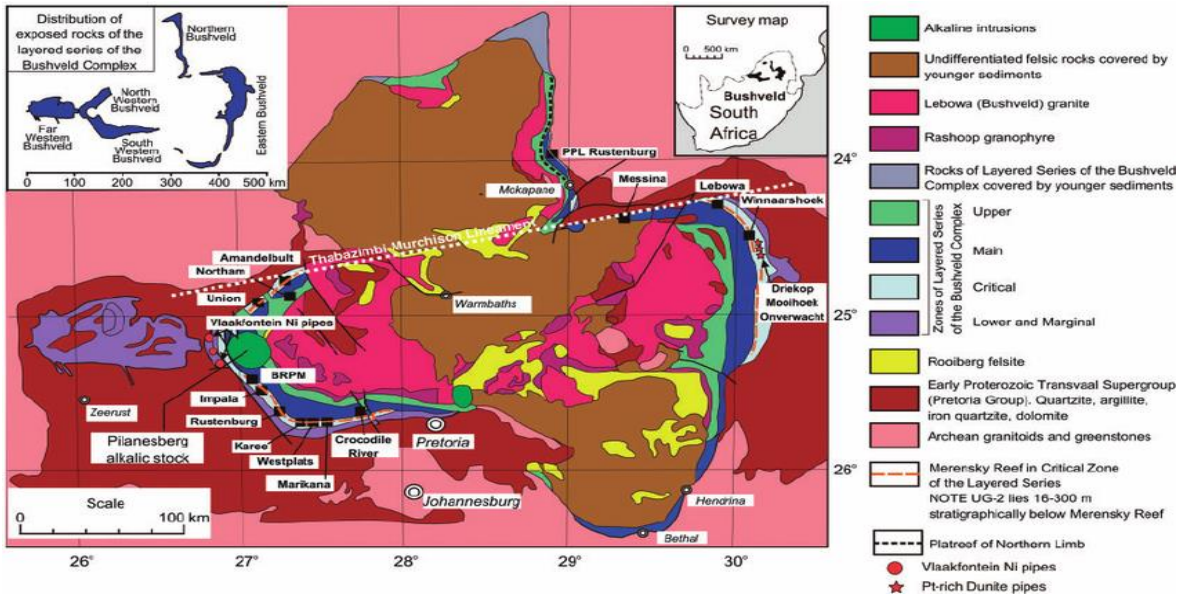


Figure 1.3 General lithostratigraphy of the Bushveld Complex (Modified after Eales and Cawthorn, 1996).

According to Pollard *et al*., (1991) the Lebowa Granite Suite (LGS) is divided into two units namely; the Nebo Granite (from which the Lease and Bobbejaankop Granite are formed), and the Makhutso Granite. The Makhutso Granite is the youngest of the three units and is medium-grained with a relatively high content of mafic minerals compared to the other granites (Walraven, 1988).

The roof of the Lebowa Granite Suite (LGS) in the northern limb of the Bushveld Complex, generally dips at 10° to 15° to the southwest, parallel to the dipping strata in the overlying granophyric granite (de Waal, 1972). This inclination conforms to the regional basin structure of the Palala Plateau and north-eastern flank of the Transvaal basin (Strauss, 1954). In the region, there is an angular unconformity between the tilted Rooiberg series and the overlying Waterberg sediments (Strauss, 1954). Several faults trending southwest to northeast occur in the area (Strauss, 1954). Some fault-planes occupied by large dolerite dykes suggest that they are normal faults, possibly of Post-Karroo age (Strauss, 1954).

1.3. Local geology

The geology of the farms is dominated by the acid phase of the northern limb of the Bushveld Complex (Fig. 1.4). Four major types of granite occurring include; the Rashoop Granophyric Suite and pegmatites, together with the Nebo, Bobbejaankop and Lease granites (Fig.1.4).

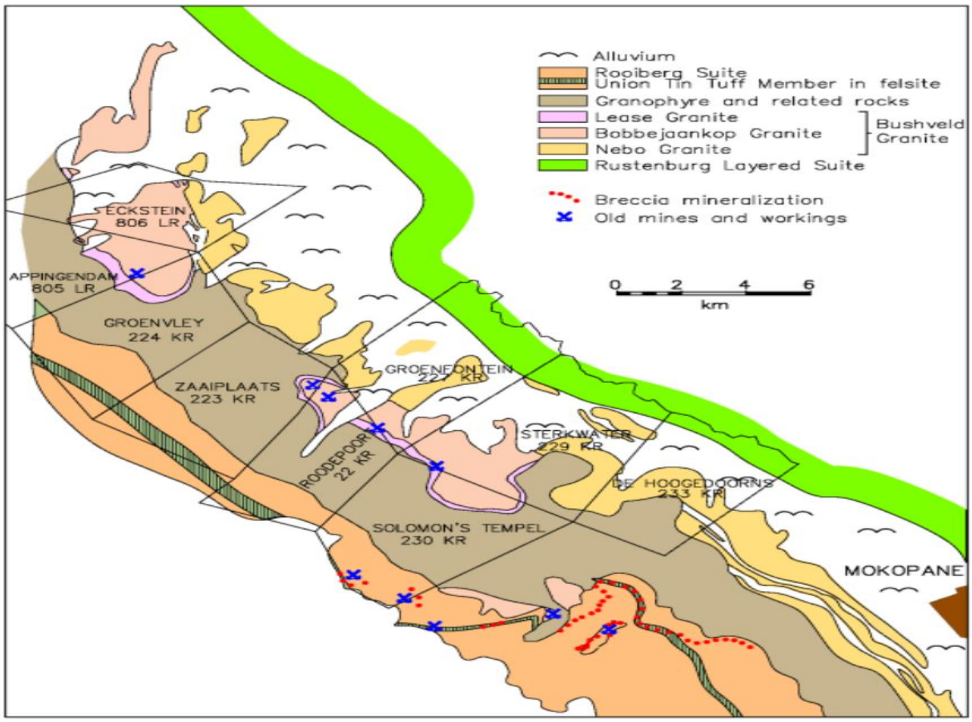


Figure 1.4 Geological map of the location of various cassiterite deposits in the study area in relation to the granites of the Bushveld Complex and other geological formations (Image courtesy of Bushveld Minerals).

1.3.1. *Lebowa Granite Suite*

The Nebo (Main) Granite is the most abundant lithology in the study area, and forms low, undulating topography (Crocker *et al*., 2001). Typically the Nebo (Main) Granite is mostly found on the flat plain (Fig. 1.5 a), as observed in the southwestern portion of Groenfontein Farm (Groenfontein 227 KR). The Nebo Granite is coarse-grained (Fig. 1.5 b), and is typically grey to pinkish-red in colour (Fig. 1.5 c). The Nebo Granite is composed of quartz and perthite with lesser amounts of sodic plagioclase, hornblende and biotite.



Figure 1.5 Nebo Granite outcrop SW of Groenfontein farm 227 KR in the Northern Lobe of the Bushveld Complex. (a) Flat Plain (b) Coarse grained facies (c) Grey-pinkish red facies.

The Bobbejaankop Granite is suggested to be a hydrothermally altered facies equivalent of the Nebo Granite (Coetzee and Twist, 1989). These authors further reported that on a regional scale, the Bobbejaankop Granite usually occurs in the upper part of the sheet-like Nebo pluton and shows a gradational contact with the underlying Nebo Granite, forming as a number of large-scale 'domes' (Coetzee and Twist, 1989). The Bobbejaankop granite is medium- to coarse-grained, with a distinctive texture composed of linked chains of quartz (Fig. 1.6 a). The Bobbejaankop Granite is a red, biotite and potassic-feldspar bearing granite which is overlain by a fine-grained leucocratic Lease Granite (Fig. 1.6 b).

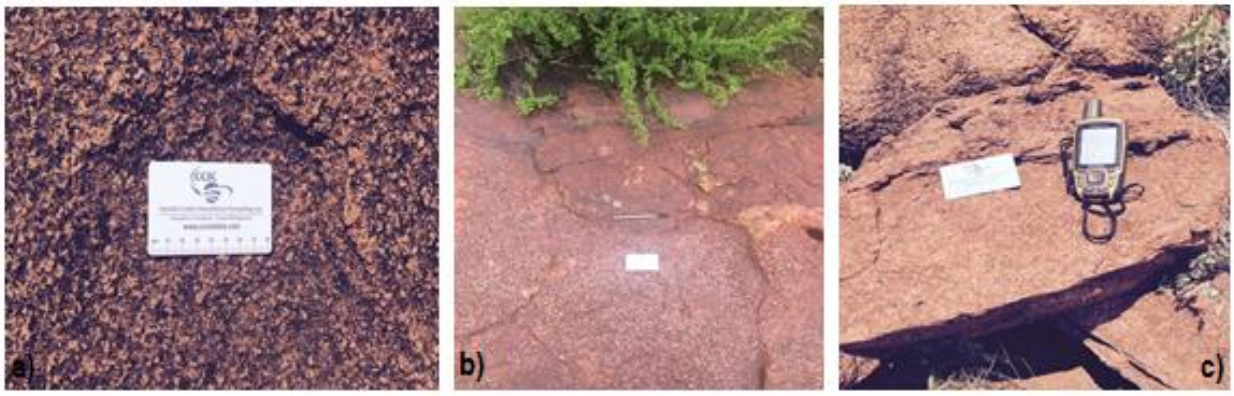


Figure 1.6 Field photographs of Bobbejaankop granite. (a) Typical example of Bobbejaankop Granite with linked chained quartz (Locality 0680676/7338623); (b) An example of Bobbejaankop Granite overlain by fine-grained Lease Granite (Locality 0680953/7338841); (c) Hydrothermal coarse grained and pinkish-reddish Bobbejaankop Granite (Locality 0681096/7338974).

The Lease Granite is a fine-grained, grey, pinkish-red aplite (Fig. 1.6 a). The contact between the Lease Granite and the overlying Rashoop Granophyre Suite is always sharp and marked by a very coarse quartz-feldspar pegmatoid (von Gruenewaldt and Strydom, 1985). The high-grade pipe mineralisation may penetrate into the Lease Granite, but does not penetrate into the older, overlying granophyre (Coetzee and Twist, 1989). In the Lease Granite disseminated cassiterite (SnO_2) crystals are fine-grained, mostly less than 0.4 mm (Fig. 1.7 a) and miarolitic cavities are common, which range from 3 mm to 4 cm in size (Fig. 1.7 c).



Figure 1.7 Field photographs of Lease granite. (a) An a example of fine-grained Lease Granite (Locality 0680118/7337099); (b) A sharp contact between Bobbejaankop Granite and Lease Granite

outcrop NW of mineralisation zone on Groenfontein farm 227KR (Locality 0680953/7338841); (c) A typical example of Lease Granite with abundant miarolitic cavities from Zaaiplaats.

The Lease Granite is regarded as a lithological variation of the Bobbejaankop Granite (Clementson, 1979). Economic cassiterite mineralisation has only been found in the Lease and Bobbejaankop Granites. The mineralisation on Groenfontein and Zaaiplaats farms is within the fine-grained Lease Granite and coarse grained Bobbejaankop Granite. The pegmatite is coarse-grained, and consists of large quartz and feldspar crystals (Fig. 1.8). Groves and McCarthy (1978) indicated that the pegmatite material was derived from an early tin-poor phase, while other researchers have attributed the formation to boiling process, resulting in rapid crystallisation forming the fine-grained Lease Granite with lost volatiles eventually crystallising to form the pegmatite (Lenthall and Hunter, 1977).

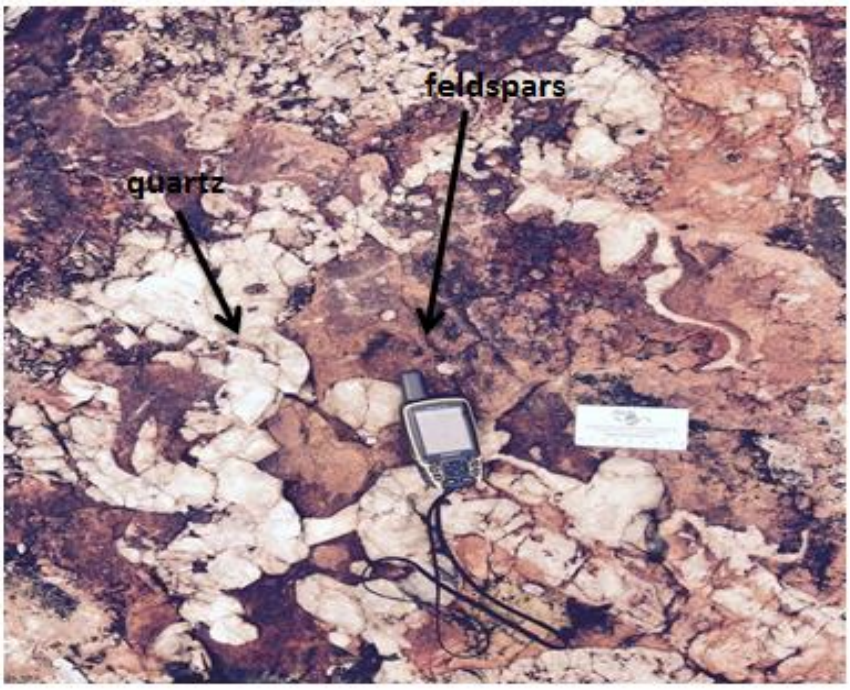


Figure 1.8 An example of pegmatite outcrop with large quartz and feldspar crystals (Locality 0680223/7336887).

1.3.2. *Rashoop Granophyre Suite*

Granophyres may have formed by melting of the overlying volcanic roof rocks by the underlying Rustenburg Layered Suite (RLS), or by recrystallisation of Rooiberg volcanic rocks, or by metamorphism of sedimentary roof rocks (Walraven, 1988). The granophyre at Zaaiplaats is a shallow intrusive sheet below the Rooiberg Group and meta-porphyritic granophyre (de Waal, 1972; Crocker, 1986 & Crocker *et al*., 2001). The granophyre is fine-grained (innermost) and coarse-grained (outwards), and consists of inter-grown quartz and feldspar (Fig. 1.9).



Figure 1.9 Rashoop Granophyre outcrop situated in Groenfontein farm 227 KR in the Northern Lobe of the Bushveld Complex (Locality 0679680/7337495).

1.4. Style of mineralisation

Cassiterite mineralisation is restricted to the Lease and Bobbejaankop Granites, and occurs in pipe-like bodies, sub-horizontal lenticular bodies and as sub-horizontal disseminated low-grade bodies within both granites (Strauss, 1954). All cassiterite mineralisation is in the form of cassiterite (SnO_2) and is of endogenic (formed within host rock that crystallised directly from the fractioned liquids) and epigenetic (emplaced within host rocks older than the fractioned source liquid) originating within the granites (Fig.1.10).

