

Comparison of Mineralised and Unmineralised A-Type Granitic Systems in Southern Africa

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Declaration

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

A handwritten signature in dark ink, appearing to read 'Vonopartis', written over a horizontal line.

Leonidas C. Vonopartis

11th of August 2021.

“Somewhere, something incredible is waiting to be known.”

– Carl Sagan

Abstract

The Palaeoproterozoic Lebowa Granite Suite is the largest A-Type granitic system on Earth, and it is associated with one of the largest tin provinces in Africa. Tin mineralisation occurs as both endo- and exogranitic styles, within the roof facies of the Lebowa Granite Suite and the surrounding rocks of the Pretoria Group and overlying Rooiberg Group volcanics. The Zaaipplaats tin field is historically the second largest tin producer in South Africa and comprises the hydrothermally altered and stanniferous Bobbejaankop and Lease granites.

Cassiterite in the Zaaipplaats tin field occurs as low-grade disseminations and within high-grade swarms of tourmaline-quartz hydrothermal pipes and greisenised lenticular ore-bodies. The formation and mineralisation of these granites and hydrothermal features have been topics of debate since their discovery in the early 1900s. Thus, the formation of the Zaaipplaats tin field was re-investigated using a modern integrated approach, incorporating: field mapping; petrography; multi-spectral remote sensing; whole-rock geochemistry; and mineral chemistry.

The formation of the Zaaipplaats tin field granites is a culmination of several sequential and interdependent factors. The extensive fractionation of the Nebo granite allowed the concentration of an F, B, Cl, Fe and incompatible element-rich magmatic-hydrothermal fluid towards the granitic cupola. This accumulation of fluid resulted in the alteration of the roof facies and developed the chloritised, greisenised, tourmalinised and partially mineralised Bobbejaankop granite. The continued accumulation and saturation of these magmatic-hydrothermal fluids caused the sub-solidus alteration of the roof of the Bobbejaankop granite. This resulted in the formation of the texturally variably and mineralised Lease microgranite.

The sequence of petrological events is demonstrated using incompatible element fractionation proxies such as TEDI, Zr/Hf and Rayleigh Fractionation modelling, which indicate an extensive degree of granitic fractionation from the Nebo to Bobbejaankop then Lease granite. Moreover, the fluid-sensitive ratios of Nb/Ta and Y/Ho highlight an increasing degree of F-rich magmatic-hydrothermal fluid interaction from the Bobbejaankop to the Lease granite. In addition, multi-spectral remote sensing, in conjunction with pXRF mapping, highlights the increased accumulation of magmatic-hydrothermal fluids towards the roof of the granitic system. This interpreted increase in hydrothermal fluid accumulation is validated by an increase in chloritisation and greisenisation in the predicted locations. This integrated mapping approach proved effective in identifying regions of increased alteration, which are commonly associated with disseminated cassiterite mineralisation. Therefore, the synergetic use of remote sensing and pXRF mapping is proposed as a useful tool in exploration.

Tourmaline, cassiterite and quartz mineral chemistry provided novel insights into the magmatic to magmatic-hydrothermal evolution of the Zaaipplaats tin field. The tourmaline mineral chemistry reveals two compositionally different tourmalinisation events: an initial schorl–foitite evolution in the Bobbejaankop granite; and a later-stage and more Fe³⁺-rich, Fe³⁺-rich schorl–schorl–foitite tourmaline in the Lease granite and hydrothermal pipes. The petrographic associations and compositions of cassiterite revealed a predominantly hydrothermal origin for the ore, and an association with the late-stage Fe³⁺-rich tourmalinisation. Therefore, the composition of tourmaline can be used to vector potential endogranitic tourmaline-associated cassiterite mineralisation.

Trace elemental proportions and their ratios (Al/Ti and Ge/Ti) in quartz reveal an increasing degree of granitic fractionation and influence of the magmatic-hydrothermal fluid. The trace elemental signature of the quartz from the hydrothermal pipes is distinct, in comparison to the magmatic and magmatic-hydrothermal signatures of the quartz within the granites. The trace elements-in-quartz demonstrate an ability to identify the sequence of granitic evolution and infer the point of fluid-saturation. This allows the identification and targeting of the most fractionated and hydrothermally influenced lithologies to guide exploration.

A comparison of the Zaaipplaats tin field with other Africa A-Type granite suites, in particular the Gaborone Granite Suite, highlights multiple factors that influence metallogenic potential. A whole-rock geochemical review of the selected granite suites, together with a mica and chlorite comparison of the Zaaipplaats and Gaborone granites, reveal differences between mineralised and barren A-Type granites. The mica compositions from mineralised suites exhibit a Fe-Li trend, whereas barren granitoids tend to evolve along a more Mg-rich trend. Moreover, a useful mica–chlorite ternary diagram, K₂Ox10 – Al₂O₃ – (FeO+TiO₂+MgO+MnO), is proposed to geochemically illustrate the degree of chloritisation and subsequent muscovitisation of sheet silicates.

A sequence of events in the formation of an A-Type granite is proposed that promotes metallogenic potential: (i) the generation of a melt from an enriched mantle source; (ii) high temperature melting beneath an Archean craton; (iii) extensive and prolonged fractionation of a granitoid; (iv) the formation of Fe-rich trioctahedral micas and their evolution along a Fe-Li compositional trend; (v) the concentration and saturation of a metal-, F- and Cl-rich magmatic-hydrothermal fluid; and (vi) mineralisation that is induced during late-stage greisenisation by the acidic, saline and metal-bearing magmatic-hydrothermal fluid.

Thesis Structure and Co-authorship statement

This dissertation comprises eight chapters, four of which (Chapters 2, 3, 4 and 5) are in manuscript format and have been submitted to scientific journals. Due to the nature of a dissertation by publication, there is an overlap between chapters, such that portions of their introductions, geological setting and discussion are repeated. However, the results, discussions and conclusions of each chapter provide unique insight and value to the research goal of this project. Chapters 3, 4 and 5 are in review, Chapter 4 has been accepted subject to minor revisions and Chapter 2 has been published.

The content of each of the chapters in the manuscript is presented according to the style of the journal, to which the paper has been submitted. Although, the size and position of selected images, tables and the style of referencing have been adapted to better fit the dissertation format and maintain consistency throughout this thesis. The thesis was written in British English, however the manuscripts in chapters 2, 4 and 5 were required by their respective journals to be submitted with Americanised spelling. Mineral abbreviations are based on Whitney and Evans (2010), apart from Chapter 5, which adheres to “The Canadian Mineralogist” list of preferred mineral abbreviations. A glossary of important terms is provided in Appendix A. The contribution of each author for the manuscripts is declared as a percentage, however the thesis author was the main contributor to all manuscripts. A complete reference list is provided at the end of the thesis. Therein, the manuscript chapters are referenced as journal articles and their respective “in-text” citation and current stage in the publication process are summarised below:

- **Vonopartis et al. (2020a) – Chapter 2**

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- **Vonopartis et al. (2020b) – Chapter 3**

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- **Vonopartis et al. (2021b) – Chapter 5**

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The geochemical comparison of the Lebowa and Gaborone granite suites includes a whole-rock geochemical investigation and comparison of mica and chlorite mineral chemistry. Although valuable to this research, the data presented in Chapters 6 and 7 have not yet been structured for publication. This suite of analyses requires augmentation by further analytical work and the addition of other minerals and their compositions, before being suitable for

publication. In addition, a pilot study was attempted to set up a trace-elements-in-quartz methodology on the LA-ICP-MS at the University of the Witwatersrand. This technique was used to obtain the trace elemental compositions of quartz from the Zaaiplaats tin field. As a consequence of unforeseen instrumental issues, combined with delays and obstacles brought about by the global COVID-19 pandemic, analytical time was limited. The anticipated number and scope of the quartz analyses was therefore reduced. However, the mineral compositions presented in Chapter 7 are sufficient to provide valuable geological insight and address the primary aims of this research project. These quartz compositions will be later combined with additional quartz analyses to become suitable for publication.

Portions of Chapter 8 are similar to the discussions in previous chapters. The final chapter provides a summary of the presented data and integrates the key findings discussed throughout the previous chapters.

This PhD research project was funded by the National Research Foundation (NRF) and Technology and Human Resources for Industry Programme (THRIP), in partnership with V.M. Investments (Ltd.) and Bushveld Minerals (Ltd.). The whole-rock XRF and ICP-MS analyses for Chapters 2 and 4 were done by the EarthLab at the University of the Witwatersrand. The remaining sample collection, preparation and analyses was performed by myself with the training provided by the staff of the School of Geosciences, with notable advice and guidance from Prof. P. Nex, Prof. J. Kinnaird, Prof. L. Robb, Prof. D. van Niekerk, Prof. R. Bolhar, Dr. W. Fuchsloch and Dr. G. Bybee. The development and progression of this research was driven by myself, with the continuous guidance and advice from my supervisors and various collaborators (see acknowledgements).

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Chapter 1

Introduction

1.1. Preamble

Granitic rocks make up approximately 86% of the of Earth's continental crust and commonly host a variety of economically significant metals (Bonin et al., 2002; Bonin, 2007). The A-Type Lebowa Granite Suite is the felsic component of the Bushveld Igneous Complex, and is associated with the most important tin mines in South Africa (Crocker et al., 2001). The Zaaipplaats tin mine is host to both low-grade disseminated cassiterite and higher-grade cassiterite-bearing hydrothermal pipes and lenticular greisenised ore-bodies (Strauss and Truter, 1944; De Waal, 1972; Crocker, 1979; Coetzee, 1984; Coetzee and Twist, 1989). This thesis explores this expression of endogranitic tin mineralisation in the Lebowa Granite Suite and discusses the evolution of the granites and hydrothermal features of the Zaaipplaats tin field. This is accomplished by a combined mapping, petrographic, mineral chemistry and whole-rock geochemical investigation.

This research provides a comprehensive modern petrological, whole-rock geochemical and petrogenetic interpretation for the formation and eventual mineralisation of the Zaaipplaats tin granites. Additionally, this work produces the first comprehensive mineralogical descriptions, compositions and classification of tourmaline, cassiterite, mica and quartz from the Bushveld Granites. Furthermore, the stanniferous granites of Zaaipplaats are geochemically compared to the unmineralised granites of the Gaborone Granite Suite. This investigation aims to identify any evolutionary or inherited geochemical differences that may have influenced their metallogenic potential. The geochemical data from these Southern African granites, are compared to published data from mineralised and barren A-Type granites across Africa. This broadens the scope of this research to include a geochemical review of the metallogenic potential of African A-Type granites suites.

The first chapter of the thesis summarises the characteristics, mineralisation and origin of the A-Type granite classification. It provides a general geological context of the two sampled southern African granite suites, including: an expression of endogranitic tin mineralisation in the Lebowa Granite Suite of the Bushveld Igneous Complex; and the unmineralised granites of the Gaborone Granite Suite from the Gaborone-Kanye Igneous Terrane.

1.2. A-Type Granites

The diversity of granitoids was concisely expressed by Read (1957), who stated that “there are granites and granites” as, at the time, there were over 20 classifications of granitoid rocks (Barbarin, 1999; Chen and Grapes, 2007). Later, during the 1970s, Chappel and White (1974) and White (1979) suggested a simpler classification scheme, by proposing four types of granites: S-Type; I-Type; M-Type; and an unnamed group. This scheme was later amended by Loiselle and Wones (1979), who replaced the “unnamed group” of granites with the term “A-type” granites. An alternative “Residual” or “R-Type” group was proposed to replace the unnamed group, however A-type was favoured as it provided a more descriptive term (Eby, 1990; Bonin, 2007; Frost and Frost, 2011). The S-I-M-A or the “alphabet-soup” classification of granitoids (Table 1.1) remains the most common granite classification terminology, despite numerous debates and the suggested use of alternative classifications (Barbarin, 1999; Frost et al., 2001; Bonin, 2007; Chen and Grapes, 2007; Frost and Frost, 2011). Later refinements resolved some issues, such as the geochemical overlap of I- and M-Type granites, by reconsidering M-Type to be a subset of I-Type granites. However, the alphabet-soup classification of granites remains in dispute (Whalen et al., 1987; Clarke, 1992; Barbarin, 1999; Frost et al., 2001; Bonin, 2007).

The term “A-Type” refers to “Anorogenic”, “Anhydrous” or “Alkaline” granitoids, initially thought to be a partial melting product of the lower crust. The A-type group subsequently began to include a greater spectrum of granitoids, which range in composition, mineralisation, tectonic setting and age (Eby, 1990; Bonin, 2007; Frost and Frost, 2011). The typical characteristics of A-type granites include: an anorogenic or intra-plate setting; crystallisation within an H_2O - and f_{O_2} - poor environment; an increased high-field-strength (HFS) and Rare Earth Element (REE) content; and a complementary depletion in refractory elements (relative to I- and S-Type granites) (Table 1.1). Mineralogically, A-Type granites comprise hypersolvus to subsolvus alkali-feldspars with micrographic intergrowth of quartz, interstitial annite–siderophyllite micas, hastingsite–ferroedenite–ferrohornblende amphiboles, accessory zircon, Fe–Ti-oxides, fluorite and a suite of economically significant metals (Table 1.1) (Whalen et al., 1987; Clarke, 1992; Barbarin, 1999; Chappell and White, 2001; Bonin, 2007).

Table 1.1. Characteristics of the S-I-M-A granitoid classification scheme (Whalen et al., 1987; Clarke, 1992; Barbarin, 1999; Chappell and White, 2001; Frost et al., 2001; Bonin, 2007)

	S-Type	I-Type	M-Type	A-Type
Specific Mineralogy	Peraluminous assemblage, Al-rich silicates	Metaluminous assemblage	Variable Metaluminous assemblage	Alkaline feldspars, Fe-rich silicates
Major Elemental Signature	Compositionally restricted to felsic granites High SiO ₂ , Variable CaO	Broad spectrum of compositions, from mafic to felsic granites High CaO	Broad spectrum of compositions, from mafic to felsic granites	Restricted to granitic composition High SiO ₂ Low CaO
Trace Elemental Signature	Enriched in V, Cr, Co, Ni, Cu, Zn, Ba, Rb, Th, La, Ce, Y compared to I-type	Depleted in V, Cr, Co, Ni, Cu, Zn, Ba, Rb, Th, La, Ce, Y compared to S-type	Depleted in V, Cr, Co, Ni, Cu, Zn, Ba, Rb, Th, La, Ce, Y compared to S-type	Enriched in Nb, Sn, Hf, Zr, Ga, Rb, Th, U, Ta, REEs Depleted in V, Ni, Co, Cr compared to S- and I-type
Isotopic Signature	⁸⁷ Sr/ ⁸⁶ Sr > 0.708 $\delta^{18}\text{O} < 9\text{‰}$	⁸⁷ Sr/ ⁸⁶ Sr = 0.704-0.706 $\delta^{18}\text{O} > 9\text{‰}$	⁸⁷ Sr/ ⁸⁶ Sr < 0.705 $\delta^{18}\text{O} < 9\text{‰}$	⁸⁷ Sr/ ⁸⁶ Sr = 0.703 to >0.720 $\delta^{18}\text{O}$ highly variable
Al₂O₃ vs Alkalis	>1.1	<1.1	<1.0	>1.0
Proposed Source	Partial melting of sedimentary rocks	Partial melting of igneous rocks	Mantle source by partial melting of subducted oceanic crust, or extended fractional crystallisation	Partial melting of felsic granulite residue remaining after extraction of previous granite melt
Associated Mineralisation	Sn, W, Th, U, Li and REE	Cu, Mo $\pm$ Ni, Co, Au, Ag and U	Cu and Au	Sn, W, Mo, Zn, Pb, F, Li, Th, U $\pm$ REE

Despite their mineralogical and geochemical variability, A-type granites plot discretely within the *Within-Plate Granite* (WPG) field of trace element granitic discrimination diagrams (Pearce et al., 1984). Eby (1992) further improved the classification of A-Type granites by subdividing these granitoids into A1 and A2 groups, based on their large-ion-lithophile (LIL) elemental ratios. This sub-classification was proposed with the strict caveat that it be used on rocks that are both WPG and A-Type granites (Eby, 1992). Granitoids with an A1 classification have a lower Y/Nb ratio (<1.2) and are suggested to be differentiates of ocean island basalt (OIB) and hot-spot magmas. Granitoids that are classified as A2, exhibit higher Y/Nb ratios (>1.2), and are proposed to be differentiates from tholeiitic magmas or partial melts of the lower continental crust.

The most recent contribution to granite classification was proposed by Frost et al. (2001), who abandoned the S-, I- and A-Type classification for a geochemically based classification: ferroan–magnesian; alkaline–alkali–calcic–calc-alkaline–calcic; and peraluminous–metaluminous–peralkaline. These classifications are based on their major mineralogical and chemical characteristics, *i.e.* SiO₂, alumina saturation index (ASI) $[\text{Al}_2\text{O}_3 / ((\text{CaO} - 3.33 \times \text{P}_2\text{O}_5) + \text{NaO} + \text{K}_2\text{O})]$, Fe number (Fe#) $[\text{FeO}^{\text{tot}} / (\text{FeO}^{\text{tot}} + \text{MgO})]$, and modified alkali-lime index (MALI) $[\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}]$. Moreover, this classification scheme retains the original A-Type

classification of granitoids, and is used to define high silica ferro-potassic lithologies (Frost et al., 2001; Bonin, 2007; Frost and Frost, 2011). However, the S-, I- and A-Type classification scheme is used for the characterisation of granitoids in this research.

A-Type granites are not the most abundant granitoid type, but they do occur across a multitude of geological contexts and ages (Bonin et al., 2002; Bonin, 2007). They are also the only known granitoids to have formed on other terrestrial planets and large asteroids. Therefore, A-Type granites are the predominant felsic igneous rock on telluric planetary bodies (Bonin et al., 2002; Bonin, 2007). Two distinct groups of terrestrial A-Type granites are identified, within-continental plate and within-oceanic plate (Table 1.2) (Bonin, 2007). However, the focus of this study is on continental A-Type magmatism within Africa. In particular, the mineralised Lebowa Granite Suite of the Bushveld Igneous Complex and the unmineralised Gaborone Granite Suite of the Gaborone-Kanye Igneous Terrane.

Table 1.2. Summary of known A-Type granite systems. Table modified from Bonin (2007).

Setting	Orogenic Stage	Geological Context	Examples	Age	
Continental	Post -Collision	Transcurrent Shear Zone	Finland–Russia border	2.44	Ga
			Post-kinematic suite of Finland	1.87 to 1.88	Ga
			Taourirt suite, Hoggar, Algeria	530	Ma
			Comendite, San Pietro Island	15	Ma
	Cratonic	Re-activation of Transcurrent Shear Zone During Uplift and Swells	Gaborone granite suite SE. Botswana	2.78	Ga
			Lebowa granite suite, South Africa	2.05	Ga
			Rapakivi magmatism, S. Finland	1.5 to 1.7	Ga
			Niger Younger Granites, N. Nigeria	141 to 213	Ma
	Rifting	Extensional Regime	Oslo Rift	280	Ma
			Topaz rhyolites, W. USA	50	Ma
			Jibisi ring complex, E. African Rift	15 to 20	Ma
Oceanic	Passive Margin	Diverging Plate Extensional Regime	Limmo massif, Afar, Ethiopia	23	Ma
			Western border of the Yemen Plateau	20 to 30	Ma
	Active Margin	Converging Plate Extensional Regime	Papua-New Guinea and Mayor Island, NZ	0 to 5	Ma
			Ashizuri massif, S. Japan	14	Ma
	Ridge	Diverging Plate Boundary	Austurhorn, SE. Iceland	6 to 7	Ma
	Island	Within-Plate	Seychelles Archipelago	703 to 809	Ma
			Ascension Island	1.5 to 7	Ma
	Plateau	Within-Plate	Rallier-du-Baty ring complex, Kerguelen	0 to 18	Ma

Continental A-Type granites are emplaced in cratonic environments and mobile belts. They occur at various stages within Wilson's Orogenic cycle and are commonly associated with a mafic igneous phase (Frost et al., 2001; Bonin, 2007; Frost and Frost, 2011). There is little consensus on the petrogenesis and source of A-Type magmatism and thus, numerous formational models have been proposed: partial melting of the lower continental crust; the fractionation from mantle derived magmatic sources; and the remelting of felsic granulites, calc-alkaline granitoids and amphibole tonalites at the base of continental cratons (Collins et al., 1982; Anderson, 1983; Whalen et al., 1987; Eby, 1990; Creaser et al., 1991; Eby, 1992; Beyth et al., 1994; Landenberger and Collins, 1996; Bonin, 2007).

There is a current agreement that A-Type magmatism involves mantle interaction with the lower crust. The compositional variability and convective nature of the upper mantle establishes a plausible link and explanation for the heterogeneity of A-Type granites. According to Meibom and Anderson (2003), relatively small (0.1 to 100 km) pockets of endmember compositions within the mantle, are a combination of recycled crust and depleted mantle residue. These compositionally distinct mantle pockets may account for the compositional spectrum of A-type granites (Meibom and Anderson, 2003; Bonin, 2007). Therefore, the combination of random sampling of mantle by plumes, decompressive melting of the depleted mantle, partial melting of the crust and crustal assimilation is suggested to explain the intrinsic heterogeneity of these granitoids (Whalen et al., 1987; Creaser et al., 1991; Bonin, 2007; Collins et al., 2020; Vasyukova and Williams-Jones, 2020). Despite numerous attempts, the geochemical heterogeneity, source variability and range in tectonic contexts complicates the pursuit of an all-encompassing petrogenetic model for A-Type granites. Therefore, the factors that influenced their metallogenic potential are poorly constrained.

1.3. The Bushveld Igneous Complex

The Paleoproterozoic Bushveld Igneous Complex is located in the central northeast of South Africa (Figure 1.1). The Bushveld Igneous Complex has an estimated area exceeding 90,000 km², an approximate volume of 450,000 km³ and is host to some of the largest known mineral deposits on Earth (Cawthorn and Walraven, 1998; Bailie and Robb, 2004; Finn et al., 2015; Zeh et al., 2015; Scoates et al., 2021). The unique mineral wealth of the Bushveld Igneous Complex has inspired extensive research, yet its formation has continued to elude researchers

(Kinnaird et al., 2004; Zeh et al., 2015; Zeh et al., 2019). The Bushveld Igneous Complex comprises a sill-like, mafic Rustenburg Layered Suite approximately 7 to 8 km thick, which was emplaced beneath the simultaneous extrusion of the Rooiberg Group volcanics (Robb et al., 2000; Zeh et al., 2015; Skursch et al., 2020). The considerably thinner Lebowa Granite Suite is 1.5 to 3 km thick, and intruded through the Rustenburg Layered Suite to form the largest A-Type granite suite on Earth (Robb et al., 2000; Bailie and Robb, 2004; Skursch et al., 2020).

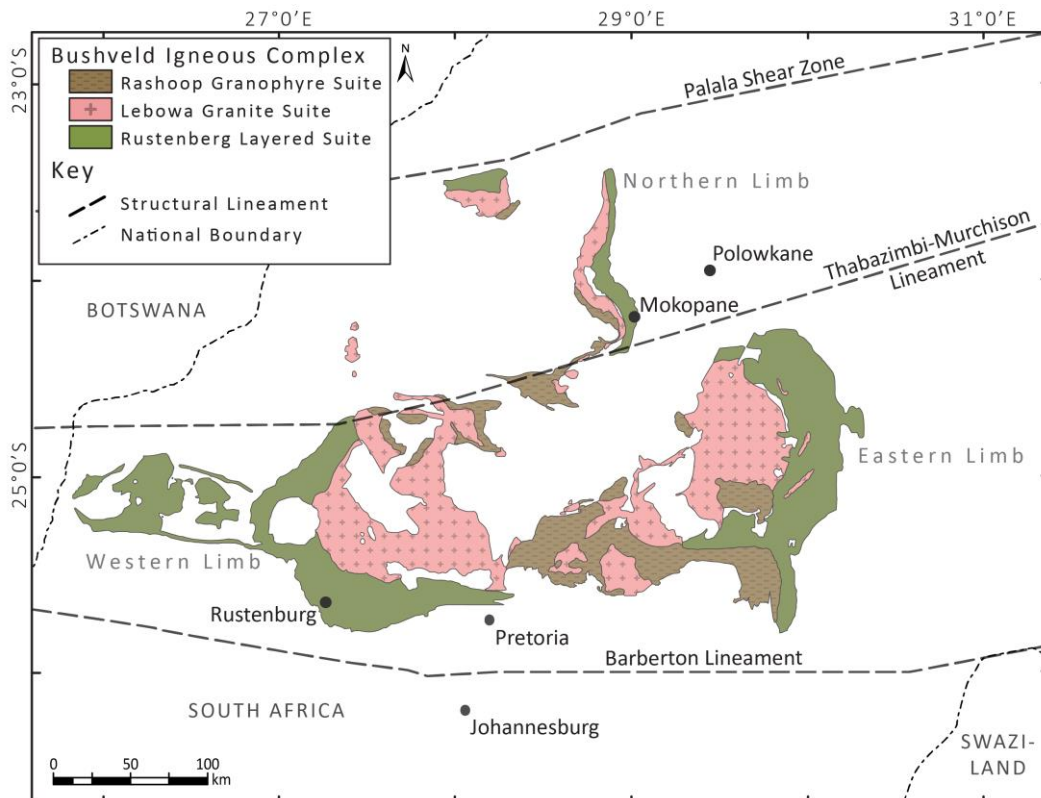


Figure 1.1. Simplified geological map of the Bushveld Igneous Complex and bounding structural lineaments. Adapted and modified after Hunter (1975), Grobler (1996) and Zeh et al. (2015).

The Lebowa Granite Suite is enclosed between the mafic Rustenburg Layered Suite below and the felsic volcanics of the Rooiberg Group and the Roshoop Granophyre Suite above (Robb et al., 2000; Bailie and Robb, 2004; Skursch et al., 2020). The Lebowa Granite Suite was emplaced in the stable Kalahari craton and is bounded by three major crustal shear zones: the Zoetfontein-Palala-Shear Zone in the North; the Thabazimbi-Murchison Lineament separating the Northern Limb from the East and West Limbs; and the Barberton Lineament in the south of the Bushveld Igneous Complex (Figure 1.1) (Zeh et al., 2009; Zeh et al., 2015). These crustal lineaments are believed to be suture zones, formed during the amalgamation of the Kaapvaal Craton (Zeh et al., 2009; Zeh et al., 2015).

The Rustenburg Layered Suite and the Lebowa Granite Suite were coevally intruded into the Kalahari craton, and are shown to have been formed over a 5 million year time interval (2,060 to 2,055 Ma) (Scoates et al., 2021). A late re-setting of radiogenic isotopic systems within the granites was noted by McNaughton et al. (1993). They discussed a long-lived hydrothermal system that persisted until approximately 1,950 Ma. This age of the Bushveld Complex and Kaapvaal Craton is corroborated through independent geochronological studies (Kinnaird et al. (2004) and references therein). Although, the source of this event remains enigmatic, it is considered capable of resetting mineral ages and reactivating hydrothermal systems (Kinnaird et al., 2004). This event is thought to potentially have caused late-stage endo- and exogranitic magmatic-hydrothermal to hydrothermal mineralisation (Robb et al., 2000).

The Lebowa Granite Suite is subdivided into seven granitic facies, although the most prominent are the coarse-grained Nebo and Makhutso granites, and the fine-grained Klipkloof granite (Table 1.3) (SACS, 1980; Robb et al., 2000; Kinnaird et al., 2004). The Nebo granite was previously known as the Main Granite, and is the most areally extensive facies of the Lebowa Granite Suite (SACS, 1980; Robb et al., 2000; Crocker et al., 2001). Unlike the mafic Rustenburg Layered Suite, the Lebowa Granite Suite does not host world class mineral deposits. However, it is host to various notable fluorite and polymetallic magmatic-hydrothermal endo- and exogranitic deposits, and is linked to the formation of the South African tin province (Wilson and Anhaeusser, 1998; Robb et al., 2000; Crocker et al., 2001).

Table 1.3. The granite subdivisions of the Lebowa Granite Suite. Current lithostratigraphic names based on SACS (1980). Historical granite names accumulated from literature (Strauss, 1954; De Waal, 1972; Lenthall and Hunter, 1977; Walraven and Hattingh, 1993).

	Current Classification	Historical Classification
Suite	Lebowa Granite Suite	Bushveld Granite or Main Granite Suite
Subdivisions	Nebo Granite	Red, Sekhukhune, Veerkraal, Magnet Heights, Steelpoort Park Granites
	Bobbejaankop Granite	Klipvoor Granite
	Lease Granite	Foothills Granite
	Balmoral Granite	Balmoral Granite
	Verena Granite	Verena Granite
	Klipkloof Granite	Foothills Granite
	Makhutso Granite	Makhutso Granite

1.3.1. Formation of the Lebowa Granite Suite

Recent geochronological research indicates approximately 5 million years of magmatism for the formation from the Rustenburg Layered Suite to the Lebowa Granite Suite (Scoates et al., 2021). The Rooiberg Group Volcanics ($2,060 \pm 2$ Ma) (Scoates et al., 2021) were extruded above the Pretoria Group of the Transvaal Supergroup. This volcanism formed an unconformity that the Rustenburg Layered Suite subsequently utilised and later the granites of the Lebowa Granite Suite then intruded. This resulted in the trapping of the Bushveld Granites beneath the overlying volcanics and underlying mafic units (Skursch et al., 2020; Scoates et al., 2021). The overlying Rashoop Granophyre Suite developed as the contact between the Lebowa Granite Suite and the overlying Rooiberg Group Volcanics (Zeh et al., 2015; Skursch et al., 2020).

The Nebo granite is the most voluminous granitoid of the Lebowa Granite Suite, and can be thought of as the main stage of the Bushveld felsic magmatism (SACS, 1980; Robb et al., 2000; Crocker et al., 2001). Despite the enormity and relatively regional homogeneous nature of this facies, consensus on the formation of the Nebo was strongly debated, and thus several models have been proposed. The geochemical homogeneity of the Nebo granite was interpreted by Kleemann and Twist (1989) to have formed from upward fractional crystallisation of a single pluton. This resulted in the accumulation of discrete fluid phases and the apparent geochemical and mineralogical variations from the base to the roof. However, this fractional crystallisation model was later contested by subsequent research. Hill et al. (1996) proposed the formation of the Nebo granite as the result of the partial melting of felsic Archean basement, initiated by the emplacement of the Rustenburg Layered Suite. This melting of the lower craton resulted in the formation of multiple ascending siliceous magmatic cells. These siliceous plutons accumulated in the centre of the Bushveld Igneous Complex, before extending laterally between the confining Rustenburg Layered Suite and Transvaal Sequence (Hill et al., 1996; Wilson et al., 2000).

The multiple magmatic injection model was later corroborated and modified by Wilson et al. (2000). They proposed that the Nebo granite comprises several similar, yet distinct magmatic pulses that are petrographically, geochemically and geophysically related. This episodic magmatic model is currently the favoured and most substantiated explanation for the formation of the Nebo granite.

1.3.2. Mineralisation of the Lebowa Granite Suite

The Lebowa Granite Suite does not compare to the economic potential and ore production of the Rustenburg Layered Suite. However, the Bushveld Granites are known for their polymetallic mineralisation, which was vital in the development of the South African economy (Falcon, 1985; Wilson and Anhaeusser, 1998; Crocker et al., 2001; Kinnaird et al., 2016). Crocker (1979) compiled a summary of the mineral and ore associations within the felsic expressions of the Bushveld Igneous Complex. These economic associations were later categorised and comprehensively discussed by Crocker et al. (2001). They classified the notable mineral occurrences in the Bushveld Granites into four types:

Type 1: Fluorspar–actinolite–hematite mineralisation

Type 2: Molybdenite–fluorite–sulphide mineralisation

Type 3: Cassiterite–tourmaline–sulphide mineralisation

Type 4: Sulphide–carbonate mineralisation

The cassiterite–tourmaline–sulphide association (Type 3) is the main focus of this research. Type 3 mineralisation includes the syn-magmatic to late magmatic-hydrothermal endogranitic tin mineralisation in the Lebowa Granite Suite.

South Africa is not currently known for tin production although, during the 20th century, the Lebowa Granite Suite was associated with the substantial production of tin and other metals (Figure 1.2) (Falcon, 1985; Wilson and Anhaeusser, 1998; Crocker et al., 2001; Kinnaird et al., 2016). South African tin mineralisation is mainly developed in either endo- or exogranitic cassiterite deposits that occur as either disseminated, vein-hosted or hydrothermal-brecciated pipes (Wilson and Anhaeusser, 1998; Crocker et al., 2001). These tin deposits are located in six major tin fields, which are located in the granites and the overlying lithologies of the Lebowa Granite Suite (Table 1.4 and Figure 1.2). Tin production from most of these tin fields was short lived, although a few regions were active for over 70 years.

These long-lived tin fields included the Rooiberg, Zaaipplaats and Nylstroom tin fields, and provided the bulk of the tin metal produced (Table 1.4) (Falcon, 1985; Wilson and Anhaeusser, 1998; Crocker et al., 2001; Kinnaird et al., 2016). The crash of the stock exchange in the late 1980s and the plummeting tin price effectively ended tin production in South Africa. However, current technological advancements and investment into renewable energy has seen

commodities, such as tin, become critical components. This technological boom and shift towards sustainability has reignited the South African and global tin industry.

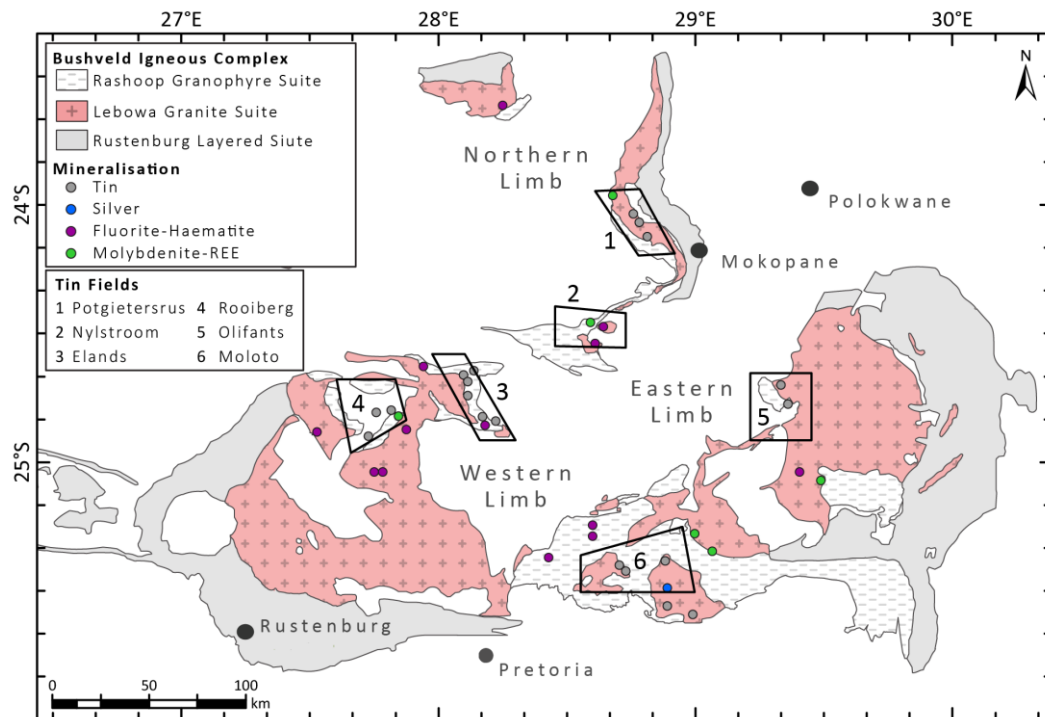


Figure 1.2. Simplified geological map of the Lebowa Granite Suite and location of the various tin fields. Localities of tin, silver, fluorite-haematite and molybdenite-REE mineralisation are displayed by coloured circles. Adapted and modified after Crocker et al. (2001); Wilson and Anhaeusser (1998); and Hunter (1975).