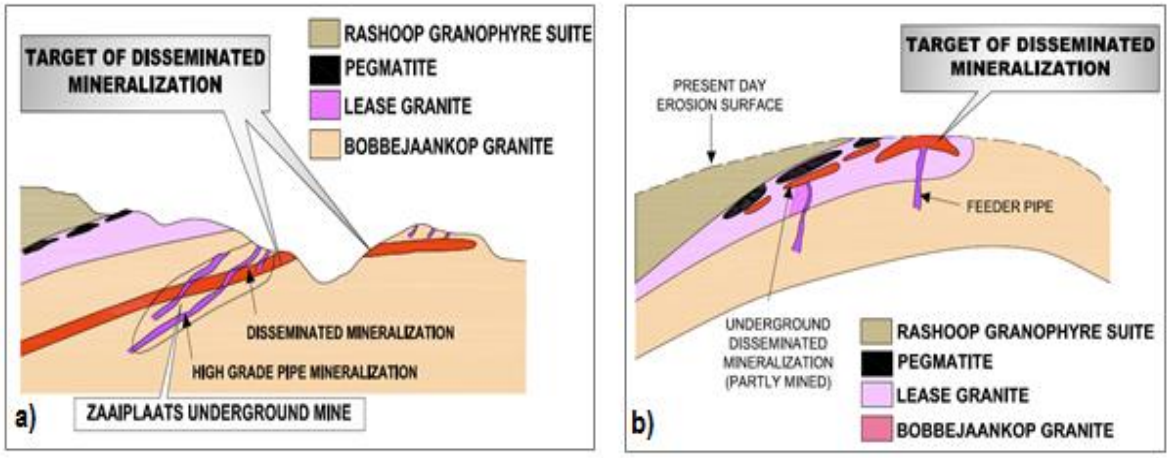


Figure 1.10 Schematic illustration of cassiterite mineralisation associated with the Zaaiplaats cassiterite field. (a) Zaaiplaats mineralisation model, and (b) Groenfontein mineralisation model (Image courtesy of Bushveld Minerals).

A series of geochemical models developed by McCarthy and Hasty (1976), Groves and McCarthy (1978), and McCarthy and Fripp (1980), suggested that the Bobbejaankop and Lease Granites were developed essentially by in situ fractional crystallisation and began forming after at least 85 % of the original magma mass had separated as cumulus crystal and intercumulus melt. Cassiterite deposits related to the Bobbejaankop Granite occur as endogenic pipes and disseminations or as exogenic fissure veins, fault breccias and replacement bodies (Lee, 1977). The potential cassiterite-bearing areas are located high in the granite succession and require a roof (e.g. granophyres, sediment, or early granite) to act as a volatile trap (Lee, 1977). Cassiterite is considered to be the only economically significant tin mineral and its pure form has a tin (Sn) content of 78.6% (Falcon, 1985). Moreover, Falcon (1985) suggested that the deposits of cassiterite (SnO_2) in South Africa can be broadly classified as follows:

- Late magmatic deposits such as pipes and disseminations in younger granites e.g. Zaaiplaats and Groenfontein;
- Epigenetic deposits as fault breccias, and replacement bodies in main granite.

Moreover, Clementson (1979) gave a description of the Mineralisation styles which is summarised below:

- **Pipe- like ore bodies in the Lease and Bobbejaankop Granite**

A major feature of the mineralisation at Zaaiplaats district is the presence of a series of cassiterite-bearing pipe orebodies (Pollard *et al*., 1989). Pipes in the Lease Granite tend to be both smaller and shorter than those in the Bobbejaankop Granite, although several pipes cut across the contact between the two granites (Strauss, 1954). The cassiterite concentration is up to 70 % with an average of between 12 % and 30 %. According to Falcon, (1985), the pipe-like bodies are roughly cylindrical in shape with a diameter varying from 10 cm to 10 m and length from few metres up 1000m. Many small pipes begin and end in the lenticular orebodies (Strauss, 1954).

- **Lenticular ore bodies in Lease Granite**

Lenticular ore bodies occur in the Lease Granite and are mainly composed mainly of cassiterite, feldspar, sericite, fluorite, scheelite and sulphides (Pollard *et al*., 1991). This ore type is similar to pipe material in that the lenticular orebodies appear to be closely associated with the upper portions of pipes. Lenticular orebodies probably formed partly by dissolution of granite quartz and feldspar, followed by infill of the resulting cavities by cassiterite and other hydrothermal phases in a manner similar to pipe formation (Pollard *et al*, 1991). Grades are reported to be 30 % to 70 % cassiterite with a maximum grain size of 3 mm (Crocker & Callaghan, 1979).

- **Disseminated cassiterite in the Lease or Bobbejaankop Granite**

The low-grade orebodies of disseminated cassiterite mineralisation occur within both granites. The low-grade disseminated orebodies generally occur in the uppermost portion of the Lease Granite, with the upper limit of the orebodies often coinciding with the base of the pegmatite zone (Pollard, *et al* 1991). Based on a cut-off grade of around 0.2 % Sn, these disseminated orebodies are irregular to elongate in plan, ranging up to 250 m diameters (Pollard *et al*, 1991). These disseminated ore-bodies are shallow outcrops exposed to the surface and have the potential for production of large

tonnages of low-grade ore (Longridge, 2016). Accordingly, the Groenfontein and Zaaiplaats deposits have been the focus for recent exploration.

- **Alluvial deposits**

These surficial deposits have been explored in the past and further economically exploitable deposits could be located. Two alluvial areas, to the north and northeast of Groenfontein Cassiterite Mine were regarded as possible targets for workable alluvial cassiterite deposits (Clementson, 1979).

1.5. Mining History

Tin was discovered in the area of Zaaiplaats Districts (Groenfontein and Zaaiplaats deposits) in 1906 by a prospector of the Transvaal Consolidated Lands and Exploration Company (Strauss, 1954). In 1907, Groenfontein Tin Mine was opened by Transvaal Consolidated Land (TCL) and Exploration Company. Furthermore, in 1930-1939, Groenfontein Tin Mine was placed on a care and maintenance basis, after which a tribute to mine tin was granted to Mr A Gilbertson. The majority of tin was produced from high grade, pipe-like ore bodies in the Lease Granite (Groenfontein farm). In the Groenfontein Tin Mine it is suggested that, only around four tons a month were produced of about 70 % cassiterite concentrate until the 1960's (Clementson 1979).

In 1908, the Zaaiplaats Tin Mining Company (ZTM) commenced mining at the farm Zaaiplaats 223 KR. In 1953 ZTM was granted a tribute to mine tin ore from certain areas of the farm Roodepoort, including areas of low-grade disseminated cassiterite (Appingendam, Salomon's Tempel etc.), within the Bobbejaankop Granite. This agreement was still in effect in 1979 (Muindisi, 2012). In the 1960s the Gilbertson tribute on Groenfontein was granted to the ZTM Company, between 1979 to 1989 ZTMC was still in effect and the company worked cassiterite pipes in the Lease Granite on a small scale and also worked with the old tailings dumps. In 2001 Quickstep 169 (Pty) was issued with a mining permit (N05/2001) to mine on the farm Zaaiplaats 223 KR. The Zaaiplaats Tin Mining Company produced cassiterite (SnO_2) and tin (Sn) metal continuously from its inception to its closure in 1989 (Crocker 1986; Crocker *et al*., 2001).

Table1.1 Summary of the tin production in the study area since 1908-1989 (Crocker, 1986).

Mine	Concentrate (t)	Tin Metal (t)
Zaaiplaats	25 929	17 300
Groenfontein	6 395	4 463
Salomon's Tempel	116	48
Welgevonden	235	125
Groenvley – Appingendam	19	12
Total	32 694	21 948

In 1906-1989 the Zaaiplaats Tin Mining Company produced 17 000 tonnes of Sn and significant concentrations of tungsten (W) and REE were also reported (Pollard, *et al*., 1991). The Zaaiplaats Cassiterite Mining Company closed as a result of depressed cassiterite prices (MSA Group Pty Ltd, 2013).

1.6. Exploration History and Recent Exploration

Renetype Pty (Ltd), a company owned by Bushveld Minerals Limited, was granted prospecting rights in 2010 for the property 2205PR (Fig. 1), comprising of six farms; Zaaiplaats 223KR, Roodepoort 222KR, Groenfontein 227KR, Groendoorn 225KR, Sterkwater 229KR and Salomon's Temple 230KR (SRK, 2013).

1.6.1. *Exploration History at Groenfontein deposit*

In 1962 an exploration target exercise was conducted by Transvaal Consolidated Land and Exploration Company. This prospecting identified Roodepoort 222 KR and Groenfontein 227 KR as targets for further exploration (Kriel, 1962).

The report identified four types of mineralisation:

- ✓ Pipe-like bodies
- ✓ Lenticular ore-bodies in Lease Granite
- ✓ Disseminated cassiterite
- ✓ Alluvial deposits

Between 1963 and 1976 the Transvaal Consolidated Land and Exploration Company drilled twelve diamond core drilled boreholes (Fig. 1.11). The boreholes (RDP001-RDP012) were drilled to investigate disseminated cassiterite in Lease Granite. Phase two of the drilling programme started in 1978, TCL drilled forty one boreholes, twenty two boreholes were reverse circulation, and the rest were diamond core drilled boreholes. The aim of drilling the boreholes (RDP013-RDP053) was to investigate the south extension of the tabular cassiterite mineralisation on Roodepoort and Groenfontein. Furthermore the boreholes (RDP054-RDP074) were drilled to investigate whether geochemical anomalies (Fig.1.11) presumed to extend to the southwest had not been misinterpreted and could actually trend to the northwest in Lease Granite or Bobbejaankop Granite (Muindisi, 2012).

During phase three drilling programme, TCL drilled (RDP075-RDP097) reverse circulation boreholes, to investigate two geochemical anomalies where disseminated cassiterite (Fig.1.10) was visible (Clementson, 1979; Muindisi, 2012). In a further drilling programme, TCL drilled (RDP098-RDP0213) boreholes into Lease Granite to determine if there is significant cassiterite mineralisation (Muindisi, 2012).

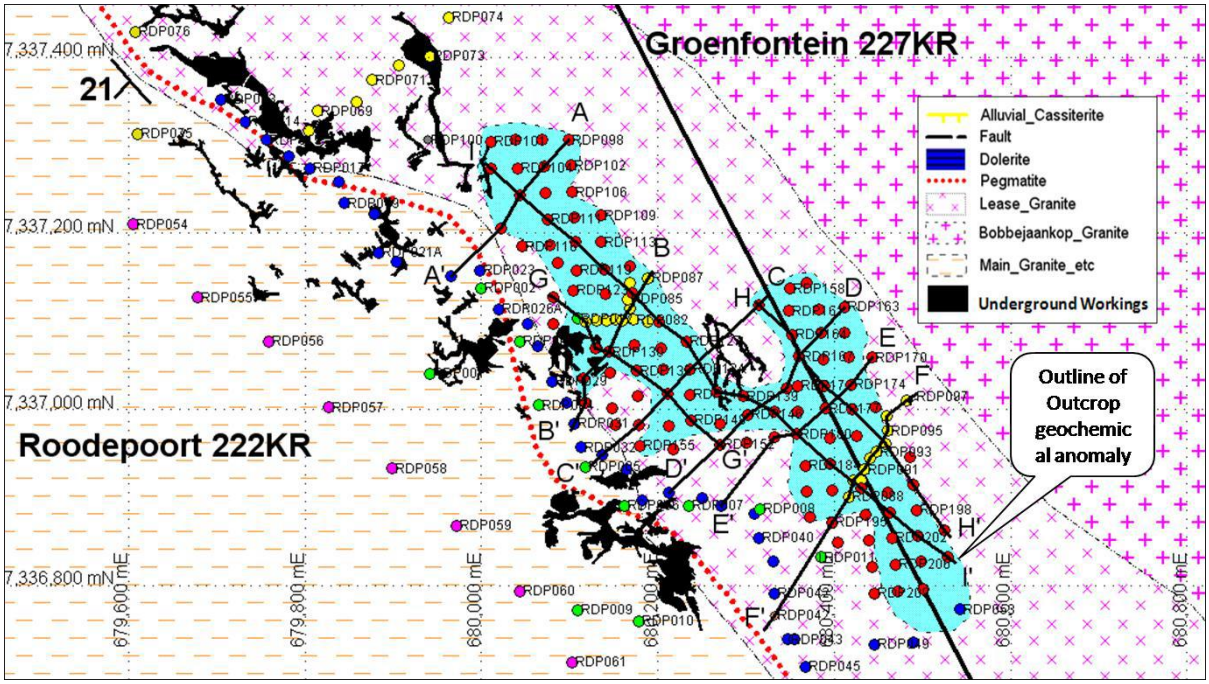


Figure 1.11. Location of boreholes (RDP001-RDP213) drilled by Transvaal Consolidated Land and Exploration Company at Groenfontein Farm (Muindisi, 2012).

1.6.2. *Recent Exploration at Groenfontein*

A drilling programme commenced in 2011, with fifty three boreholes, and out of 53 boreholes twenty two boreholes were twinned with historic boreholes (Fig. 1.12). From the 22 twinned boreholes, the aim was to compare new assay data with the historical borehole assay data in order to justify the incorporation of the historical data into the resource quantification exercise (MSA Group Pty Ltd, 2013).

The 2010-2011 drilling programme focused on an area where extensive mining activity has taken place in the past. Previous mining was focused on the high-grade pipe-like bodies, with little mining of disseminated ore. The current exploration programme targets the disseminated mineralisation occurring in the Lease Granite. The proposed cut-off grade of 0.1 % Sn would be used and drilling was therefore focused within a well-defined targeted area identified from historical drilling work.

1.6.3. *Recent Exploration at Zaaiplaats*

There is no record of previous exploration at the Zaaiplaats deposit. Renetype Pty (Ltd), was granted prospecting rights in 2010 for the property 2205PR. They initially carried out a survey of the old mine workings, both underground and in the open pit, and undertook a rock chip sampling programme. The aim was to collect rock chip and soil samples across the Bobbejaankop and Lease Granite, both of which hosted cassiterite mineralisation. The phase one diamond drilling exploration programme was led by the project geologist (Tim Marais) during later 2012 and early 2013. Forty three diamond core boreholes were drilled to investigate the tin grade and to produce an initial resource estimate.

All the boreholes were drilled into Lease and Bobbenjaankop Granite, on a 50 m by 50 m grid pattern, modified as to intersect pillars in the underground working, rather than drilling into old working (Fig.1.12).

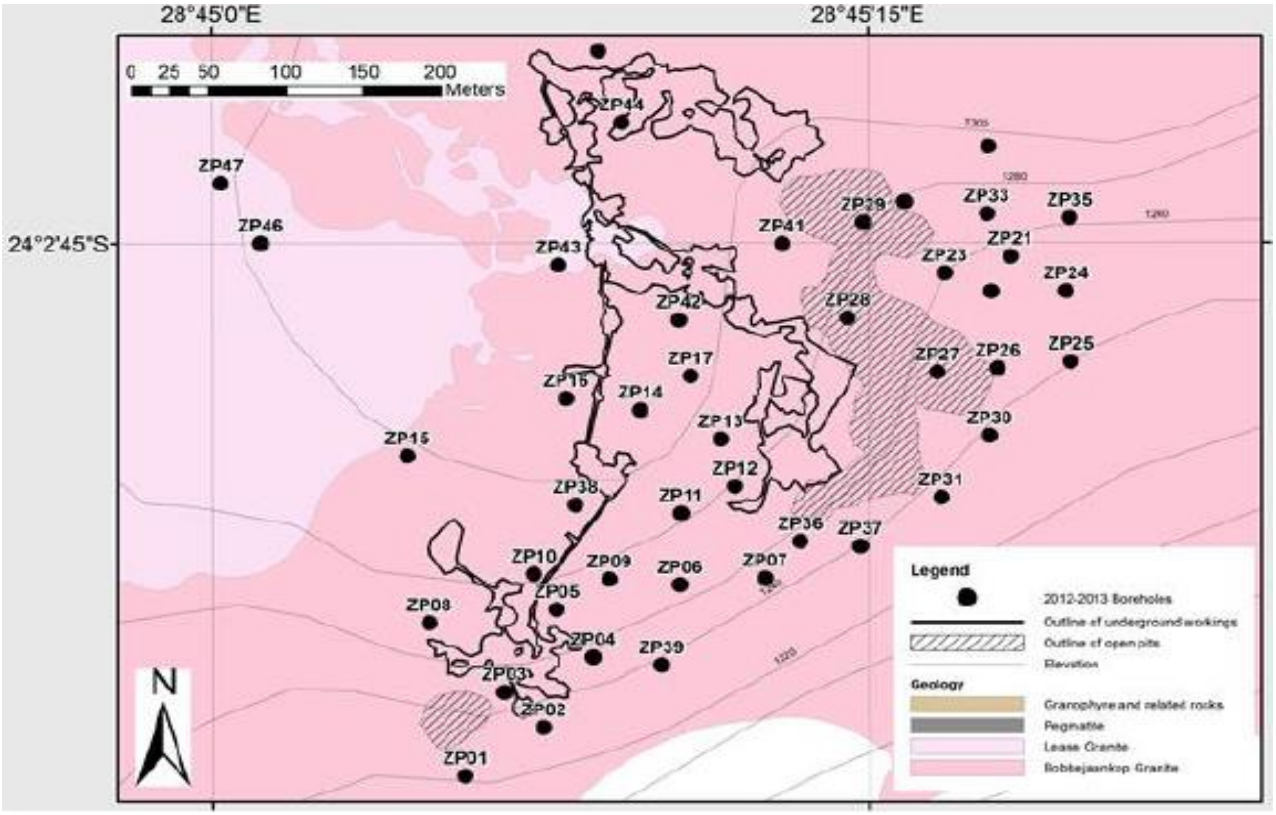


Figure 1.12 Map of boreholes drilled on the Zaaiplaats Deposit in 2012 & 2013 (Image courtesy of Bushveld Minerals).

1.6.4. *Exploration on Zaaiplaats Tailings Dumps*

The Zaaiplaats Tailings Dump drilling programme was led by Troth Saindi (Project Geologist for Bushveld Minerals) in the period from the 15th April 2014 to the 6th May 2014. A total of 15 boreholes was drilled (Fig. 1.13) into the tailings dump. A weighted average grade of 0.124 % Sn was calculated for the tailings. Additional sampling commenced on the 19th November 2016 which was led by Dr Luke Longridge (Exploration Manager for Bushveld Minerals), Simon Nethononda (a field geologist for Bushveld Minerals), and Frans van Daalen (consultant metallurgist for Farlorof). Samples were collected from an upstream borehole (ZTU01) and one from downstream (ZTD02), then sampled at a depth of five meters for each of the boreholes (Fig. 1.14). The calculated head grade of this sample material was 0.1 % Sn.



Figure 1.13 Position of upstream borehole (ZTU01) and downstream borehole (ZTD02) drilled on Zaaiplaats tailings dumps.

1.7. History of South Africa tin production and current market

Tin was one of the first metals mined by early man and its qualities and shiny finish made it a highly sought after commodity which was traded in many parts of the world (MSA Group Ltd, 2013). Currently tin is used mainly for the production of solders (53%), tin planting (16%), bronze (6%), and pewter (14%), as well in the chemical industries (MSA Group Ltd, 2013; Kinnaird *et al*., 2016). In the Republic of South Africa, Rooiberg tin fields and Zaaiplaats tin field were major tin producers, Rooiberg tin field produced 83,000 tonnes of metallic tin from 1905 until 1992 (Labuschange, 2004; Kinnaird *et al*., 2016), while Zaaiplaats tin field produced 37,079 tonnes of metallic tin from 1909 to when it closed in 1989 (Falcon, 1985). During the 1980s, the tin price became unprofitable due to the slump in international tin price (Boer, 2003). According to the LME (2017), the tin price was the best-performing base metal in terms of price in 2012, rising about 24% (Fig. 1.14) from USD 9 per pound at the end of 2012 and some analysts predicted a continuous price rise through 2013.

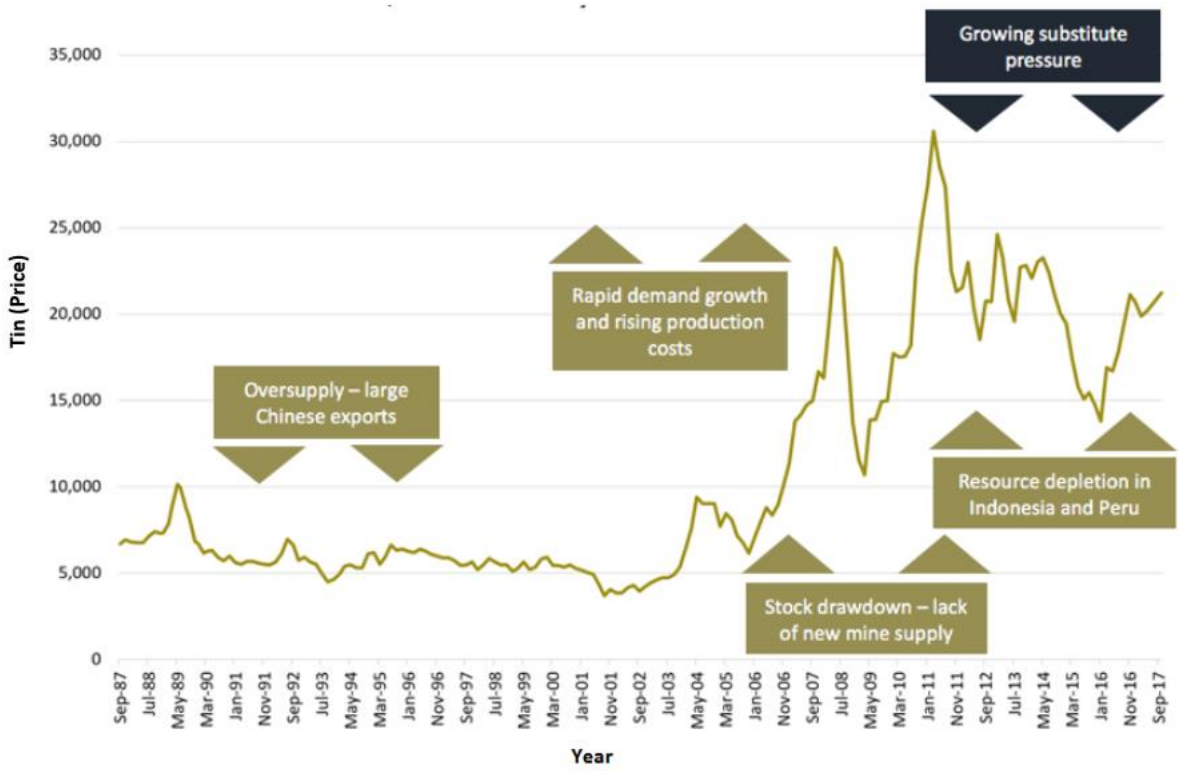


Figure 1.14 Tin historical price chart (Afritin, 2017).

Tin is a critical metal which has a high demand in electronic equipment such as upgrading phone features into touch screens, and the tin price has improved compared to the 5th September 2015 (Table 1.2). The tin price on the London Metal Exchange (LME) is USD 19,610.00 per ton on 25th November 2017 (LME, 2017).

Table 1.2 Comparison of Tin Prices from the year 2012 till 2017 Historic Data (USD per metric ton: source Forecasts 2017).

Year	2012	2013	2014	2015	2016	2017
Tin Price	21096.76	22272.66	21878.75	16053.44	17960.96	19114.50

Moreover, tin production is mainly from underground mines (56%) as secondary elluvial and alluvial resources (38%) have been depleted over the past 30 years (LME, 2017). Only 6% of tin production is currently from open cast mines (Fig. 1.15).

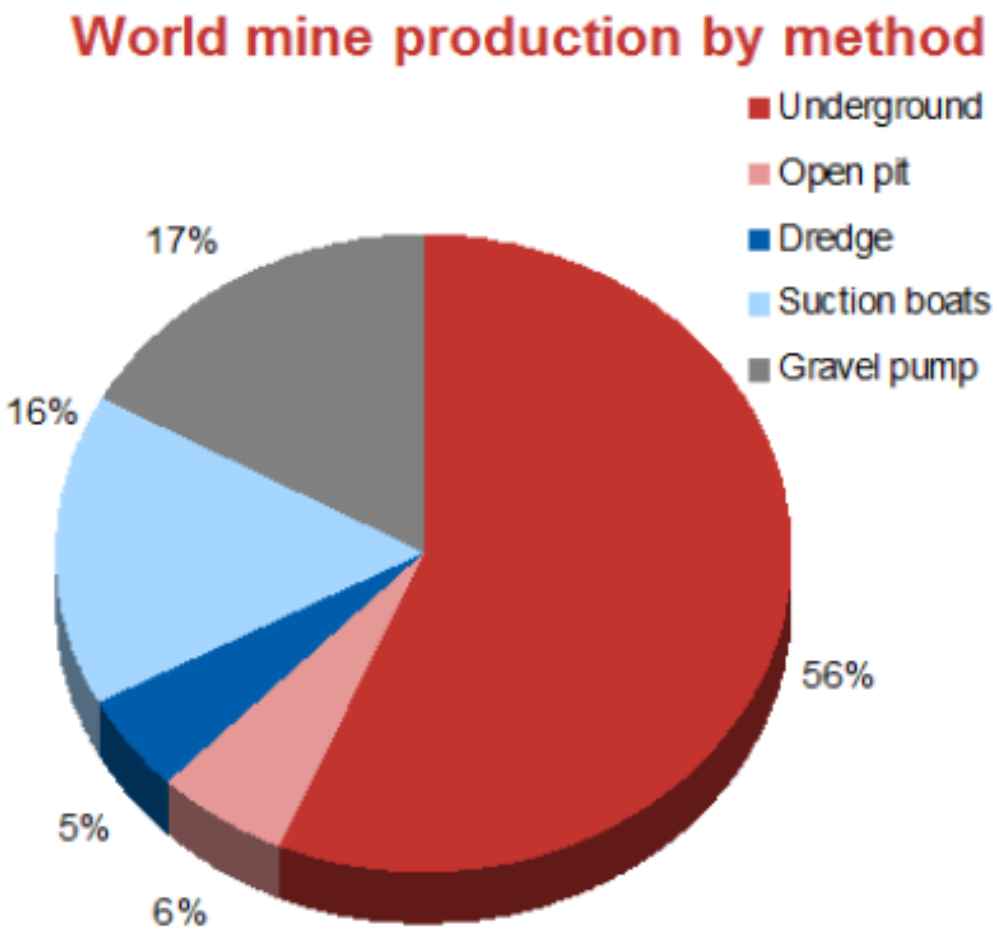


Figure 1.15 Illustration of world tin production by different methods (ITRi, 2016).

China (45%) and Indonesia (30%) are the biggest producers of tin, followed by South America (Peru, 11%; Bolivia, 5%; and Brazil, 4%) and the Democratic Republic of Congo (5%) (Fig. 1.15). Recent progress in tin prospecting in African countries has shown that Morocco has the potential to produce about 5,300 tonnes per year of tin concentrate in a life of mine of nine years. Meanwhile in the DRC, the Bisie tin project has an average grade of tin 4.34% with an estimated 9,000 tonnes of tin in concentrate, for a life of mine of 12.5 years (Kinnaird *et al*., 2016). In South Africa, Bushveld Minerals was granted prospecting rights in 2010 for the Mokopane Tin Project which hosts 18,447 tonnes of tin with average grade of 0.12% cassiterite (SnO_2) on two adjacent deposits (Groenfontein and Zaaiplaats). Bushveld Minerals proposed that the ore will be obtained from an opencast mine when production starts.

CHAPTER 2
AIM OF THE PRESENT STUDY

2.1. Geometallurgy and its importance

Geometallurgy is a multi-disciplinary applied science which integrates mining, geology and metallurgy to correctly help assess the processing needs of an ore body (Beniscelli, 2011; Lotter, 2011). Furthermore, according to Henley (1983) and Bowell *et al*., (2011) geometallurgy incorporates process mineralogy and ore characterisation principles as the tool for metallurgy to build a spatially-based model for production management that quantitatively predicts:

- Quality of concentrates and tailings
- Metallurgical performance such as metallurgical recoveries and throughput
- Environmental impact such as fresh water usage (Lishchuck *et al*., 2015).

A geometallurgical study helps to unlock the characteristic behaviour of a rock-type in different stages from drilling, blasting, to metal recovery, and tailings management. This helps to reduce the risk involved in an operation by understanding and managing one of the greatest potential variables of the ore (Cropp and Goodall, 2013).

According to Lotter et al., (2011), these geometallurgically-defined units may comprise an ore type, or several ore types, that possess a unique set of textural and compositional properties, from which it can be predicted that they will have a similar metallurgical performance. Lishchuck *et al*., (2015), proposed that the geometallurgical programs are divided into three approaches:

- Traditional approach - the metallurgical response of an ore in the mineral processing plant is calculated from chemical assays using mathematical functions, which are often called recovery functions.
- Proxies approach - uses geometallurgical tests for a large number of samples. The geometallurgical test is a small scale test which indirectly measures the metallurgical response. Normally the geometallurgical test results must be converted with certain correction factors to give estimates on the metallurgical results of the plant.
- Mineralogical approach – continuous and systematic collection of quantitative mineralogical information. This often means that accurate information on modal mineralogy is needed for the whole ore body.

According to Lishchuck et al., (2015) “The depth of usage in geometallurgy means how the geometallurgical data is used in the Mine”, for example;

- 1. Collecting data (geometallurgical data is collected but not used).
- 2. Visualizing data (the variation of data within the ore body)
- 3. Defining production constraints (for example, cut-off grade)
- 4. Forecast production
- 5. Making changes in processing based on feed quality (changes are made in the process beforehand with the knowledge of geometallurgy)
- 6. Production planning

- 7. Applying different production scenarios (geometallurgical data is used to make large scale decisions for the future; e.g. when to invest, what alternative technologies are selected (Lischuck *et al*., 2015).

Geometallurgical assessments are carried out using the techniques of geometallurgical measurements, chemical assays, milling tests, deportment studies and mineral separation tests. Mineralogical measurements involve quantitative mineralogical characterisation of coarsely crushed and milled ore to determine mineral texture, mineral association, mineral modal abundances, mineral grain sizes, grain size distribution, mineral liberation and elemental deportment by mineral (Fandrich *et al*., 2007). Gravity spirals/ heavy minerals spirals (roughers, scavengers, cleaners and re-cleaners) are used based on feed grade, particle size distribution and specific gravity (Fig. 2.1).