Table 1.4. Table of tin fields within the Bushveld Igneous Complex, their approximate location, main producer and duration of tin production (Lenthal, 1974; Falcon, 1985; Crocker et al., 2001).

Tin Field	Location	Main Producer	Farm Name and Code	Life Span
Rooiberg	60 km W of Warmbaths	Rooiberg Minerals Development Co. Ltd.	Blaauwbank 517 KQ	1909 to 1986
			Olievenbosch 506 KQ	
			Hartebeesfontein 511 KQ	
			Leeuwpoot 554 KQ	
			Nieuwpoot 516 KQ	
			Rietfontein 536 KQ	
Zaaiplaats	35 km NW of Mokopane	Zaaiplaats Tin Mining Co. Ltd.	Zaaiplaats 223 KR	1903 to 1989
			Groenfontein 227 KR	
			Rooderpoort 222 KR	
Olifants	30 km W of Marble Hall	Mutue Fides Tin Mines	Mutue Fides 648 KS	1913 to 1949
			Tygerpad 633 KS	
Nylstroom	25 km W of Naboomspruit	Union Tin Mines Ltd.	Doornhoek 342 KR	1951 to 1986
Elands	20 km NW of Warmbaths	Warmbaths Tin Syndicate	Elandsfontein 440 KR	1925 to 1929
Moloto	46 km N of Cullinan	Enkeldoom Tin Mining	Enkeldoorn 217 KR	1951 to 1968*

*Intermittent Operations

1.3.3. The Zaaipplaats Tin Field

Since the opening of the Zaaipplaats tin field in 1908 until its closure in the early 1990s, it has been the subject of numerous geological investigations (Merensky, 1908; Kynaston et al., 1909; Söhnge, 1944; Strauss and Truter, 1944; Strauss, 1954; Lenthall and Hunter, 1977; Coetzee, 1984; Von Gruenewaldt and Strydom, 1985; Coetzee, 1986; Kleemann and Twist, 1989; Pollard et al., 1991a; McNaughton et al., 1993; Crocker et al., 2001). The initial study by Kynaston et al. (1909), classified the granitic rocks of the Mokopane region into 5 different granite facies:

- Fine-grained granites and aplites
- Coarse-grained massive granites
- Medium-grained granulitic granites
- Pegmatites
- Granophyres

Although petrographically distinct, these classifications are not based on lithological relationships and petrogenetic characteristics. Subsequent attempts to classify the various granites suffered from similar pitfalls, until the work of Strauss and Truter (1944) and Strauss (1954). As the Zaaipplaats tin field was active and mine workings were accessible, the geological memoir of Strauss (1954) is considered to be the most petrographically descriptive and comprehensive study on the textures and lithological relationships from these rocks (Kynaston et al., 1909; Strauss and Truter, 1944; De Waal, 1972; Coetzee, 1984). Strauss (1954) proposed a reclassification of the granites into four distinct facies, based on detailed field relationships and petrographic descriptions:

- Main Granite (various sub-facies)
- Foothills Granite
- Bobbejaankop Granite
- Lease Microgranite and Contact Pegmatite

Each facies was thought to be a different stage of intrusive magmatism, with internal variations and mineralisation confined to late-stage intrusive bodies, such as the Bobbejaankop and Lease granites (Strauss and Truter, 1944; Strauss, 1954). As with the rest of the Bushveld Granites, the lithological nomenclature has since been changed (Strauss and Truter, 1944; SACS, 1980; Walraven and Hattingh, 1993; Crocker et al., 2001; Kinnaird et al., 2004). Consecutive geological maps of the region have largely been based on the combined

work of Söhnge (1944), Strauss & Truter (1944) and Strauss (1954). Coetzee (1984) further refined the geological map and updated the granite nomenclature through a localised study at the Zaaiplaats tin mine.

Despite the numerous petrological studies, a consensus on the formation and mineralisation of these granites has yet to be achieved. The formation of the Bobbejaankop granite has been debated but is generally considered as either the result of fractionation (McCarthy and Fripp, 1980; Pollard and Taylor, 1986; Pollard et al., 1991a; McNaughton et al., 1993; Hill et al., 1996) or the metasomatism of the roof of the Nebo granite (McCarthy and Fripp, 1980; Kleemann and Twist, 1989; McNaughton et al., 1993; Hill et al., 1996; Kinnaird et al., 2004). The more controversial aspect of these granites is the mineralisation in the cupola of the Bobbejaankop intrusion, the formation of the peripheral Lease microgranite and the high-grade hydrothermal pipe system.

The Lease microgranite has many proposed models of formation, including: the result of metasomatism; representing a chilled margin; fractionation; quenching; and the intrusion of a completely separate magmatic body between the Bobbejaankop granite and overlying granophyres (Strauss and Truter, 1944; Strauss, 1954; De Waal, 1972; Coetzee, 1984; Coetzee and Twist, 1989; Kleemann and Twist, 1989; Crocker et al., 2001). Yet none of these models adequately account for the heterogeneity of this microgranite and its geochemical similarity to the underlying Bobbejaankop granite.

A characteristic feature of the Bobbejaankop and Lease granites are the swarms of large diameter hydrothermal tourmaline-cassiterite-bearing pipes and greisenised lenticular ore bodies (Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1984; Pollard et al., 1989; Crocker et al., 2001). These anastomosing hydrothermal pipes hosted between 70 to 80% cassiterite within their greisenised cores. They radiate upwards from the centre of the Bobbejaankop into the Lease granite, before terminating below the Rashoop Granophyre Suite (Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1984; Pollard et al., 1989; Crocker et al., 2001). There are many models that have been proposed for the formation of these pipes, including: early incipient fracturing of the cupola, which resulted in permeability controlled post-magmatic replacement (Merensky, 1908; Kynaston et al., 1909); the channelling of exsolved hydrothermal fluids that were controlled by irregular crystallisation fronts (Söhnge, 1944; Strauss, 1954); the upward migration of an exsolved fluid in a partially crystallised granite,

controlled by the incipient fracturing and lateral variations in porosity (Von Gruenewaldt and Strydom, 1985); and the dissolution of quartz and feldspar that was induced by rock-fluid interaction with an exsolved alkali-chloride, fluoride- and carbonate-bearing hydrothermal fluid (Pollard et al., 1989).

Investigation into the formation of these granites and hydrothermal features was last attempted in the early 1990s. They have not been investigated using modern analytical techniques. Therefore, this study aims to elucidate the formation and mineralisation of these granites, using a modern integrated approach that incorporates: multispectral remote sensing; geochemical mapping; petrography; whole-rock geochemistry; and mineral chemistry. Moreover, the mineralised Bobbejaankop and Lease granites are an ideal example for endogranitic tin mineralisation in A-Type granites. This new data has enabled a comparison with the unmineralised Southern African A-Type granite system of the Gaborone Granite Suite, with the aim of understanding A-Type granite metallogensis.

1.4. The Gaborone–Kanye Igneous Terrane

The Gaborone–Kanye Igneous Terrane is comprised of the A-Type Gaborone Granite Suite and the Kanye Volcanics. It is located in the central region of Southern Africa, primarily within Botswana along the South African border (Figure 1.3). The plutonic and sub-volcanic lithologies of the Gaborone–Kanye Igneous Terrane intruded into, and are surrounded by, the overlying felsic Lobatse Volcanic Group. The rhyolitic Kanye Volcanics are considered as either the chilled margin of the underlying Gaborone Granite Suite or thermal alteration of the overlying Lobatse extrusives (Aldiss et al., 1989; Grobler, 1996; Key and Ayres, 2000).

The 2.78 Ga Gaborone Granite Suite has no recorded occurrences of economic mineralisation throughout its approximate area of 6,000 km² (Key and Wright, 1982; Grobler and Walraven, 1993; Moore et al., 1993; Lowe, 1995). The Gaborone Granite Suite is classically described as a mushroom shaped, structurally controlled intrusion (Key and Wright, 1982; Grobler and Walraven, 1993; Moore et al., 1993). This interpretation is supported by a concentric internal structure, in which the lithological units grade outwards from the coarse-grained Thamaga granite into a medium- to fine-grained Kgale granite (Grobler and Walraven, 1993; Lowe, 1995; Grobler, 1996).

The rapakivi-textured Thamaga granite, in the centre of the intrusion, is texturally variable and comprises large phenocrystic feldspars that are set in a black or pink groundmass. The Thamaga granite is then enclosed by the texturally variable Kgale Granite, which is further subdivided into the equigranular leucocratic Main Phase and the granophyric Marginal phase (Chaoka, 1988; Grobler and Walraven, 1993; Lowe, 1995; Grobler, 1996).

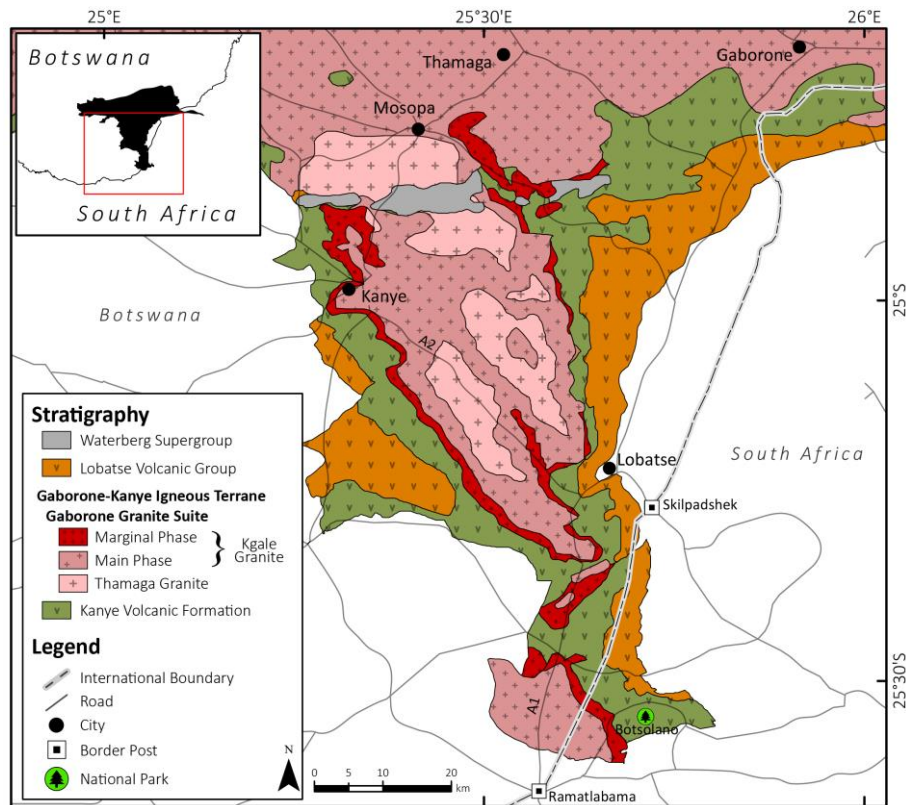


Figure 1.3. Simplified geological map of the Gaborone Granite Complex. Based on Key (1983), Grobler and Walraven (1993) and Lowe (1995).

The Lobatse Volcanic Group overlies the Gaborone–Kanye Igneous Terrane in the North West, and is unconformably overlain by the sediments of the Transvaal Supergroup. The stratigraphic units of the Transvaal Supergroup are unconformably covered by the sediments of the Waterberg Supergroup and are cross-cut by multiple dyke swarms (Key and Wright, 1982; Grobler and Walraven, 1993; Moore et al., 1993; Lowe, 1995). Two main swarms are present: an east–northeasterly trending swarm of dolerite dykes that extend into the Transvaal Supergroup and are overlain by the Black Reef Formation; and an east–west trending swarm of dolerite dykes that cross-cut the Black Reef Formation and extend upwards into dolomites of the Transvaal Supergroup (Key and Wright, 1982; Chaoka, 1988; Grobler and Walraven, 1993; Lowe, 1995; Grobler, 1996; Key and Ayres, 2000).

1.4.1. Formation of the Gaborone–Kanye Igneous Terrane

The current hypothesis for the formation of the Gaborone–Kanye Igneous Terrane is by the fractionation of an underlying magma, and the shallow emplacement beneath the Lobatse Volcanics (Grobler and Walraven, 1993; Moore et al., 1993; Grobler, 1996). This magmatism is thought to have been induced by an extensional sag-basin, from the collision that formed the Limpopo Orogenic Belt (Grobler, 1996). However, the development of the Kanye Formation and Gaborone granites have been individually disputed (Key and Wright, 1982; Chaoka, 1988; Aldiss et al., 1989; Grobler and Walraven, 1993; Lowe, 1995; Grobler, 1996; Key and Ayres, 2000).

Uncertainty regarding the formation and emplacement of the Kanye Volcanic Formation is well described and documented by numerous publications (Key and Wright, 1982; Chaoka, 1988; Grobler and Walraven, 1993; Lowe, 1995; Grobler, 1996; Key and Ayres, 2000). The debate can be summarised into a discussion of whether the Kanye Formation represents a voluminous ash-flow tuff (Aldiss et al., 1989; Lowe, 1995), or a high-level intrusion rather than an extrusive formation (Key and Wright, 1982). However, the formation of the Kanye Formation is beyond the scope of this thesis.

Two primary formational hypotheses for the Gaborone Granite Complex have been proposed, the “one-event” and “two-event” models. The “one-event” model suggests a coeval formation of the whole complex and the “two-event” model describes multiple stages of formation (Key and Wright, 1982; Chaoka, 1988; Sibiya, 1988; Grobler and Walraven, 1993; Moore et al., 1993; Lowe, 1995; Grobler, 1996). Both models agree that emplacement of the main plutonic body was structurally controlled by regional faulting, yet opinions differ as to the sequence of intrusions and the evolution of the system.

The “two-event” model proposed by Poldervaart (1954) states that the only intrusive body within the complex is the rapakivi Thamaga Granite. He postulated that the recrystallisation of the Kanye Formation, by the mobilisation of acid volcanics, resulted in the formation of the other lithological units in the complex (Key and Wright, 1982; Chaoka, 1988; Sibiya, 1988; Grobler and Walraven, 1993; Moore et al., 1993; Lowe, 1995; Grobler, 1996). The “one-event” hypothesis recommended by Key and Wright (1982) states that the entire Gaborone–Kanye Igneous complex is the result of large scale differentiation from a high-level intrusion. Subsequent zircon Pb-Pb geochronology concluded that there is no significant age difference

between the Gaborone Granite Suite and Kanye Formation, thus corroborating the “one-event” hypothesis (Grobler and Walraven, 1993; Moore et al., 1993).

1.5. Project Aims and objectives

The main aim of this thesis is to conduct a petrographical and geochemical investigation of the granites of the Zaaipplaats tin field, with a specific focus on the mines of Zaaipplaats and Groenfontein. This was achieved through a combination of field mapping, geochemical mapping, remote sensing, petrography, whole-rock geochemistry and mineral chemistry. In addition, this research provides the first set of tourmaline, cassiterite, mica and quartz mineral compositions from the granites of the Bushveld Igneous Complex. Therefore, this research explores a previously underutilised geochemical approach to understand this system.

A secondary aim is to gain a better understanding of A-Type granite mineralisation and the factors that influence metallogenic potential. The mica and chlorite mineral compositions from the mineralised granites of the Zaaipplaats tin field are compared to the barren granites from the Gaborone Granite Suite. This data is used to evaluate their potential to record differences in the magmatic to magmatic-hydrothermal evolution of these systems. In addition, the whole-rock geochemistry of these suites is used in a comparative geochemical review of mineralised and barren African A-Type granite suites. This comparative investigation aims to identify geochemical differences, commonalities and factors that influence the metallogenic potential of A-Type granites.

Chapter 2

Petrology and Geochemistry of the Zaaipplaats tin granites

2.1. Preamble

This chapter presents an article that was published in the Journal *Minerals* that describes and utilises lithological observations, petrography and whole-rock geochemistry in the interpretation of the petrological evolution of the granites in the Zaaipplaats tin field. The Northern Limb of the Bushveld Igneous Complex is historically known for tin mineralisation associated with the Bobbejaankop and Lease granites of the Zaaipplaats tin field (Söhnge, 1944; Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1984; Coetzee and Twist, 1989; Crocker et al., 2001; Robb, 2005). The aim of this chapter is to elucidate the formation of these granites and distinguish between endogranitic and hydrothermally derived Sn-mineralisation. This chapter briefly reviews and discusses previous research on the granites in the Zaaipplaats tin field. The focus of this chapter however, is on providing a comprehensive description of the lithological relationships and a detailed petrography of the various granites, features and mineralisation of the Zaaipplaats tin field.

Research on understanding the formation and evolution of these granites has been centred at the Zaaipplaats tin mine at the northern margin of the intrusion. Thus, since Strauss (1954) and the closure of the Groenfontein Tin mine, the main body of the Bobbejaankop and Lease granites has been neglected. Therefore, this study is focused on the lesser studied southern region of the Zaaipplaats tin field with the aim of elucidating the petrogenetic relationship and evolution of the Lease and the Bobbejaankop granites. An inventory of the samples collected and their respective coordinates are provided in Appendix B.

2.1.1. Author Contributions

Leonidas Vonopartis was the main contributor for this manuscript and did most of the field work, sample collection, sample preparation, data compilation and write-up of the manuscript. The co-authors, Paul Nex, Judith Kinnaird and Laurence Robb supervised and provided guidance in the development of the manuscript. Furthermore, the co-authors assisted with the field work, editorial review and the interpretation of the presented data.

Contribution percentage per author:

- | | | |
|----|---------------|-----|
| 1. | L. Vonopartis | 80% |
| 2. | P. Nex | 10% |
| 3. | J. Kinnaird | 5% |
| 4. | L. Robb | 5% |

2.2. Evaluating the Changes from Endogranitic Magmatic to Magmatic-Hydrothermal Mineralization: The Zaaipplaats Tin Granites, Bushveld Igneous Complex, South Africa

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*Published in **Minerals** | Special issue on Granite Related Mineralization Systems.*

Abstract: The stanniferous granites of the Zaaipplaats tin field are part of the A-Type Lebowa Granite Suite, within the greater Bushveld Igneous Complex of northeast South Africa. The tin field comprises three granites: (1) the Nebo, a leucocratic, equigranular biotite granite; (2) The brick-red hypidiomorphic Bobbejaankop granite, which is extensively microclinized with chloritized biotite and characteristic synneusis-textured quartz; and (3) The variably altered roof facies of the Bobbejaankop granite known as the Lease microgranite. The Bobbejaankop and Lease granites were both extensively mined for cassiterite until 1989. The cassiterite is hosted in disseminations, miarolitic cavities, and within large hydrothermal, tourmalinized, and greisenized pipes and lenticular ore-bodies. An extensive petrological and whole-rock XRF and ICP-MS geochemical study, has provided new insight into the magmatic and magmatic-hydrothermal mineralization processes in these granites. Trace elements and Rayleigh Fractionation modelling suggest the sequential fractionation of the Nebo granite magma to be the origin of the Bobbejaankop granite. Incompatible elemental ratios, such as Zr/Hf and Nb/Ta, record the influence of internally derived, F-rich, hydrothermal fluid accumulation within the roof of the Bobbejaankop granite. Thus, the Lease granite resulted from alteration of the partially crystallized Bobbejaankop granite, subsequent to fluid saturation, and the accumulation of a magmatic-hydrothermal, volatile-rich fluid in the granite cupola. The ratio of Nb/Ta, proved effective in distinguishing the magmatic and magmatic-hydrothermal transition within the Bobbejaankop granite. Elemental ratios reveal the differences between pre- and post-fluid saturation in the mineralizing regimes within the same pluton, thus highlighting the effect that the location and degree of hydrothermal alteration have had on the distribution of endogranitic tin mineralization.

Keywords: XRF and ICP-MS; Zaaipplaats tin field; A-type granites; tin granites; fractionation; hydrothermal; cassiterite mineralization.

2.2.1. Introduction

The Paleoproterozoic Bushveld Complex, in the northeast of South Africa, is the largest known layered igneous complex on Earth. It exceeds an area of 90,000 km² and has a magma volume estimated at 450,000 km³, hosting some of the world's largest mineral deposits (Bailie and Robb, 2004; Finn et al., 2015; Zeh et al., 2015). Despite decades of research, its origin is still debated (Kinnaid et al., 2004; Zeh et al., 2015). Although recent work by Zeh et al. (2019) on the origin of the Rustenburg Layered Suite has made a significant contribution, the origin of the granites remains poorly understood. The Lebowa Granite Suite of the Bushveld is the largest A-Type batholith on Earth. It is subdivided into various facies that includes the coarse-grained Nebo, Bobbejaankop, and Makhutso granites, and the fine-grained Klipkloof and Lease granites (De Waal, 1972; Lenthall and Hunter, 1977; Robb et al., 2000; Crocker et al., 2001; Kinnaid et al., 2004).

The Makapansberg escarpment, part of the Northern Limb of the Bushveld Igneous Complex, is known for tin mineralization, particularly within the Zaaipplaats tin fields (Figure 2.1) (Lenthall and Hunter, 1977; Robb et al., 2000; Crocker et al., 2001). The Lebowa Granite Suite is host to polymetallic magmato-hydrothermal, endo- and exogranitic deposits, including the notable, world-class, Vergenoeg fluorite mine (Robb et al., 2000; Crocker et al., 2001). Cassiterite mineralization was discovered in 1908 in the roof of the Bobbejaankop and in the Lease granites and, soon after, two mines were established by the Zaaipplaats Tin Mining Company, on the farms of Groenfontein and later Zaaipplaats (Figure 2.2) (Falcon, 1985; Crocker et al., 2001). Approximately 37,079 tons of tin were produced before the closure of the Zaaipplaats tin field in 1989 (Falcon, 1985; Crocker et al., 2001). Cassiterite mineralization is hosted as low-grade disseminations, pods and unique, large, and remarkably mineralized hydrothermal pipe- and lens-shaped ore-bodies (Strauss and Truter, 1944; De Waal, 1972; Coetzee, 1984; Von Gruenewaldt and Strydom, 1985; Coetzee and Twist, 1989; Pollard et al., 1989; Pollard et al., 1991b).

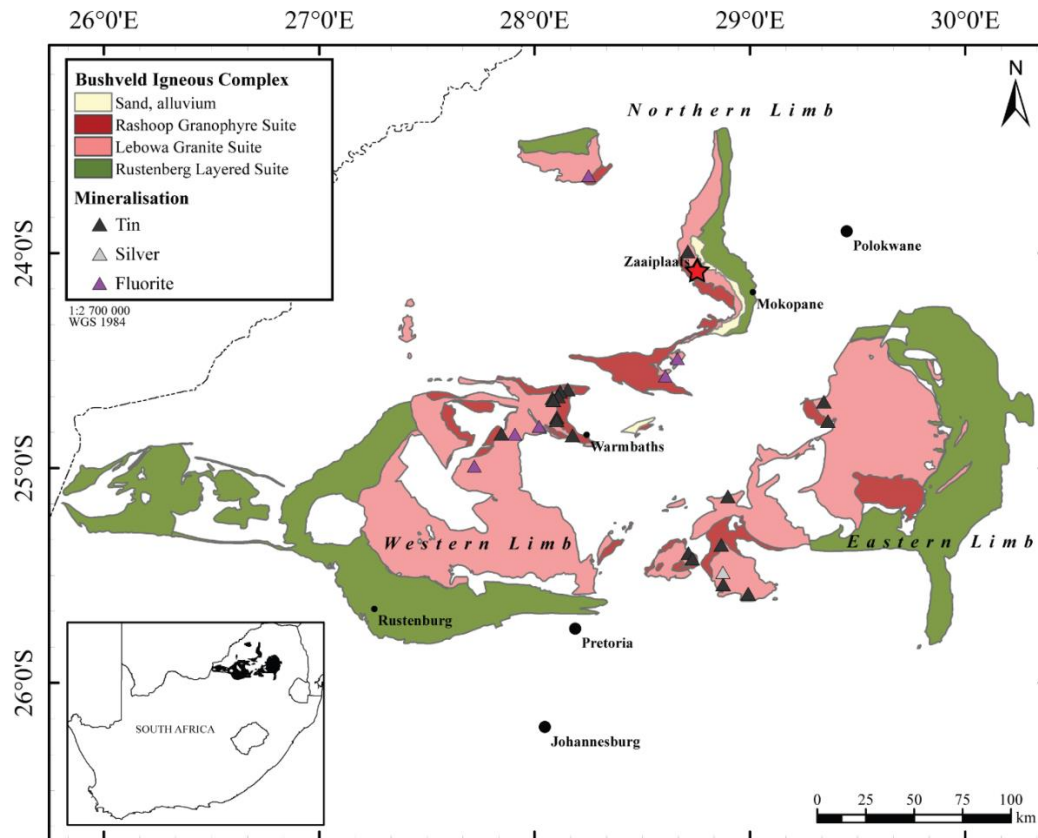


Figure 2.1. Simplified geological map of the Bushveld Igneous Complex showing the location of the Zaaiplaats tin field (red star) with other occurrences of tin, silver, and fluorite mineralization. Adapted from Hunter (1975).

Various petrogenetic models for the formation of the granites and hydrothermal features of the Zaaiplaats tin field have been suggested. The Nebo granite was suggested to be the result of fractional crystallization from a bulk Nebo parent (Kleemann, 1985; Coetzee and Twist, 1989; Kleemann and Twist, 1989; Hunt, 2005). However, this model has subsequently been contested. For example, Hill et al. (1996), suggested the formation of the granites from the partial melting of the Archean basement during the emplacement of the mafic to ultramafic Rustenburg Layered Suite. This resulted in multiple episodic ascending batches of siliceous melt. Wilson et al. (2000) also proposed several different magmatic pulses that are petrographically, geochemically, and geophysically similar, yet distinct. The Bobbejaankop granite was suggested to be a metasomatised roof of the Nebo granite (McCarthy and Fripp, 1980; Kleemann and Twist, 1989; McNaughton et al., 1993; Hill et al., 1996; Wilson et al., 2000; Kinnaird et al., 2004), whereas other models maintain that the Bobbejaankop granite was produced by fractional crystallization of the underlying Nebo granite (McCarthy and Fripp, 1980; Pollard and Taylor, 1986; Pollard et al., 1991b; McNaughton et al., 1993; Hill et al., 1996).

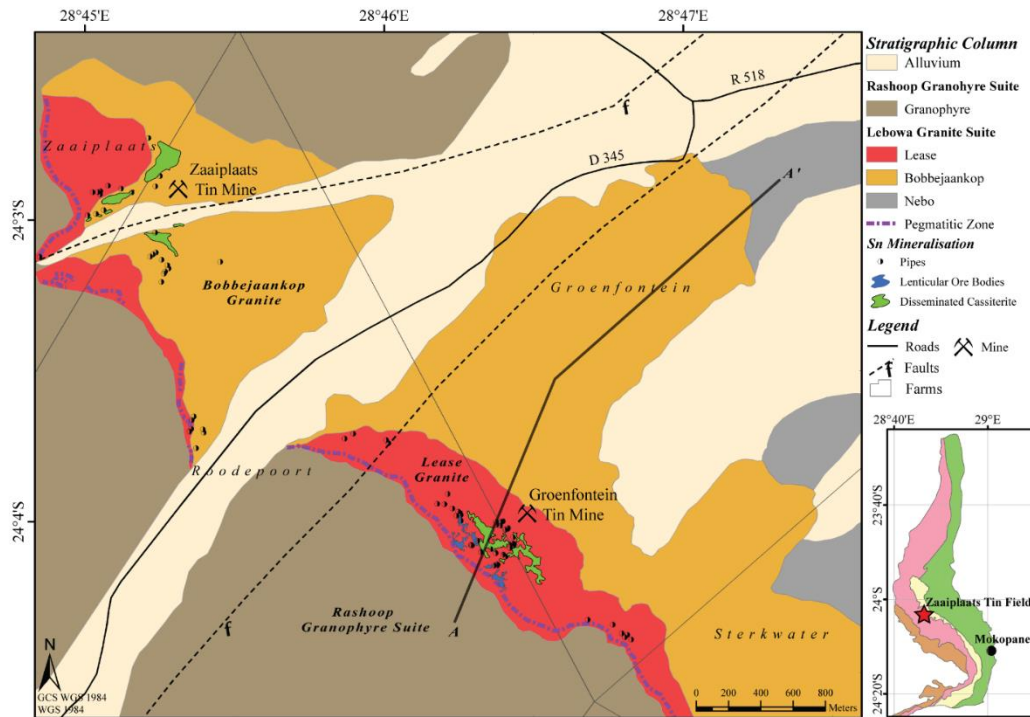


Figure 2.2. Revised geological map of the Zaaipplaats tin field. Lithological boundaries, disseminated mineralization, hydrothermal pipes and lenticular ore-bodies were validated by the integration of published geological maps and extensive field mapping (Strauss, 1954; Coetzee, 1984). Lithological nomenclature is based on SACS (1980). Cross section, shown in Figure 2.3, is along the line A–A'. The bottom right insert shows the location of the Zaaipplaats tin field (red star) on the Northern Limb of the Bushveld Igneous Complex. The lithological units are the same as in Figure 2.1.

The Lease granite was originally interpreted as a chilled margin to the Bobbejaankop granite, implying that it crystallized before the latter, although this concept has now been discarded (Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1986; Pollard et al., 1991b; Crocker et al., 2001). Strauss and Truter (1944) then proposed that the Lease granite formed as a post-reaction product from the accumulation of volatiles along the roof of the Bobbejaankop granite (Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1986; Pollard et al., 1991b; Crocker et al., 2001). Alternative models suggest that the Lease granite resulted from quenching, induced by the fracturing of the volcanic roof rocks, or that the Bobbejaankop and Lease granites were produced by the local metasomatism of various types of Klipkloof granites (McCarthy and Fripp, 1980; Kleemann and Twist, 1989; Pollard et al., 1991a; Pollard et al., 1991b). However, most of the research conducted on understanding these granites has been focused on the Zaaipplaats tin mine, which is on the northern edge of the intrusion. Thus, since Strauss (1954) and the closure of the Groenfontein tin mine in the early 1930s, the main body of the Bobbejaankop and Lease granites has been more or less neglected. Therefore,

this study is focused at Groenfontein, with the aim of defining the petrogenetic relationship between the Lease and the Bobbejaankop granites, and to explain their origin and mineralization.

2.2.2. Regional Geology

The Groenfontein tin mine is situated 30 km northwest of Mokopane and 2 km southeast of the Zaaipplaats tin mine (Figure 2.2). A sequence of sheeted granites comprise the majority of the region; the Nebo granite which is overlain by the Bobbejaankop and Lease granites, respectively. These granites are capped by the Rashoop Granophyre Suite and the entire sequence dips conformably between 10° and 15° westward (Figures 2.2 and 2.3) (Strauss and Truter, 1944; McNaughton et al., 1993; Crocker et al., 2001). The Nebo granite is a 1.5 to 2.5 km thick sheeted granitic intrusion, composed of equigranular quartz, perthitic alkali-feldspar, hornblende, and biotite (Kleemann and Twist, 1989; Pollard et al., 1991b; Hill et al., 1996; Crocker et al., 2001; Kinnaird et al., 2004). The Nebo progressively evolves from a grey, coarse-grained, mesocratic hornblende-bearing granite at its base, to a finer-grained, pinkish-red biotite granite in its roof facies within the Zaaipplaats region (Kleemann and Twist, 1989; Hill et al., 1996; Kinnaird et al., 2004). The Bobbejaankop granite is characterized as a brick-red, coarse-grained facies that is primarily composed of alkali-feldspar and synneusis-textured quartz, forming linked aggregates. It has variably chloritized biotite and miarolitic cavities, which are occasionally filled with cassiterite and minor tourmaline (McCarthy and Fripp, 1980; Coetzee, 1984; Kleemann and Twist, 1989; Pollard et al., 1991b; McNaughton et al., 1993; Kinnaird et al., 2004).

The Lease granite is a relatively thin (120 m thick), lenticular sheet that is restricted to the roof of the Bobbejaankop granite, beneath the Rashoop Granophyre Suite (Figure 2.3). The Lease granite is described as a metasomatically altered red microgranite, exhibiting pervasive sericitic alteration in feldspars, extensive chloritization of biotite, patches of epidotization, and zones of disseminated cassiterite (Strauss and Truter, 1944; Coetzee, 1986; Pollard et al., 1991b; Crocker et al., 2001; Kinnaird et al., 2004). The mineralization at Groenfontein is confined to the upper 20 m of the Lease granite, 3 to 10 m below the contact pegmatite (Figure 2.3) (Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1984; Coetzee and Twist, 1989; Pollard et al., 1991b; Crocker et al., 2001; Kinnaird et al., 2004). These discontinuous lensoidal pegmatites are 2 to 5 m in length and have been used to demarcate the otherwise cryptic

contact between the Lease granite and the Rashoop Granophyre Suite. The pegmatite lenses are usually unmineralized and primarily composed of pegmatitic quartz and reddened feldspars. Cassiterite is typically disseminated, although it does occur as small clusters and within lenticular and pipe-like ore bodies (Figure 2.3) (Strauss and Truter, 1944; Coetzee, 1986; Coetzee and Twist, 1989; Crocker et al., 2001). The mineralization at Zaaiplaats occurs dominantly as cassiterite with accessory scheelite, sulfides, fluorite, and molybdenite, compared to Groenfontein, which is mainly cassiterite, with minor scheelite, and molybdenite (Strauss and Truter, 1944; Coetzee, 1986; Coetzee and Twist, 1989; Pollard et al., 1991b; Crocker et al., 2001).