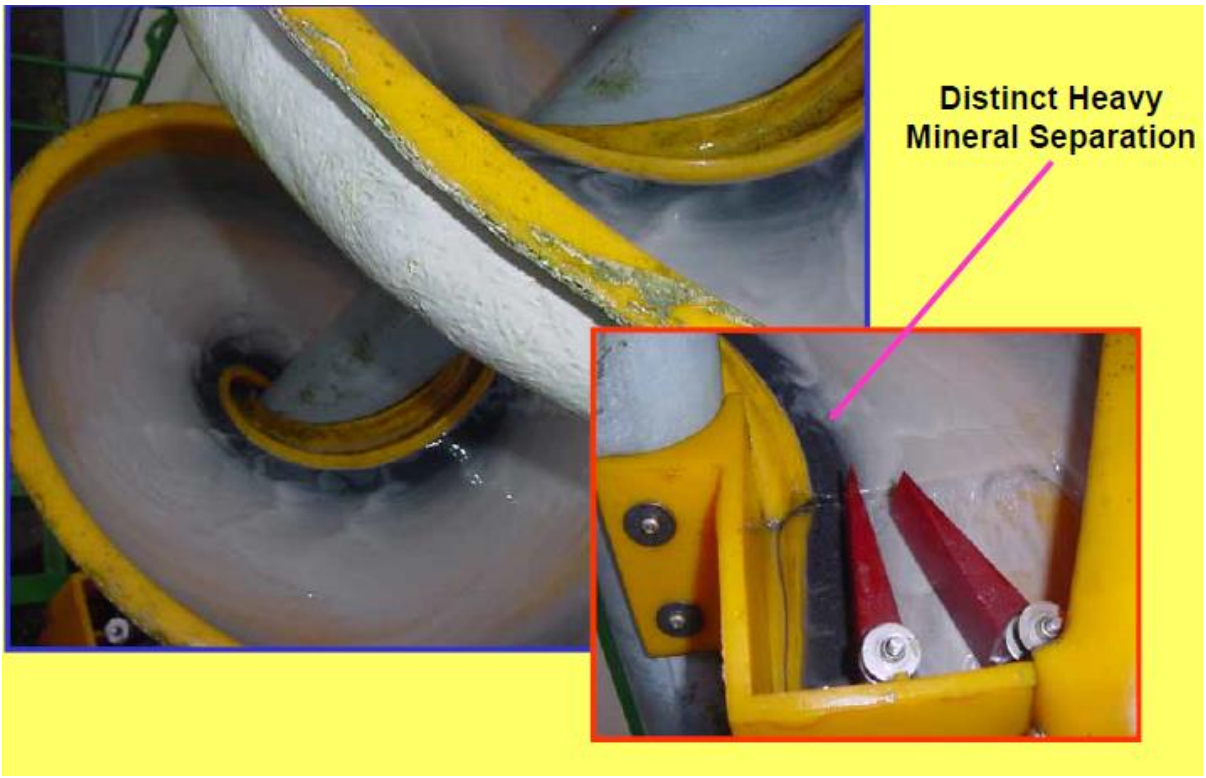


Figure 2.1 Gravity spirals showing distinct heavy mineral separation (Goodman, 2014).

The shaking table separator is used to separate tailings, middlings and concentrate and is also used as cleaner for final upgrading of gravity concentrate from spirals (Fig. 2.2). The concentrate and tailings are all subjected to chemical analysis to determine the mineralogical characteristics that cause poor metallurgical performance such as recovery loses (Kormos *et al*., 2010).

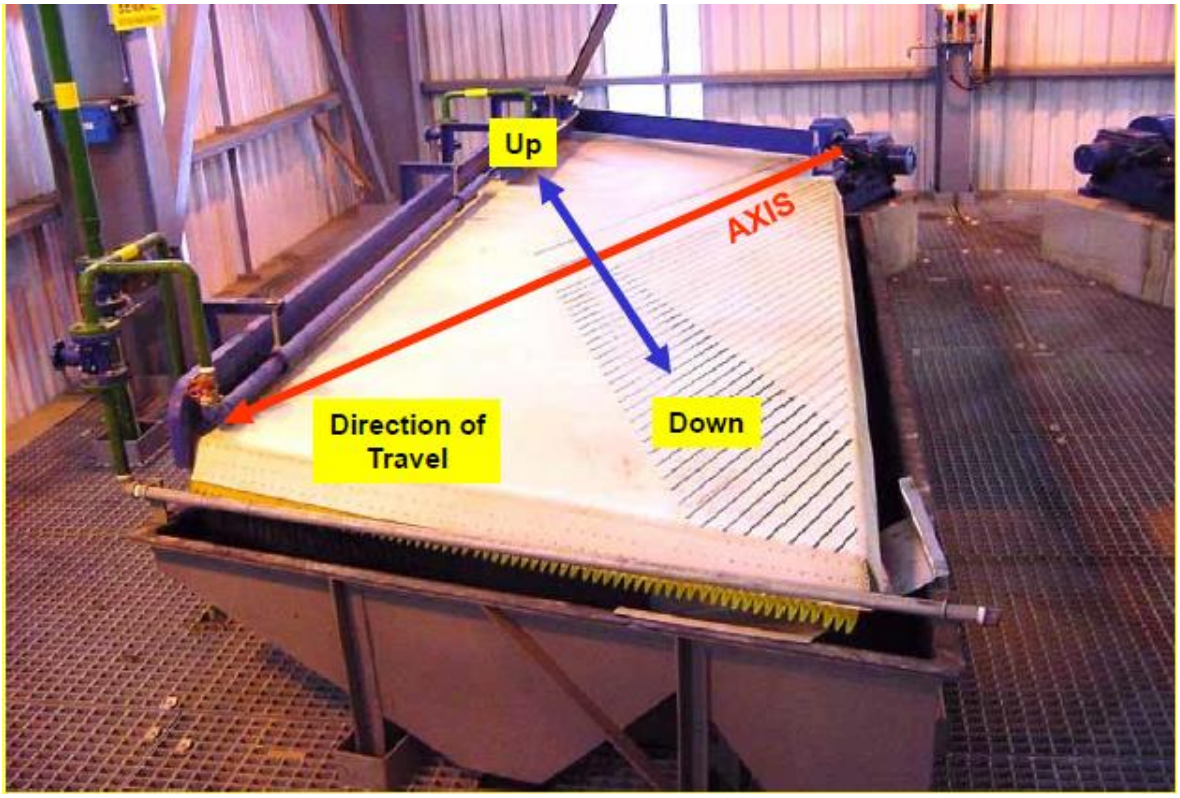


Figure 2.2 Shaking table showing movement direction of the feed (Up and down arrows represent a cassiterite concentrate) (Goodman, 2014).

2.2. Objectives and methodology of the present study

The main focus of the present study is to investigate the geometallurgical characterisation of cassiterite in the ore of the Groenfontein and Zaaiplaats deposits, and Zaaiplaats tailings dump. The geometallurgical parameters such as mineralogical constituent, grading analysis, grain size distribution, element deportment and recovery, are compared in the grab samples of the hard-core ore of the Groenfontein and Zaaiplaats deposits, and Zaaiplaats tailings dump.

The following methodology was used during the study:

- Selection of area to be sampled and sample collection in Groenfontein dump ores;
- Samples from drilled core (Groenfontein and Zaaiplaats drilled core);
- Metallurgical test work and geometallurgical analysis;
- Pilot-scale test work on the Groenfontein samples;
- Gravity spirals and shaking tables are used to identify the grain size of the different cassiterite size fractions, the liberation characteristics of cassiterite at different cassiterite size fractions, and the recovery characteristics of cassiterite.

2.3. Motivation for the present study

The research aims to provide a geometallurgical assessment of cassiterite (SnO_2) at the hard-rock ore of Groenfontein and Zaaiplaats deposits, and Zaaiplaats tailings dumps. This assessment aims to:

- Obtain quantitative mineralogical characterisation.
- Determine the critical characteristics of processing behaviour.

- Optimize operational design and extraction methods that maximise tin recovery and textural information.

The aim was accomplished by obtaining quantitative mineralogical information, combined with chemical assays, laboratory scale milling and pilot-scale test work using gravity spirals and shaking tables from SGS Laboratory, Setpoint Laboratory, Maelgwyn Mineral Services Africa Pty (Ltd) and METQUIP Pty Ltd, respectively. Characteristics of other ore minerals (fluorite, scheelite etc.) are noted where these minerals are present.

Although the present study focused only on investigating the geometallurgical characterization of cassiterite in Groenfontein and Zaaiplaats deposits, and Zaaiplaats tailings dump, it was however, hoped that the study will contribute knowledge on the development strategies at the Renetype Pty Ltd operation in the future, and also serve as a basis for further research such as flotation conditions and the optimisation and grade optimisation of the concentrates.

2.4. Previous work and studies

2.4.1. Characteristics of tin and cassiterite

- Cassiterite is considered to be the only economically significant tin mineral in the earth's crust.
- In its purest form, cassiterite contains 78.6 % Sn.
- Cassiterite has a high relatively density of 7.29.
- Non-magnetic.
- Fairly resistant to corrosion.
- Non-combustible.

2.4.2. Historical production at Groenfontein and Zaaiplaats

Cassiterite occurs in irregular pipe-like orebodies with diameters of the pipe ranging from about 10 cm to 10 m, in lenses and, as fine disseminations in granite with average grains sizes of the cassiterite of 4 mm (Falcon, 1985). The majority of tin was produced from pipe-style mineralisation (both Groenfontein and Zaaiplaats) between 1906 and 1926 (Strauss, 1954; Lenthall and Hunter, 1977; Crocker *et al*., 2001). In both the Groenfontein and Zaaiplaats deposits the disseminated mineralisation became the primary interest for cassiterite, and the ore was mined at an average depth of 150 m depth from surface (Falcon, 1985).

2.4.3. Historical metallurgical characterisation at Groenfontein and Zaaiplaats deposits

The cassiterite from Groenfontein and Zaaiplaats deposits has physical characteristics of high density relative to its gangue, and is therefore an ideal mineral for the application of gravity separation techniques (Fig 2.3). Between 1906 and 1989, the ore was processed through a crushing and screening circuit with intermediary separation via shaking tables before entering a grinding and sulphide floatation circuit to remove pyrite (Falcon, 1985). It is pertinent to mention that froth flotation can be used to upgrade particles less than 43 µm, while particle sizes of less than 6 µm are not able to be treated. In some cases, the ~6 µm size fraction can account for as much as ~6 % of the cassiterite entering a plant (Falcon, 1985). The conventional gravity-separation processes are applied successfully only to liberated size particles larger than 40 µm. Some gravity separators, for example

the Bartles-Mozley tables, separate a fine size, but with a low recovery and also additionally the product needs further upgrading on conventional shaking tables (Falcon, 1985). Cassiterite is reduced under conditions very similar to those for iron oxide, and it is very difficult to separate the two metals during smelting.

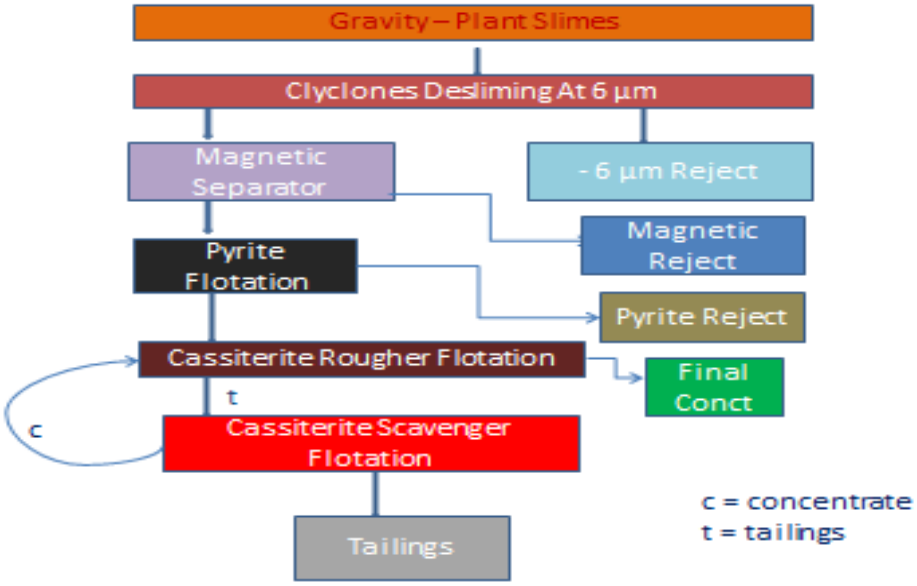


Figure 2.3 Flow chart showing conventional process of froth flotation to recover fine cassiterite at Zaaiplaats and Groenfontein.

2.4.4. Metallurgical characterisation of the tailings dump

Based on the report by Boer (2003), the Zaaiplaats tailings dump to be treated consisted of 3 600 000 tons of material with a tin content of 0.125 % which implies 4 500 tons of tin. From this material 68.6 % of the cassiterite was of a size smaller than 75 µm; this size fraction amounts to only 21 % of the material present in the 3 600 000 tons of tailings.

In the spiral banks only cassiterite particles greater than 25 µm reports to the concentrate stream and the –25 µm fraction is lost in the final tailings; the rougher/scavenger/cleaner systems were designed to form recycling loops that will ensure the maximum recovery of cassiterite. The Sn content of the concentrate going to the Mozely Gravity Separator should be above 69 % to 72 %. After processing through the Mozely Separator, the grade could be as high as 75 % (Boer, 2003). The mine dump was put on a care and maintenance program during 1991 when operations were suspended, due to the slump in international tin prices. The amount of tailings that have been re-treated since 1980 is not known.

CHAPTER 3
SAMPLE COLLECTION, SAMPLE DESCRIPTION AND MINERALOGY

3.1. Sample collection

In the present study the samples were collected from the Groenfontein ore dump, exploration drill core, Zaaiplaats open pit quarry and Zaaiplaats tailings dump. A quarter core was collected from exploration borehole core from Groenfontein farm 227 KR. Furthermore, a Zaaiplaats grab sample was collected from the quarry and sandy material was collected from the tailing dump.

Table 3.1 Samples collected with lithology and weight of the samples.

Samples Name	GPS Location	Host Lithology	Weight (kg)
GHT011	680290/7337121	Lease Granite	20
GHT2016/2017	680178/7336876	Lease Granite	20
ZP2016/2017	678354/7339545	Bobbejaankop Granite	20
ZTU01	678622/7339178	Sandy soil	50
ZTD02	679516/7339265	Sandy soil	50

3.2. Sample Description

3.2.1. Groenfontein exploration drilled quarter core (GHT011) and grab sample (GHT2016/2017)

The GHT011 borehole drilled from 0.00 m to 43.10 m into Lease Granite, and sampled from 0.00 m to 22 m, is characterised by fine to medium-grain size (Fig. 3.1a). The grab sample (GHT2016/2017) of Lease Granite, is medium to fine-grained with small vugs with cassiterite (~ 9mm width) (Fig. 3.1b).

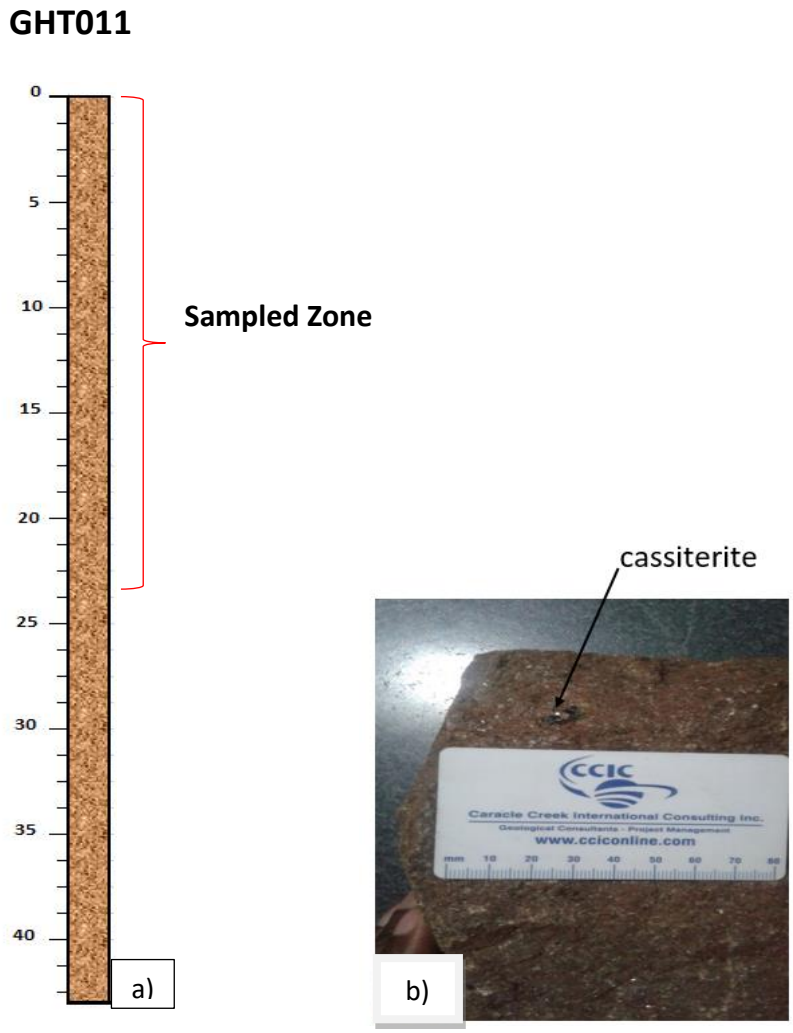


Figure 3.1 Groenfontein samples from the study area. (a) Geological log showing lithology of the half core of GHT011, and (b) a typical grab sample (GHT2016/2017) from Groenfontein ore dump.

3.2.2. Zaaiplaats grab sample (ZP2016/2017)

The Zaaiplaats grab sample (ZP2016/2017) is characterised by Bobbejaankop Granite which is coarse-grained, reddish in colour with linked quartz chains, feldspar, tourmaline and chalcopyrite (Fig. 3.2).



Figure 3.2 A grab sample collected from Zaaiplaats quarry (ZP2016/2017).

3.2.3. Zaaiplaats tailings dump (ZTU01 and ZTD02)

The upstream borehole (ZTU01) drilled into Zaaiplaats tailings dump was from 0.00 m to 5.00 m deep. The tailings comprised of mixed material with medium to coarse sandy soil and varies in colour from pinkish orange to pinkish grey (Fig. 3.3a). Also the downstream borehole (ZTD02) drilled from 0.00 m to 5.00 m, is composed of medium- to fine-grained sandy soil and light brownish to grey-brownish colour (Fig. 3.3b).

3.3. Mineralogical characterisation of the samples

Prior to mineralogical characterisation by XRD, each sample was crushed to 100% passing ~6 mm and then blended, and crushed further to 100% passing ~2 mm. For qualitative mineralogical characterisation by XRD a 20g aliquot of ~2 mm material from each sample (i.e. GHT2016/2017, ZP2016/2017, and ZTU01) was pulverised for XRD analysis. The samples were analysed using a Panalytical X'Pert Pro diffractometer (Co-radiation). The data was interpreted using High Score analytical software.

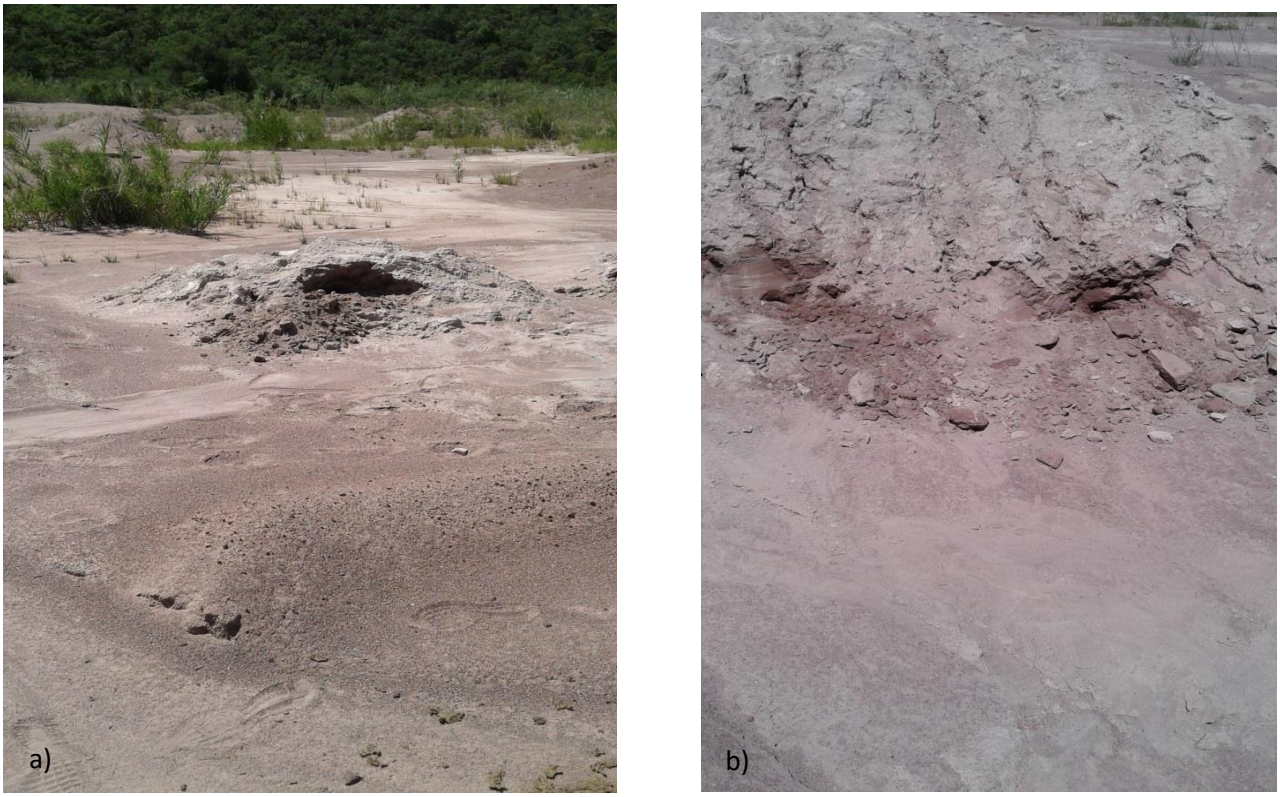


Figure 3.3 Zaaiplaats tailings dump. (a) Shows the sandy material collected from upstream borehole (ZTU01), and (b) shows sandy material collected from downstream borehole (ZTD02).

CHAPTER 4

RESULTS

4. SAMPLE CRUSHING, XRD ANALYSIS, GRADING ANALYSIS, ELEMENT DEPORTMENT

A geometallurgical study involves a combined set of geological and metallurgical tests, the results of which are then interpreted in terms of plant performance (Mishra, 2014). To achieve this, a detailed mineralogical characterisation was performed on various samples using a set of standard analytical techniques such as XRD, ICP-OES, and QEMSCAN. Figure 4.1 is a demonstration of the primary methods implemented in the present study. All the crushing, milling and flotation tests were conducted at the SGS laboratory and Maelgwyn Mineral Services Africa, respectively.

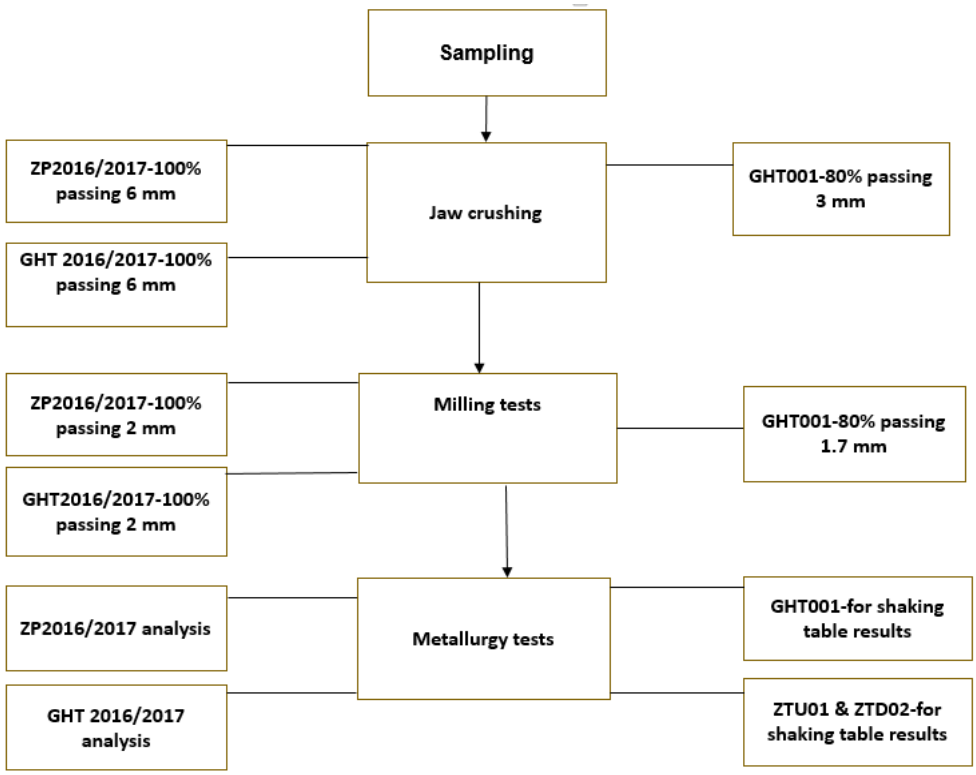


Figure 4.1 Simplified methodology flow chart.

4.1. Comminution

According to Wills (2006), comminution deals with the relationship between energy input and the particle size made from a given feed size. In this case, most of the minerals are disseminated and intimately associated with gangue minerals. However, the minerals must initially be unlocked or liberated before separation can be undertaken. Furthermore, Will's (2006) reported that comminution is where the particle size of the ore is progressively reduced until the clean particles of minerals can be separated by such methods as are available.

4.1.1. Crushing

Crushing is the first mechanical stage in the process of comminution in which the main objective is to liberate the valuable minerals from the gangue minerals (Wills, 2006). Furthermore, crushing can be divided into three units as described below:

- Primary crushers (coarse crushing) whereby the run-of-mine ore (up to 1 m in size) is crushed down to about 10 cm with the use of jaw or gyratory crusher.
- Secondary crushers (intermediate crushing) whereby the ore is crushed from 10 cm to less than 1-2 cm size, for this present study jaw crusher was used.

Tertiary crushers where the ore is crushed from 1-2 cm to less than 0.5 cm (Wills, 2006). In the present study a jaw crusher was used to reduce the ore size by the compression force, in which the ore is pressed against two plates (Fig. 4.2). The jaw crusher consists of a set of vertical jaws, whereby one jaw is fixed and the other moved back and forth relatively by a pitman mechanism, which is mounted such that the stationary jaw provide the breaking surface and the moving jaw exerts the compressive force (Wills, 2006). A half inch core sample from GHT011 was crushed using a jaw crusher to produce a product of 80 % passing 3 mm, while ore dump samples from GHT2016/2017 and ZP2016/2017 were both crushed to 100 % passing -6 mm.



Figure 4.2 Typical example of laboratory jaw crusher.

A cone crusher (Fig. 4.3) is similar in operation to a gravity crusher, with less steepness in the crushing chamber and more of a parallel between the crushing zones (Fig. 4.3). The half core sample from GHT001 obtained from the jaw crusher was crushed using a cone crusher which produces a product of 80 % passing 1.7 mm. The ore dump samples from GHT2016/2017 and ZP2016/2017 were further crushed to 100 % passing -2 mm.



Figure 4.3 Typical example of laboratory cone crusher.

4.1.2. Milling

Milling or grinding is commonly referred to as the final stage of comminution, which is a wet process that produces a slurry feed for further concentration (Wills, 2006). The high energy consumption associated with the milling process is critical such that the right size fraction required to attain an optimum liberation (Wills, 2006). In the present study each 4 kg of ore dump sample obtained from GHT2016/2017 and ZP2016/2017 was screened into seven size fractions (+ 1000 µm, + 425 µm, +212 µm, + 106 µm, + 75 µm, + 38 µm, - 38 µm). A 200 g sample from each fraction was separated by a rotary splitter for pulverisation and analysed for tin by ICP-OES. On the other hand, a 1 kg of GHT001 half core sample was wet screened at 38 µm. The -38 µm and +38 µm fraction were oven dried overnight at 60 °C. Subsequently, the +38 µm sample was dry screened. A 200 g sample of the crushed material was pulverised. The ZTU01 and ZTD02 samples were screened at 106 µm using a Rolligon screen, and the -106 µm fraction of each sample was submitted for the Deister shaking table tests.

4.2. XRD Analysis

X-ray diffraction (XRD) spectrometry was performed on pulverised aliquot of samples from Groenfontein (GHT2016/2017) and Zaaiplaats (ZP2016/2017) deposits, and Zaaiplaats tailings dump (ZTU01) to qualitatively determine the relative abundance of minerals within the samples. Table 4.1 presents the mineralogical analysis within the samples in the study area.

Table 4.1 Mineralogical abundance (%) in hard-rock ore samples from Groenfontein and Zaaiplaats deposits, and Zaaiplaats tailings dump.

MINERAL	GHT2016/2017	ZP2016/2017	ZTU01
QUARTZ	36.78	36.03	38.45
K-FELDSPAR	33.64	31.63	32.10
PLAGIOCLASE-FELDSPAR	21.79	19.62	19.79
CHLORITE	3.13	9.41	6.97
FLUORITE	1.26	1.76	1.41
MUSCOVITE	1.80	0.11	0.53
CASSITERITE	0.07	0.59	0.16
CALCITE	0.90	0.11	0.13
CHALCOPYRITE	0.03	-	0.035
MAGNETITE	0.06	0.11	-
SCHEELITE	-	0.24	-
OTHER	0.32	0.39	0.42
TOTAL	100.00	100.00	100.00

From Table 4.1, XRD analysis showed the relative abundance of quartz, K-feldspar, plagioclase feldspar, fluorite, muscovite, and traces of cassiterite, calcite, chalcopyrite, and magnetite (<1%) in all the analysed samples.

4.3. Grading Analysis

Figure 4.4 depicts tin grades (ppm) for core grab samples (GHT011), hard-rock ore samples in Groenfontein (GHT2016/2017) and Zaaiplaats (ZP2016/2017) deposits, and Zaaiplaats tailings dump (ZTU01 and ZTD02) plotted against the size fraction in µm. In sample GHT011, tin grade increased significantly to ~15,500 ppm in the -75/+38 µm size fraction when compared to other samples (GHT 2016/2017, ZP2016/2017, ZTU01, and ZTD02), although there is a notified sharp decrease of sample GHT011 in the -38 µm due to difference in size fraction. However, in the Zaaiplaats tailings dump samples (ZTU01 and ZTD02) tin showed an increase towards the -38 µm size fraction due to the fine nature of tailings dump. Although, samples GHT2016/2017 and ZP2016/2017 follow a similar trend, although they differ in sampling location under the same deposit.