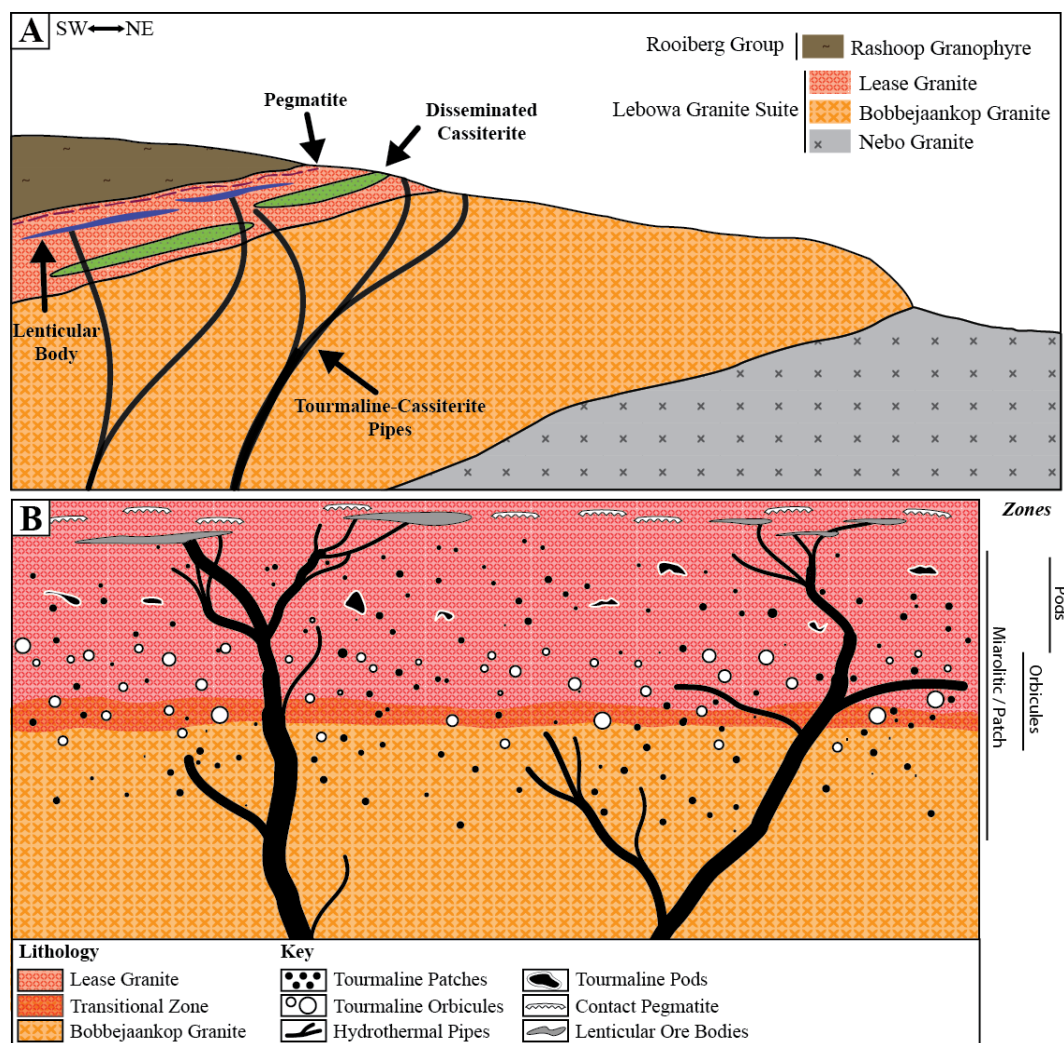


Figure 2.3. Schematic geological cross sections across the Groenfontein tin mine. (A) Schematic cross section from the Rashoop Granophyre Suite towards the Nebo granite (SW to NE) along line A–A' shown in Figure 2.1. (B) Schematic representation of a vertical cross section through the Lease and Bobbejaankop granites (NW to SE). A transitional zone rather than a sharp contact between the Bobbejaankop and Lease granites is suggested. The zones where the various types of tourmaline features occur are represented by the bars on the right side of the diagram.

2.2.3. Petrography and Field Relationships

The network of hydrothermal pipes and lenticular ore-bodies have been comprehensively discussed in a number of publications (Söhnge, 1944; Strauss and Truter, 1944; Strauss, 1954; Von Gruenewaldt and Strydom, 1985; Pollard et al., 1989; Pollard et al., 1991b; McNaughton et al., 1993; Crocker et al., 2001). Therefore, these features are only briefly described here.

The contact between the Nebo and Bobbejaankop granites is marked by an upward gradational reddening of the feldspars and increasingly aggregated quartz. This gradation is almost imperceptible, as the contact zone occurs over several meters and is marked by a subtle break in slope. The nature of the obscure contact is corroborated by observations made by Strauss and Truter (1944), Strauss (1954) and Coetzee (1984). The Bobbejaankop granite forms an elongated sheeted intrusion, extending from the middle of the farm Zaaiploots 223 KR in the northwest, towards the southeast along the strike of the Northern limb (Figure 2.2). It extends from Roodepoort 222 KR through Groenfontein 227 KR, before terminating along the boundary of Sterkwater 296 KR and Solomons Temple 230 KR.

The Bobbejaankop granite is typically composed of subhedral quartz (0.5 to 3 mm, 35%) with sub- to anhedral alkali-feldspar (0.5 to 6 mm, 35%) and plagioclase (<0.1 to 0.5 mm, 25%), as well as extensively chloritized, interstitial magmatic biotite (<0.1 to 1 mm, <5%). The quartz grains are transparent, granular, hypidiomorphic and typically display synneusis-textures, for which the Bobbejaankop is well known. Small (<0.1 mm) feldspar and chlorite inclusions are a common feature within the quartz grains. The perthitic feldspars of the Bobbejaankop granite are remarkably turbid in the thin section. The perthite (0.5 to 3 mm) exhibits randomly distributed irregular patches (<0.1 to 1 mm) of exsolved plagioclase, delineated by a diffuse contact zone between the two species (Figure 2.4A). The exsolution of plagioclase within the host alkali-feldspar exists as patch, chessboard, and veined variants (Figure 2.4B). The plagioclase exhibits polysynthetic twinning and is selectively sericitized (Figure 2.4). Microclinized feldspars become brick-red, which is considered a result of hematitic coating by the exclusion of Fe from the feldspar (Figure 2.4A). This is accomplished during the crystallographic reordering of the feldspar lattice during deuteric sub-solidus microclinization, allowing the precipitation of Fe, which then lined microcavities within the feldspars as hematite (Putnis, 2002; Putnis et al., 2007). Plagioclase is selectively sericitized

within the perthites by a very fine-grained pale green/white micaceous aggregate. Sericitization has replaced feldspar, biotite, and chlorite, in the upper facies of the granite.

Essentially, all magmatic biotites (<0.1 to 1 mm) are extensively chloritized and partially stained red from the exclusion of Fe along the mineral boundaries and cleavages. Relict brown magmatic biotites are visible within the dark-green/brown chlorite (Figure 2.5A). Small anhedral grains of quartz, feldspar, and purple fluorite are intergrown with, and form inclusions within, the chlorite (Figure 2.5B). Chloritization of the biotite and feldspars increases towards the Lease granite. Mirolitic cavities (0.5 to 5 cm) are common and typically filled with small clusters of intergrown spherulitic tourmaline and quartz (Figure 2.6). These cavities are scattered throughout the upper facies of the Bobbejaankop granite, although concentrated proximal to larger pipes. Some mirolitic cavities display a unidirectional solidification texture of quartz, reddened feldspars, fluorite, and calcite (Figure 2.5B). Fluorite is ubiquitous in the Bobbejaankop granite as inclusions in quartz and feldspar, within mirolitic cavities and interstitially. It is typically purple, with lesser transparent, white, and green varieties. Tourmaline within the Bobbejaankop granite primarily occurs as orbicules and in hydrothermal pipes, although it is also present in mirolitic cavities. Tourmaline-bearing mirolitic cavities comprise a central zone of calcite, subhedral cassiterite and fluorite, surrounded by a radial blue/green to brown tourmaline (Figure 2.6).

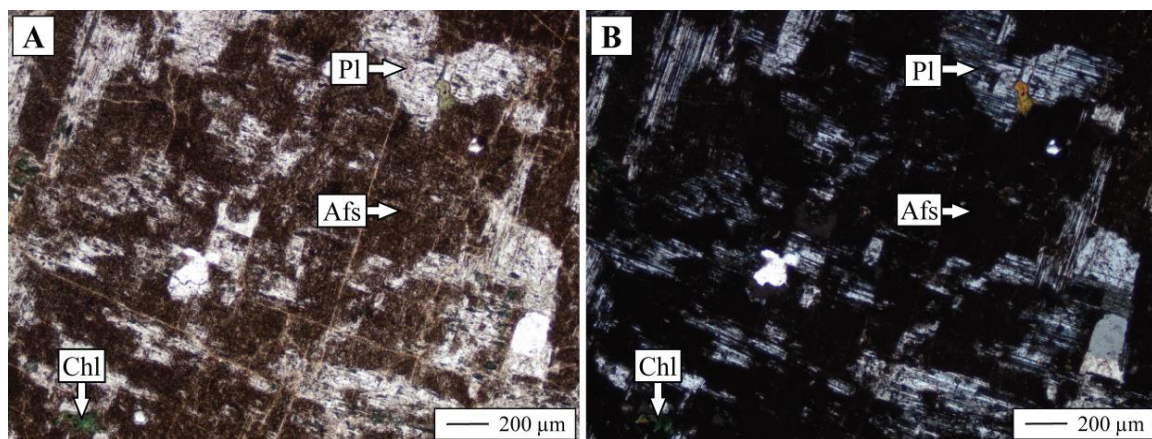


Figure 2.4. Photomicrographs of the Bobbejaankop granite. **(A)** PPL image of patch perthite. Within the perthite there are red alkali-feldspars (Afs), with patches of plagioclase (Pl) exsolution, which follows no apparent crystallographic orientation. Chlorite (Chl) is seen selectively replacing plagioclase within the perthite grain. **(B)** XPL image of (A), depicting the polysynthetic twinning of the plagioclase exsolution within the perthite.

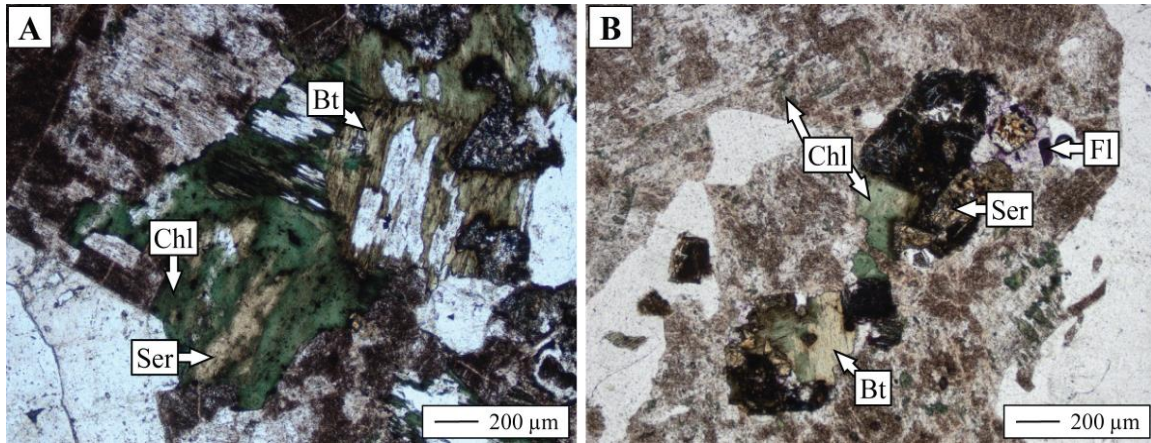


Figure 2.5. Photomicrographs of the Bobbejaankop granite. (A) PPL image of interstitial magmatic biotite (Bt) exhibiting chloritization (Chl) followed by sericitization (Ser). (B) PPL image of the intergrowth of biotite with fluorite (Fl) within a miarolitic cavity that was subsequently chloritized and sericitized.

Ilmenite and sulfides (0.5 to 1.5 mm) such as pyrite and chalcopyrite with lesser arsenopyrite are uncommon, although, where they do occur, they are associated with chloritization. The paragenetic sequence of the sulfides is suggested as early arsenopyrite, followed by pyrite and later chalcopyrite. Cassiterite is uncommon in the Bobbejaankop granite at Groenfontein and is restricted to tourmaline-bearing miarolitic cavities. Minor subhedral 100 μm-sized zircons are associated with biotite. Most miarolitic cavities appear to have experienced various stages of hydrothermal alteration, with a suggested sequence of microclinization, chloritization, sericitization then hematization.

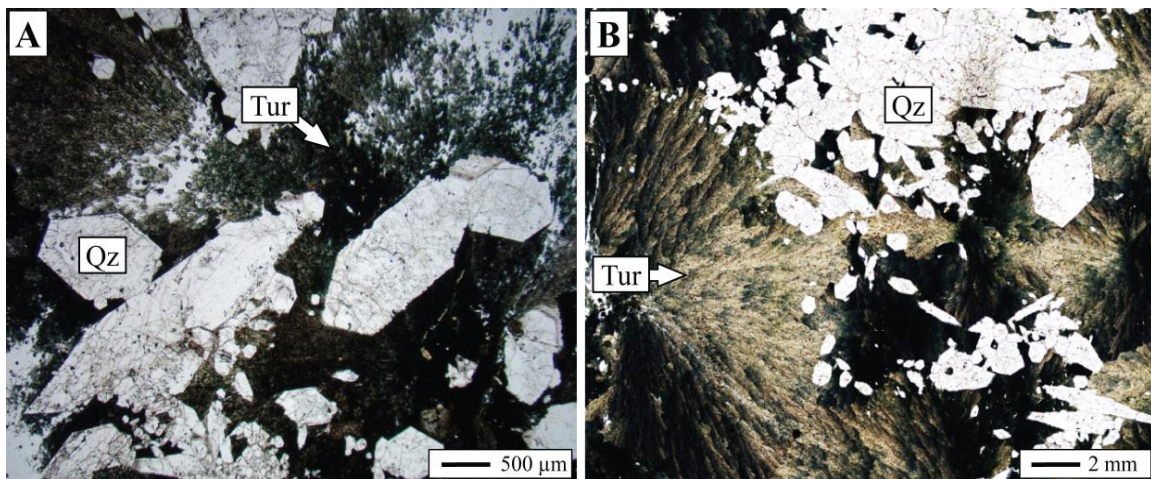


Figure 2.6. Photomicrographs from the Bobbejaankop granite. (A) PPL image of a tourmaline-quartz vug exhibiting acicular brown/green tourmaline (Tur) intergrown with euhedral quartz (Qz). Doubly terminated quartz crystals occur within these vugs. (B) PPL image of a tourmaline-quartz vug showing radial blue/brown tourmaline with euhedral quartz.

Towards its upper contact, the Bobbejaankop granite exhibits features characteristic of the Lease granite, such as an increase in microclinization, chloritization, sericitization, granophyric intergrowths, and fluorite. A radial granophyric texture forms around the edges of the larger feldspar grains, becoming finer-grained and increasingly intergrown with perthite. The pervasive microclinization, associated with the hematization of feldspars, resulted in a purple/maroon coloration (Figure 2.7).

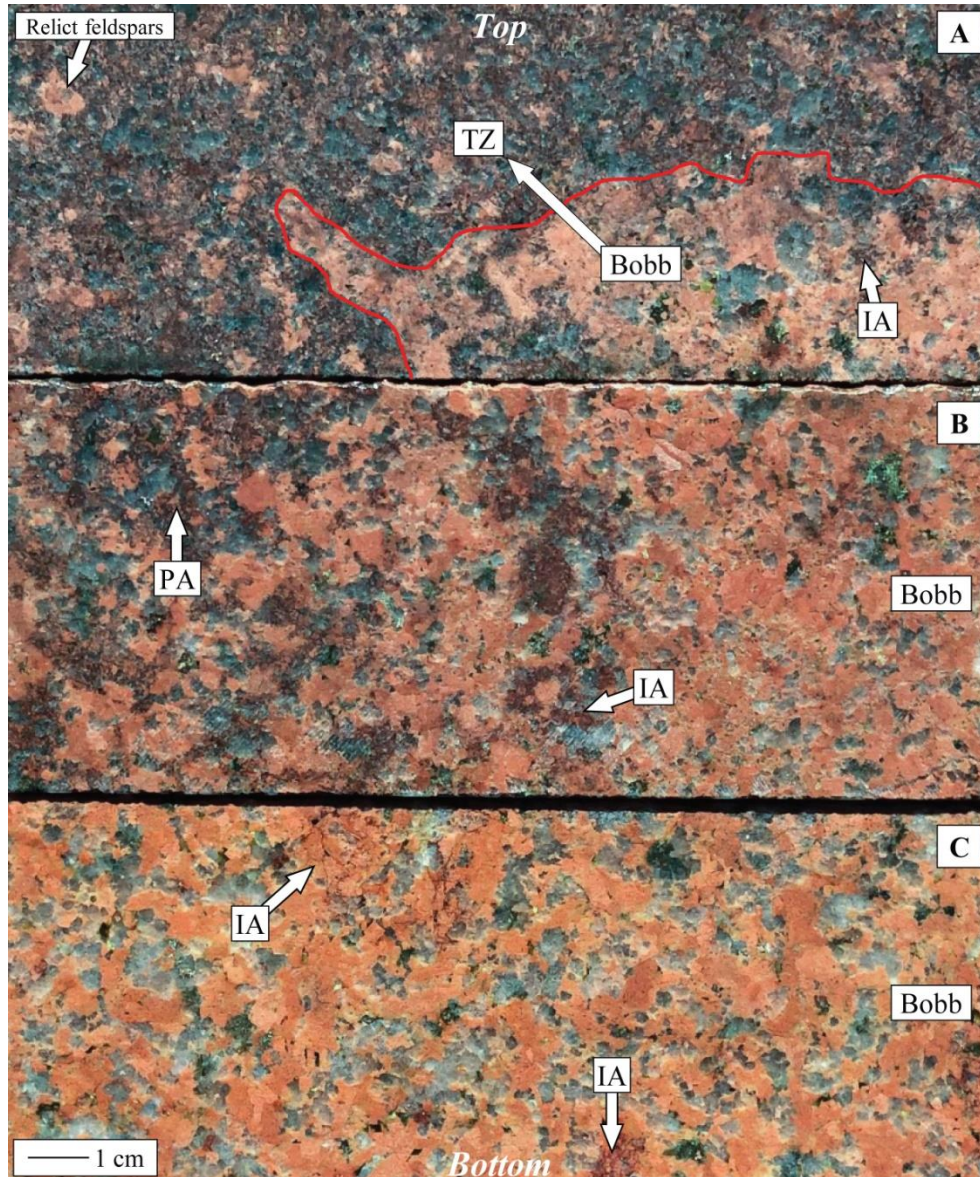


Figure 2.7. A collage of images of core from the top of the Bobbejaankop granite into the transitional zone. (A) Pink Bobbejaankop granite (Bobb) altering into the transitional zone (TZ). Selective microclinization of the feldspars is present as a maroon incipient alteration (IA) within the pink Bobbejaankop granite. However, from the transitional zone it is present as pervasive alteration (PA). (B) Brick-red Bobbejaankop granite exhibits patches of selective incipient microclinization that become pervasive towards the upper contact. (C) Typical Bobbejaankop granite towards the bottom of the core, showing minor incipient purple patches of microclinization.

Initially, microclinization selectively affected the feldspars, however, towards the Lease granite, the alteration gradually destroys the synneusis-textured quartz and increased granophyric intergrowths, resulting in an overall reduction in grain size (Figure 2.7). Although the contact between the Bobbejaankop and Lease granites has been described as sharp (Strauss, 1954; Coetzee, 1984; Coetzee, 1986; Crocker et al., 2001), it appears to be gradational over 0.5 to 4 m. As microclinization intensified, quartz synneusis was replaced by granophyric intergrowths and grain-size was reduced within the Bobbejaankop granite as it grades imperceptibly into the fine-grained Lease granite (Figure 2.7).

The Lease granite is heterogeneous, alternating between fine- and coarse-grained, and between a dull-red, pale-green, and a maroon-purple facies with no obvious systematic control (Figure 2.8). Overall it is typically finest-grained in its roof facies (<0.5 mm) and coarsest at the base (1 to 2 mm). However, differences in grain size, color, and mineralogy provide a basis for the distinction of three facies of Lease (Table 1). The transitions between these types are either sharp or gradational and occasionally meet at a nexus (Figure 2.8). The mineralogy varies depending on the facies of Lease granite, however, it is characteristically composed of hypidiomorphic quartz and red feldspars with variable amounts of chlorite, biotite and fluorite. Quartz-lined miarolitic cavities (2 to 10 cm) are composed of calcite, white-purple fluorite, and, occasionally, large euhedral cassiterite (0.1 to 2 cm) with minor tourmaline.

Table 1. Mineralogical variations in the different facies of Lease granite.

Type	Color	Grain Size	Mineralogy	Alteration	Mineralization	Description
1	Red	<0.2 to 0.5 cm	Quartz and reddened feldspars, minor chlorite and biotite	Microclinization and chloritization	Minor cassiterite within miarolitic cavities	Typical appearance of the Lease granite. Generally coarser-grained at the base and finer in the roof facies.
2	Maroon	<0.1 to 0.5 mm	Increased fluorite, epidote, miarolitic cavities, and chloritization of biotite	Increased microclinization, chloritization, and epidotization	Disseminated cassiterite hosted in miarolitic cavities	Finest-grained facies of the Lease granite. Associated with disseminated cassiterite
3	Green	<0.2 cm	Increased quartz, chlorite, sericite, and tourmaline	Greater degree of greisenization	Minor cassiterite present in cavities and dissemination	Similar mineralogy and grain size to Type 1 although has greater greisenization resulting in the green tinge. This facies usually exists as an alteration halo around pipes

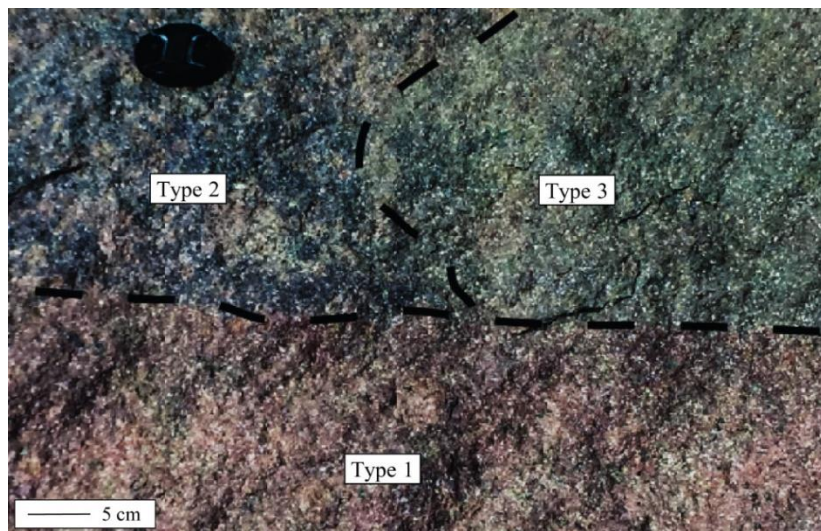


Figure 2.8. Surface features of the three Lease granite variants.

Type 1 is the most abundant, and can be considered the typical, “baseline” Lease granite. Typical Lease is brick-red, fine-grained, and composed of sub- to anhedral graphically intergrown quartz and perthite (Figure 2.9A). Quartz has lost its synneusis texture, becoming fine-grained, more rounded and anhedral (0.2 to 1.2 mm, 35%) (Figure 2.9). The feldspars become more turbid and redder than in the Bobbejaankop granite, with the alkali-feldspar (0.5 to 1 mm, 35%) and plagioclase grains (<0.2 mm, 20%) becoming smaller and increasingly altered. Biotite is larger (0.5 to 1 cm, 8%) than in the Bobbejaankop granite and typically interstitial, sub- to anhedral, and extensively chloritized with subsequent sericitization (Figure 2.9D). The exclusion of Fe and Ti from the biotite during chloritization results in reddening of the mineral edges and rutile crystallization within the chlorite (Figure 2.9D). Interstitial subhedral fluorites (0.1 to 0.4 mm, 1%) are more common, with lesser amounts of epidote and calcite (0.1 to 0.4 mm, <1%). Feldspars exhibit patch, snowball, and chessboard exsolution textures and are highly sericitized. The zones of granophyric intergrowth are purely quartz and feldspar with few interstitial or included phases. Mirolitic cavities are common in these facies of the Lease, with amygdales composed of calcite and inward-projecting euhedral quartz and feldspars. Small (<10 μm) inclusions of chloritized biotite and fluorite are present within quartz and perthite. (Figures 9C and 9D).

Miarolitic cavities are common within the Type 1 Lease, particularly proximal and parallel to the Bobbejaankop contact and roof. Cross-cutting calcite veins are associated with a minor sulfide assemblage of pyrite and lesser chalcopryrite. Miarolitic cavities are typically

surrounded by a 1 to 1.5 cm wide zone of highly sericitized granophyric quartz and perthite. Approximately 5 m above and parallel to the Bobbejaankop–Lease contact, there is a 1 m thick zone of circular, tourmaline orbicules (1 to 20 cm), comprising a melanocratic tourmaline-quartz core surrounded by a halo of leucocratic quartz-tourmaline with minor cassiterite, fluorite and calcite.

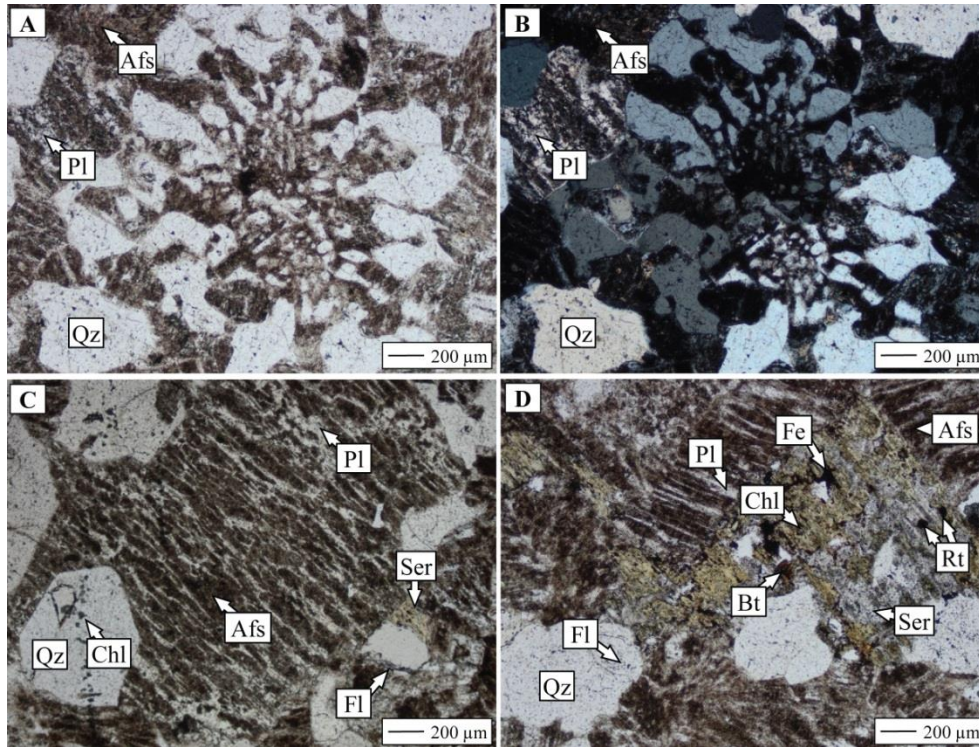


Figure 2.9. Photomicrographs from the Lease granite. (A) PPL image of granophyric texture of the Lease granite. (B) XPL image of alkali-feldspar (Afs), showing the granophyric overprinting of larger quartz (Qz) grains, which are optically continuous. The plagioclase (Pl) exsolution within the perthite exhibits selective replacement by sericite. (C) PPL image showing veined exsolution of perthite and multiple small chlorite (Chl) inclusions within quartz and a miarolitic cavity filled with sericite (Ser) and fluorite (Fl). (D) PPL image showing chloritized, and later sericitized, interstitial biotite (Bt). Iron-staining (Fe) coats the edges of the chloritized biotite and small growths of rutile (Rt) are present. Small fluorite inclusions are scattered within the quartz and perthites.

Type 2 Lease granite is a maroon/purple variety, mineralogically similar to Type 1, although exhibiting a distinct decreased grain size (<0.1 to 0.5 mm), increase in microclinization, granophyric texture, and accessory fluorite. Granophyric quartz displays an optical continuity that delineates much larger grains (Figure 2.9B). Increased microclinization and hematization of the feldspars produced a maroon appearance, which was subsequently overprinted by chloritization then sericitization. Accessory ilmenite and sulfides, associated with biotite alteration, including pyrite and chalcopyrite (0.2 to 0.3 mm), are more abundant than in the Bobbejaankop granite. Cassiterite is red-brown, medium-grained (0.5 to 0.7 mm), sub- to

euohedral and rarely shows zonation. It occurs within miarolitic cavities as inclusions, and it appears to have exsolved during chloritization, alongside sulfides, decorating relict biotite cleavage. These exsolutions amalgamate on the mineral edges, forming euohedral crystals (Figure 2.10).

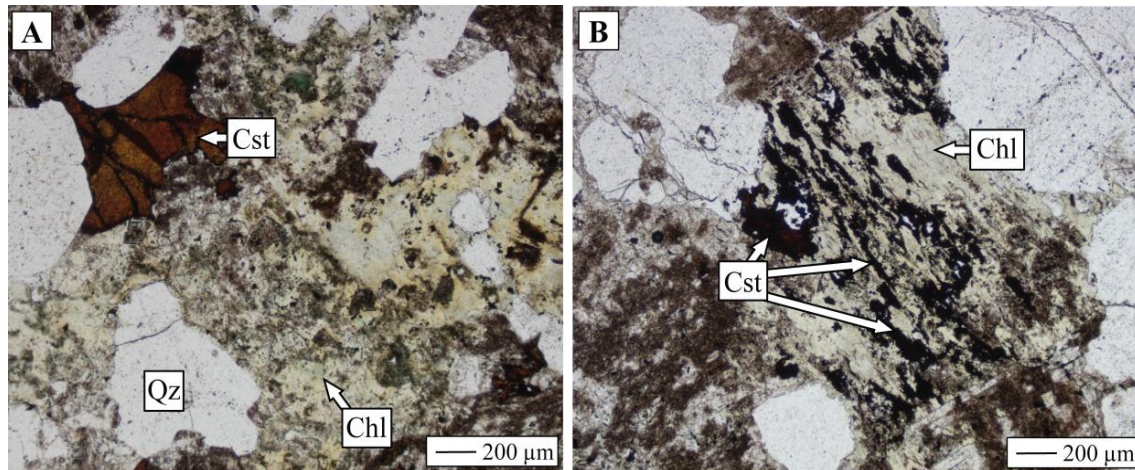


Figure 2.10. Photomicrographs from the Type 2 Lease. **(A)** PPL image of an anhedral cassiterite (Cst) grain associated with extensively chloritized (Chl) biotite surrounded by perthite and quartz (Qz). **(B)** PPL image showing the exclusion of Sn along the cleavages of the chloritized biotite, which accumulated into discrete grains of cassiterite along the periphery of the chlorite.

Type 3 is the pale green facies of the Lease granite that is restricted to zones of extensive sericitization, particularly surrounding pipe-like and lenticular bodies. This facies is similar to Type 1, however there is a notable increase in pervasive over-printing of sericitization and, to a lesser extent, silicification. Perthites are extensively digested with only skeletal perthites remaining (Figure 2.11A, B). Plagioclase is replaced by very fine-grained white mica, quartz, and fluorite, leaving the anhedral, reddened alkali-feldspars in a fine-grained greisenized groundmass. Microcrystalline or fine-grained anhedral quartz appears to have replaced the original quartz grains within and surrounding the relic feldspar grains, retaining their graphic texture. Tourmaline within this facies is more prominent, and displayed as incipient tourmalinization of feldspars that has produced nests and interlocking fans of acicular radiating blue-green tourmalines (Figure 2.11C, D). These tourmaline nests are intergrown with white mica and quartz within miarolitic cavities and occasionally host euohedral cassiterite (Figure 2.11D).

The roof of the Lease granite is poorly exposed and demarcated by a zone of discontinuous, laterally extensive pegmatites which are interfingered with Type 1 Lease (Figure 2.2). These irregularly shaped, lensoidal pegmatites are 5 m below the Rashoop Granophyre Suite contact

and range from 1 × 5 cm to 0.05 × 0.7 m in size. They are composed of pegmatitic quartz and red feldspar, exhibiting perpendicular growth inwards from the roof and base, indicative of a unidirectional silicification texture (UST). Subhedral biotite, variably coloured fluorite, and calcite are commonly interstitial phases. Söhnge (1944) recorded mineable occurrences of cassiterite and scheelite, but these were not observed in the present study.

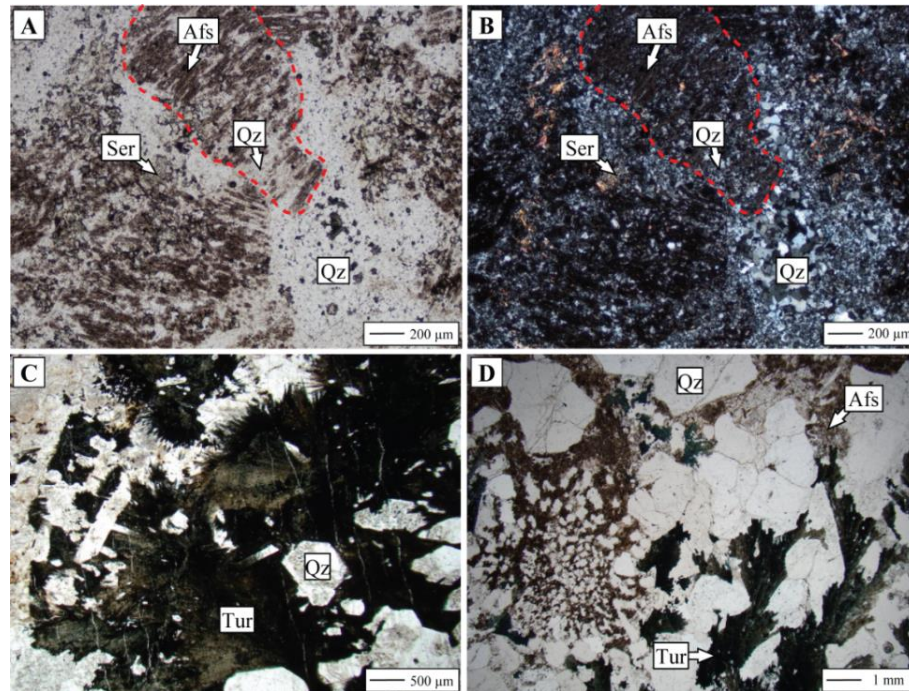


Figure 2.11. Photomicrographs from Type 3 Lease granite. (A) PPL image showing the complete replacement of the plagioclase component of a perthite by greisenization, leaving behind patches of sericite (Ser) and skeletal alkali-feldspars (Afs). (B) An XPL image of (A) illustrating the extent of greisenization experienced by the primary mineral assemblage. The relict perthite is outlined in red. (C) A PPL image of a miarolitic cavity within the Lease granite hosting tourmaline (Tur) and doubly terminated quartz (Qz). (D) A PPL image from Type 2 showing the pervasive and destructive tourmalinization of the alkali-feldspars resulting in the growth of radial blue/green tourmaline.

Cassiterite Mineralization

There are three styles of mineralization within the Zaaiplaats tin fields: disseminated miarolitic zones, tourmalinized–greisenized hydrothermal pipes and lenticular ore bodies. The 600 m long, 15 to 30 m wide zones of disseminated mineralization at Groenfontein are hosted within Type 2 Lease granite, 20 to 40 m below the contact pegmatite. However, at Zaaiplaats mineralization is hosted in both the upper Bobbejaankop and lower Lease granites. Cassiterite in the low-grade disseminated zones occurs in various coexisting styles: (1) free euhedral cassiterite crystals that appear to occur interstitially and to have replaced quartz; (2) sub- to anhedral cassiterite which are associated with the chloritization of biotite and

subsequent sericitization of the chlorite; and (3) clusters of euhedral cassiterites within miarolitic cavities (1 to 3 cm) surrounded by euhedral quartz and red feldspars.

The majority of the cassiterite was mined from an anastomosing network of high-grade greisenized, pipe-like and lenticular ore bodies (Strauss, 1954; Arth, 1976; Coetzee, 1984; Coetzee, 1986; Coetzee and Twist, 1989; Crocker et al., 2001). The grades of these pipes ranged between 10% and 70%, with rare occurrences of up to 80% cassiterite in offshoots. The swarms of hydrothermal pipes radiate upwards through the Bobbejaankop, terminating into lenticular ore bodies in the upper facies of the Lease granite. The pipes shrink from 25 to 3 m wide in the Bobbejaankop to 5 to 1 m within the Lease granite. The pipe swarms stem from a single, larger pipe and share a common plunge towards the northwest (Strauss and Truter, 1944; Crocker et al., 2001). These hydrothermal pipes are composed of three parts: (1) a core of almost pure sericite that contains up to 60% to 80% cassiterite (Strauss and Truter, 1944; Crocker et al., 2001); (2) an annular melanocratic zone composed of radial and botryoidal tourmalines, intergrown with anhedral quartz and minor feldspar; and (3) a thin (1 to 5 cm) white quartz rim. There is a halo (2 to 15 cm) of highly hematized feldspars and silicification of the surrounding granite.

The lenticular ore-bodies are inaccessible as they were mined out and backfilled but detailed descriptions can be found in Kynaston et al. (1909), Söhnge (1944), Strauss (1954), and Coetzee (1984). These lenses are 5 m below and contiguous to the contact pegmatite and although similar are distinctly different from the pipes (Kynaston et al., 1909; Strauss, 1954; Crocker et al., 2001). The main ore grade is recorded between 30% to 70% cassiterite hosted in a highly greisenized groundmass composed of sericite, cassiterite, chlorite, fluorite and pyrite similar to the pipes, although distinctly tourmaline-poor (Strauss and Truter, 1944; Pollard et al., 1991b; Crocker et al., 2001). The Lease granite, below these lenses, shows an increased dissemination of fluorite and cassiterite (0.5% to 2%) that was mined alongside these bodies. In order to determine the petrogenetic relationship between the Lease and Bobbejaankop granite, and to get a better constraint on their formation and mineralization, a number of geochemical analyses were undertaken to complement the petrographic descriptions and contact relationships described.

2.2.4. Methods and Materials

Whole-rock geochemical analyses were undertaken using the Norrish Fusion (Norrish and Hutton, 1969) technique with in-house correction procedures and using a Panalytical PW2404 X-ray fluorescence (XRF) spectrometer at the Earth Lab of the University of the Witwatersrand, Johannesburg (Appendix C). Samples for XRF majors and ICP-MS traces were prepared and run according to standard procedures using methodology outlined in Wilson (2012). Samples were crushed in a carbon-steel jaw crusher and milled by a carbon-steel swing mill. Major elements were fused using Johnson Matthey Spectroflux 105 at 1100 °C, and raw data corrected using in-house software. Standard calibrations were made using synthetic oxide mixtures and international standard rocks as well as in-house controls. Calibration standards were primary International Reference Materials USGS series (USA) and NIM series (South Africa). Trace elements were determined using the Perkin Elmer DRC-e inductively coupled plasma mass spectrometer (ICP-MS), and analyzed against certified primary solution standards. International reference materials AGV-2, BCR-1 and BR-1 were analyzed with every run, ensuring the reliability of the data. Of the forty five samples collected in situ, five were of Nebo granite, sixteen of Bobbejaankop granite, twenty of Lease granite, and four of the Transitional Zone. Due to a large degree of overlap, the geochemical data obtained from both the Zaaiplaats and Groenfontein samples are combined under the broader category of “Zaaiplaats tin field”. The geochemical data of the samples from their respective mines can be found in Appendix C. The historical data of the Nebo granite have been compiled from various parts of the Lebowa Granite Suite, while the Bobbejaankop and Lease granites were sampled specifically from the Zaaiplaats tin mine (Kleemann and Twist, 1989; Pollard et al., 1991a; Hill et al., 1996; Labuschagne, 2004).

2.2.5. Results

Whole Rock XRF and ICP-MS

The granites of the Zaaiplaats tin field have a typical granitic composition, ranging from SiO_2 = 74.22% to 77.35 %, TiO_2 = 0.05% to 0.14 %, Al_2O_3 = 10.99% to 12.85 %, $\text{FeO}^{(\text{tot})}$ = 0.96% to 3.95 %, with a relatively high alkali content of Na_2O = 0.90% to 3.09 %, K_2O = 4.57% to 6.3 %, variable CaO and low MgO (Figure 2.12). These ferroan alkali granites exhibit the weakly peraluminous characteristic of A-type granites, with an A/CNK between 0.95 and 1.33, plotting with other global mineralized and unmineralized A-type granites (Figure 2.13)

(Juniper and Kleeman, 1979; Frost and Frost, 2011; Singh and Vallinayagam, 2012; Li et al., 2014; Gao et al., 2016; Jiang et al., 2016; Zhou et al., 2017).

The trace element differentiation index (TEDI, $(Ba \times Sr)/Rb$) (Walraven, 1986; Bailie and Robb, 2004) has proved to be useful as a fractionation proxy and in distinguishing the various granite facies of the study area (Figure 2.12). The TEDI defines a progressive fractionation trend from the Nebo, through Bobbejaankop to Lease granite (Figure 2.12). The major element compositions of the Bobbejaankop and Lease granites are comparable, and distinct in terms of alkali and incompatible element enrichment to the Nebo granite (Figure 2.12E–G).

The Bobbejaankop and Lease granites are enriched in Si, Li, Sn, Cu, and Th and depleted in Ti, Al, Fe, and Na compared to the Nebo granite (Figure 2.12). The CaO content of the Nebo granite steadily decreases with fractionation, compared to the Bobbejaankop and Lease granites, which conversely become more calcic with fractionation (Figure 2.12E). This is enigmatic, as other alkali elements do not replicate this trend.

Although they are geochemically similar, there are discernible chemical differences between the Lease and Bobbejaankop granites based on their locations, from the mines of Groenfontein or Zaaipplaats. Generally, the granites at Zaaipplaats are more peraluminous and exhibit a greater alkali and incompatible element enrichment than their Groenfontein equivalents. Lithium in the Nebo and Bobbejaankop are similar between <1 to 24 ppm, although they increase to 30.86 ppm in the Lease granite (Figure 2.12H). There is a sharp increase in Th from the Nebo to the Lease granite, from 10 to 95.85 ppm, respectively, however, samples from the transitional contact zone appear to be noticeably depleted (Figure 2.12L). The Sn content of the Bobbejaankop and Lease granites is generally greater than in the Nebo, although certain samples containing disseminated cassiterite have Sn contents greater than 100 ppm and, according to published data, can be as high as 1085 ppm (Pollard et al., 1991b) (Figure 2.12I). The Bobbejaankop granite at Zaaipplaats and the Lease granite at Groenfontein have the highest Sn contents, although Sn at Zaaipplaats is significantly higher. Similarly, Cu in the Zaaipplaats Bobbejaankop and Lease granites reaches 248 and 2410 ppm, respectively, although comparatively, at Groenfontein, only the Lease granite exhibits a Cu enrichment of up to 400 ppm (Figure 2.12J). The transitional zone typically plots between the Bobbejaankop and Lease clusters, but is unusually Th- and Li-depleted.

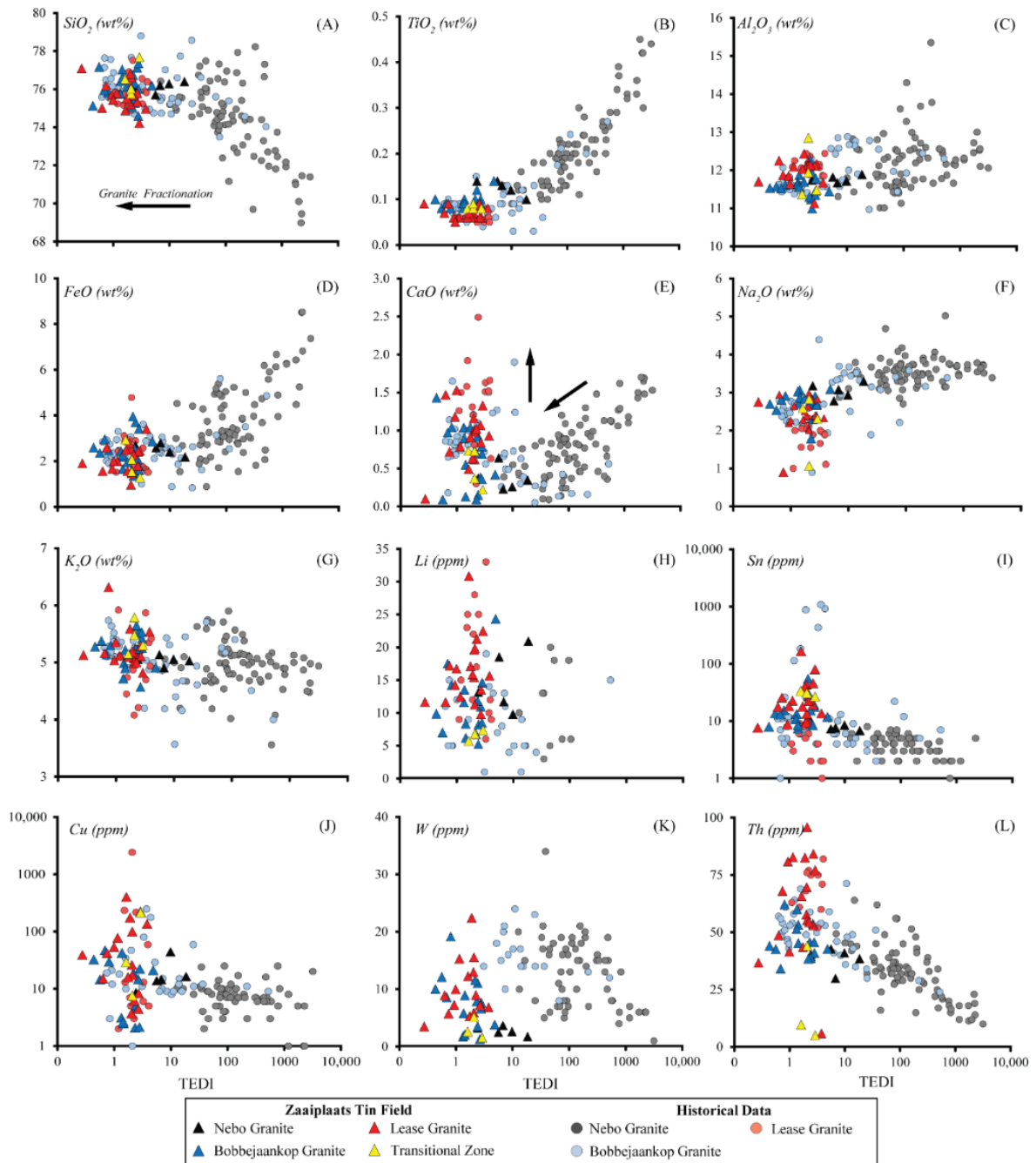


Figure 2.12. Harker style graphs showing major and trace element distribution within the granites of the Zaaipplaats tin field. The trace element differentiation index (TEDI) by Walraven (1986) is used in all graphs. A decrease in TEDI represents an increase in fractionation vs. (A) SiO_2 showing an increase from the Nebo to the Lease granite. (B) TiO_2 showing a decrease from the Nebo to the Lease granite. (C) Al_2O_3 exhibiting a slight decrease from Nebo to Bobbejaankop, however, it does not vary between the Bobbejaankop and Lease granites. (D) FeO^{tot} showing a decrease from the Nebo to the Lease granite. (E) CaO exhibiting a decrease from the Nebo to the Bobbejaankop before increasing in the Lease granite. (F) Na_2O showing a slight decrease from the Nebo to the Lease granite. (G) K_2O showing very little variation. (H) Li reveals a distinct increase in the Lease granite. (I) Sn is enriched in the Bobbejaankop and Lease granites. (J) Cu is relatively consistent apart from the increase in the Lease granite. (K) W showing very little variation. (L) Th increases from the Nebo to the Lease granite. Oxides and elements are in wt% and ppm, respectively.

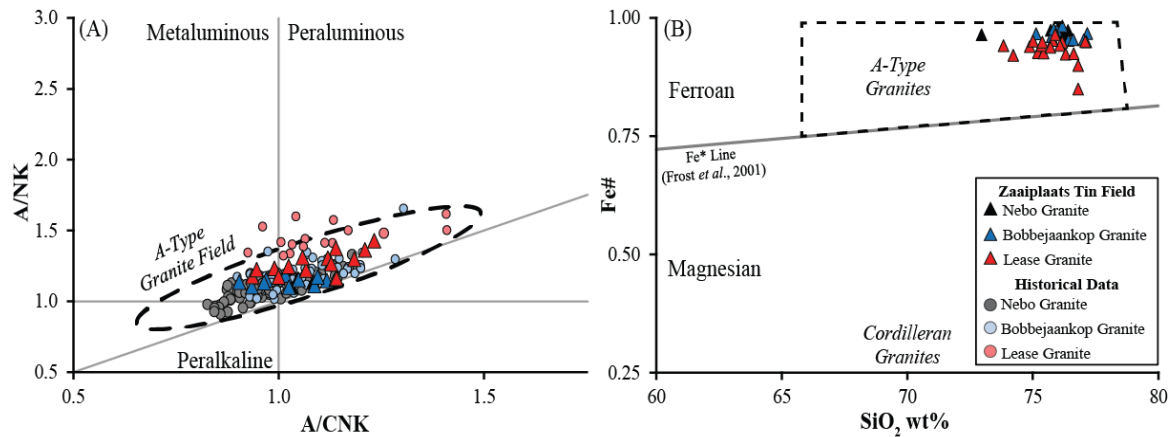


Figure 2.13. Alumina saturation and ferroan classification diagrams comparing the Zaaiploats tin field granites with literature data. **(A)** A/CNK vs. A/NK granite discrimination diagram. The range of global mineralized and unmineralized A-Type granites shown within the dashed ellipse, compiled from published data (Juniper and Kleeman, 1979; Frost and Frost, 2011; Singh and Vallinayagam, 2012; Li et al., 2014; Jiang et al., 2016; Zhou et al., 2017). Circular datapoints represent the range of geochemical analyses taken from the literature; Nebo granite (grey), Bobbejaankop granite (blue), and Lease granite (red) (Kleemann and Twist, 1989; Pollard et al., 1991a; Hill et al., 1996; Labuschagne, 2004). **(B)** Ferroan classification diagram after Frost et al. (2001) displaying the ferroan nature of these granites.

The normative Qz-Or-Ab ternary diagram displays an evolution of these granites from the Nebo, which plots between the hydrous minima of 0.4 and 0.07 H_2O activity (a_{H_2O}), towards a more Qz > Or composition (Figure 2.14). The most primitive Nebo granite compositions plot just above the hydrous minimum at 5 kb, and cluster at the 2 kb (0.5 a_{H_2O}) minimum. The majority of the Bobbejaankop and some of the Lease granite compositions cluster along the 2 kb hydrous cotectic line with an H_2O activity below 1, and migrate towards the Qz-Or boundary (Figure 2.14). The Groenfontein granites are more tightly clustered and are not as fractionated as their Zaaiploats equivalents.

The apparent fractionation from the Nebo to Bobbejaankop and then to the Lease granite is demonstrated by ratios such as Rb/Sr and TEDI (Figure 2.15A) (Walraven, 1986; Bailie and Robb, 2004) and can be modelled in terms of Rayleigh Fractionation. A representative assemblage for the Nebo granite of 50% alkali-feldspar, 30% quartz, 10% plagioclase, and 10% hornblende was used, and the partition coefficients (K_D) for Rb, Sr, and Ba are given in Appendix D. The concentration of Rb, Sr, and Ba within the residual liquid (C_{liquid}) was calculated using Equation (1). The bulk partition coefficient was calculated by multiplying the mineral proportions and the respective K_D of Rb, Sr, and Ba.

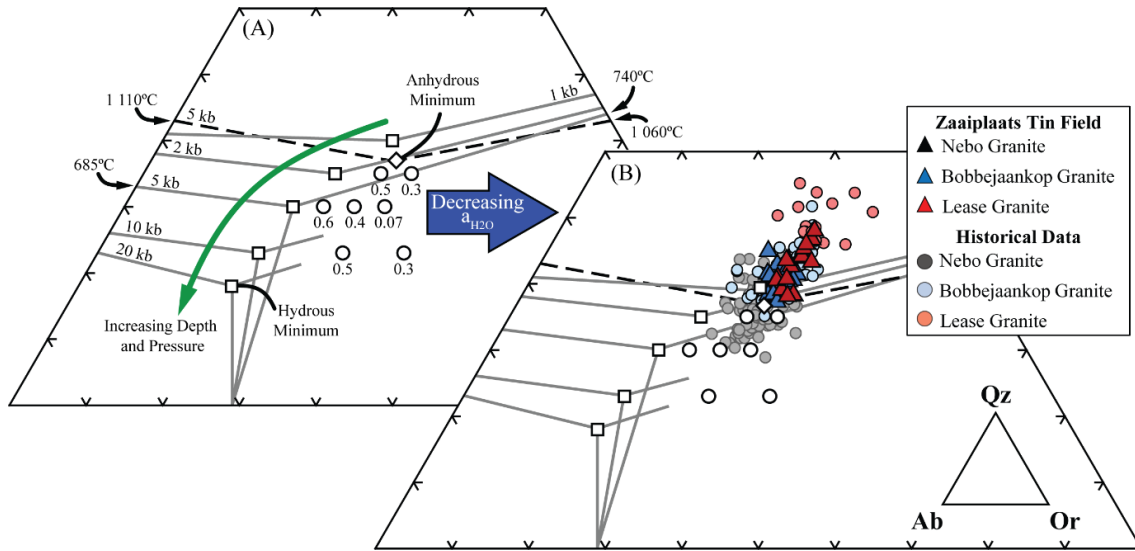


Figure 2.14. Normative Qz-Ab-Or plot of the granites from the Zaaipiaats tin field (Triangles). (A) White squares and solid lines represent haplogranite, hydrous eutectic points and cotectic lines respectively, which vary due to pressure (Tuttle and Bowen, 1958; Luth, 1969; Huang and Wyllie, 1981; Anderson, 1983; Bartoli et al., 2016). The white diamond represents the anhydrous minimum (Wyllie, 1977). White circles represent the displacement of eutectic points as a function of H₂O activity (a_{H2O}). (B) Circular datapoints represent the Nebo granite (grey), Bobbejaankop granite (blue) and Lease granite (red) from the literature (Kleemann and Twist, 1989; Pollard et al., 1991a; Hill et al., 1996; Labuschagne, 2004).

The K_D values for K-feldspar, plagioclase, biotite, hornblende, and quartz are within ranges of published values (Appendix D) (Nash and Crecraft, 1985; Bacon and Druitt, 1988; Bea et al., 1994; Sisson, 1994). The Nebo granite, in the vicinity of the Zaaipiaats tin field, is considered close to its roof and would inherently be the most evolved Nebo granite facies. Therefore, the initial composition and modal proportions were selected to represent the most primitive facies of the Nebo granite, taken from the literature data (Kleemann and Twist, 1989; Hill et al., 1996; Labuschagne, 2004).

$$C_{liquid} = C_{initial} \times F^{(K_D-1)} \quad (1)$$

Rayleigh Fractionation modelling identifies a linear fractionation trend from the Nebo to the Lease granite (Figure 2.15B). The Nebo granite clusters tightly along the fractionation trend, while the Bobbejaankop and Lease granite data are considerably more scattered. Modelling indicates that 10% fractionation of the Nebo granite is required to produce the first compositions of the Bobbejaankop granite. After 60% fractionation, the Nebo granite ends and the Bobbejaankop granite composition becomes dominant (Figure 2.15B). At approximately 65% fractionation, the composition of the Lease granite appears and both the Lease and Bobbejaankop granite compositions are present before ending at 80%.

Fractionation modelling of the Nebo granite reveals little distinction between the Lease and Bobbejaankop granites. However, elements such as Rb, Sr, and Ba may be problematic as they are susceptible to modification by later hydrothermal interaction, so other fractionation ratios are considered.

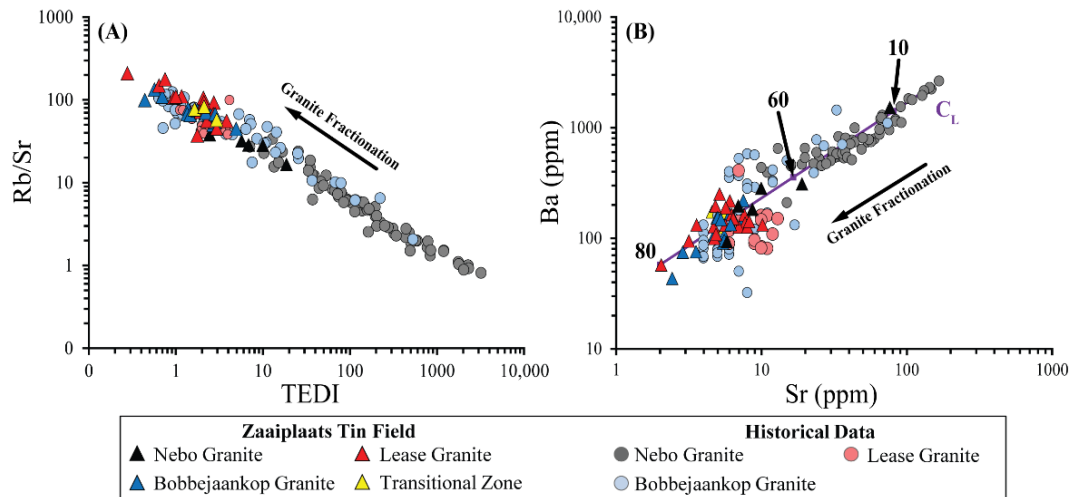


Figure 2.15. Diagrams illustrating the extent of fractionation of the Zaaipplaats tin field granites, comparing them to the literature data. (A) Plot of TEDI vs. Rb/Sr exhibiting the fractionation trend from Nebo (grey) to Lease (red). (B) Rayleigh Fractionation of the Zaaipplaats tin field granites, showing the percentage fractionation along the purple line (Concentration in Liquid, C_L). Circular data points represent the range of the literature's geochemical analyses; Nebo granite (grey), Bobbejaankop granite (blue) and Lease granite (red) (Kleemann and Twist, 1989; Pollard et al., 1991a; Hill et al., 1996; Labuschagne, 2004).

The TEDI parameter is able to distinguish the Nebo and Bobbejaankop granites, but is unable to differentiate the Lease from the Bobbejaankop granite. The inferred TEDI fractionation trend is replicated with other, more robust, large ion lithophile element (LILE) ratios such as Zr/Hf and K/Rb, which are regarded as effective indices of granite fractionation (Butler et al., 1962; Shaw, 1968; Dostal and Chatterjee, 2000; Aseri et al., 2015; Ballouard et al., 2016). These fractionation indices proved more effective in distinguishing between the two granites, although the complete differentiation of the Bobbejaankop and Lease granites was similarly unsuccessful.

Incompatible element ratios such as Nb/Ta and Zr/Hf are suggested to remain constant within closed, fractionating magmatic systems (Green and Pearson, 1987; Green, 1995; Aseri et al., 2015). The Lease granite, from Groenfontein and Zaaipplaats, has an average Zr/Hf ratio of 18.49 and 20.18, respectively. The Bobbejaankop from Groenfontein and Zaaipplaats shows a higher average Zr/Hf of 23.41 and 20.92, respectively, whereas the Nebo granite displays a

larger range from 19.74 to 88.57 (Figure 2.16A). Additionally, comparing Nb/Ta against Zr/Hf, the Bobbejaankop and Lease granites of Zaaipiaats display a significant decreased Nb/Ta ratio compared to the equivalent lithologies from Groenfontein, while maintaining an expected decreasing Zr/Hf ratio (Figure 2.16D). The Zr/Hf fractionation proxy shows a progression from the Nebo through Bobbejaankop to Lease granite, as does the TEDI and Rayleigh Fractionation (Figures 15 and 16).

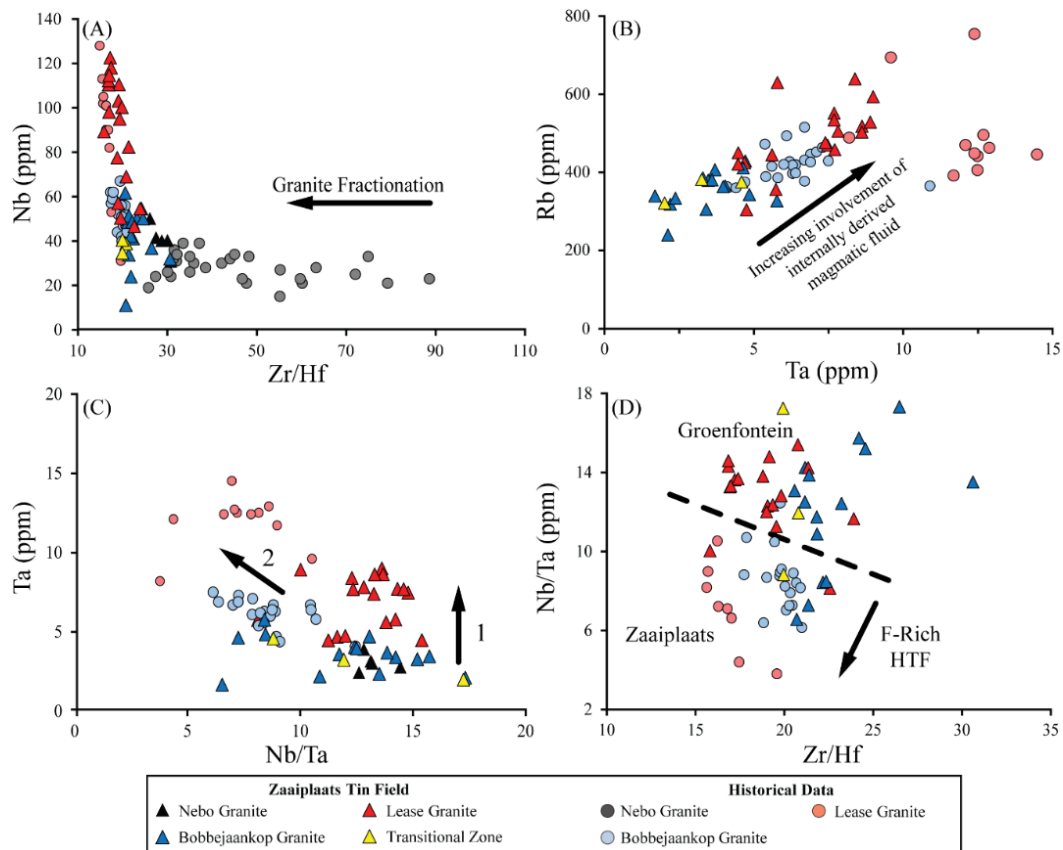


Figure 2.16. Diagrams illustrating the LILEs and different indexes of fractionation from the Zaaipiaats tin field granites **(A)** Graph of Zr/Hf vs. Nb indicating an increasing Nb with decreased Zr/Hf. **(B)** Plot of Ta vs. Rb that represents the geochemical signature of internally derived magmatic fluids, displaying a spectrum of increasing hydrothermal activity of the Bobbejaankop and Lease granites from Groenfontein and Zaaipiaats. **(C)** The Nb/Ta vs. Ta graph shows two trends: (1) increased Ta without variation in the Nb/Ta ratio; and (2) increase in Ta with deviation in the Nb/Ta ratio. **(D)** The Zr/Hf vs. Nb/Ta graph highlights the decoupling of the Nb/Ta magmatic signature producing two different ratios for the Bobbejaankop and Lease granites (dashed line) caused by F-rich hydrothermal fluids (HTF). Circular datapoints represent the range of the literature geochemical analyses; Nebo granite (grey), Bobbejaankop granite (blue) and Lease granite (red) (Kleemann and Twist, 1989; Pollard et al., 1991a; Hill et al., 1996; Labuschagne, 2004).

The granites of Zaaipiaats and Groenfontein, although part of the same granitic pluton, exhibit different Nb/Ta ratios. The Nebo and Bobbejaankop granites from Groenfontein and Zaaipiaats do not significantly differ in Nb, whereas the Lease granite is considerably enriched

(Figure 2.16A). Moreover, the Nb/Ta ratios of the Bobbejaankop and Lease from the two mines, are significantly different (Figure 2.16B, C). The granites from Groenfontein have a comparatively lower Ta than their counterparts at Zaaipiaats, however the Lease granite is generally more enriched in Ta than the Bobbejaankop granite (Figure 2.16B, C). Two trends are observed within these granites; the first trend shows an increased Ta of the Groenfontein Lease without variation from the Nb/Ta ratio. The second trend exhibited by the Bobbejaankop and Lease from Zaaipiaats shows both an increased Ta content and a deviation in the Nb/Ta ratio (Figure 2.16C).

REE and other trace element patterns display a slight enrichment in light rare earth elements (LREE), a negative Eu anomaly and a plateauing of the heavy rare earth elements (HREE), with high Zr, Nb, Y, U, Th, REE and negative Ba, Nb, Sr, P, Ti and Eu anomalies, consistent with typical A-types (Figure 2.17) (Collins et al., 1982; Whalen et al., 1987; Kleemann and Twist, 1989; Walraven and Hattingh, 1993; Bonin, 2007; Frost and Frost, 2011). There is little separation between the granites apart from the enrichment of incompatible and mobile elements such as Rb, Ba, Th, U, Sr, P, Sn and HREEs in the Lease granite (Figure 2.17B). The transitional zone, however, exhibits an atypical trend compared to the other granites. With the exception of one sample that plots similarly to the Bobbejaankop granite, the transitional zone is significantly REE-, Ce-, La-, Th-, Sm- and U-depleted (Figure 2.17A, B).

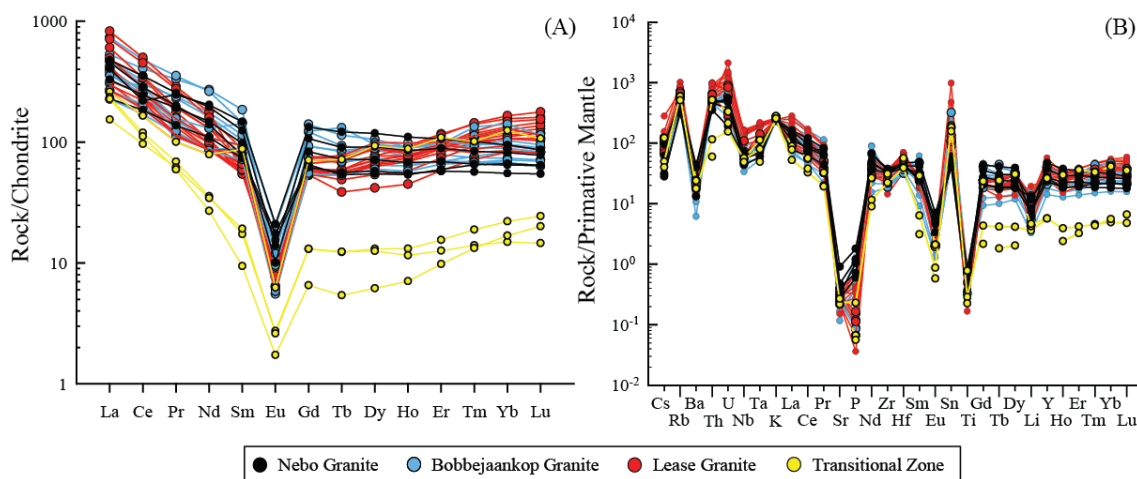


Figure 2.17. Rare earth element (REE) and multi-element diagrams of the granites from the Zaaipiaats tin field **(A)** Chondrite-normalized REE patterns for the Nebo, Bobbejaankop and Lease granites. Values normalized using data from McDonough and Sun (1995). **(B)** Primitive mantle-normalized multielement patterns for the Nebo, Bobbejaankop and Lease granites. Normalized using values from Sun and McDonough (1989).

2.2.6. Discussion

The mineralogical evolution of the Nebo granite, from its hornblende-bearing base to the biotite-bearing roof, suggests in situ fractionation of the granite (McCarthy and Fripp, 1980; Kleemann and Twist, 1989; McNaughton et al., 1993; Hill et al., 1996; Wilson et al., 2000; Kinnaird et al., 2004). Therefore, it is sensible to suggest that the gradual evolution from the Nebo to the Bobbejaankop granite would represent a continuation of this fractionation trend. Trace element fractionation proxies and Rayleigh Fractionation display a linear trend from the Nebo to the Bobbejaankop and Lease granites, supporting the origin of the Bobbejaankop by fractionation of the Nebo granite (Figure 2.15). Rayleigh Fractionation shows the Lease and Bobbejaankop granites to be the upper limit of what can be considered a reasonable degree of fractionation (Figure 2.15B). However, taking the relative scales of these plutonic bodies into account, the degree of fractionation is not as unrealistic as initially thought. The Nebo granite has an approximate volume of 100,000 km³ and is internally fractionated (Fourie and Harris, 2011). Thus, as the Bobbejaankop granite is only several hundred meters thick, approximately 65% fractionation of the Nebo granite is probable (Kleemann and Twist, 1989; Fourie and Harris, 2011). However, the inability to geochemically distinguish between the Bobbejaankop and Lease granites, using fractionation ratios suggests that fractionation alone is not responsible for the formation of Lease granite.