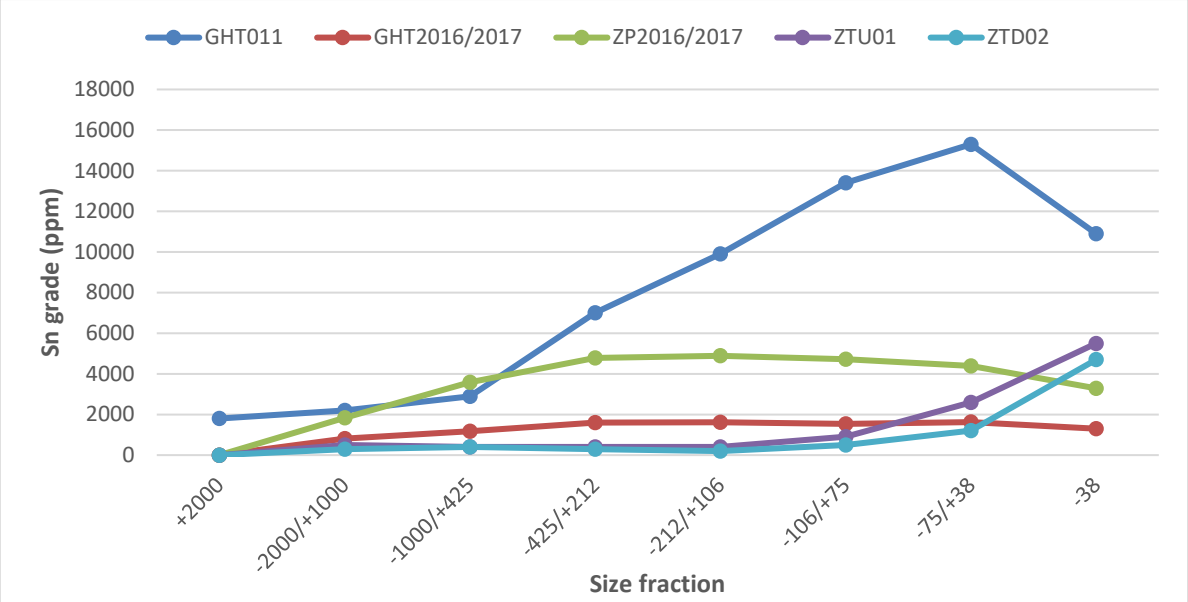


Figure 4.4 The tin grade as a function of size fraction (µm).

4.4. Element deportment

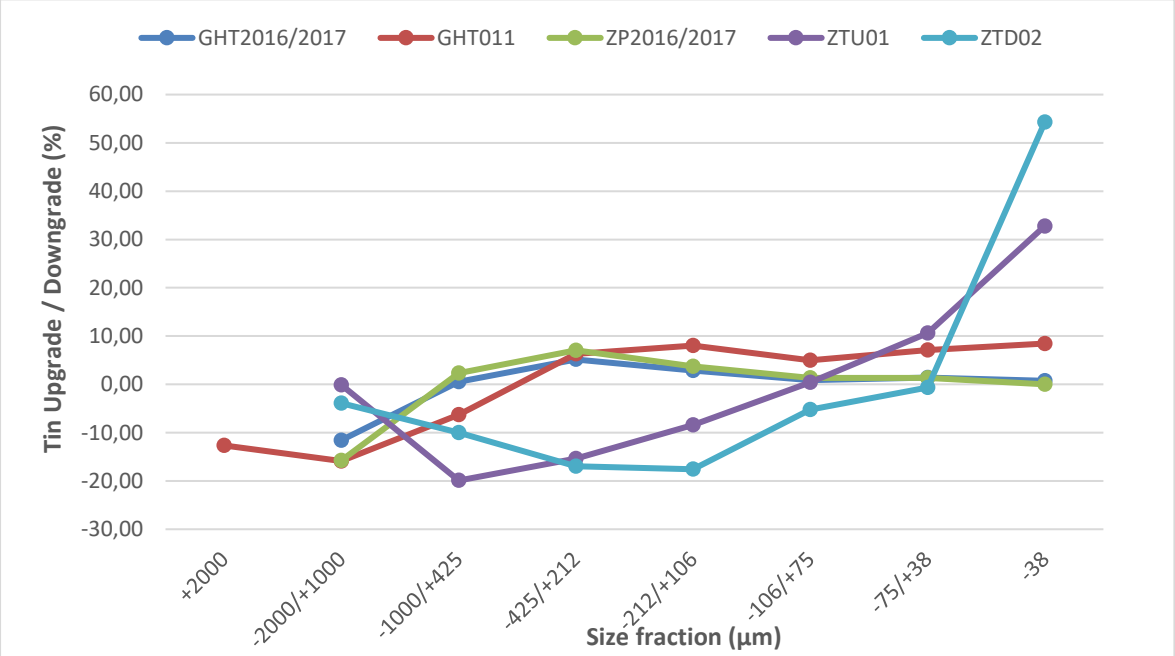


Figure 4.5 Upgrade/downgrade graph for tin in different size fractions for samples GHT011, GHT2016/2017, ZP2016/2017, ZTU01, and ZTD02 tin samples in the size fractions of the milled ore.

Tin downgrade towards the coarser size fractions (-1000/+425 to -425/+212) in samples ZTU01 and ZTD02, and upgrade towards the finer fractions (-38). Similarly, in sample GHT011 tin downgrade towards coarser size fraction (-2000/+1000) and further upgrade towards finer size fractions (-38). Nonetheless, tin initially downgrade in coarser size fraction (-2000/+1000) in samples GHT2016/2017, and ZP2016/2017 and further upgrades towards coarser size fraction (-425/+212). In contrast, in sample GHT011 tin downgrade towards coarser size fraction (-2000/+1000) and alternatively upgrade towards finer size fraction (-38).

4.5. Mass distribution (%)

In Fig. 4.6 the mass distribution is significantly higher in coarser size fraction (-2000/+1000) and further becomes lower at finer size fraction (-106/+75 to -38). However, tin distribution percentage in this sample is higher at coarse size fraction (-2000/+1000, -425/+212, -212/+106), and finer size fraction (-38).The mass distribution percentage in the sized sample fractions (µm) was calculated as shown in Appendix A1.3. Fig. 4.6-4.10 presents the results of tin mass distribution percentage in different size fractions (µm). Most of the tin mass distribution is in the coarser fractions (Fig. 4.6-4.8). However, the mass distribution for tin in Fig. 4.9 and 4.10 follows a different trend towards finer size fractions.

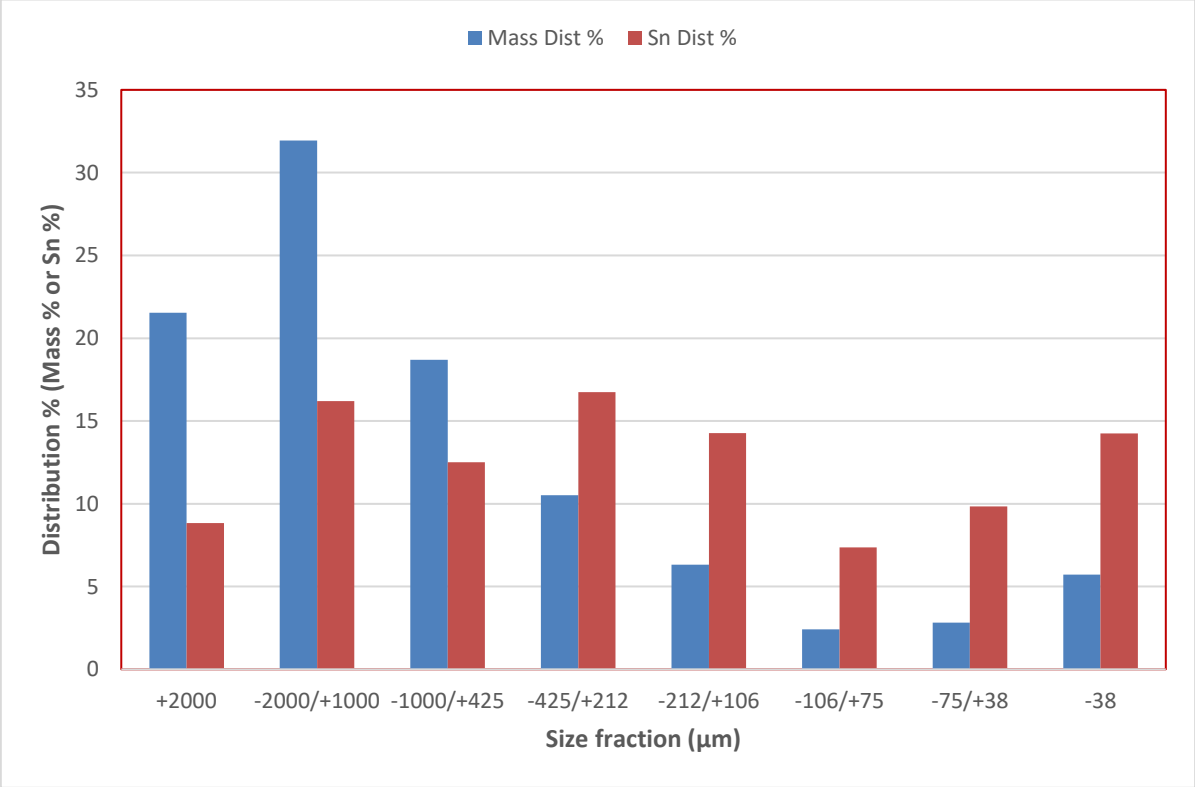


Figure 4.6 Mass distribution of Sn over the different size fractions in sample GHT011.

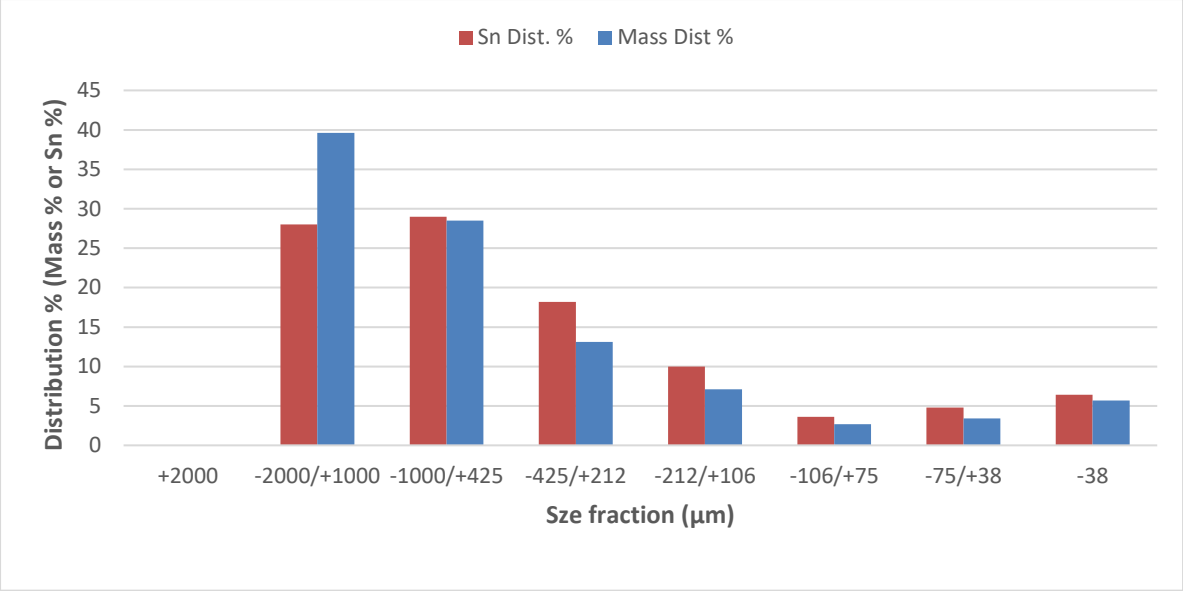


Figure 4.7 Mass distribution of tin in sample GHT2016/2017.

In fig.4.7 mass distribution percentage and tin distribution percentage show a similar trend in sample GHT2016/2017, whereby there is a decrease from coarse size fraction (-2000/+1000) towards finer size fraction (-38). This distribution trend differs when compared to that in sample GHT011.

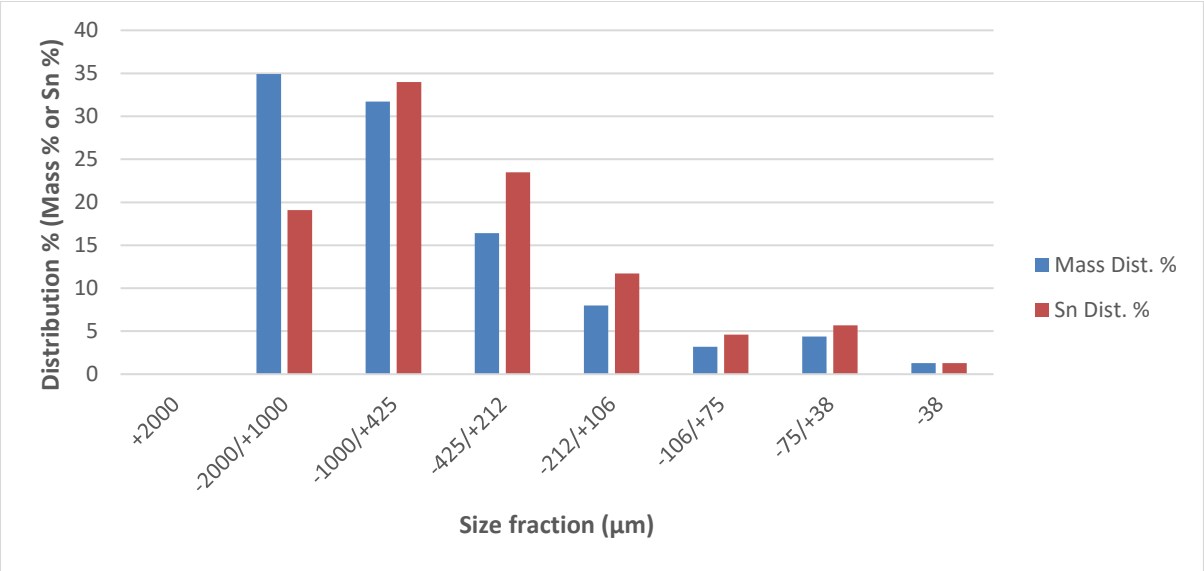


Figure 4.8 Mass distribution for tin in sample ZP2016/2017.

In sample ZP2016/2017 the mass distribution is higher in coarse size fraction (-2000/+1000), and then becomes lower in finer size fraction (-38). In contrast, the tin distribution is higher at coarse size fraction (-1000/+425) and becomes lower to finer size fraction (-38).

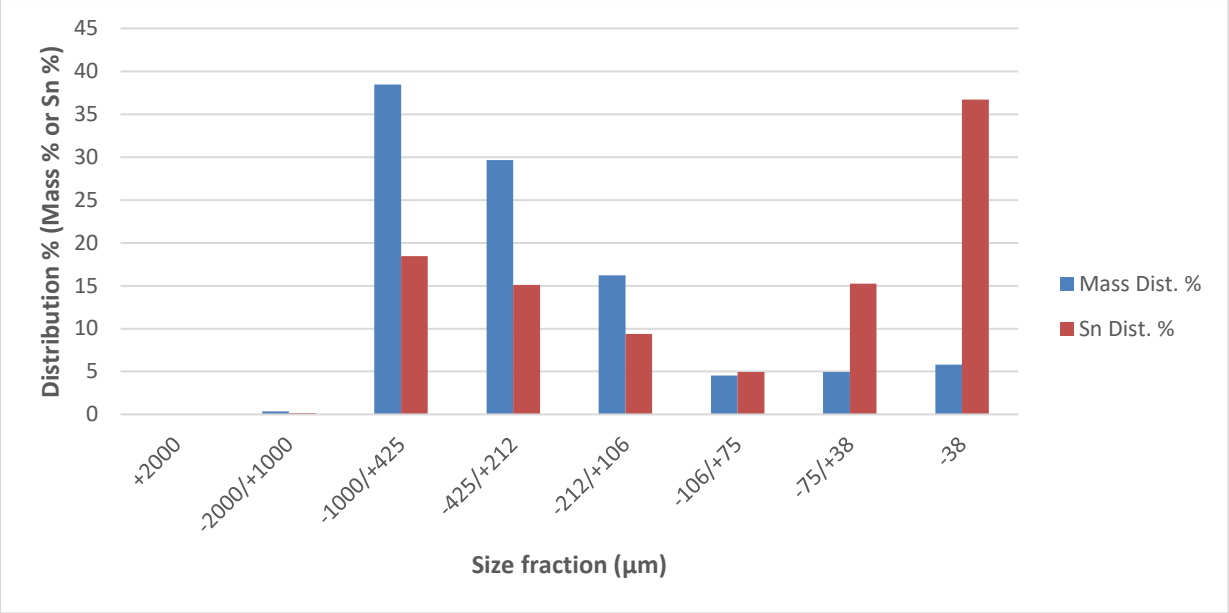


Figure 4.9 Mass distribution percent for tin in sample ZTU01.