Petrographically, the differences between the Bobbejaankop and the Lease granite are granophyric grain-size reduction and increased microclinization, chloritization, and sericitization (Figures 7 and 13A). Geochemically the differences are more subtle, mainly pertaining to increased incompatible and large ion lithophile elements, such as Ce, Cs, Cu, Li, Lu, Nb, Rb, Sn, Ta, Th, U, and Yb (Figure 2.17). These elements are readily mobilized by hydrothermal fluids and, as there was no exogranitic fluid escape (Pollard et al., 1991a), can be inferred to represent the accumulation of late-stage fractionated hydrothermal fluids. The increased calcium content of the Lease compared to the Bobbejaankop granite is seen by the increased presence of fluorite and epidotization of the plagioclase. Chloritization, the dominant alteration within the Bobbejaankop granite, becomes increasingly subordinate to microclinization, sericitization, and occasionally epidotization within the Lease granite. A geochemical representation of this shift in alteration is proxied by $(K_2O + CaO)/Na_2O$, where an increased ratio represents a corresponding increase in microclinization (K) and

epidotization (Ca) and the loss of Na-plagioclase. The Na depletion, is the result of the breakdown of plagioclase and the loss of Na, which resulted from more intense greisenization particularly apparent within the Type 3 Lease (Figures 11B and 12F) (Viswanathan, 1972; Štemprok, 1987; Dill, 2010). Generally, $(K_2O + CaO)/Na_2O$ increases from the Nebo to the Bobbejaankop granite, however, the Lease granite at Zaaipplaats is significantly more altered (Figure 2.18A). Similarly the migration of the data for the Lease granites, on the Qz-Ab-Or diagram, away from the Nebo and Bobbejaankop clusters suggests that the Lease experienced a greater degree of microclinization and greisenization (Figure 2.14) (Hunt, 2005). Furthermore, by combining the feldspar alteration proxy with a biotite chloritization proxy $TiO_2/FeO^{(tot)}$ (Viswanathan, 1972), a shift in the dominant style of hydrothermal alteration is identified (Figure 2.18B). Additionally, combining alteration with Sn content reveals a concentration of Sn at the transition from chloritization to microclinization and epidotization as the dominant styles of alteration (Figure 2.18B). Therefore, the highest Sn grade, at both mines coincides with the change in alteration from chloritization to microclinization and epidotization (Figure 2.18B). Mineralized granites from both mines occur at this transition between alterations, suggesting a “goldilocks” region of alteration. Moreover, it appears that the disseminated mineralization is not associated with specific lithologies, but is rather dependent on the dominant style of hydrothermal alteration.

The contact between the Bobbejaankop and Lease granites is not as sharp as previously described (Strauss, 1954; Coetzee, 1984; Coetzee, 1986; Crocker et al., 2001). The shift from an unaltered Bobbejaankop through a transitional contact zone is defined by the incipient and selective alteration of feldspars and granophyric grain-size reduction. This develops a texture that is intermediate between that of the Bobbejaankop and Lease granites (Figure 2.7). Geochemically, this transition zone is marked by a distinct REE and incompatible element depletion, suggesting that before being depleted and incompletely altered to Lease granite, this zone was originally typical Bobbejaankop granite (Figures 12 and 17).

Where present, the transitional zone at Groenfontein is several centimetres thick, however at Zaaipplaats the transitional zone reaches up to 4 m wide. This is explained by a combination of factors; first the downward migrating of a dynamic alteration front which, as fluid accumulated in the cupola, prograded downwards into the Bobbejaankop magma, stripping mobile elements before regressing. The transitional zone represents a region where the

alteration front regressed before completing the alteration of the Bobbejaankop granite. Secondly, the variability in the permeability of the Bobbejaankop mush, controlled by the degree of crystallization, would have variably facilitated or inhibited the infiltration of the hydrothermal fluids. This would have resulted in gradational or sharp contacts, where the permeability was either high or low, respectively.

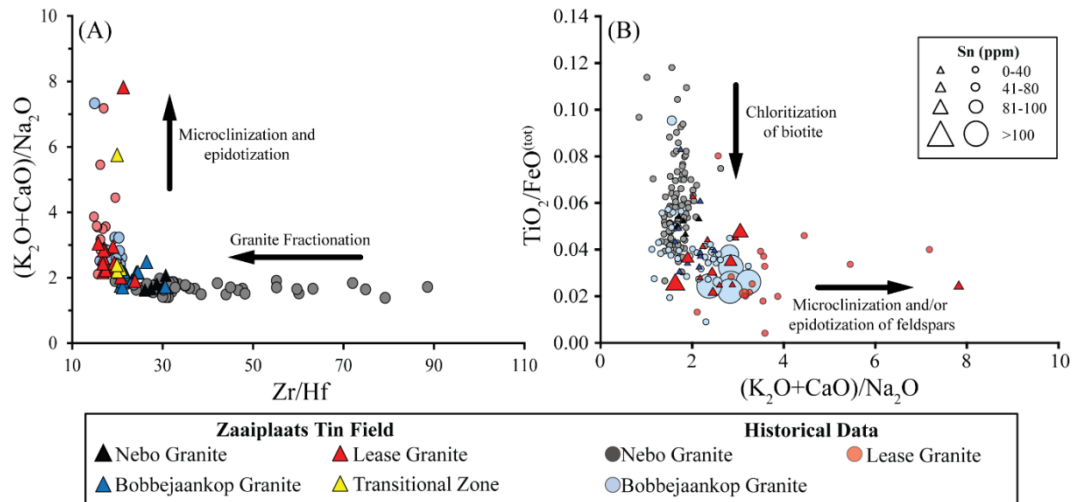


Figure 2.18. Diagrams showing the various alteration proxies and their correlation with Sn in the Zaaipiaats tin field granites (A) Graph of Zr/Hf vs $(K_2O + CaO)/Na_2O$ indicate the increase in microclinization and epidotization in the highly fractionated granite phases. (B) Graph of $(K_2O + CaO)/Na_2O$ vs $TiO_2/FeO^{(tot)}$ describing the dominant style of hydrothermal alteration. Scaling of the symbols represents the concentration of Sn (ppm) within the samples. Circular datapoints represent the range of the literature's geochemical analyses; Nebo granite (grey), Bobbejaankop granite (blue) and Lease granite (red) (Kleemann and Twist, 1989; Pollard et al., 1991a; Hill et al., 1996; Labuschagne, 2004).

The geochemical decoupling of incompatible elements between the Lease and Bobbejaankop granites from the two mines is due to an increased hydrothermal signature at Zaaipiaats, suggesting a greater accumulation of hydrothermal fluids towards the Zaaipiaats end of the pluton (Figure 2.16). Incompatible Zr and Hf are concentrated in a silicic magmas at a constant ratio, although the crystallization of zircon decreases the Zr/Hf ratio and which then can be used to monitor the evolution of granitic magmas (Bau, 1996; Pan, 1997; Dostal and Chatterjee, 2000; Zarsky et al., 2009). This is evident in the consistent Zr/Hf decrease from the Nebo through Bobbejaankop to the Lease granite at both Groenfontein and Zaaipiaats. A decrease in Zr/Hf below 30 has also been linked to the enrichment of LILE and HFSE such as Sn, W, Mo, Ta, Nb, Li, Zr and Hf, to the point of economic viability (Bau, 1996; Pan, 1997; Dostal and Chatterjee, 2000; Zarsky et al., 2009). The Lease and Bobbejaankop granites, unsurprisingly, have Zr/Hf ratios between 15 and 30, which correspond to greisen

related Sn-W-Mo-Be deposits, whereas the unmineralized Nebo granite has a Zr/Hf ratio higher than 30 (Bau, 1996; Dostal and Chatterjee, 2000; Zraisky et al., 2009).

Similarly, the Nb/Ta parameter is used as an index of fractionation as the ratios should remain broadly similar in an evolving magmatic system (Green and Pearson, 1987; Green, 1995; Bau, 1996; Pan, 1997; Dostal and Chatterjee, 2000; Zraisky et al., 2009; Aseri et al., 2015; Ballouard et al., 2016; Simons et al., 2017). However, an increase in Ta (decrease in Nb/Ta) is attributed to the involvement of fluorine-rich, autometasomatic, mineralizing and greisenizing fluids (Green and Pearson, 1987; Green, 1995; Dostal and Chatterjee, 2000; Aseri et al., 2015; Ballouard et al., 2016; Simons et al., 2017). The Bobbejaankop and Lease granites deviate from the Nb/Ta ratio of the Nebo, displaying an enrichment of Ta, particularly at Zaaipplaats (Figure 2.16). The deviation from the magmatic Nb/Ta ratio is attributed to increased interaction with internally derived magmatic fluids. The correlation of incompatible elements such as Ta vs. Rb, suggest the involvement of such internally derived magmatic fluid prior to greisenization (Figure 2.16B) (Halter et al., 1998; Dostal and Chatterjee, 2000). The deviation from the magmatic Nb/Ta ratio highlights a transition from a magmatically dominated, to an F-rich, magmatic-hydrothermal dominant environment (Figure 2.16D). Therefore, the main difference between the granites of the two mines is the increased accumulation and influence of pre-greisenization, F-rich magmatic-hydrothermal fluids at Zaaipplaats.

These fluids have been shown to be CO₂-bearing and hypersaline, containing KCl, NaCl, and FeCl (Pollard et al., 1991a). Thus, coupled with the abundance of hematite and fluorite, it is reasonable to suggest these granites were altered by an extremely, F⁻, Cl⁻, and Fe-rich fluid (Pollard et al., 1991a; Migdisov and Williams-Jones, 2014). The presence of Cl⁻ and CO₂ within granitic magmas enhanced the complexation and mobility of HREEs in the magmatically-derived hydrothermal fluids, as well as reducing the activity of H₂O, as evident in the low H₂O activity shown in Figure 2.14B. However, the anomalous Cu enrichment within the Lease granite may be related to the exsolution of an aqueous fluid phase. The mobility and concentration of Cu in hydrothermal fluids is largely a function of the salinity of the aqueous fluid because the solubility of a likely CuCl₂ complex is proportional to the Cl⁻ concentration of the fluid (Nagaseki and Hayashi, 2008; Sherman, 2010). As the granites of the Zaaipplaats tin field are thought to have intruded at approximately 4 to 5 km depth, it is very likely that the

magmas underwent fluid saturation as evident in the abundant manifestations of magmatic-hydrothermal alteration and mineralization described herein (Von Gruenewaldt and Strydom, 1985; Pollard et al., 1991a; Robb, 2005). This would have occurred at around 1 to 2 kb of pressure, as shown in Figure 2.14 and assuming a 0.3kb/km pressure gradient in the continental crust (after Winter (2010)).

Evidence for fluid saturation, by decompression of the crystallizing magma, is provided by the abundant miarolitic cavities. Fluid saturation may have been caused by continuous crystallization and/or decompression of the magma. The decreasing volume, caused by crystallization, may have led to shrinking of the volume occupied by the magma and partial detachment from the roof, allowing the formation of the marginal pegmatitic zone. The abundance of hematized feldspars, suggests a relatively oxidizing environment, which could have been achieved by fluid mixing or boiling (Taylor and Wall, 1993; Heinrich et al., 1999; Sherman, 2010). Pollard et al. (1991a) showed that these granites evolved in a closed system with little to no external influence, thus oxidation via boiling is the most likely mechanism. Furthermore, the abundance of fluorite and particularly tourmaline within the Lease granite would suggest a reasonable amount of F and B within the fluid. During the exsolution of a vapour-rich fluid, these volatiles would have preferentially partitioned into the vapour phase, therefore, together with the coexisting brine, they were transported and accumulated into the granite cupola.

The solubility of metals improves with increasing volatile concentration and acidity, facilitating their transportation within these magmatic-hydrothermal fluids (Wolf and London, 1997; Heinrich, 2007; Sherman, 2010; Duchoslav et al., 2017; Hong et al., 2017). Thus, internally derived magmatic fluid, produced by the crystallizing Bobbejaankop granite, would have become enriched in various metals, such as Fe, Al, and Sn. Such fluids would have had the ability to concentrate and transport significant concentrations of Sn, however they would not necessarily have precipitated cassiterite. During fluid saturation, Sn preferentially partitions into the aqueous phase, possibly as a SnCl_2 complex in a relatively saline, acidic fluid (Heinrich, 1990; Sherman, 2010; Duchoslav et al., 2017). Therefore, the loss of H, F, and B into a vapour phase, would have simultaneously buffered and oxidized the aqueous phase, precipitating SnO_2 (Heinrich, 1990; Sherman, 2010; Duchoslav et al., 2017). The process of neutralization-induced greisenization of the surrounding granite caused the decomposition

of feldspars and precipitation of cassiterite. Cassiterite mineralization, where present within the hydrothermal pipes, is concentrated within the sericitized core, and partially within the surrounding melanocratic tourmaline-rich layer. Similarly, miarolitic and pod-like mineralization within the Lease granite is associated with the greisenized decomposition of feldspars. The disseminated mineralization within the Bobbejaankop granite was the result of the neutralization of the Sn-rich aqueous phase, while the B- and F-rich fluid accumulated in the roof. Thus, the Lease granite is proposed to be the altered product of a semi-crystallized Bobbejaankop magma, by the saturation and accumulation of a magmatic-hydrothermal acidic, saline-rich fluid. Therefore, the Lease granite represents the transition from a magmatic to a magmatic-hydrothermal dominant system.

Formation of the Lease and Bobbejaankop Granites

The results of this study strongly support the formation of the Bobbejaankop granite by fractionation of the Nebo granite. The linear trend displayed by the normative Qz-Ab-Or diagram suggests that the Lease granite is neither a separate intrusion nor a chilled margin of the Bobbejaankop granite (Figure 2.14). Rather, it suggests that the Lease granite gradually evolved in the cupola of the Bobbejaankop mush by fluid saturation and subsequent hydrothermal alteration.

The extensive microclinization and reordering of the Bobbejaankop feldspars increased their porosity, allowing pervasive fluid movement (Walker et al., 1995; Putnis et al., 2007). The inward crystallization of the Bobbejaankop granite would have concentrated LILE and incompatibles into a late-stage, acidic, and F-rich autometasomatic magmatic-hydrothermal fluid. Eventual fluid exsolution and the porosity of the feldspars facilitated the upwards migration and accumulation of the fluids in the upper facies of the Bobbejaankop mush. The gradual effervescence and fluid saturation produced ubiquitous miarolitic cavities and the subsequent precipitation of cassiterite within them. The migration and accumulation of these volatile-rich bubbles would have concentrated B, F, H, and Cu in the granite cupola.

The process of devolatilization and bubble migration is referred to as the “bubble laden plume theory” and was proposed by Candela (1991). This model describes the formation of boron, alkali-, and metal-rich bubbles that migrated upwards through a crystallizing granitic magma, accumulating in the roof. At low degrees of crystallization, these bubbles would have coalesced and formed large, bubble-laden plumes that streamed through conduits in the

semi-crystalline mush. Granitic systems, such as Zaaiplaats, that have significant concentrations of Li, B, F, and H will have a higher diffusivity, greater H₂O solubility, and lower viscosity, facilitating the migration of bubbles and increasing permeability for pervasively altering fluids (London et al., 1989; Candela, 1991; London, 1999). Some of the hydrothermal pipes have large central cavities or voids, surrounded by a melanocratic zone of tourmaline-quartz. Thus, they may represent large bubble-laden plumes, formed by the accumulation and channelling of these exsolved greisenizing volatile and metal-rich fluids. The alumina required for the formation of the aluminosilicates within the pipes and Lease granite were sourced from the decomposition of feldspars by greisenization (London, 1999; Williamson et al., 2000; Drivenes et al., 2015; Duchoslav et al., 2017). Thus, the neutralization of Sn-bearing fluids within the pipes explains the high-grade deposition of cassiterite within the sericitized cores.

The accumulation of these fluids resulted in the complete alteration of the Bobbejaankop granite and the formation of various types of Lease granite. The transitional zone, regarded as the contact between the granites, represents a region of incomplete alteration of the Bobbejaankop granite. A possible combination of the topographic variations in the roof of the Bobbejaankop magma chamber, convection, porosity, and microstructure, channelled the fluids towards Zaaiplaats. Therefore, the peripheral Lease microgranite is the result of a magmatically derived hydrothermal fluid alteration in the semi-crystallized Bobbejaankop granite cupola.

2.2.7. Conclusion

The meta- and peraluminous, ferroan granites of the Zaaiplaats tin field, exhibit the typical characteristics of A-Type granitoids. Trace element geochemistry indicates that the Bobbejaankop granite resulted from extensive fractionation of the Nebo granite, whereas the Lease granite represents the hydrothermal alteration of the semi-crystallized Bobbejaankop magmatic mush by an incompatible element rich, acidic, magmatically derived hydrothermal fluid. Incipient microclinization and chloritization, followed by a pervasive and destructive style of alteration, resulted in the fine-grained Lease in the roof of the Bobbejaankop granite. The textural and mineralogical variants in the Lease granite were dependent on the extent and dominant style of hydrothermal alteration. Fluid saturation mobilized and concentrated volatiles and incompatible elements, resulting in the ubiquitous tourmalinization and

greisenization within the Lease granite. The coalescence and migration of the magmatically-derived hydrothermal fluids resulted in the formation of large tourmaline-quartz hydrothermal pipes. Neutralization of the Sn-bearing hydrothermal fluids precipitated cassiterite within miarolitic cavities, and hydrothermal pipes within the Lease and upper portions of the Bobbejaankop granite. Therefore, the Lease microgranite represents the alteration in the cupola of the semi-crystalline Bobbejaankop granite, by the accumulation of internally derived metal and volatile-rich magmatic-hydrothermal fluids.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Table S1: Complete list of whole rock XRF and ICP-MS results of the sampled Zaaipplaats tin field granites; Table S2: Partition coefficients (K_D) and representative modal proportions of the Nebo granite used in Rayleigh Fractionation calculations.

Author Contributions: Conceptualization, Investigation, and Writing—original draft, L.V.; Project administration, Supervision, Writing—review and editing, and assistance in field investigations, P.N., J.K. and L.R.

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Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Chapter 3

Remote Sensing and Geochemical Exploration of the Zaaipplaats Tin Field

3.1. Preamble

This chapter comprises a manuscript that is currently in review with the *South African Journal of Geology*. It describes and discusses data obtained by multi-spectral remote sensing and field-based geochemistry, and their combined use in the identification and mapping of tin mineralisation in the Zaaipplaats tin field. The stanniferous granites of the Zaaipplaats tin field had previously been comprehensively mapped in the 1950s and the mineralisation had been well defined. However, the most recent mapping of the granites and the extent of cassiterite mineralisation was conducted by Coetzee (1984), but was focused at the Zaaipplaats Tin Mine, whereas, the geological mapping of Groenfontein, the southern extension of the tin field, has not been updated since Strauss (1954). Therefore, the goal of this chapter is to evaluate the integration of space-borne remote sensing and pXRF geochemical mapping in the lithological and alteration mapping of the Zaaipplaats tin field. This research improved the current lithological mapping of the area and demonstrates the potential for these techniques to discriminate and vector towards tin mineralisation within A-Type granites.

3.1.1. Author Contributions

Leonidas Vonopartis was the main contributor for this paper and did most of the field work, sample collection, sample preparation, data compilation, spectral interpretation, portable XRF mapping and write-up of the manuscript. The second author, René Booysen, processed most of the satellite imagery and produced the remote sensing images for the final manuscript. The co-authors, Paul Nex, Judith Kinnaird and Laurence Robb supervised and provided guidance in the development of the manuscript. Furthermore, these co-authors assisted with the field work, editorial review and the interpretation of the data.

Contribution percentage per author:

- | | |
|------------------|-----|
| 1. L. Vonopartis | 60% |
| 2. R. Booysen | 20% |
| 3. P. Nex | 10% |
| 4. J. Kinnaird | 5% |
| 5. L. Robb | 5% |

3.2. Combining ASTER Remote Sensing and Portable X-Ray Fluorescence Vectoring of Endogranitic Tin Mineralisation of the Zaaiplaats Tin Field, Bushveld Igneous Complex, South Africa.

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3.2.1. Abstract

The Zaaiplaats tin field is host to two of the historically most significant tin mines in South Africa. Geological mapping at Zaaiplaats and Groenfontein has not been updated since the 80s and 50s respectively, and is in need of a renewed investigation. Cassiterite is hosted in the Bobbejaankop and Lease granites of the Zaaiplaats and Groenfontein tin mines, which are part of the Lebowa Granite Suite of the Bushveld Igneous Complex. Tin mineralisation is primarily hosted in low-grade disseminations and within networks of high-grade hydrothermal pipes and lenticular ore-bodies. One difficulty in mapping such formations arises from the limited lithological variability between mineralised and unmineralised granitic facies. In order to map the granitic lithologies and discriminate alteration zones an integrated approach is taken by integrating modern remote sensing mapping and in-situ portable X-ray fluorescence spectrometer (pXRF). The pXRF large ion lithophile (LIL) element distribution mapping, specifically correlating Rb, Sr and Ba with Sn, points to the evolution and concentration of late-stage magmatic-hydrothermal fluids associated with endogranitic mineralisation. The use of the Rb/Ba ratio highlights regions of late-stage magmatic-hydrothermal alteration and successfully delineates various granites, identifying zones of potential tin mineralisation. Modern image processing techniques were selected as tools to support the mapping of granitic units, their variable degrees of magmatic-hydrothermal alteration and to isolate regions of endogranitic disseminated mineralisation. We thus demonstrate that an expert-based and synergic approach combining inexpensive in-situ pXRF and freely available satellite remote sensing data, supports the mapping and identification of endogranitic mineralisation in early exploration stages. Furthermore, due to its versatility, this approach can easily be applied to any style of plutonic mineralisation.

3.2.2. Introduction

The Paleoproterozoic Bushveld Igneous Complex, in the northeast of South Africa, is the largest layered igneous complex on Earth. It covers an area exceeding 90 000 km² and has an approximate volume of 450 000 km³, hosting some of the world's largest mineral deposits (Wilson and Anhaeusser, 1998; Bailie and Robb, 2004; Finn et al., 2015; Zeh et al., 2015). The Lebowa Granite Suite of the Bushveld Igneous Complex is the largest known A-Type granite complex, and is subdivided into several granitic facies, including the coarse-grained Nebo, Makhutso and Bobbejaankop granites, and the fine-grained Klipkloof and Lease granites (Hill et al., 1996; Robb et al., 2000; Kinnaird et al., 2004).

The northern limb of the Bushveld Igneous Complex, along the Makapansberg escarpment, exposes the Bobbejaankop and Lease granites of the Zaaipplaats tin field (Figure 3.1) (Strauss and Truter, 1944; Strauss, 1954; Lenthall and Hunter, 1977; Robb et al., 2000; Crocker et al., 2001; Vonopartis et al., 2020a). Cassiterite mineralisation, hosted in the Bobbejaankop and Lease granites, was discovered in 1908 and mining was thereafter established by the Zaaipplaats Tin Mining Company on the farms of Groenfontein 227 KR and later Zaaipplaats 223 KR (Figure 3.2) (Strauss and Truter, 1944; Strauss, 1954; Falcon, 1985; Wilson and Anhaeusser, 1998; Crocker et al., 2001). The Zaaipplaats tin field is host to low-grade disseminated cassiterite and high-grade greisenised hydrothermal pipe and lenticular ore-bodies, which were extensively mined until production ceased in 1989 (Strauss and Truter, 1944; Lenthall and Hunter, 1977; Coetzee, 1984; Falcon, 1985; Pollard et al., 1991b; Robb et al., 2000; Crocker et al., 2001; Vonopartis et al., 2020a).

The stanniferous Zaaipplaats granites were mapped by Coetzee (1984), while the geological mapping of Groenfontein, had not been updated since Strauss (1954), until a recent petrographical and geochemical investigation by Vonopartis et al. (2020a). The endogranitic tin mineralisation is associated with the fractionation and subsequent hydrothermal alteration of the Bobbejaankop and Lease granites (Coetzee and Twist, 1989; Pollard et al., 1991b; McNaughton et al., 1993; Crocker et al., 2001; Robb, 2005; Vonopartis et al., 2020a). Incompatible, high field strength (HFS) elements, such as Sn and other economically significant elements, were concentrated by the fractionation of a granitic body and readily mobilised by late-stage magmatically-derived hydrothermal fluids (Walraven et al., 1990; Blevin and Chappell, 1992; Williamson et al., 2010; Simons et al., 2017; Vonopartis et al., 2020a). Therefore, Large Ion Lithophile (LIL) elements and their ratios, particularly Rb, Sr and

Ba, are commonly used as proxies for granitic fractionation and the accumulation of late-stage magmatic-hydrothermal fluids (El Bouseily and El Sokkary, 1975; Ekwere, 1985; Walraven et al., 1990).

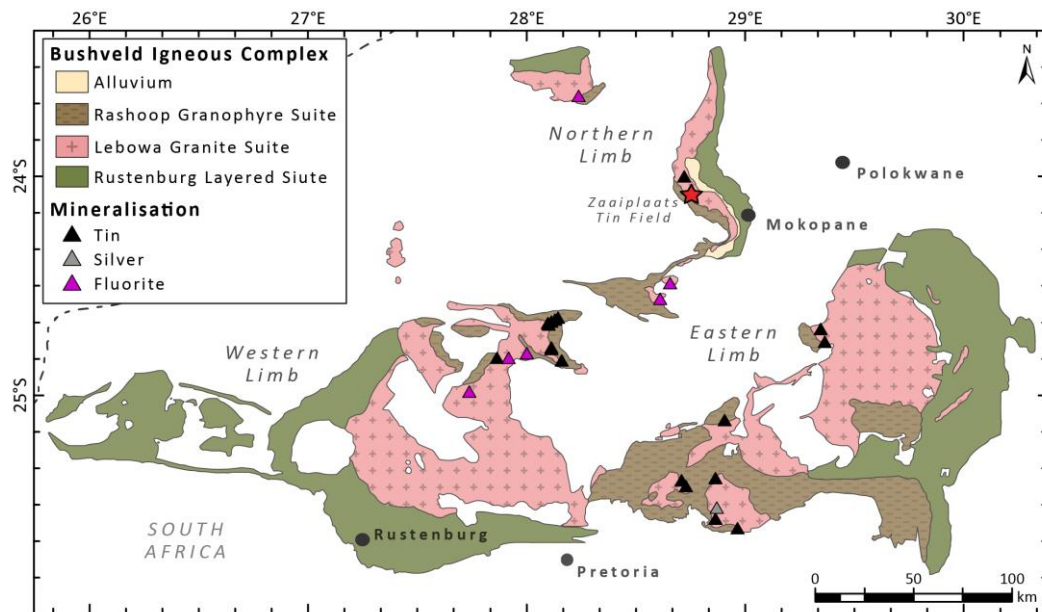


Figure 3.1. Simplified geological map of the Bushveld Igneous Complex, showing the location of the Zaaipiaats tin field (red star) with other occurrences of tin, silver and fluorite mineralisation. Modified after Hunter (1975).

Geochemical mapping, such as soil sampling and in-situ field-portable X-ray fluorescence (pXRF) are now routine tools in the exploration of mineral deposits (Cocker, 1999; Benn, 2012; Durance et al., 2014; Le Vaillant et al., 2014; Le Vaillant et al., 2016; Lemièrre, 2018). Real-time, in-situ analyses have been successfully used in lithological discrimination and alteration mapping of mineral deposits and geological terranes (Durance et al., 2014; Le Vaillant et al., 2014; Lemièrre, 2018), although they are not commonly utilised in vectoring mineralisation.

The use of remote sensing in geological sciences has advanced in the previous decades with the advent of new satellite technology, improving the capability of accurate lithological discrimination (Sabins, 1999; Crosta et al., 2003; Yamaguchi and Naito, 2003; van der Meer et al., 2012).

Various geological terranes and deposits have been structurally and lithologically mapped with the use of freely available multispectral remote sensing, providing an inexpensive and rapid exploration tool (Sabins, 1999; Crosta et al., 2003; Yamaguchi and Naito, 2003; van der Meer et al., 2012). However, remote sensing has not commonly been used in targeting endogranitic mineralisation, due to muted lithological variability. Thus, the Zaaipiaats tin

granites provide an ideal situation to evaluate the applicability of low level satellite-borne multispectral mapping to improve local lithological discrimination and identification of potential areas of mineralisation.

The proposed approach focuses on variations in hydrothermal alteration by primarily mapping typical granitic patterns and key mineral alterations. This study exemplifies the applicability of combined geochemical mapping and multispectral satellite-based remote sensing, as tools in the exploration of mineralised felsic intrusions. We propose an approach combining modern geological remote sensing mapping, based on freely available satellite data, and a limited geochemical dataset acquired by a standard instrument in mineral exploration. We attempt to map the spatial distribution of LIL elements, by pXRF, as proxies for late-stage magmatic-hydrothermal fluid accumulation utilising their known magmatic and hydrothermal behaviours, and by comparing their associated hydrothermal alteration using innovative satellite image processing.

3.2.3. Regional Geology

The Zaaipplaats tin field includes the Groenfontein and Zaaipplaats tin mines that are characterised by a sequence of granites: the Nebo granite in the southeast; then the Bobbejaankop granite; and the Lease granite in the northwest. In the west, these granites lie beneath the Rashoop Granophyre which caps the granitic suite and dips between 10° to 15° to the west (Figures 3.2 and 3.3) (Strauss and Truter, 1944; McNaughton et al., 1993; Crocker et al., 2001; Vonopartis et al., 2020a). The Nebo granite is a 1.5 to 2.5 km thick sheeted granitic intrusion, composed of equigranular quartz, perthitic alkali-feldspar, hornblende and biotite (Kleemann and Twist, 1989; Pollard et al., 1991b; Hill et al., 1996; Crocker et al., 2001; Kinnaird et al., 2004). Within the Zaaipplaats tin field, the Nebo progressively evolves from a grey coarse-grained mesocratic hornblende-bearing granite at its base, to a finer-grained, grey to pinkish-grey biotite granite towards the roof (Kleemann and Twist, 1989; Hill et al., 1996; Kinnaird et al., 2004).

The overlying Bobbejaankop granite is proposed to have fractionated from the underlying Nebo granite and subsequently been hydrothermally altered (Strauss and Truter, 1944; McCarthy and Fripp, 1980; Kleemann and Twist, 1989; McNaughton et al., 1993; Hill et al., 1996; Kinnaird et al., 2004; Vonopartis et al., 2020a). The brick red coarse-grained Bobbejaankop granite is principally composed of red alkali-feldspar, discrete synneusis-

textured quartz grains and interstitial, variably chloritised biotite. Mirolitic cavities are disseminated throughout the granite and are filled with euhedral quartz, red alkali-feldspars, fluorite with minor cassiterite and tourmaline (McCarthy and Fripp, 1980; Coetzee, 1984; Kleemann and Twist, 1989; Pollard et al., 1991b; McNaughton et al., 1993; Kinnaird et al., 2004; Vonopartis et al., 2020a).

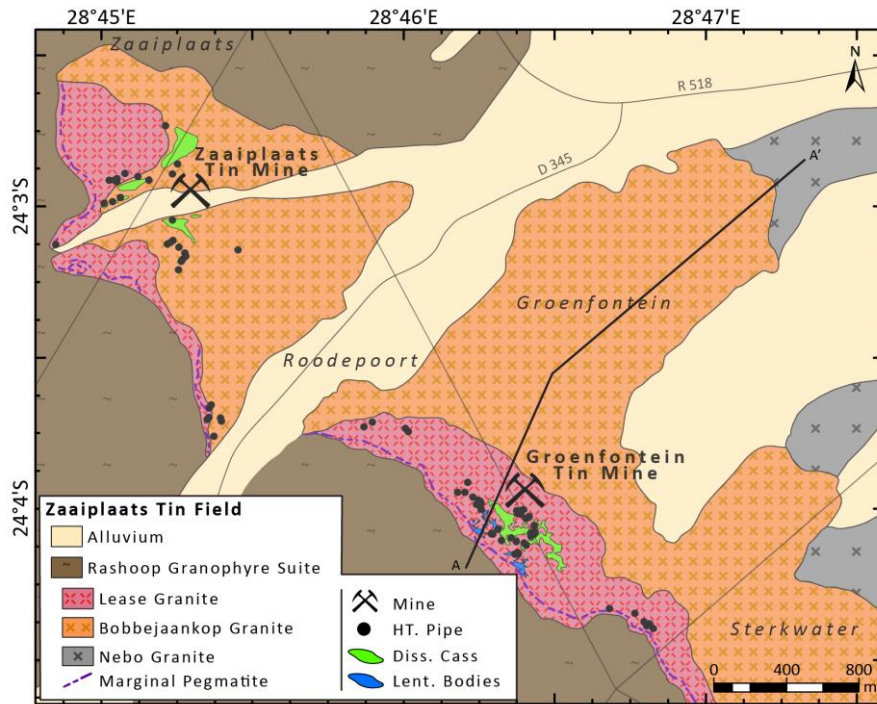


Figure 3.2. Geological map of the Zaaipplaats tin field modified after Vonopartis et al. (2020) showing lithological boundaries defined by published maps (Strauss, 1954; Coetzee, 1984). Cross section along line A – A' shown in Figure 3.3. Lithological nomenclature from SACS (1980). Abbreviations: Hydrothermal (HT); disseminated (Diss); cassiterite (Cass); lenticular (Lent).

The Lease granite is a relatively thin (120 m thick) aplitic facies restricted to the roof of the Bobbejaankop granite and is the result of late-stage magmatic-hydrothermal alteration of the underlying Bobbejaankop granite (Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1984; Crocker et al., 2001; Vonopartis et al., 2020a). It is a metasomatically altered red, microgranitic facies, exhibiting extensive chloritisation, subsequent sericitic alteration of feldspars and biotite with minor patches of epidotisation (Strauss and Truter, 1944; Coetzee, 1986; Pollard et al., 1991b; Crocker et al., 2001; Kinnaird et al., 2004; Vonopartis et al., 2020a). The low-grade disseminated mineralisation at Groenfontein is confined to the upper 20 m of the Lease granite, 3 to 10 m below the contact pegmatite and is associated with the extensive chloritisation and sericitisation of the granite (Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1984; Coetzee, 1986; Coetzee and Twist, 1989; Vonopartis et al., 2020a).

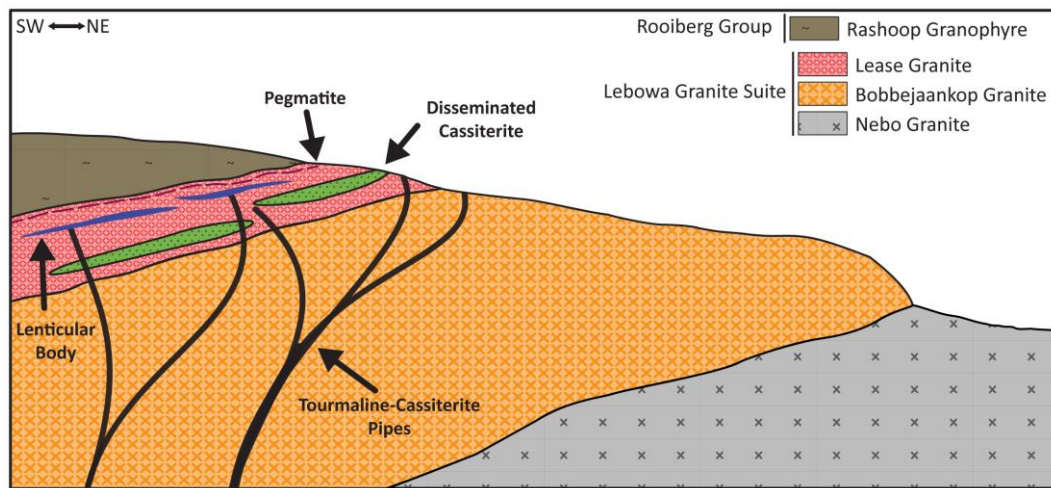


Figure 3.3. Schematic geological cross section across the Groenfontein tin mine from the Rashoop Granophyre Suite towards the Nebo granite (SW to NE) along line A-A' shown in Figure 3.2. After Vonopartis et al. (2020a).