In sample ZTU01 mass distribution percentage is higher at -1000/+425 in the coarser size fraction, and becomes lower at the finer size fraction (-38). Similarly, in terms of tin distribution, the percentage in the coarse size fraction is higher at -1000/+425, but in the finer size fraction the percentage is higher at -38 size fraction.

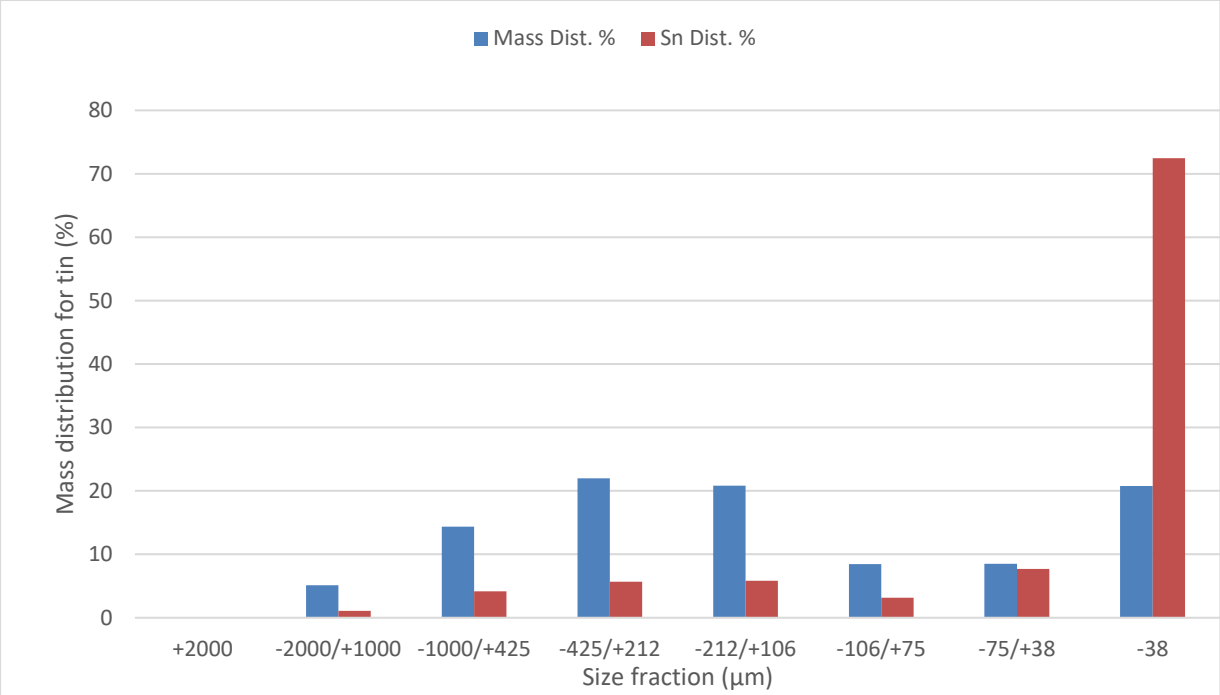


Figure 4.10 Mass distribution percentage for tin in sample ZTD02.

In sample ZTD02 mass and tin distribution percentage follows a similar trend, although mass distribution is higher at -425/+212 and -212/+106 in coarser size fraction. Meanwhile, tin distribution is significantly higher at -38 finer size fraction.

CHAPTER 5

GRADE, RECOVERY ANALYSES, AND GRAIN-SIZE DISTRIBUTION OF CASSITERITE

5.1. Grain-Size Distribution of Cassiterite

The grain-size distribution of cassiterite was only done for samples GHT2016/2017 and ZP2016/2017. Grain-size distribution was calculated from sized cumulative Sn grade (%) and cumulative Sn recovery (%). The results are shown in Table 5.1 and Figure 5.1. Grain-size distribution of between the two samples report different patterns. In samples GHT2016/2017, about 396 grains and >60 % of the mass of cassiterite was within the finest fractions (-75 µm size class), and no grains reporting to the coarser fractions. For the same ore sample, six large grains accounting for 10 % of the total cassiterite grains were in the +106/-212 µm size class. In contrast, ore sample ZP2016/2017 there were 2551 grains of cassiterite with > 40 % by mass of cassiterite within the +425/-1000 µm size fraction. This differences and trends is attributed to the difference in particle grain size, as the Zaaiplaats tailings (ZP2016/2017) is more finer compared to the core sample (GHT2016/2017) where there are increasing grains reporting to the intermediate and coarser fractions.

Table 5.1 Grain-size distribution of the cassiterite.

Sample Name	Size class (µm)	Mass % Cassiterite	Grains
GHT2016/2017	-75	62.57	385
	+75/-106	27.23	5
	+106/-212	10.23	6
	+212/-425	0	0
	+425/-1000	0	0
	+1000	0	0
Sample Name	**Size class (µm)**	**Mass % Cassiterite**	**Grains**
ZP2016/2017	-75	16.25	2535
	+75/-106	4.08	5
	+106/-212	8.28	6
	+212/-425	29.83	3
	+425/-1000	41.55	2
	+1000	0	0

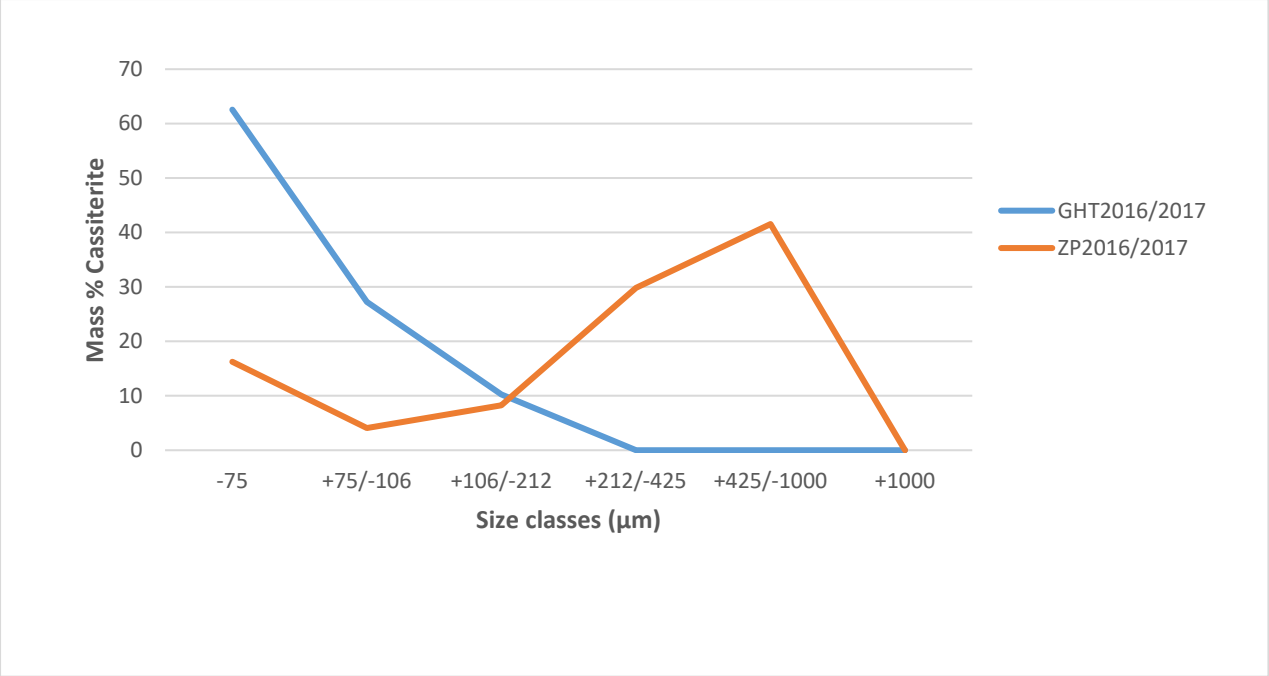


Figure 5.1 Cumulative grain-size distribution for the GHT2016/2017 and ZP2016/2017 milled feed between +75/-106 µm to +106/-212 µm and +212/-425 µm to +425/-1000 µm fraction (as in diameter) in microns.

5.2. Grade and Recovery Analyses

Grade and recovery tests were only performed for samples GHT011, ZTU01, and ZTD02 in order quantify and compare percentage Sn grade versus Sn recovery within the respective samples. The results of the cumulative Sn grade percentage and cumulative Sn recovery percentage are shown in Figure 5.2 and Appendix A1.4.

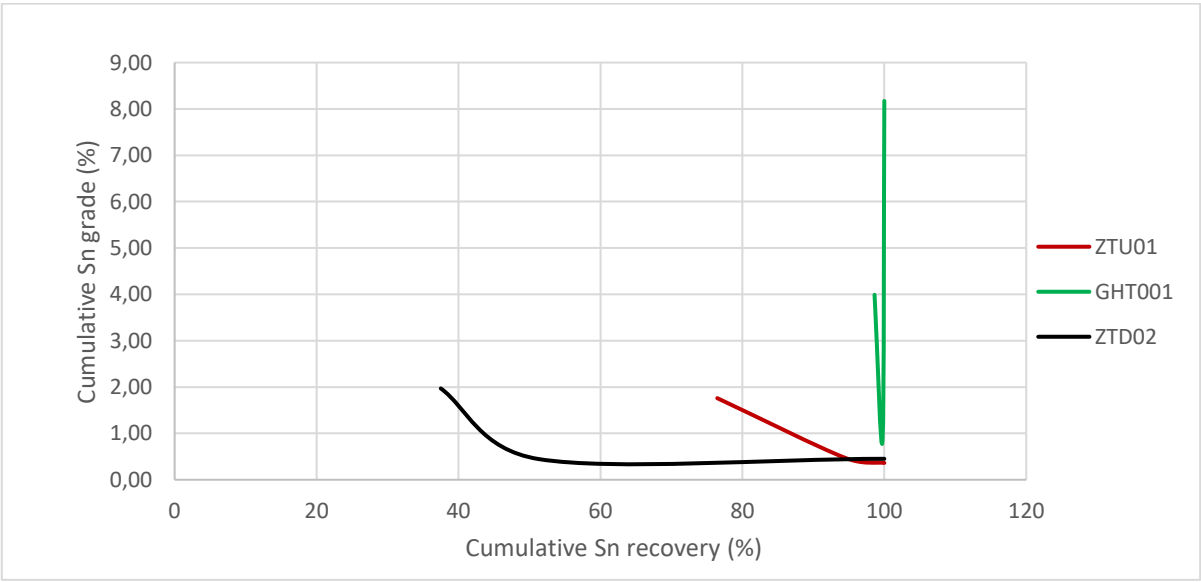


Figure 5.2 Percent cumulative Sn grade versus Sn recovery in GHT011, ZTU01 and ZTD02 samples.

Cumulative Sn grade and recovery values in sample ZTU01 and ZTD02 are the similar, both sample having cumulative Sn grade <2 %, although cumulative Sn recovery in sample ZTU01 ranges between 80-100%, and in sample ZTD02 cumulative Sn recovery ranges between 40-100%. The similarity in

cumulative Sn grade and recovery values within the respective samples is in good agreement as they are both collected from the tailings dump. However, cumulative Sn grade and recover values in sample GHT011 varies significantly with that of ZTU01 and ZTD02. Cumulative Sn grade in sample GHT011 is high (8.2 %) and cumulative Sn recovery is also high (100%). The difference in cumulative Sn grade and recovery for sample GHT011 with other respective samples can be contributed to the fact that sample GHT011 was collected from the hard rock (drilled core sample). Furthermore, the low cumulative Sn grade and recover in samples ZTU01 and ZTD02 when compared to sample GHT01 is because the hard rock sample is easily recovered for Sn grade when compared to finer material i.e. tailings dump sample. The cumulative grades (%) and recoveries (%) in a sample of GHT011, ZTU01 and ZTD02 have 100 % Sn recovery. GHT011 has the highest grade and the ZTU01 and ZTD02 have the lowest grades. The sample (GHT011) also has the highest Sn grade and Sn recovery, while samples (ZTU01 and ZTD02) has the highest recoveries and lowest grades (Figure 5.2). This investigation indicates that the low grades of some of the concentrates of ZTU01 and ZTD02 are related mostly to the low head grade rather than the concentrating process.

CHAPTER 6

DISCUSSION

6.1. Summary and Discussion

With most of the past studies focusing on disseminated and pipe-style mineralisation at the Zaaiplaats deposit (Coetzee and Twist, 1989; Pollard *et al*., 1991), there is a lack of knowledge regarding the geometallurgy of the disseminated mineralisation at Groenfontein and Zaaiplaats deposits in the northern limb of the Bushveld Complex. The present research has attempted to investigate the geometallurgical characterisation of cassiterite in the hard-rock ore of Groenfontein and Zaaiplaats deposits, and Zaaiplaats tailings dump. XRD analyses revealed that the dominant gangue minerals are quartz, K-feldspar, plagioclase feldspar, chlorite, fluorite, and muscovite. These minerals occur in association with cassiterite. Sample GHT011 had the highest tin grade in the finer size fractions, reaching a maximum of 15500 ppm in the -75/+38 µm size fractions. This implies that care must be taken during processing of cassiterite to avoid overgrinding. However, the tin grade plateaus and then decreases into the finer -38 µm size fraction. In contrast to other samples, the high tin grade in the core sample GHT011 is suggested to be due to the in situ characteristics of the core sample GHT011 compared to tailings samples. In all the studied samples, the downgrading of tin was more intense in the coarser size fractions. The downgrade of tin towards the coarser fractions could be mainly due to the incomplete liberation of silicate minerals which hosts the metals. Larger grains of cassiterite were distributed in Zaaiplaats samples (ZP2016/2017) reaching 2535 in -75 µm size fraction, meanwhile moderate grains were distributed in Groenfontein samples (GHT2016/2017) reaching 385 in -75 µm size fraction. Grade and recovery analysis was performed only for samples GHT011, ZTU01, and ZTD02. Sample GHT011 has a high cumulative tin recovery and high cumulative tin grade percentage compared to ZTU01 and ZTD02 with low cumulative tin recovery and cumulative tin grade percentage. The high tin recovery for sample GHT011 is attributed to the drilling phase location as this was underlain by a high-grade mineralisation zone and coarser cassiterite than the finer tailings material.