The discontinuous lensoidal 2 to 5 m long pegmatites were historically used to demarcate the cryptic contact between the Lease granite and the Rashoop Granophyre Suite. They are typically barren, and primarily composed of pegmatitic quartz and reddened feldspars. At the Zaaipplaats tin mine cassiterite occurs in low-grade disseminated zones and in small clusters within the Bobbejaankop and Lease granites, additionally cassiterite is concentrated in large, high-grade lenticular and pipe-like ore bodies that are up to 25 m in diameter (Strauss and Truter, 1944; Coetzee, 1986; Coetzee and Twist, 1989; Crocker et al., 2001; Vonopartis et al., 2020a). In contrast, at the Groenfontein tin mine, all styles of mineralisation are restricted to the Lease granite (Strauss and Truter, 1944; Coetzee, 1986; Coetzee and Twist, 1989; Crocker et al., 2001; Vonopartis et al., 2020a).

3.2.4. Data and Methods

Acquired Data

Multispectral Satellite data

Geological spectral features are mostly situated in the short-wave infrared (SWIR) region of the electromagnetic spectrum, thus making the many SWIR bands available in the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data ideal for geological investigations (Rowan and Mars, 2003). ASTER data has a spatial resolution between 15 m and 30 m, with 14 multispectral bands; four bands in the visible and near-infrared (VNIR) range of the electromagnetic spectrum, six bands in the short wave infrared (SWIR) range and five bands in the thermal infrared (TIR) range (Table 3.1). The 90 m spatial resolution of the

TIR bands is too low for our investigation, therefore only the VNIR and SWIR spectral bands were utilised. Sentinel-2 data has a higher spatial resolution of 10 m to 20 m, with 13 multispectral bands; of these, 10 bands are situated in the VNIR range while only three bands are located in the SWIR region (Table 3.1). Characteristic spectral features of iron-oxides are located in the red-edge and near infrared region of the electromagnetic spectrum. Despite Sentinel-2 data being better suited for vegetation studies, the position of the VNIR bands make it advantageous for identifying iron-oxides (Van der Werff and Van der Meer, 2015). The satellite data used in this study was acquired over the Northern Limb of the Bushveld Igneous Complex during daytime with minimal cloud coverage. The ASTER data was downloaded from <http://earthexplorer.usgs.gov> and the Sentinel-2 data from <https://scihub.copernicus.eu> respectively.

The satellite data was processed and analysed with ENVI and ArcGIS. The geometrically corrected ASTER data was radiometrically corrected before the image processing stage. The conversion of the digital number (DN) to radiance was accomplished by radiometric calibration at sensor and corrected for radiometric artefacts (Schowengerdt, 2007; Young et al., 2017). Subsequently, the data underwent Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) atmospheric correction (with aerosol retrieval), that provided true surface reflectance values, accounting for the absorption effects of atmospheric gases, water vapour and aerosols (Matthew et al., 2002; Perkins et al., 2005; Schowengerdt, 2007; Young et al., 2017). Level 2A Sentinel-data is provided geometrically, radiometrically and atmospherically corrected, therefore making it ready to use.

The study area is located in a relatively dry region with an adequate amount of rock outcrop but in order to eliminate any remaining influence from vegetation, a vegetation mask was applied to both data sets. The mask is based on a normalised difference vegetation index (NDVI), which indicates areas with chlorophyll production and thus active vegetation. NDVI is an indicator of plant health based on how the plant reflects light at certain frequencies. NDVI is a simple band ratio: $(\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red})$ (Deering and Haas, 1980). Geological interpretation of the Sentinel-2 and ASTER imagery were validated by several field visits between 2017 and 2018, together with multiple surface traverses and a complementary field-portable XRF study of the area.

Table 3.1. Table of ASTER and Sentinel-2 spectral and spatial resolution.

ASTER				Sentinel-2			
	Band	Resolution			Band	Resolution	
		Spectral	Spatial			Spectral	Spatial
VNIR	1	520 - 600	15	Vis	1	423 - 463	60
	2	630 - 690	15		2	425 - 555	10
	3N	780 - 860	15		3	525 - 595	10
	3B	780 - 860	15		4	635 - 695	10
SWIR	4	1,600 - 1,700	30	NIR	5	690 - 720	20
	5	2,145 - 2,185	30		6	725 - 755	20
	6	2,185 - 2,225	30		7	763 - 803	20
	7	2,235 - 2,285	30		8	727 - 957	10
	8	2,295 - 2,365	30		8A	845 - 885	20
	9	2,360 - 2,430	30		9	925 - 965	60
TIR	10	8,125 - 8,475	90	SWIR	10	1,345 - 1,405	60
	11	8,475 - 8,825	90		11	1,520 - 1,700	20
	12	8,925 - 9,275	90		12	2,010 - 2,370	20
	13	10,250 - 10,950	90				
	14	10,950 - 11,650	90				

*Spectral resolution given in nanometres (nm) and spatial resolution given in metres (m).

*Abbreviations: Visible light (Vis); visible near-infrared (VNIR); short-wave infrared (SWIR); thermal infrared (TIR); and near-infrared (NIR).

Shuttle Radar Topography Mission (SRTM) digital elevation model

Numerous studies have shown the potential of Digital Elevation Models (DEMs) for analysing surface lineaments and, with geological inference, faults (e.g., Koike et al. 1998; Andreani et al. 2014). SRTM elevation data at a resolution of 1 arc-second (30 metres) was used in this study to delineate faults. The data was downloaded from the USGS Earth Explorer portal (<http://earthexplorer.usgs.gov>) and cropped to the study site. No prior processing was required.

In-situ pXRF measurements

A Thermo Scientific Niton XL3t GOLDD+ XRF Handheld Analyser gun, using an Ag anode (6-50 kV, 0-200 μ A max) was used for real-time in-situ lithochemical analyses of outcrop. The “Niton” was set up to analyse trace elements and placed flush against a flat outcrop surface. Concentrations of major and trace elements were recorded by the software provided with the Niton. Internal calibration by the on board Niton software, was run every 50 analyses. A total of 130 outcrops were analysed, each consisting of three discrete 90 second scans, within a 10 to 15 m radius. These points were subsequently averaged to represent one analysed outcrop. Relative standard deviation ($RSD = (stdv_i / mean_i) \times 100$) is used to assess precision

of the pXRF analyses (EPS, 2007; Durance et al., 2014). The RSD of Rb = 6.28 % , Sr = 12.40 %, and Ba = 6.38 %, which are all well below the accepted level of 20% for pXRF analyses, except for Sn which is slightly higher, at 26.47 %, and is attributed to values close to the detection limit of the pXRF (EPS, 2007; Durance et al., 2014). Keeping this in mind, without the normalisation of the pXRF data by a complementary whole-rock XRF analyses of analysed localities, this mapping technique is better suited for qualitative rather than quantitative approaches. While the pXRF is capable of analysing a suite of elements, this study exclusively discusses trace elements which are hydrothermally mobile such as Rb, Sr and Ba, whereas Sn was included as it is the commodity of focus within these granites. These elements are common proxies for the differentiation and fractionation of granites and we aimed to evaluate their viability as potential vectors for endogranitic tin mineralisation. The complete list of results for each analysed element during the pXRF mapping is provided in Appendix G. Other incompatible elements, such as Zr and Hf, were not included as they do not show a systematic spatial distribution or were not part of the suite of analysable elements by the Niton. The computer program ArcGIS was used for the spatial interpolation and construction of the geochemical isopleths.

3.2.5. Satellite data processing methods

Band ratios

Band ratios have been shown to be robust, long-established tools to discriminate lithologies in the field of geological remote sensing (e.g., Sabins, 1999; Yamaguchi and Naito, 2003; van der Meer, et al. 2012). A band ratio is the simple division of spectral bands to produce relative band intensities that can be displayed as images. This technique enhances specific spectral features within a multispectral data (Corrie et al., 2010; Rockwell, 2012; Lillesand et al., 2014; Asran et al., 2017).

Highlighting specific mineralogical/spectral features such as lithologies that are Fe-rich, oxidised or contain high proportions of select minerals, can be accomplished by exploiting their unique spectral characteristics (Sabins, 1999; van der Meer et al., 2012). This is achieved by dividing the wavelength corresponding with the maximum reflectance by the maximum absorption of the feature of interest (Corrie et al., 2010; Rockwell, 2012; Lillesand et al., 2014; Asran et al., 2017). The matching pixels are subsequently given a higher digital number (DN) value, enhancing specific spectral features in the resulting image (Corrie et al., 2010; Lillesand

et al., 2014; Asran et al., 2017). Iron-oxides have a characteristic spectral feature in the VNIR. Generally, the feature peaks around 750 nm then slopes down, forming a gully between 860 nm and 950 nm, depending on the specific iron-oxide mineral. Numerous studies have established the potential of using band ratios to distinguish iron-oxides (E.g., Van der Werff and Van der Meer, 2015; Ducart et al., 2016). A band ratio of B6/B8A was applied to the Sentinel-2 data to enhance iron-oxide occurrences. Band ratio $B63/(B7*B8*B9)$ (Bierwirth, 2002) was used on the ASTER data to identify chloritised areas and $(B5+B7)/B6$ (Rowan and Mars, 2003) was applied to identify muscovitic areas. Chloritised and muscovitic/sericitic zones have characteristic absorption features in association with FeOH around 2260 nm and AlOH around 2200 nm, respectively, and are used to discriminate typical alterations.

Support vector-machine (SVM)

Support vector-machine (SVM) is a supervised learning algorithm used for binary classifications or regressions first described by Cortes and Vapnik (1995). The idea is that there must be a function that explains patterns in terms of labels that should be estimated from training data but should also be able to explain unseen data, thus introducing a test error or risk function. Minimising the bounds of the test error leads to the principle of Structural Risk Minimisation based on the VC-Theory (Vapnik, 2000). SVM solves the classification problem by constructing an optimal hyperplane that separates the data in a so-called feature space, the dimension of which can be estimated using the VC-theory. Finding the hyperplane requires an optimisation based on a kernel (e.g. polynomial, Gaussian Radial Basis Function) and a relaxation term that allows the classification of non-separable cases. Cross-validation determines the kernel and regularisation parameters. It is important to note that not all the available training examples are used in the specification and description of the dividing hyperplane. The vectors that lie on the margin (known as support vectors) are the only points that designate the hyperplane of maximum margin (Mountrakis et al., 2011). SVM is therefore robust to unbalanced and noisy sample sets. SVM was applied to the ASTER data to classify the highly concentrated alteration zones in the Groenfontein and Zaaipplaats areas. Pixels in known areas of increased alteration were used as input training data.

Minimum noise fraction (MNF)

Minimum Noise Fraction (MNF) transformation is a noise filtering and dimensionality reduction method (Green et al., 1988). MNF is a type of principal component transformation

ordering the data based on the signal-to-noise ratio with the first few components or bands containing the most relevant information and the last components mainly containing noise (Boardman and Kruse, 1994). The method is composed of two steps; firstly a noise filtering using a covariance matrix, and secondly a linear transformation of mutually uncorrelated pixels with maximum variance applied (Schowengerdt, 2007; Gad and Raef, 2012; Lillesand et al., 2014). An MNF transformation is applied to the Sentinel-2 data in order to differentiate between zones of high variance when compared to the existing geological map, combined with field work, to extend specific lithological regions.

Topographic Position Index (TPI)

TPI is a topographic analysis method that provides a landscape classification, with positive values representing elevations higher than the neighbourhood and negative values when they are lower (Jenness, 2006). In doing so, the results are dependent on R, where large radii highlights major landscape units and smaller values reveal minor valleys and ridges. With a small window, the TPI enhances sharp prominent features in the landscape and helps fault mapping (Shahzad and Gloaguen, 2011).

3.2.6. Results

Satellite data

Lithological units were identified from a combination of visual interpretation of the remote sensing results, published geological maps and field investigations. Band combinations such as ASTER 248 allow a first order lithological mapping and the discrimination of the Rashoop Granophyre Suite, Bobbejaankop granite and Nebo granite, although they were unable to resolve the thin lenticular Lease microgranite.

The result from the band ratio $B6/B8A$, applied to Sentinel-2 data, indicates a differentiation between iron-rich and iron-poor regions (Figure 3.4a). A clear contact shown as a dashed line can be seen in Figure 3.4a that correlates with the contact between the Bobbejaankop and Lease granite in the Groenfontein area (Figure 3.2). The increased alteration zones, which are interpreted as hosting the cassiterite mineralisation, can be roughly distinguished by their increased amount of iron-oxides (Figure 3.4a). Chloritised areas are shown in red by the ASTER imagery based on a band ratio $B6^3/(B7*B8*B9)$ (Figure 3.4b). Contacts between highly and poorly chloritised areas in both the Zaaipplaats and Groenfontein regions are shown in dashed lines on Figure 3.4b. These contacts follow the same trend as

the contacts between the granites and alluvium lithologies seen in the Zaaipplaats and Groenfontein areas (Figure 3.2).

Muscovitic/sericite zones are represented in red on the ASTER imagery based on band ratio $(B5+B7)/B6$ (Figure 3.4c). The zones can be discriminated from muscovite-poor areas by the dashed lines on Figure 3.4c. The muscovite-rich zones follow a similar trend to that of the contacts between the granite and granophyre suite at Zaaipplaats and Groenfontein as seen in Figure 3.2. Increased alteration zones were classified using SVM on ASTER data (Figure 3.4d). The results illustrate the clear overlap of regions of classified alteration and previously mapped cassiterite occurrences known from field mapping and geochemical surveys.

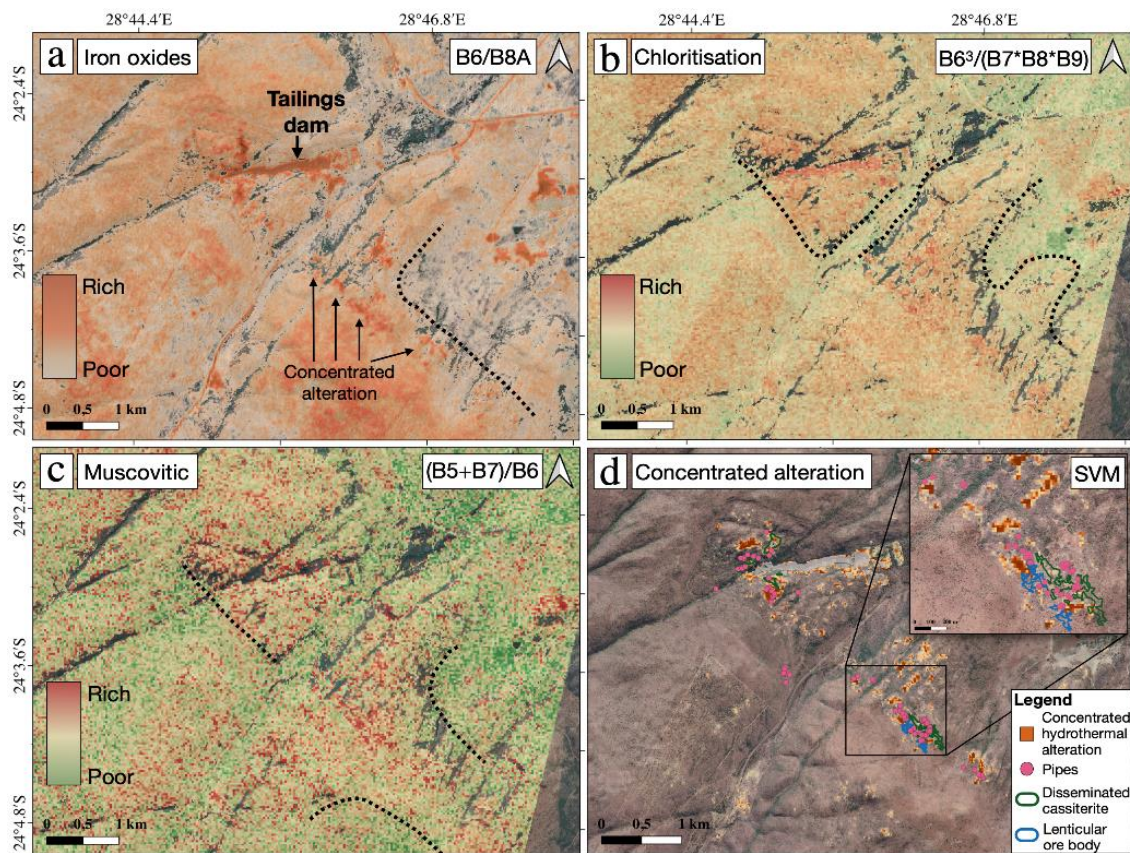


Figure 3.4. Band combination and SVM results from Sentinel-2 and ASTER data. (a) Result indicating iron-oxides occurrences in red on Sentinel-2 imagery based on band ratio $B6/B8A$. The dashed line indicates a contact between iron-poor and iron-rich regions while arrows point to highly concentrated alteration. (b) Image of band ratio $B6^3/(B7*B8*B9)$ indicating chloritised zones in red on ASTER imagery. Dashed lines show contacts between high chlorite content and low chlorite content regions. (c) Image based on band ratio $(B5+B7)/B6$ indicating muscovite rich areas in red on ASTER imagery. Dashed lines indicate contacts between muscovite-rich and muscovite-poor zones. (d) SVM result showing zones of highly concentrated alteration. The close-up inset highlights the overlapping of the classified concentrated zones and mapped occurrences of cassiterite.

The MNF result on the Sentinel-2 data set shows the 1st, 5th and 3rd components in the red, green and blue channels respectively (Figure 3.5). The main spectral differences that can be

observed in the resulting colour combination correspond with known lithological units. Thus, by comparing the MNF result with the geological map in Figure 3.2, trends in the lithological contacts can be delineated. Two clear contacts that correlate with the geological map are indicated with dashed lines named “A” and “B” in Figure 3.5. Line A on the MNF result follows the same trend as the known contacts between the Nebo and Bobbejaankop granites at the northern edge of Groenfontein. Line B follows the same trend as the contact that separates Lease granites from the Rashoop granophyre suite in existing geological maps.

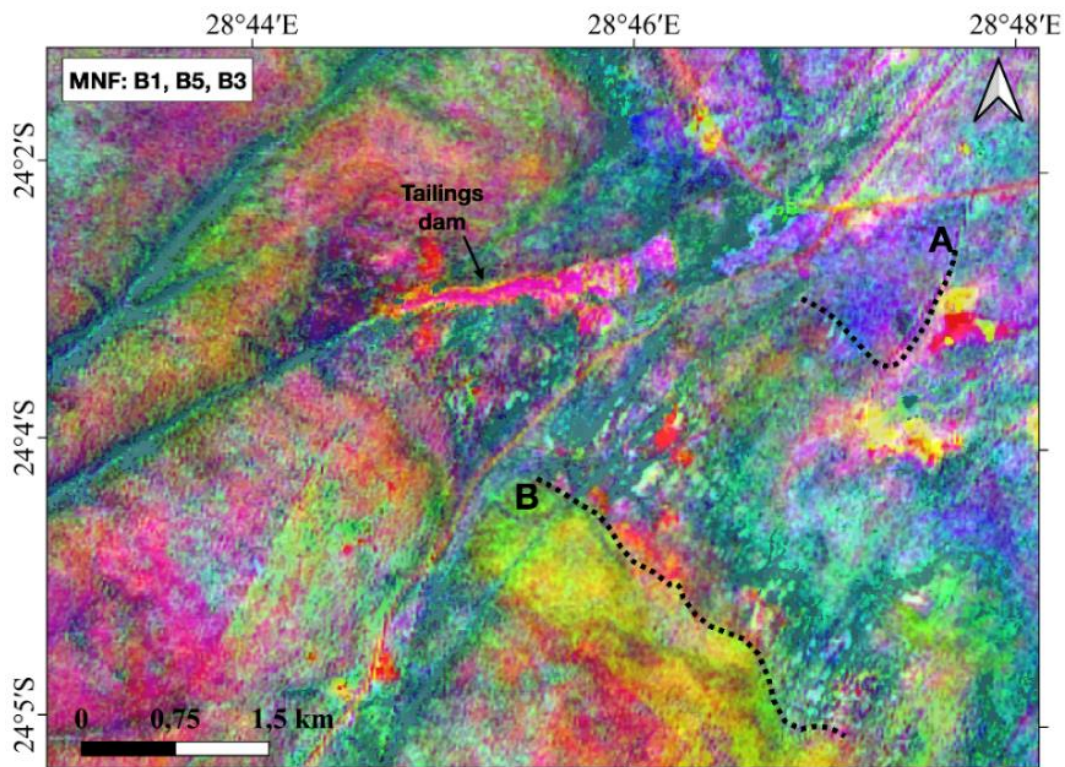


Figure 3.5. MNF result of Sentinel-2 data showing band 1, band 5 and band 3 in the red-green-blue channel respectively. Dashed lines A and B indicate clear spectral differences between areas corresponding with lithological contacts on the existing geological map.

A DEM was used to map the major faults in the region (Figure 3.6a). The TPI result shows values based on a pixel’s elevation relative to the average elevation of its neighbouring pixel. Faults would show up as lineaments in the result making them easier to delineate and are mapped in Figure 3.6b.

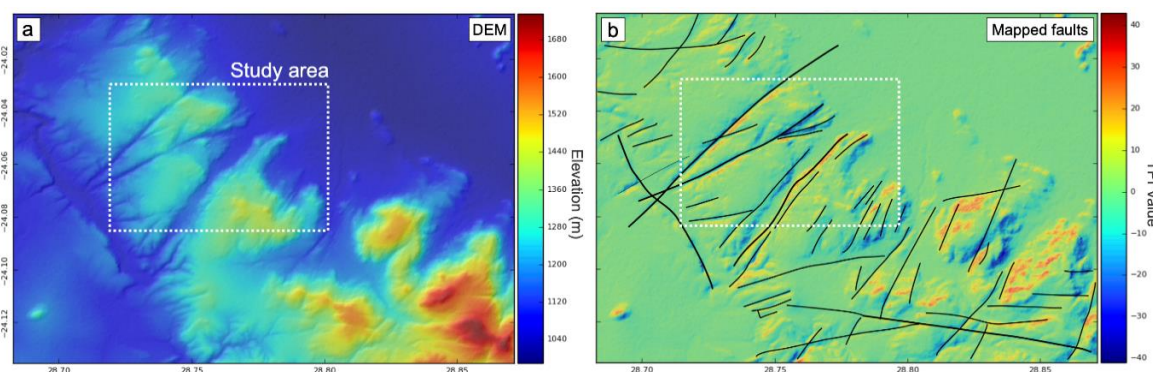


Figure 3.6. Digital elevation model and Topographic Position Index figures of the Zaaipplaats tin field. (a) DEM of the region indicating the location of the study area. (b) TPI result showing the mapped faults.

pXRF Geochemical Mapping

The samples selected to represent the lithological units were taken from reference locations (Figure 3.7). The standard rock types are shown in Figure 3.7a to d, whereas hydrothermally altered samples were selected from altered Bobbejaankop granite (Figure 3.7e) and Lease granite (Figure 3.7f).

Handheld XRF measurements from the Nebo and Bobbejaankop granites do not show an obvious geochemical distinction, which is not surprising given the wide gradational lithological contact described in field observations (Figure 3.8) (Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1984; Vonopartis et al., 2020a). There is a notable gradual increase in Rb from the Nebo granite in the northeast towards the Bobbejaankop and Lease granites in the southwest (Figure 3.8a). The Sr and Ba distribution displays a similar upward enrichment, although this abruptly decreases, defining a horizon, at the Bobbejaankop – Lease contact (Figures 3.7c and d). The Sn values mirror those of the LIL elements with an upward enrichment, reaching a maximum below the Bobbejaankop – Lease contact and a further concentration in the centre of the Lease granite (Figure 3.8e). The contact between the Lease granite and overlying Rashoop Granophyre Suite is delineated by a sharp increase in LIL elements which extend parallel to the marginal pegmatite along the contact with the Rashoop Granophyre Suite (Figures 3.8b and c).

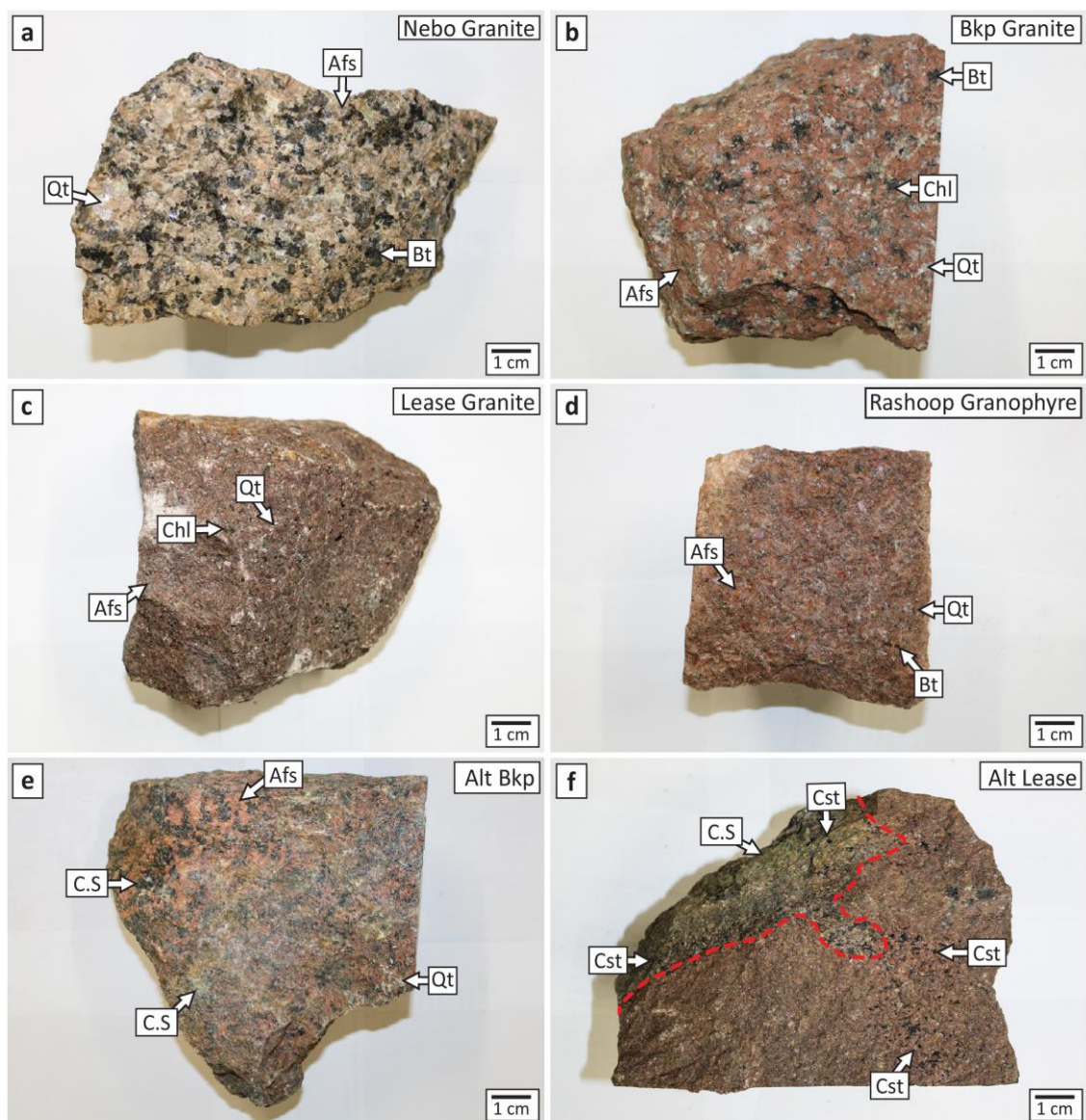


Figure 3.7. Hand specimen photographs of the lithologies and the hydrothermal alteration from the Zaaipplaats tin field. (a) Photograph of the Nebo granite composed of grey to pinkish/white alkali-feldspars (Afs), quartz (Qt) and interstitial biotite (Bt). (b) Photograph of the Bobbejaankop (Bkp) granite composed of synneusis-textured quartz grains, red alkali-feldspars and chloritised (Chl) biotites. (c) Photograph of the Lease granite composed of fine-grained quartz, red-alkali feldspar and chloritised biotites. (d) Photograph of the overlying Rashoop granophyre showing porphyritic alkali-feldspars, fine-grained quartz and interstitial biotite. (e) Photograph of an altered variety of the Bobbejaankop granite exhibiting variable chloritisation and sericitisation (C.S) of the biotite and alkali-feldspar. (f) Photograph of a partially chloritised and sericitised Lease granite associated with disseminated cassiterite (Cst). Dashed red line delineates the boundary between chloritisation and sericitisation within the fine-grained Lease granite.

The concentration of Rb increases towards the centre of the Lease granite, however the enrichment occurs in zones and does not span the length of the granitic body (Figure 3.8). These zones of Rb concentration commonly correspond with high Sn values and concomitant Sr and Ba lows (Figure 3.8).

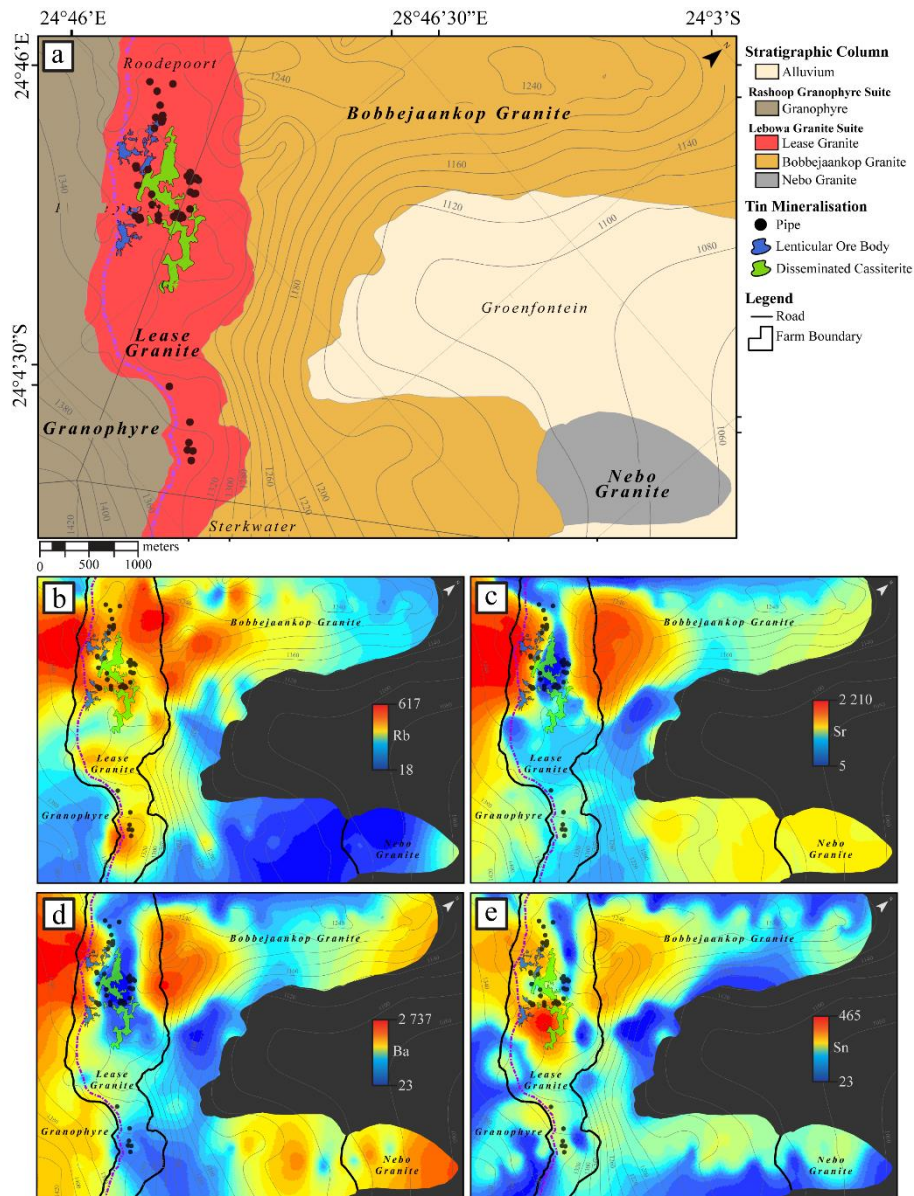


Figure 3.8. Geochemical isopleths produced by the pXRF mapping of the Groenfontein tin mine and surrounds. (a) Geological map of the field area covered by the pXRF mapping at the Groenfontein tin mine. Geochemical isopleths display the spatial distribution of (b) Rb, (c) Sr, (d) Ba and (e) Sn at the Groenfontein tin mine. Isopleths are overlain by lithological boundaries shown by black lines and locations of tin mineralisation same as in (a). Concentrations displayed on isopleths are in ppm. Grey regions (null data) identify alluvial cover.

The Bobbejaankop granite, stratigraphically below the disseminated mineralisation, exhibits the highest values of Rb, Sr, Ba and Sn. These high values abruptly terminate along the Bobbejaankop – Lease contact resulting in a horizon depleted in these elements (Figure 3.8). The Rb/Ba isopleth over the Groenfontein tin mine proves the most lithologically discriminative, as it effectively delineates the Lease granite sheet from the underlying Bobbejaankop granite (Figure 3.9). The Rb/Ba ratio increases from the base of the Bobbejaankop granite in the northeast towards the Lease granite in the southwest, which

displays the highest Rb/Ba ratios. The high Rb/Ba signatures are located towards the centre of the Lease granite and are spatially associated with regions of disseminated cassiterite (Figure 3.9). Furthermore, it is observed that the Bobbejaankop granite, stratigraphically below the Rb/Ba highs in the Lease granite, exhibit anomalously low Rb/Ba ratios (Figure 3.9).

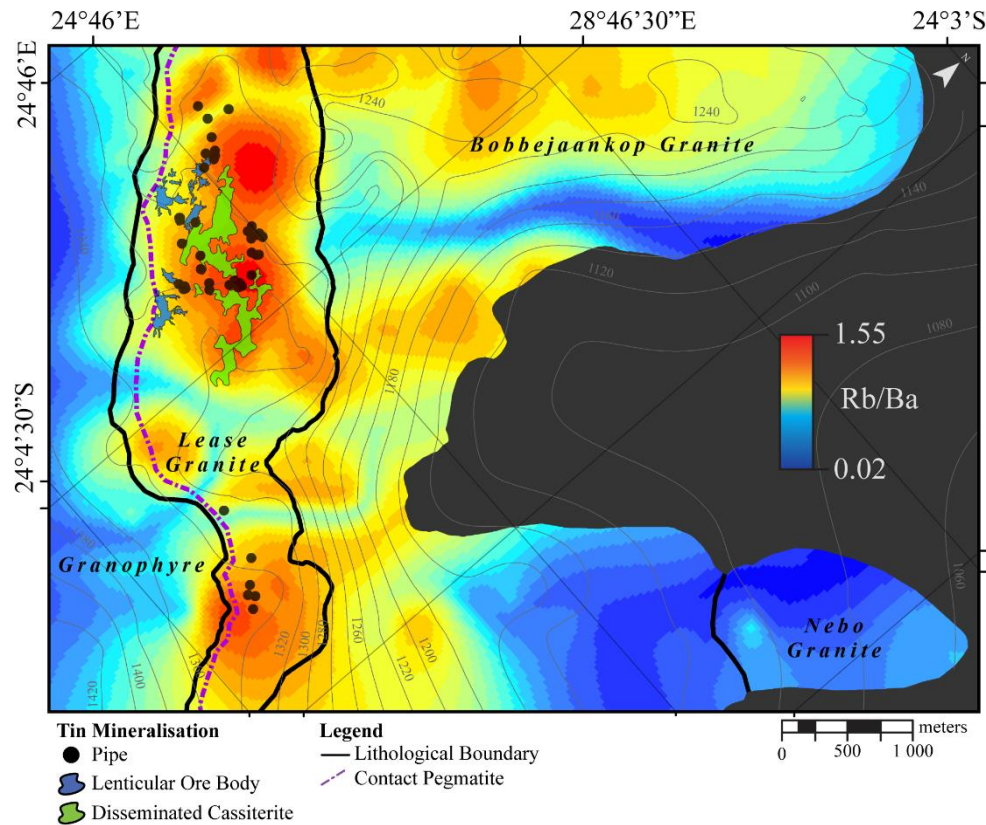


Figure 3.9. Chemical isopleth using Rb/Ba as an indicator for the extent of fractionation and magmatic-hydrothermal fluid accumulation within the granites of the Groenfontein tin mine. Features and lithologies are the same as in Figure 3.8.

The distribution of Sn is not as uniform within the Lease granite as that of Rb, Sr and Ba (Figure 3.10). The disseminated mineralisation appears to be restricted to regions that have Sn and Rb/Ba highs, whereas the mineralised hydrothermal pipes are also associated with a high Rb/Ba ratio, although they do not always share an increased Sn signature (Figure 3.8e). The location of the disseminated mineralisation appears to be correlated with a higher background concentration of Sn within the host granite. In contrast, the mineralised hydrothermal pipes do not share a spatial correlation with the distribution of Sn. However, the lenticular lenses are located directly above Rb/Ba highs, proximal to zones of Sn enrichment (Figure 3.9).

Integration of pXRF and satellite data

The pXRF analyses validate and complement the remote sensing results. For example, the SVM classification from Figure 3.4d, that indicates concentrated alteration zones, was overlaid with the in-situ pXRF results for Sn values at Groenfontein (Figure 3.10). A cluster of pXRF points enriched with Sn are located in the same area as the SVM classified concentrated alteration zones, which host cassiterite mineralisation.

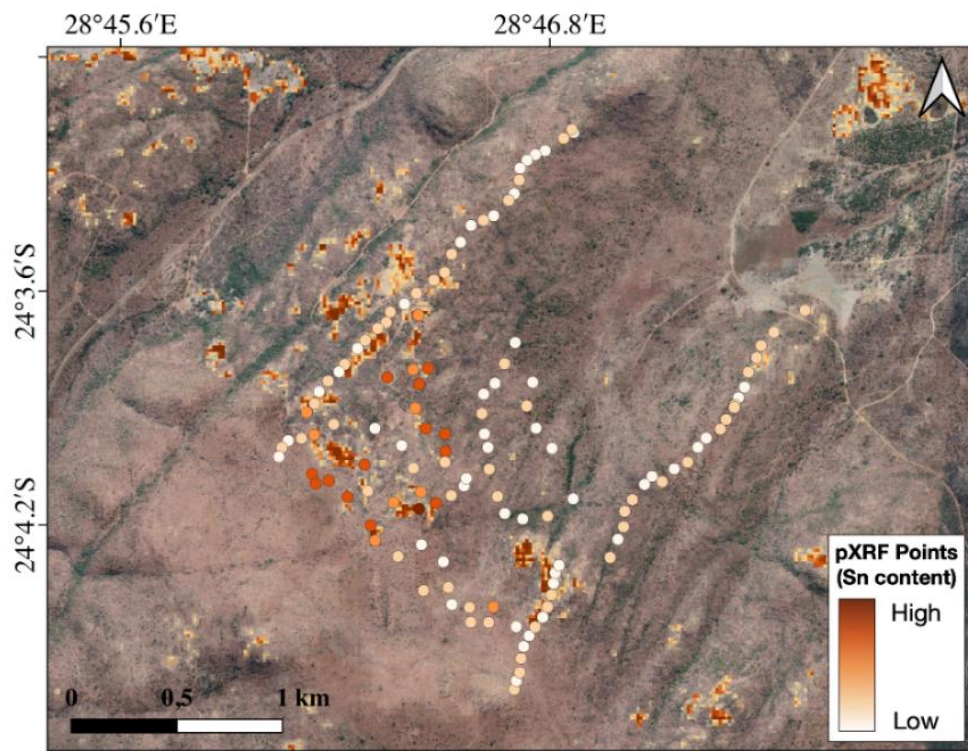


Figure 3.10. Integration of the in-situ pXRF results from Groenfontein and SVM result from the ASTER data in Figure 3.4d. The pXRF points indicate their relative Sn concentrations with deep red being enriched in Sn and light beige being Sn-poor.

The band ratios, SVM and MNF results were used in conjunction with the existing geological map and in-situ pXRF measurements to supplement fieldwork mapping and sampling strategy and to update the local geological map.

3.2.7. Discussion

The use of space-borne remote sensing for lithological mapping and mineralisation targeting has been successfully used in porphyry, gossan, greenstone, VMS, epithermal and other geological terranes (Sabins, 1999; Crosta et al., 2003; Yamaguchi and Naito, 2003; Corrie et al., 2010; van der Meer et al., 2012). However, the technique has not previously been used to identify areas of disseminated endogranitic cassiterite mineralisation. This research has shown that multispectral data processing over the Zaaiplaats tin field was able to distinguish

between the Rashoop Granophyre Suite, the Bobbejaankop granite and the Nebo granite, as well as zones of increased hydrothermal alteration associated with endogranitic tin mineralisation (Figure 3.11).

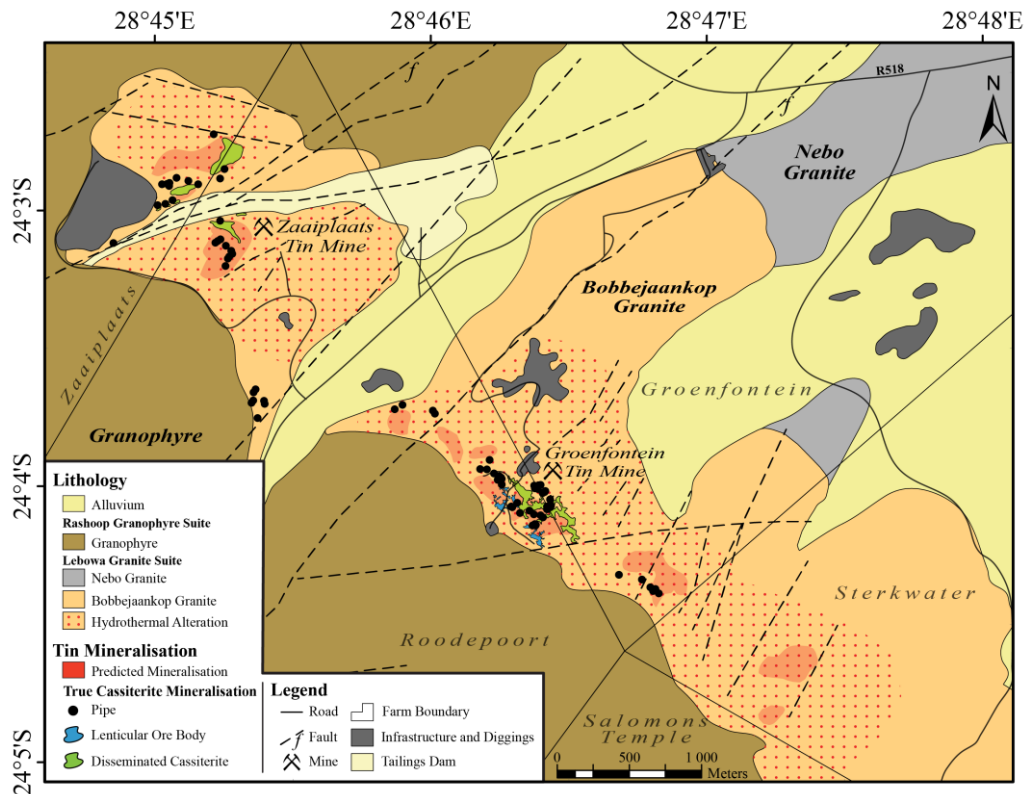


Figure 3.11. Alteration and geological map of the Zaaipplaats tin field generated from satellite data processing, field mapping and petrographic studies. Faults were mapped using TPI results and field verification. Locations of known cassiterite mineralisation have been superimposed on zones of predicted cassiterite mineralisation for comparison.

However, the space-borne multi-spectral data does not so easily distinguish the relatively thin Lease granite, which is mineralogically similar to and considered a hydrothermally altered facies of the Bobbejaankop granite (Coetzee, 1984; Vonopartis et al., 2020a). However, using the extent of the chloritisation and muscovitic signatures from the SWIR band ratios (Figure 3.4b, c), satellite imagery was able to infer the extent of the Lease granite, from the alignment of alteration hotspots, whereas pXRF mapping was geochemically able to distinguish the Lease from the Bobbejaankop granite (Figure 3.11). The overlap between the geochemical pXRF and spectral congruencies of the SVM result from the ASTER data is emphasised in Figure 3.10. Both methods highlight the same locations for strongly hydrothermally altered facies that commonly host disseminated cassiterite, thus demonstrating the compatibility of these methods and how their integration enhances their potential as exploration aids.

The combination of remote sensing data and pXRF isopleths shows an increasing magmatic-hydrothermal fluid overprint upwards towards the roof of the Bobbejaankop granite which allows a distinction to be made between altered and unaltered Bobbejaankop granite. Immediately beneath the Lease facies this intense hydrothermal overprint resulted in discrete zones of alteration, which typically host cassiterite mineralisation (Figure 3.11).

Distribution of trace elements such as Rb, Sr and Ba in granitic systems strongly depends on two factors. Firstly, the similarities in ionic properties that Rb^+ and Ba^+ share with K^+ , and Sr^{2+} shares with Ca^{2+} facilitates their substitution in feldspars (El Bouseily and El Sokkary, 1975; Ekwere, 1985; Icenhower and London, 1996). Therefore, the proportional difference in feldspar between the different granites is fundamental to the understanding of the variations in Rb, Sr and Ba distribution. The Nebo, Bobbejaankop and Lease granites in the study area are dominated by alkali-feldspar and share similar modal proportions (Strauss and Truter, 1944; Coetzee and Twist, 1989; Pollard et al., 1991b; Vonopartis et al., 2020a), thus the variation in Rb, Ba and Sr cannot be attributed to variations in feldspar abundance, rather, the distribution of Rb, Sr and Ba was controlled by their hydrothermal mobility (McCarthy and Hasty, 1976; Allegre and Minster, 1978; Hanson, 1978; Walraven et al., 1990; Icenhower and London, 1996; Spera et al., 2007). Fluid inclusion studies by Pollard et al. (1991a), show that the Zaaipplaats tin field evolved within a closed system, thus the LIL elements distribution reflects concentration by granitic fractionation and the subsequent mobilisation and accumulation of a late-stage magmatic-hydrothermal fluid.

Similarly, Sn and other HFS incompatible elements are concentrated during the fractionation of granites, and are readily mobilised by such magmatic-hydrothermal fluids, forming areas of economic mineralisation (Walraven et al., 1990; Williamson et al., 2010; Duchoslav et al., 2017; Simons et al., 2017). Therefore, mapping LIL elements distribution reveals regions of magmatic-hydrothermal fluid accumulation within these granites, providing a simple exploration tool in the identification of potential endogranitic mineralisation. Within the Groenfontein granites, we observe an accumulation of a LIL-element and Sn-enriched magmatic-hydrothermal fluid towards the roof of the intrusion. The areas where the Rb/Ba ratios are low, signifies zones of concentrated late-stage magmatic-hydrothermal rock-fluid interaction, in which LIL elements and Sn were scavenged, and subsequently concentrated in the overlying Lease granite. The disseminated mineralisation

and hydrothermal features of the lenticular ore-bodies and mineralised pipes, identified by the SVM classification, are clearly coupled to the Sn enrichment of the hosting granite (Figure 3.11). Additionally, hydrothermal alteration, such as greisenisation, further reduced the Ba content of granites, as it is leached from the feldspars by the fluid during alteration and not accepted in the new mica lattice (Ekwere, 1985; Walraven et al., 1990; Blevin and Chappell, 1992; Williamson et al., 2010; Simons et al., 2017). Moreover, Rb increased with late-stage magmatic-hydrothermal fluid alteration (Walraven et al., 1990; Williamson et al., 2010; Simons et al., 2017) therefore, together with a decreased Ba content, produces a higher Rb/Ba ratio of fractionated granites which have been altered by late-stage, possibly greisenising magmatic-hydrothermal fluids.

Regions that display a high Rb/Ba ratio and Sn content were subsequently verified by fieldwork to host disseminated cassiterite, and are mineralogically associated with increased chloritisation and sericitisation, attributed to the interaction with late-stage magmatic-hydrothermal greisenising fluids (Strauss and Truter, 1944; Coetzee, 1984; Coetzee and Twist, 1989; Vonopartis et al., 2020a). This emphasises that understanding and mapping the distribution and accumulation of such fluids within granites, together with remote sensing alteration mapping, can identify potential targets for endogranitic mineralisation.

3.2.8. Conclusions

The complementary combination of remote sensing and pXRF techniques, effectively enhances target identification in the exploration for endogranitic mineralisation in the Zaaipplaats tin field. The synergetic integration of these techniques proved capable of identifying existing zones of mineralisation, additionally highlighting previously unmapped regions of disseminated cassiterite. Approaching multispectral image processing with a geological understanding of the exploration area, proves effective in mapping and vectoring zones of potential mineralisation, by the targeting of key alteration signatures and geological characteristics. Various geologically informed and tailored processing techniques were able to discriminate the various granitic lithologies, while highlighting regions of increased hydrothermal (chloritised and sericitised) alteration. Integrating remote sensing with a pXRF trace element distribution study further enhances lithological mapping, and can compensate for muted lithological variations and the low spatial resolution of satellite imagery. Therefore, the qualitative pXRF mapping of the LIL element distribution, in conjunction with remote

sensing mapping demonstrates the ability to identify zones of magmatic-hydrothermal fluid accumulation.

The use of pXRF is not proposed as a substitute for traditional XRF analyses however, but is encouraged as a first order qualitative mapping and exploration technique. The combination of the evaluated techniques can be applied to other mineralised endogranitic terranes and would theoretically be effective in mapping other hydrothermally mineralised systems. The incorporation of hyperspectral analyses and geophysical exploration methods with these techniques would only enhance the efficiency and accuracy of exploration projects to evaluate mineralisation targets.

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Chapter 4

The metallogenic potential of African A-Type granites

4.1. Preamble

This chapter includes a review paper published in the journal *Lithos*, on the use of comparative geochemistry to investigate the overall similarities and contrasts between mineralised and unmineralised A-Type granite suites throughout the African continent. This has not previously been attempted. The mineralisation associated lithologies from the Lebowa Granite Suite, Nigerian and Namibian ring complexes are compared to the barren examples from the same suites, and granites from the unmineralised Gaborone Granite Suite and Sudanese Ring Complexes. The goal of this manuscript is to identify key differences and understand the underlying factors that separate mineralised and unmineralised A-Type granites. This provides valuable insight into the petrogenetic criteria that influences metallogenic potential and provides a clearer and more rapid discriminant for distinguishing economic from uneconomic A-Type granite suites.

4.1.2. Author Contributions

Leonidas Vonopartis was the main contributor to this paper. He did most of the field work, sample collection, sample preparation, data compilation and write-up of the manuscript. The co-authors, Paul Nex, Judith Kinnaird and Laurence Robb supervised and provided guidance in the development of the manuscript. Furthermore, the co-authors assisted with the field work, editorial review and the interpretation of the data.

Contribution percentage per author:

- | | |
|------------------|-----|
| 1. L. Vonopartis | 80% |
| 2. J. Kinnaird | 10% |
| 3. P. Nex | 5% |
| 4. L. Robb | 5% |

4.2. African A-Type granites: A geochemical review on metallogenic potential

L. C. Vonopartis, J. A. Kinnaird, P. A. M. Nex and L. J. Robb

*Published in **Lithos***

4.2.1. Abstract

Tin and other high-field-strength (HFS) elements are becoming increasingly significant, driven by technological advancements and a global effort to develop alternative energy solutions. A-type granites are associated with the mineralisation of these critical metals and therefore, investigating the influences on their metallogenic potential is essential for future exploration. The geochemical comparison between selected mineralised and unmineralised African A-Type granites, highlights the importance and implications of fractionation, crustal contamination, crustal emplacement and the composition and evolution of the magmatic-hydrothermal fluid in the development of endogranitic Sn mineralisation. Trace elemental ratios such as Zr/Hf, Nb/Ta and Y/Ho demonstrate the relationship between the degree of fractionation and interaction with acidic, F- and Cl-rich magmatic-hydrothermal fluids in these mineralised and barren African examples. Circumstantial differences in magmatic origin, not only directly influence the metallogenic budget of a granite but also influence the F and B content of the later stages of felsic magmatism. These volatiles prolong fractionation, consequently facilitating the likelihood of HFS element saturation and the development of an economic deposit. Moreover, the combination of continental setting and the enrichment of HFS and volatile elements by the assimilation of fortuitous crustal lithologies can upgrade an originally unfavourable magma composition, to one with a potential for mineralisation. It is therefore shown that mineralisation is ultimately achieved through a series of sequential, incompatible and HFS element enrichment stages which culminate in the accumulation of sufficient metals to produce economically significant mineralisation.

Keywords: A-Type, Anorogenic, African granites, Tin granites, Trace element geochemistry, metallogenic potential.

4.2.2. Introduction

The A-Type granite concept was originally defined by Loiselle and Wones (1979), referring to “Anorogenic”, “Anhydrous” or “Alkaline” granites, and has become a widely used term in granitoid petrology. The A-Type classification however, has subsequently been criticised by petrologists who argue ambiguity which stem from inherent assumptions. A comprehensive

review of this issue is discussed by Bonin (2007). A-type granitoids, although compositionally variable, share distinctive geochemical and mineralogical characteristics, justifying their classification within the granite family. They are characterised by high concentrations of large-ion lithophile (LIL) and high field-strength (HFS) elements, particularly Cs, Ga, Nb, Rb, Ta, Th, U, Y, Zr and REEs, and a depletion in Ba, Co, Cr, Ni, P, Sr, Ti and V compared to S- and I-Type granites (Collins et al., 1982; Eby, 1990, 1992; Bonin, 2007). These geochemical signatures are complimented by elevated SiO_2 , $\text{Na}_2\text{O} + \text{K}_2\text{O}$, F, Fe/Mg, Ga/Al and decreased Mg#, MnO and CaO (Collins et al., 1982; Eby, 1990; Bonin, 2007). Mineralogically, they comprise ferrous and alkali assemblages, including annite-siderophyllite, hastingsite-ferrohornblende and discrete perthitic alkali-feldspar phases (Collins et al., 1982; Eby, 1990; Bonin, 2007).

A-Type granites are not directly associated with orogenic events and develop in diverse geodynamic settings including continental and oceanic environments, and even other terrestrial planetary bodies. Despite their geological range, they characterise Earth's "Within Plate" terranes of stabilised crustal blocks (Bonin et al., 2002; Bonin, 2007). Their dynamic tectonic contexts and variable mineralogical and geochemical characteristics complicate the pursuit of an all-encompassing petrogenetic model. Thus, various hypotheses have been suggested for their genesis, including: the fractional crystallisation of mantle derived melts; partial melting of the mantle and lower crust; and mantle-crustal magma mixing (Collins et al., 1982; Eby, 1990, 1992; Bonin et al., 2002; Bonin, 2007; Frost and Frost, 2011; Grebennikov, 2014). Work by Eby (1992) improved the geochemical discrimination of A-Types. He proposed a further subdivision, based on LIL element variations inferring source and protolithic characteristics (Bonin, 2007; Grebennikov, 2014). Granitoids with a lower Y/Nb ratio (<1.2) are designated A1 and considered differentiates of ocean island basalt (OIB) and hot-spot magmas. Granitoids assigned as A2, exhibit higher Y/Nb ratios (>1.2) and are considered differentiates from tholeiitic magmas or partial melts of the lower continental crust.

Although A-Types are not as prolific as other granitoids, currently their association with critical metals such as Sn, Li, Nb, W and Rare Earth Elements (REE) make them economically relevant (Bonin, 1990, 2007; Grebennikov, 2014; Vasyukova and Williams-Jones, 2020). With the increasing economic importance of these metals, investigations into the metallogenic potential of A-Type granites call for greater attention. A-Type granite complexes, in an African context, are linked to the endo- and exogranitic mineralisation of various tin mineralised

regions, notably the Namibian, Nigerian and South African tin provinces (Kinnaird et al., 2016; Lehmann, 2020). The five African anorogenic complexes to be compared within this paper include the mineralised Nigerian, partially mineralised Namibian and barren Sudanese ring complexes, with the large igneous provinces (LIP) of the mineralised Lebowa Granite Suite and barren Gaborone Granite Suite (Figure 4.1). These A-Type occurrences cover a variety of crustal terranes including Archean cratons and Pan-African orogenic belts, with ages ranging from the Palaeoproterozoic to Mesozoic (Figure 4.1) (Norrish and Hutton, 1969; Milner et al., 1995; Wigand et al., 2004; Zeh et al., 2015; Girei et al., 2019; Kamaunji et al., 2020; Salih et al., 2020).

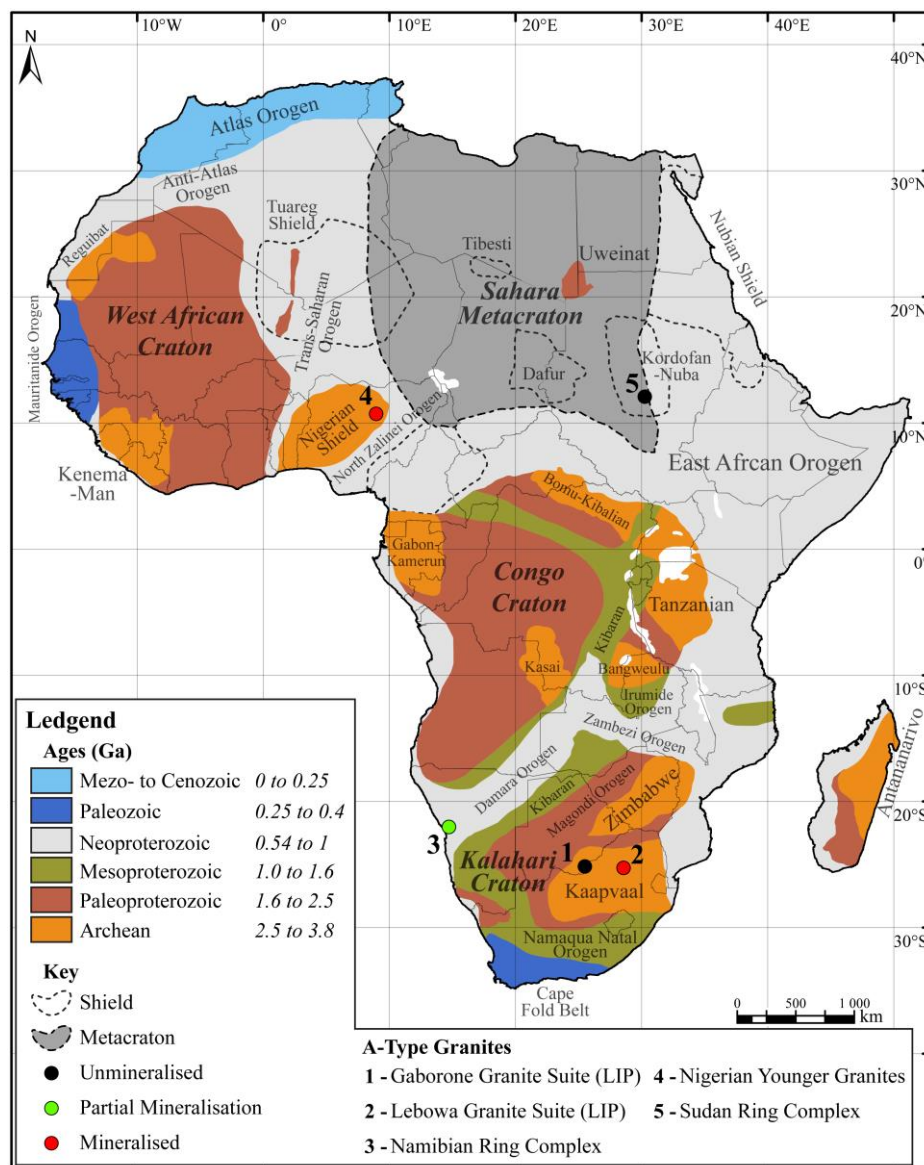


Figure 4.1. Simplified cratonic map of Africa showing various crustal terranes and their ages, modified after Van Hinsbergen et al. (2011) and Thiéblemont et al. (2016). The discussed African A-Type granite suites are shown with their corresponding mineralisation characterisation.

Despite the widespread occurrence of African A-Type magmatism, appreciable mineralisation is limited not only to a few granitic suites but also to particular facies therein. The stanniferous mineralisation of A-Type granites is commonly associated with fractionation and late-stage magmatic-hydrothermal fluids (Wolf et al., 2018; Girei et al., 2019; Vonopartis et al., 2020a), although the conditions which facilitate suitable fluid evolution and eventual mineralisation are poorly constrained. Therefore, the geochemical comparison of the main-stage granites from each of these examples, attempts to identify any variations or inheritances that influenced their metallogenic potential.

4.2.3. Regional Geology and Granite Petrography

This comparative investigation briefly describes the geological contexts and petrography of each locality. Greater detail on each granite suite can be sourced from cited publications.

Botswana

The A-Type Gaborone Granite Suite (GGS) and Kanye Volcanics comprise the Gaborone-Kanye Igneous Terrane in southeastern Botswana (Figure 4.1, 2). The granite suite covers approximately 6,000 km², from Jwaneng towards Derdepoort and southwards towards Mafikeng in South Africa (Figure 4.2). The GGS intruded into the Lobatse Volcanic Group and Archean basement granites, and is described as a mushroom-shaped, structurally-controlled intrusion with a concentric internal structure that grades outwards from coarse- to finer-grained granites (Sibiya, 1988; Aldiss et al., 1989; Grobler, 1996). The granitic suite is subdivided into the rapakivi textured Thamaga granite, at the centre, surrounded by the leucocratic Kgale granite, which is further divided into the coarse-grained leucocratic Main Phase and the texturally variable fine- to medium grained peripheral Marginal Phase (Figure 4.2) (Sibiya, 1988; Grobler, 1996).

The Thamaga Granite

The Thamaga rapakivi granite, is host to large white ovoid alkali-feldspar phenocrysts rimmed by a halo of grey plagioclase (Sibiya, 1988; Aldiss et al., 1989; Lowe, 1995; Grobler, 1996). The subhedral and slightly lobate plagioclase grains exhibit chloritisation and minor sericitisation. The fine- to medium-grained matrix comprises variable proportions of sub- to anhedral alkali-feldspar, subhedral plagioclase and quartz, intergrown with interstitial biotite, hornblende and accessory zircon, apatite, magnetite, rutile and aegirine (Sibiya, 1988; Aldiss et al., 1989;

Lowe, 1995; Grobler, 1996). The groundmass colour depends on the relative abundance and size of the phenocrysts and mafic components, resulting in categorisation of pink, leucocratic and melanocratic varieties (Sibiya, 1988; Aldiss et al., 1989; Lowe, 1995; Grobler, 1996).

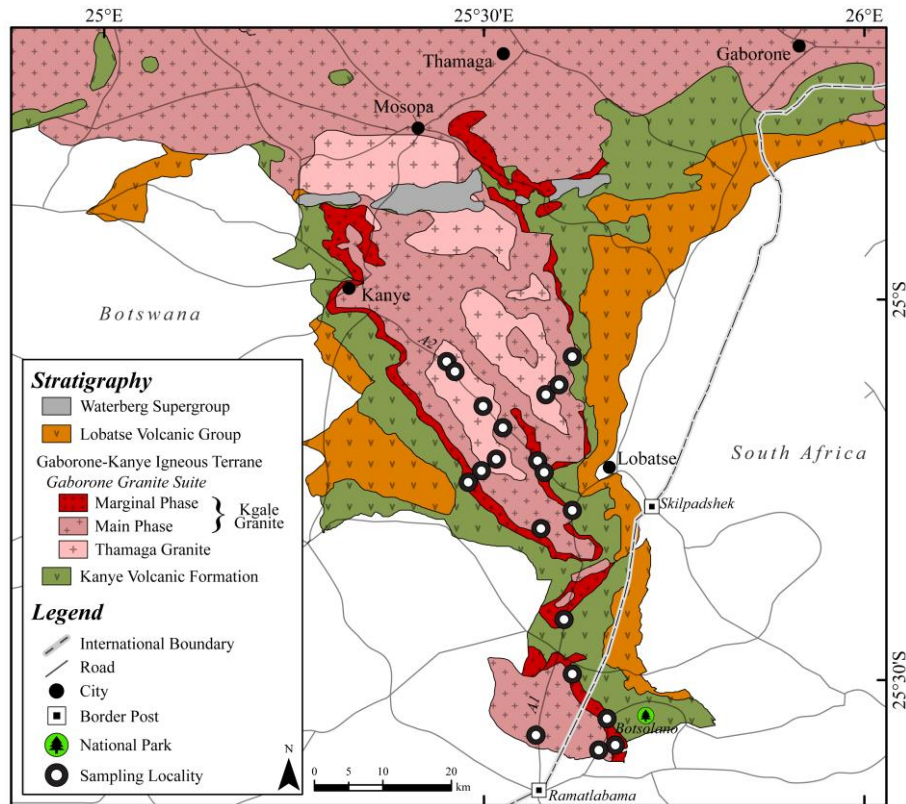


Figure 4.2. Regional geological map of the Gaborone-Kanye Igneous Terrane and sampling localities. Map produced from field validation and combination of published geological maps (Crockett, 1972; Lowe, 1995; Grobler, 1996).

The Kgale Granite

The *Main Phase* of the Kgale granite, is a coarse-grained leucogranite, principally composed of subhedral equigranular “blue” quartz, perthite and interstitial biotite. The rounded, quartz grains display a characteristic blue hue, attributed to acicular rutile inclusions (Grobler, 1996). Large braided micropertthites are rimmed by very fine-grained anhedral quartz crystals with interstitial aggregates of dark brown biotites, which have replaced hornblendes. The surrounding feldspars have been subsequently chloritised. Accessory phases include sub- to euhedral zoned zircons and anhedral grains of pyrite, ilmenite, rutile and magnetite (Lowe, 1995; Grobler, 1996).

The distinctly redder *Marginal Phase* of the Kgale granite is finer-grained, significantly more granophyric and hosts globular quartz. Although variable, the general mineralogy

consists of sub- to anhedral quartz and perthitic feldspars phenocrysts. The finer-grained groundmass comprises multiple types of granophyric intergrowth and fine-grained chlorite, biotite and acicular strings of aegirine (Grobler, 1996). The extensively chloritised micas host few relic brown biotites within a chlorite aggregate. Magnetite, rutile and zircon are accessory phases and occur interstitially and as inclusions (Grobler, 1996). The Marginal Phase becomes increasingly finer-grained and porphyritic towards the contact with the overlying Kanye Volcanics, marked by a simultaneously decreasing amount of aegirine and increasing proportions of hornblende and biotite proportions (Grobler, 1996).

Namibia

A series of anorogenic alkali ring complexes, part of the Paraná–Etendeka Igneous Province, is evidence of the hot-spot/plume which initiated the Cretaceous rifting of Gondwana and break away of South America (Pirajno, 1994; Renne et al., 1996). On the Namibian side, these complexes are subdivided into four provinces: the Damaraland alkaline province; the Auas province; the Luderitz province; and the Kuboos-Bremen igneous province (Pirajno, 1994). The Damaraland province hosts 21 alkaline volcano-plutonic A-Type ring complexes that intrude the Damara orogen and Karoo sequence (Figure 4.3a) (Bowden et al., 1990; Pirajno, 1994; Pirajno et al., 2000). The Erongo Ring Complex is one of the most notable and mineralised complexes of the Damaraland province, while the neighbouring Spitzkoppe complexes are uneconomic (Figure 4.3). The Erongo and Spitzkoppe granites are considered geochemically and mineralogically similar, although the Erongo is associated with tourmaline, NYF pegmatites and W, F, Sn, Be and U occurrences, whereas the Spitzkoppe only hosts semi-precious stones (Bowden et al., 1990; Pirajno, 1994; Haapala et al., 2007; Trumbull et al., 2008; Falster et al., 2018).

The Erongo Granite

The felsic intrusives of the Erongo Igneous Complex, known as the Erongo granites, are emplaced along the southern line of the Damaraland Alkaline Ring Complexes (Figure 4.3b) (Bowden et al., 1990; Pirajno, 1994). The 130 to 132 Ma Erongo granite was eccentrically emplaced alongside the basaltic ring dykes, brecciated ash flows/tuffs and rhyolitic plugs of the Erongo volcanics (Pirajno, 1990; Pirajno et al., 2000; Wigand et al., 2004). The main-stage Erongo biotite leucogranite is coarse- to medium-grained and principally composed of quartz, perthitic alkali-feldspar, albite with chloritised biotite and muscovite. Accessory minerals

include zircon, titanite, rutile, fluorite, apatite and topaz (Bowden et al., 1990; Pirajno, 1990, 1994; Pirajno et al., 2000; Trumbull et al., 2008; Boudreaux, 2014; Falster et al., 2018). A hallmark of the Erongo granite, which has been the basis of numerous studies, are the tourmaline orbicules concentrated in the granite cupola (Bowden et al., 1990; Pirajno, 1990, 1994; Pirajno et al., 2000; Trumbull et al., 2008). These are linked to the evolution of late-stage B- and F-rich magmatic-hydrothermal fluids that tourmalinised and mineralised the cupola. Additionally, these fluids subsequently escaped at various localities, greisenising and mineralising the overlying Erongo volcanics and Damara sequence, forming vein and stockwork HFS element mineralised greisens and NYF pegmatites (Pirajno, 1990, 1994).