CHAPTER 7
CONCLUSION AND RECOMMENDATIONS

7.1. Conclusions

In the present study cassiterite occurs in all the samples (GHT011, GHT2016/2017, ZP2016/2017, ZTU01, and ZTD02). The calculated head grade of samples GHT011, GHT2016/2017, ZTU01 and ZTD02 was 0.44 %, 0.12 %, 0.1 %, 0.13 %, and 0.13 % respectively. In samples ZP2016/2017, GHT2016/2017, and GHT011, Sn mass occurs in finer size fractions, while in samples ZTU01 and ZTD01 Sn mass occur in coarse and fine in -38 µm size fraction. Shaking table results shows that in sample ZTU01, 50 % of Sn reported to the concentrate of 8 % and gravity tests at 0.2 % of Sn. In sample ZTD02, 40 % of Sn was recovered in the concentrate consisting of about 5 % mass and a final gravity tails of 0.22 % of Sn. In the core sample GHT011 it was possible to upgrade the Sn concentrate to as high as 15 % into the concentrate, indicating that the core sample was controlled by gravity concentration. In samples GHT2016/2017, ZP2016/2017, and GHT011 most of the tin mass is in the coarse fractions. Furthermore, the highest tin grade is 1624 ppm in the -75/+38 µm size fraction. Nonetheless, in sample ZP2016/2017 the highest tin grade is 4887 ppm in the -425/+212 µm to -212/+106 µm size fraction. In sample GHT011 the highest tin grade in the -75/+38 µm size fraction, meanwhile in samples ZTU01 and ZTD02 the highest tin grade is in the -38 µm size fraction, respectively.

7.2. Recommendations

- Based on core sample and ore dump material, this study recommends a thorough evaluation based on the suitability of density medium separation prior to shaking table or spirals, or by doing heavy liquid separation test-work at two different top sizes and two different densities (2.8 and 3).
- The tin grade is low in Zaaiplaats tailings dump samples (ZTU01 and ZTD02), and the potential with regards to multiple stream gravity steps could exist perhaps using Falcon gravity concentrators. However, the cost of processing will have to be carefully weighed against the lower tin grade of the material and the current tin price to determine if this material could be economically processed.

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Appendix-

Table A1.1 Grading Analysis results for GHT001, GHT2016/2017, ZP2016/2017, ZTU01 and ZTD02.

		Mass		Mass - Cumulative		Tin		
Sample Name	**Size Fraction (µm)**	**Mass (g)**	**Mass Dist. %**	**% pass**	**% retain**	**Grade (ppm)**	**Grade (%)**	**Dist. %**
GHT001	+2000	213,4	21,54	78,46	21,54	1800	0,18	8,83
	-2000/+1000	316,4	31,94	46,52	53,48	2200	0,22	16,21
	-1000/+425	185,3	18,7	27,82	72,18	2900	0,29	12,51
	-425/+212	104,2	10,52	17,3	82,7	7000	0,7	16,75
	-212/+106	62,7	6,33	10,97	89,03	9900	0,99	14,26
	-106/+75	23,9	2,41	8,56	91,44	13400	1,34	7,36
	-75/+38	28	2,83	5,73	94,27	15300	1,53	9,84
	-38	56	5,73	0	100	10900	1,09	14,24
	Totals	**990,7**	**100**			**4400**	**0,44**	**100**
GHT2016/2017	+2000	0	0	100	0	0	0	0
	-2000/+1000	880,2	39,6	60,4	39,6	814	0,81	28
	-1000/+425	633,4	28,5	31,9	68,1	1171	0,12	29
	-425/+212	290,9	13,1	18,8	81,2	1602	0,16	18,2
	-212/+106	157,8	7,1	11,7	88,3	1618	0,16	10
	-106/+75	60,2	2,7	9	91	1530	0,15	3,6
	-75/+38	75,3	3,4	5,7	94,3	1624	0,16	4,8
	-38	125,8	5,7	0	100	1293	0,13	6,4
	Totals	**2223,5**	**100**			**1150**	**0,12**	100
ZP2016/2017	+2000	0	0	100	0	0	0	0
	-2000/+1000	664,5	34,9	65,1	34,9	1833	0,18	19,1
	-1000/+425	604,8	31,7	33,4	66,6	3586	0,36	34
	-425/+212	313,3	16,4	17	83	4778	0,48	23,5
	-212/+106	153	8	8,9	91,1	4887	0,49	11,7
	-106/+75	61,6	3,2	5,7	94,3	4725	0,47	4,6
	-75/+38	83,2	4,4	1,3	98,7	4389	0,44	5,7
	-38	25,7	1,3	0	100	3289	0,33	1,3
	Totals	**1906,1**	100			**3343**	**0,33**	**100**
ZTU01	+2000	0	0	100	0	0	0	0
	-2000/+1000	1,7	0,34	99,66	0,34	500	0,05	0,18
	-1000/+425	189,7	38,46	61,2	38,8	400	0,04	18,44
	-425/+212	146,2	29,64	31,56	68,44	400	0,04	15,11
	-212/+106	80	16,22	15,34	84,66	400	0,04	9,38
	-106/+75	22,4	4,54	10,79	89,21	900	0,09	4,94
	-75/+38	24,5	4,96	5,84	94,16	2600	0,26	15,25
	-38	28,7	5,82	0	100	5500	0,55	36,7
	Totals	**493,2**	100			**1000**	**0,1**	**100**
ZTD02	+2000	0	0	100	0	0	0	0
	-2000/+1000	27,9	5,1	94,9	5,1	300	0,03	1,09
	-1000/+425	78,5	14,35	80,55	19,45	400	0,04	4,17
	-425/+212	120,4	22	58,55	41,45	300	0,03	5,66
	-212/+106	113,9	20,82	37,73	62,27	200	0,02	5,81
	-106/+75	46,3	8,46	29,26	70,74	500	0,05	3,13
	-75/+38	46,6	8,52	20,75	79,25	1200	0,12	7,69

-38	113,5	20,75	0	100	4700	0,47	72,45
Totals	**547,1**	**100**			**1300**	**0,13**	**100**

Table A1.2 Tin deportment results for GHT001, GHT2016/2017, ZP2016/2017, ZTU01 and ZTD02 ore milled feeds.

Sample Name	Size fraction (µm)	Sample fraction mass (g)	Sample fraction mass (%)	Sn assay in fraction (ppm)	Sn assay in fraction (%)	Sn mass in fraction (g)	Sn mass % in fraction	Sn upgrade/downgrade (%)
GHT011	+2000	213,4	21,54	1800	0,18	0,38412	8,88	-12,66
	-2000/+1000	316,4	31,94	2200	0,22	0,69608	16,08	-15,86
	-1000/+425	185,3	18,7	2900	0,29	0,53737	12,42	-6,28
	-425/+212	104,2	10,52	7000	0,7	0,7294	16,86	6,34
	-212/+106	62,7	6,33	9900	0,99	0,62073	14,35	8,02
	-106/+75	23,9	2,41	13400	1,34	0,32026	7,4	4,99
	-75/+38	28,0	2,83	15300	1,53	0,4284	9,9	7,07
	-38	56,0	5,73	10900	1,09	0,6104	14,11	8,38
	Total	990	100	63400	0,44	4,32672	100	0
GHT2016/2017	+2000	0	0	0	0	0	0	0
	-2000/+1000	880,2	39,6	814	0,81	0,7164828	28,02	-11,58
	-1000/+425	633,4	28,5	1171	0,12	0,7417114	29,01	0,51
	-425/+212	290,9	13,1	1602	0,16	0,4660218	18,23	5,13
	-212/+106	157,8	7,1	1618	0,16	0,2553204	9,99	2,89
	-106/+75	60,2	2,7	1530	0,15	0,092106	3,6	0,9
	-75/+38	75,3	3,4	1624	0,16	0,1222872	4,78	1,38
	-38	125,8	5,7	1293	0,13	0,1626594	6,36	0,66
	Total	2223,5	100	1150	0,12	2,56	100	0
ZP2016/2017	+2000	0	0	0	0	0	0	0
	-2000/+1000	664,5	34,9	1833	0,18	1,218	19,12	-15,78
	-1000/+425	604,8	31,7	3586	0,36	2,169	34,05	2,35
	-425/+212	313,3	16,4	4778	0,48	1,497	23,5	7,1
	-212/+106	153	8	4887	0,49	0,748	11,74	3,74
	-106/+75	61,6	3,2	4725	0,47	0,291	4,57	1,37
	-75/+38	83,2	4,4	4389	0,44	0,365	5,73	1,33
	-38	25,7	1,3	3289	0,33	0,085	1,33	0,03
	Total	1906,1	100	3343	0,33	6,37	100	0
ZTU01	+2000	0	0	0	0	0	0	0
	-2000/+1000	1,7	0,34	500	0,05	0,00085	0,21	-0,13
	-1000/+425	189,7	38,46	400	0,04	0,07588	18,56	-19,9
	-425/+212	146,2	29,64	400	0,04	0,05848	14,3	-15,34
	-212/+106	80	16,22	400	0,04	0,032	7,83	-8,39
	-106/+75	22,4	4,54	900	0,09	0,02016	4,93	0,39

	-75/+38	24,5	4,96	2600	0,26	0,0637	15,58	10,62
	-38	28,7	5,82	5500	0,55	0,15785	38,6	32,78
	Total	493,2	100	1000	0,1	0,41	100	0
ZTD02	+2000	0	0	0	0	0	0	0
	-2000/+1000	27,9	5,1	300	0,03	0,00837	1,2	-3,9
	-1000/+425	78,5	14,35	400	0,04	0,031	4,41	-9,94
	-425/+212	120,4	22	300	0,03	0,036	5,12	-16,88
	-212/+106	113,9	20,82	200	0,02	0,023	3,3	-17,52
	-106/+75	46,3	8,46	500	0,05	0,023	3,3	-5,16
	-75/+38	46,6	8,52	1200	0,12	0,056	7,1	-1,42
	-38	113,5	20,75	4700	0,47	0,533	75,82	55,07
	Total	547,1	100	1300	0,13	0,71	100	0

Table A1.3 Mass and tin distribution percentage for GHT001, GHT2016/2017, ZP2016/2017, ZTU01 and ZTD02.

Sample Name	**Size Fraction (µm)**	**Mass**		**Mass - Cumulative**		**Tin**		
		Mass (g)	**Mass Dist. %**	**% pass**	**% retain**	**Grade (ppm)**	**Grade (%)**	**Dist. %**
GHT011	+2000	213.4	21.54	78.46	21.54	1800	0.18	8.83
	-2000/+1000	316.4	31.94	46.52	53.48	2200	0.22	16.21
	-1000/+425	185.3	18.7	27.82	72.18	2900	0.29	12.51
	-425/+212	104.2	10.52	17.3	82.7	7000	0.7	16.75
	-212/+106	62.7	6.33	10.97	89.03	9900	0.99	14.26
	-106/+75	23.9	2.41	8.56	91.44	13400	1.34	7.36
	-75/+38	28	2.83	5.73	94.27	15300	1.53	9.84
	-38	56	5.73	0	100	10900	1.09	14.24
	Totals	990.7	100			4400	0.44	100
GHT2016/2017	+2000	0	0	100	0	0	0	0
	-2000/+1000	880.2	39.6	60.4	39.6	814	0.81	28
	-1000/+425	633.4	28.5	31.9	68.1	1171	0.12	29
	-425/+212	290.9	13.1	18.8	81.2	1602	0.16	18.2
	-212/+106	157.8	7.1	11.7	88.3	1618	0.16	10
	-106/+75	60.2	2.7	9	91	1530	0.15	3.6
	-75/+38	75.3	3.4	5.7	94.3	1624	0.16	4.8
	-38	125.8	5.7	0	100	1293	0.13	6.4
	Totals	2223.5	100			1150	0.12	100
ZP2016/2017	+2000	0	0	100	0	0	0	0
	-2000/+1000	664.5	34.9	65.1	34.9	1833	0.18	19.1

	-1000/+425	604.8	31.7	33.4	66.6	3586	0.36	34
	-425/+212	313.3	16.4	17	83	4778	0.48	23.5
	-212/+106	153	8	8.9	91.1	4887	0.49	11.7
	-106/+75	61.6	3.2	5.7	94.3	4725	0.47	4.6
	-75/+38	83.2	4.4	1.3	98.7	4389	0.44	5.7
	-38	25.7	1.3	0	100	3289	0.33	1.3
	Totals	1906.1	100			3343	0.33	100
ZTU01	+2000	0	0	100	0	0	0	0
	-2000/+1000	1.7	0.34	99.66	0.34	500	0.05	0.18
	-1000/+425	189.7	38.46	61.2	38.8	400	0.04	18.44
	-425/+212	146.2	29.64	31.56	68.44	400	0.04	15.11
	-212/+106	80	16.22	15.34	84.66	400	0.04	9.38
	-106/+75	22.4	4.54	10.79	89.21	900	0.09	4.94
	-75/+38	24.5	4.96	5.84	94.16	2600	0.26	15.25
	-38	28.7	5.82	0	100	5500	0.55	36.7
	Totals	493.2	100			1000	0.1	100
ZTD02	+2000	0	0	100	0	0	0	0
	-2000/+1000	27.9	5.1	94.9	5.1	300	0.03	1.09
	-1000/+425	78.5	14.35	80.55	19.45	400	0.04	4.17
	-425/+212	120.4	22	58.55	41.45	300	0.03	5.66
	-212/+106	113.9	20.82	37.73	62.27	200	0.02	5.81
	-106/+75	46.3	8.46	29.26	70.74	500	0.05	3.13
	-75/+38	46.6	8.52	20.75	79.25	1200	0.12	7.69
	-38	113.5	20.75	0	100	4700	0.47	72.45
	Totals	547.1	100			1300	0.13	100

Table A1.4 Cumulative mass, grades and recoveries in a sample of GHT011, ZTU01 and ZTD02 ore milled feeds.

Sample Name	**Product**	**Mass**		**Cum. Mass (%)**	**Assay Sn (%)**	**Sn Mass (g)**	**Recovery (%)**	**Cum. Sn Mass (g)**	**Cum. Sn Grade (%)**	**Cum. Sn Recovery (%)**
GHT011		**(g)**	**(%)**							
	Concentrate	628.6	16.49522	16.4952241	3.99	25.08114	98.62629412	25.08114	3.99	98.62629412
	Middlings	2871	75.33851	91.8337357	0.01	0.2871	1.128960208	25.36824	0.883602926	99.75525432
	Tailings	311.2	8.166264	100	0.02	0.06224	0.244745675	25.43048	8.171748072	100
	Head	3810.8	100			25.43048				

ZTU01	Product	Mass		Cum. Mass (%)	Assay Sn (%)	Sn Mass (g)	Recovery (%)	Cum. Sn Mass (g)	Cum. Sn Grade (%)	Cum. Sn Recovery (%)
		(g)	(%)							
	Concentrate	629	16.50572	16.50572058	1.76	11.0704	76.46148746	11.0704	1.76	76.46148746
	Middlings	2900	76.09951	292.6052272	0.09	2.61	18.0268538	13.6804	0.471737931	94.48834125
	Tailings	3990	104.7024	397.3076519	0.02	0.798	5.511658747	14.4784	0.362867168	100
	Head	7519	197.3077		0.29	14.4784				
ZTD02	Product	Mass		Cum. Mass (%)	Assay Sn (%)	Sn Mass (g)	Recovery (%)	Cum. Sn Mass (g)	Cum. Sn Grade (%)	Cum. Sn Recovery (%)
		(g)	(%)							
	Concentrate	992	5.355504	5.355503968	1.97	19.5424	37.50249474	19.5424	1.97	37.50249474
	Middlings	6001	32.39756	37.75306376	0.12	7.2012	13.81933463	26.7436	0.445652391	51.32182938
	Tailings	11530	62.24694	100	0.22	25.366	48.67817062	52.1096	0.451947962	100
	Head	18523	100			52.1096	100			