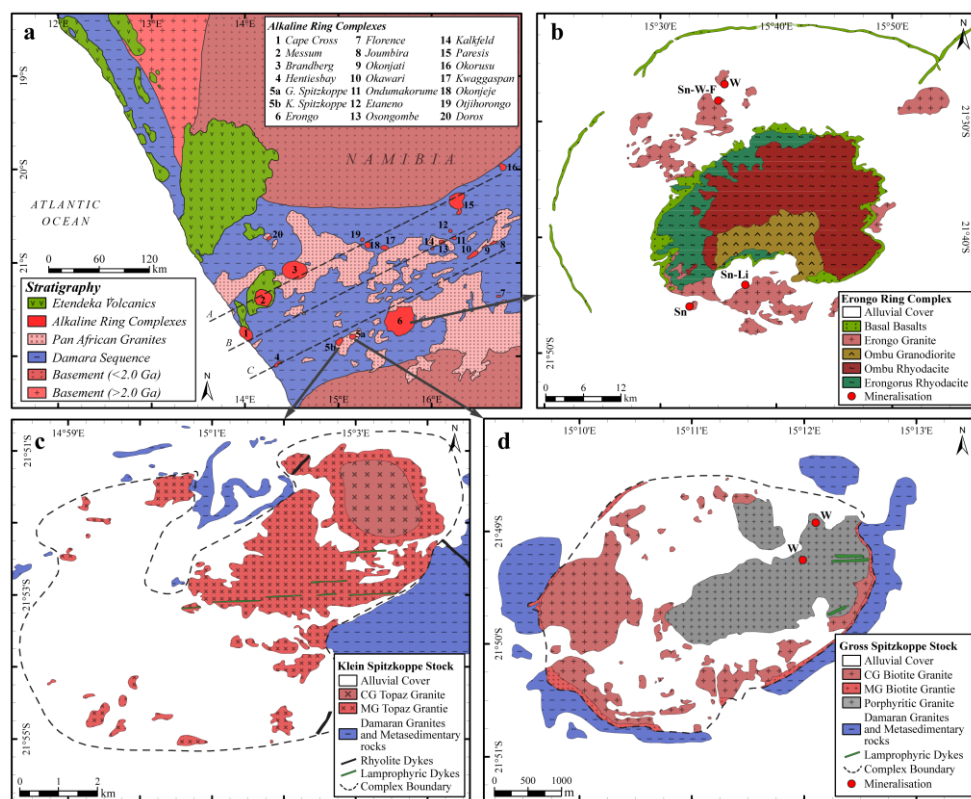


Figure 4.3. Simplified geological maps of the Namibian Damaraland A-Type Ring Complexes. (a) Regional overview of the Damaraland A-Type Ring Complexes. Dashed lines A, B and C represent the Northern, Central and Southern structural lineaments respectively. Simplified geological maps of (b) the Erongo Ring Complex, (c) the Klein Spitzkoppe Ring Complex and (d) the Gross Spitzkoppe Ring Complex. Geological maps constructed from the incorporation and modification of published geological maps (Pirajno, 1990, 1994; Frindt et al., 2004a; Haapala et al., 2007; Trumbull et al., 2010; Falster et al., 2018).

The Gross and Klein Spitzkoppe Granites

The Spitzkoppe granite stocks intruded the Kuiseb Formation along the southern structural lineament of the Damaraland Orogen, approximately 30 km southwest of the Erongo Complex

(Figure 4.3a, c, d) (Pirajno, 1994; Kandara, 1998; Frindt et al., 2004a; Frindt et al., 2004b; Haapala et al., 2007). These granites are composed of porphyritic to coarse-grained, fluorite-, apatite- and topaz-bearing leucogranites. Unlike the Erongo granite, the Spitzkoppe intrusives lack disseminated and orbicular tourmaline, although they host late-stage tourmaline-, amazonite-, topaz-, beryl-, aquamarine- and fluorite-bearing pegmatitic veins and cavities (Pirajno, 1994; Frindt et al., 2004a; Frindt et al., 2004b; Haapala et al., 2007).

The Gross Spitzkoppe stock comprises a central porphyritic granite, the main-stage coarse-grained biotite leucogranite and a medium-grained porphyritic marginal granite (Pirajno, 1994; Frindt et al., 2004a; Frindt et al., 2004b; Haapala et al., 2007). The volumetrically dominant biotite leucogranite is primarily composed of quartz, alkali-feldspar and partially altered, yet well preserved, interstitial biotite. There is notable topaz with accessory fluorite, alongside zircon, magnetite, rutile, columbite and monazite with miarolitic cavities in the marginal facies, containing gem-quality topaz and aquamarine (Pirajno, 1994; Kandara, 1998; Frindt et al., 2004a; Frindt et al., 2004b; Haapala et al., 2007). The co-genetic Klein Spitzkoppe stock is petrographically similar to the Gross Spitzkoppe and is subdivided into the coarse- and medium-grained topaz-bearing leucogranites composed of quartz, perthitic alkali-feldspar, plagioclase and partially greisenised biotite.

Nigeria

The Nigerian Younger Granites are the classic example of anorogenic ring complexes, which represent episodic magmatism and volcanism during plate migration over a hot-spot/plume (Bowden et al., 1976; Rahaman et al., 1984; Kinnaird, 1985; Kinnaird, 1987). The Nigerian Ring Complexes extend over 400 km from Dutse (213 Ma) in the north to Afu (141 Ma) in the south, systematically younging southwards from the Triassic to late Jurassic (Figure 4.4a) (Rahaman et al., 1984; Kinnaird, 1985; Kamaunji et al., 2020). Each complex represents an exposed volcanic root, which intruded the migmatitic gneisses of the Precambrian basement (Bowden et al., 1976; Rahaman et al., 1984; Kinnaird, 1985; Kinnaird, 1987). These ring complexes are structurally controlled by N-S trending shear zones and cratonic lineaments from the amalgamation of Gondwana and the later Pan-African Orogeny. The complexes host economically significant tin, niobium, molybdenum and other HFS and REE mineralisation (Kinnaird, 1985; Kinnaird, 1987; Kamaunji et al., 2020) and provide significant geological insight into anorogenic magmatic processes. Therefore, the main-stage biotite granites of the

considerably mineralised Ririwai Complex and the neighbouring and similarly aged yet barren Kudaru Complex, are used as contrasting examples of the Nigerian Younger Granites (Figure 4.4).

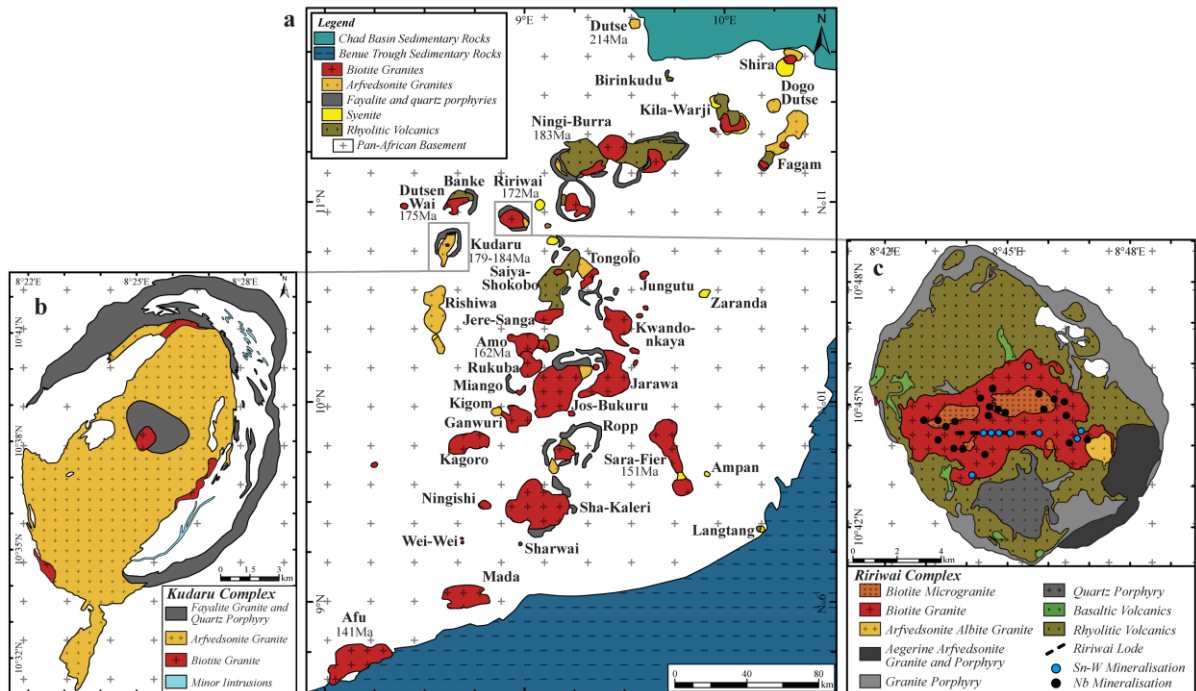


Figure 4.4. Simplified geological map of the Nigerian Ring Complexes. (a) Simplified geological overview of the Younger Granite ring complexes of Nigeria. Simplified geological maps of (b) the Kudaru Ring Complex and (c) the Ririwai Ring Complex. Geological maps constructed from the incorporation and modification of published geological maps (Kinnaird, 1985; Kinnaird et al., 1985; Girei et al., 2019; Kamaunji et al., 2020).

The Kudaru Ring Complex

The 179 to 184 Ma Kudaru Complex, 25 km southwest of the Ririwai Complex, intruded the polymetamorphic Precambrian gneisses to form a 168 km² ring complex (Figure 4.4a, b) (Bain, 1934; Kinnaird, 1985; Kamaunji et al., 2020). The main lithologies consist of a ring dyke of fayalite quartz-porphyry, surrounding a predominantly arfvedsonite granite core and exposures of Precambrian basement (Figure 4.4b) (Bain, 1934; Kamaunji et al., 2020). Multiple smaller plutons of biotite granite are scattered within the ring complex, sporadically intruding the arfvedsonite granite. The medium-grained biotite leucogranite consists of perthitic alkali-feldspar, quartz, plagioclase and interstitial partially chloritised biotites with accessory zircons (Bain, 1934; Kamaunji et al., 2020).

The Ririwai Ring Complex

The slightly younger (169 to 172 Ma) Ririwai Complex may be one of the most well studied anorogenic ring complexes, as it was one of the first in Nigeria to be identified in addition to hosting significant Sn-W and Nb mineralisation (Figure 4.4c) (Kinnaird, 1985; Kinnaird et al., 1985; Kinnaird, 1987; Ogunleye et al., 2006; Girei et al., 2019). The Ririwai Complex consists of a marginal ring of granitic-, quartz- and aegirine-arfvedsonite porphyries, which surround rhyolitic-ignimbrites and exposures of Precambrian basement (Kinnaird et al., 1985; Girei et al., 2019). A coarse-grained biotite leucogranite forms the centre of the complex, with a fine-grained biotite microgranitic core and a satellite arfvedsonite granite intrusion to the east (Kinnaird et al., 1985; Girei et al., 2019). The biotite granite is composed of microperthitic alkali-feldspar, quartz, plagioclase, chloritised biotites with accessory zircon and fluorite. There is extensive alteration of the biotite granite, associated with the 3 km long quartz-greisen vein system of the central lode (Kinnaird et al., 1985; Girei et al., 2019). Alteration around the central lode grades outwards from greisen to a reddened microclinised and chloritised granite (Kinnaird, 1985; Kinnaird et al., 1985; Girei et al., 2019). The central lode hosts most of the mineralisation (Sn-W-Nb and sulphides) with disseminated cassiterite and columbite in the granite cupola (Kinnaird, 1985; Kinnaird et al., 1985; Girei et al., 2019).

South Africa

The Lebowa Granite Suite (LGS) is the felsic component of the Bushveld Igneous Complex (BIC) and comprises the coarse-grained Nebo, Makhutso and Bobbejaankop granites and the fine-grained Klipkloof and Lease granites (Robb et al., 2000; Zeh et al., 2015). The Nebo granite intruded above the Rustenburg Layered Suite (RLS), into the Palaeoproterozoic upper Pretoria Group and beneath the overlying Rhashoop Granophyre Suite and Rooiberg Group (Figure 4.5) (SACS, 1980; Crocker et al., 2001; Skursch et al., 2020). The homogeneous Nebo granite gradually evolved from a hornblende-bearing granite at its base to a biotite granite in the roof. Mineralisation, directly associated with the Nebo granite is restricted to the roof of the pluton, within distinct facies such as the Bobbejaankop and Lease granites, and occasionally within the overlying sediments, as seen in the Rooiberg tin fields (Wilson and Anhaeusser, 1998; Crocker et al., 2001; Labuschagne, 2004).

The BIC contains six tin fields, of which the most notable and economically significant are the exogranitic tin-bearing veins of the Rooiberg tin field and the endogranitic mineralisation

of the Zaaipplaats tin field (Figure 4.5a) (Wilson and Anhaeusser, 1998; Crocker et al., 2001). At Zaaipplaats, between 1908 and 1989, approximately 37,079 t of tin metal was mined from disseminated, as well as highly mineralised hydrothermal pipes and lenses from the Bobbejaankop and Lease granites (Figure 4.5c) (Wilson and Anhaeusser, 1998; Crocker et al., 2001; Kinnaird et al., 2016; Vonopartis et al., 2020a). These stanniferous granites of the Zaaipplaats tin field are interpreted to be the result of an increasing degree of hydrothermal alteration in the roof facies of the Nebo granite (Vonopartis et al., 2020a), and are therefore used as an analogue for endogranitic A-Type tin mineralisation.

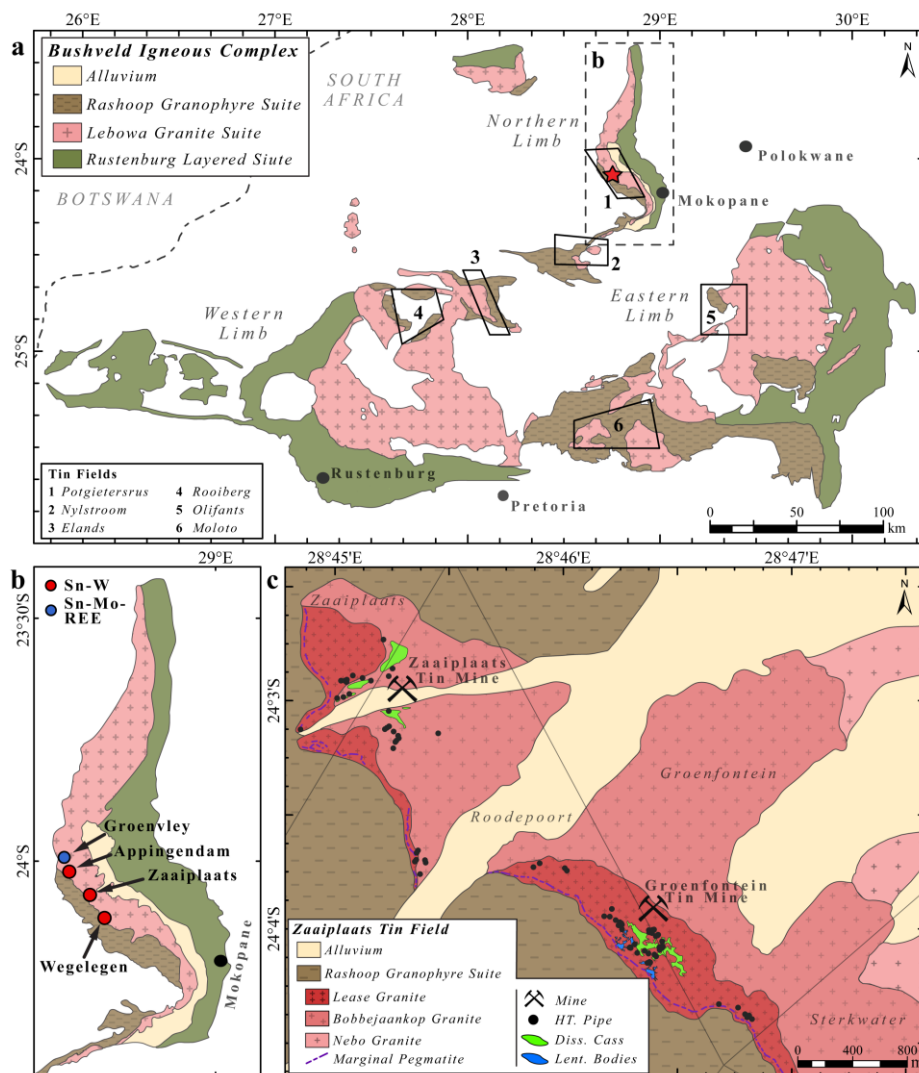


Figure 4.5. Simplified geological maps of the Bushveld Igneous Complex and Zaaipplaats tin field of the Northern Limb. (a) Regional scale geological map of the Bushveld Igneous Complex and the various tin fields. (b) Simplified geological map of the Northern Limb of the Bushveld Igneous Complex. (c) Geological map of the Zaaipplaats tin field showing various styles and locations of endogranitic cassiterite mineralisation. Red star represents Zaaipplaats tin field. Geological maps constructed from the incorporation and modification of published geological maps (Hunter, 1975; Coetzee, 1984; Wilson and Anhaeusser, 1998; Vonopartis et al., 2020a).

The Nebo Granite

Within the vicinity of Zaaiplaats, the Nebo is a coarse-grained leucogranite and composed of sub- to anhedral quartz, larger subhedral turbid alkali-feldspars and minor plagioclase (Strauss, 1954; Kleemann and Twist, 1989; Hill et al., 1996; Vonopartis et al., 2020a). Interstitial pale-green/blue hornblendes are replaced by brown biotites that are subsequently altered to a pale-green chlorite (Strauss, 1954; Kleemann and Twist, 1989; Hill et al., 1996; Vonopartis et al., 2020a). Perthitic feldspars exhibit braided, patchy and chessboard exsolution textures commonly hosting biotite inclusions. Individual plagioclase crystals are rare as most appear to be microclinised, becoming increasingly turbid. Accessory euhedral zircons are present and occurrences of interstitial fluorite are recorded closer to the contact with the overlying Bobbejaankop granite (Strauss, 1954; Kleemann and Twist, 1989; Hill et al., 1996; Vonopartis et al., 2020a).

The Bobbejaankop Granite

Fractional crystallisation of the Nebo granite and subsequent alteration by F-rich hydrothermal fluids resulted in the brick-red Bobbejaankop granite that crystallized in the apical portions of the former (Strauss, 1954; Coetzee, 1984; Coetzee and Twist, 1989; Kleemann and Twist, 1989; Vonopartis et al., 2020a). It is composed of subhedral synneusis-textured quartz, sub- to anhedral perthitic alkali-feldspars, and extensively chloritised interstitial brown biotites (Strauss, 1954; Coetzee, 1984; Coetzee and Twist, 1989; Kleemann and Twist, 1989; Vonopartis et al., 2020a). The biotites are largely chloritised and become increasingly more altered and sericitised towards the contact with the overlying Lease granite. Small inclusions of rutile, cassiterite and Fe-oxides decorate the relict cleavages of the chloritised biotite (Vonopartis et al., 2020a). Greisenisation has resulted in a very fine-grained pale green/white micaceous aggregate that replaced feldspar, chlorite and biotite, which occasionally developed larger grains of highly birefringent white dioctahedral micas (Coetzee, 1984; Vonopartis et al., 2020a). Fluorite is a ubiquitous interstitial phase closely associated with sericitisation. Mirolitic cavities are typically filled with inward-projecting quartz crystals, reddened feldspars, fluorite and occasionally cassiterite. Tourmalinisation is present in the upper facies of the Bobbejaankop, primarily occurring as radial fans of blue/green to brown tourmaline within orbicules and hydrothermal pipes (Strauss, 1954; Coetzee, 1984; Vonopartis et al., 2020a).

The Lease Granite

The microgranitic Lease facies beneath the overlying Rashoop Granophyre Suite, forms the altered roof facies of the Bobbejaankop granite (Figure 4.5c) (Strauss, 1954; Coetzee, 1984; Crocker et al., 2001; Vonopartis et al., 2020a). The Lease microgranite is described as a metasomatically altered brick-red microgranite, composed of sub- to anhedral graphically intergrown quartz and perthitic alkali-feldspar. The Lease granite shows pervasive sericitic alteration, complete chloritisation of biotite and patches of epidotisation (Crocker et al., 2001; Vonopartis et al., 2020a). Mirolitic cavities are characterised by inward-projecting euhedral quartz, reddened feldspars, calcite, fluorite, epidote and occasionally cassiterite. Cassiterite is typically interstitially disseminated, although it also occurs as small clusters and is most abundant within large tourmaline-rich hydrothermal pipes (Coetzee and Twist, 1989; Crocker et al., 2001; Vonopartis et al., 2020a). Fluorite is interstitially disseminated and commonly associated with mica alteration and greisenisation, alongside accessory phases such as zircon, pyrite with minor chalcopyrite and scheelite. Small disseminated patches and tourmaline orbicules, similar to the Erongo granite, are common in the Lease granite, although tourmaline is significantly more abundant in the large mineralised hydrothermal pipes (Vonopartis et al., 2020a).

Sudan

Detailed geochemical analyses and research on the petrogenesis and mineralisation of the alkali-ring complexes of Sudan is limited, in spite of their extent from the North to the South of Sudan, and into the neighbouring countries of Libya, Egypt, Ethiopia and Uganda (Vail, 1985, 1989; Salih et al., 2020). There is no major recorded economic mineralisation associated with these ring complexes, although a minor fluorite occurrence is noted in the Nuba Mountains of central Sudan (Vail, 1985, 1989; Ismail et al., 2015). These alkaline intrusions have been grouped into three belts: the South-Western; Central; and North-Eastern belts (Vail, 1985, 1989), of which the El Dair Ring Complex, part of the Central Belt of the Nuba Mountains, has been selected for this investigation (Figure 4.6).

The El Dair Complex

The Neoproterozoic (560 to 600 Ma) El Dair Complex 10 km southwest of the J. Dumbeir syenite-carbonate complex, is part of the North-Eastern Belt, intruding the high-grade gneissic basement of the Nuba Mountains inlier (Figure 4.6) (Vail, 1985; Salih et al., 2020).

The granites of the El Dair Complex comprise primarily pink to grey, alkaline-peralkaline coarse-grained granites, composed of perthitic alkali-feldspar, quartz, plagioclase, biotite and hornblende with accessory zircon (Vail, 1985; Salih et al., 2020). This ring complex, with many others, does not host, nor is associated with any recorded forms of HFS element mineralisation.

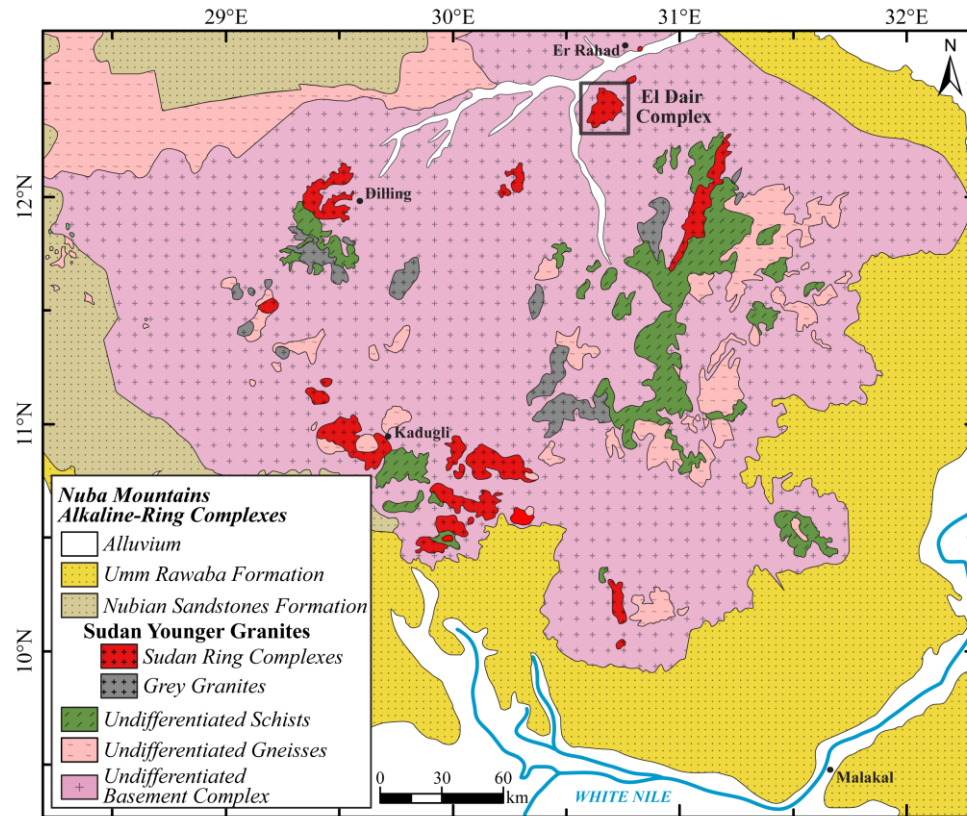


Figure 4.6. Simplified geological map of the Younger Granites of the Nuba Mountains region, Central Sudan. Geological map constructed from the modification and incorporation of published geological maps (GMRD-Sudan, 1981; Vail, 1985; Salih et al., 2020).

4.2.4. Analytical Techniques

Whole-rock geochemical analyses of the Thamaga and Kgale granites were undertaken using the Norrish Fusion (Norrish and Hutton, 1969) technique with in-house correction procedures and using a Panalytical PW2404 X-ray fluorescence (XRF) spectrometer at the Earth Lab of the University of the Witwatersrand, Johannesburg (Appendix C-2). Samples for XRF majors and ICP-MS traces were prepared and run according to standard procedures using the methodology described in Wilson (2012). Samples were crushed in a carbon-steel jaw crusher and milled in a carbon-steel swing mill. Major elements were fused using Johnson Matthey Spectroflux 105 at 1100 °C. The raw data was corrected using in-house software and standard

calibrations were made using synthetic oxide mixtures, international standard rocks and in-house controls. Primary International Reference Materials USGS series (USA) and NIM series (South Africa) were used as calibration standards. Trace elements were determined using the Perkin Elmer DRC-e inductively coupled plasma mass spectrometer (ICP-MS) and analysed against certified primary solution standards. International reference materials AGV-2, BCR-1 and BR-1 were analysed with every run, ensuring the reliability of the data. A total of nineteen samples from the GGS including six from the Thamaga granite, six from the Kgale Main Phase granite and seven from the Kgale Marginal Phase granite were collected in-situ (Figure 4.3). The geochemical data from the other African A-Type granitic suites is compiled from recent publications and, where possible, augmented by older whole-rock analyses (Table 4.1).

Table 4.1. A summary of the various African A-Type granite whole rock geochemical sources and mineralisation grouping.

Lithology/Complex	Granite Type	Mineralisation	Age	Data Sources
Botswana				
Thamaga Granite	Hbl/Bt Rapakivi Granite	Unmineralised	2.78 Ga	This Study
Kgale – Main Phase	CG Hbl/Bt Granite	Unmineralised		
Kgale – Marginal Phase	FG Hbl/Bt Granite	Unmineralised		
Namibia				
Erongo Complex	CG Bt Granite	Minor	130 to 132 Ma	Frindt et al. (2004a); Wigand (2005); Haapala et al. (2007) and Falster et al. (2018).
Gross Spitzkoppe	CG/MG Bt Granite	Unmineralised	125 ± 1 Ma	
Klein Spitzkoppe	CG/MG Bt Granite	Unmineralised		
Nigeria				
Kudaru Complex	CG Bt Granite	Unmineralised	179 to 184 Ma	Batchelor and Bowden (1986); Kinnaird (1987); Ogunleye et al. (2006); Girei et al. (2019) and Kamaunji et al. (2020).
Ririwai Complex	CG Bt Granite	Mineralised	169 to 172 Ma	
South Africa				
Nebo Granite	CG Hbl/Bt Granite	Unmineralised	2.056 Ga	Kleemann (1985); Hill et al. (1996); Bailie and Robb (2004); Labuschagne (2004) and Vonopartis et al. (2020a).
Nebo Granite (ZP)	CG Bt Granite	Minor		
Bobbejaankop Granite	CG Bt Granite	Mineralised		
Lease Granite	FG Bt Granite	Mineralised		
Sudan				
El Dair	CG Hbl/Bt Granite	Unmineralised	560 to 600 Ma	Salih et al. (2020)

Abbreviations: Coarse-grained (CG); Medium-grained (MG); Fine-grained (FG); Hornblende (Hbl); Biotite (Bt); Zaaipiaats (ZP).

4.2.5. Results

Whole Rock Geochemistry

The A-Type affinity of these African examples is well documented on numerous tectonic discrimination diagrams (see citations in Table 4.1), yet their alumina saturation index (ASI) classification ranges from *peralkaline*, *metaluminous* to *peraluminous* (Figure 4.7a and b). The barren granites have a larger ASI range although are primarily *metaluminous*, with the El Dair and select samples of the greater Nebo granite plotting as *peralkaline* (Figure 4.7a), whereas mineralised complexes are more *peraluminous* (Figure 4.7b).

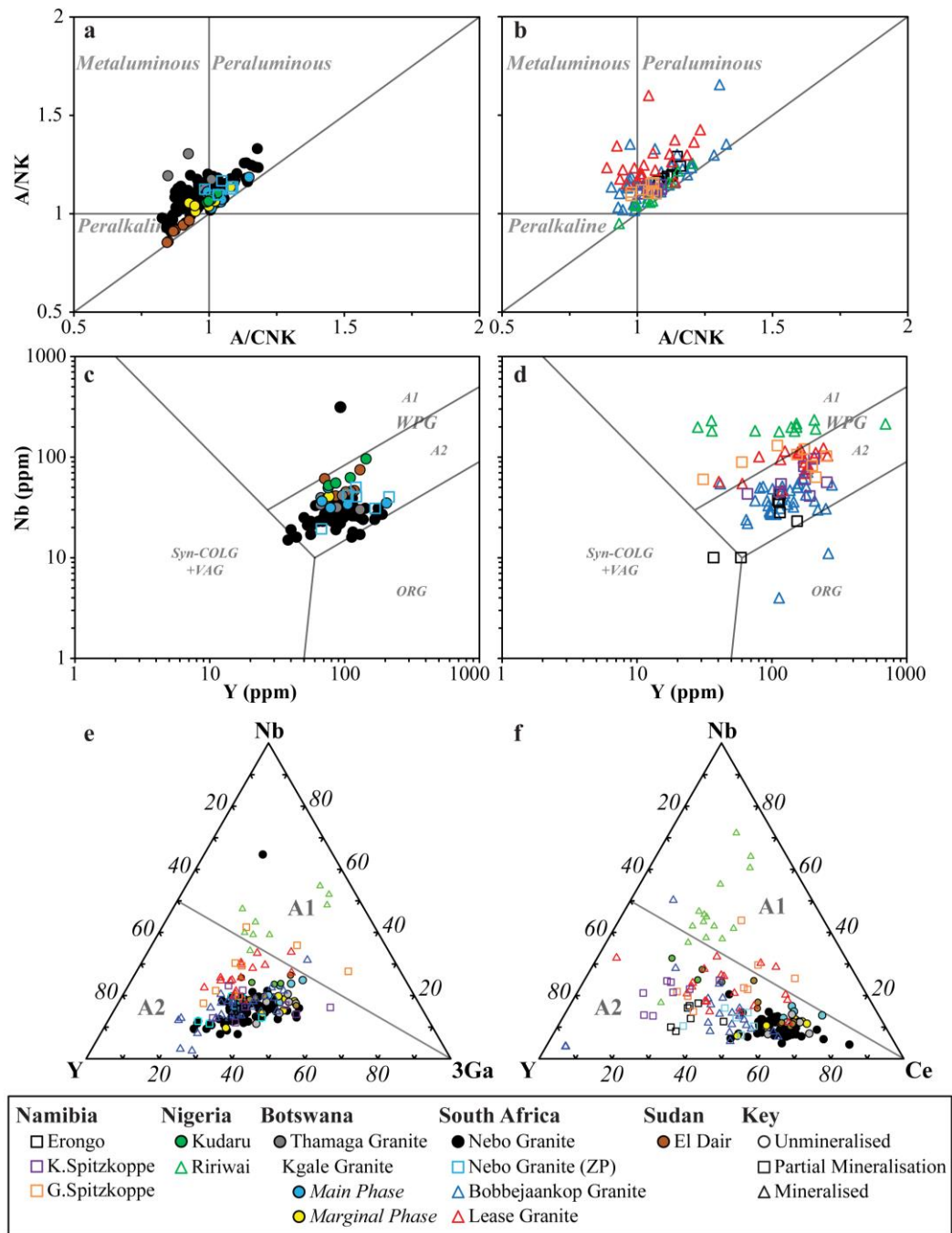


Figure 4.7. Tectonic discrimination diagrams indicating the A-Type affinity of the various African granite complexes. Alumina saturation diagrams showing the ASI of the (a) unmineralised and (b) mineralised African A-Type granites. The Y vs Nb tectonic discrimination diagram showing the A-Type nature of (c) unmineralised and (d) mineralised complexes. Granite fields: WPG – Within Plate Granites; VAG – Volcanic Arc Granites; Syn-COLG – Syn-Collisional Granites; ORG – Ocean-Ridge Granites, after Eby (1990). A-Type discrimination ternary diagrams after Eby (1992) of (e) 3Ga-Nb-Y and (f) Ce-Nb-Y. Circles represent unmineralised granites, squares represent granites with minor mineralisation and triangles represent mineralised granites.

These African A-Types are unsurprisingly *Within Plate Granites* (WPG), although are split into A1 and A2 populations (Figure 4.7c-f). The unmineralised granites cluster within the

anorogenic A2 field compared to the mineralised granites which are more variable. For instance, the Ririwai granites together with the Gross Spitzkoppe are A1, while the Bobbejaankop, Lease, Erongo and Klein Spitzkoppe granites are predominantly A2 (Figure 4.7c-f).

A comparison of major elements reveal insignificant compositional variations although silica ranges from 64 to 78% and clusters between 73 and 78% (Figure 4.8). This increasing silica content is generally correlated with a decrease of major elements, with the exception of Na_2O and K_2O (Figure 4.8). The mineralised granites display a lower Ti and Fe^{tot} in comparison to barren granites, and are restricted to the higher silica compositions (>74%), indicating a sense of evolution from the more primitive and barren to more evolved and mineralised granites (Figure 4.8). The Bobbejaankop, Lease and Gross Spitzkoppe granites display unusually high Ca and low Na contents, contrary to the decreasing trends of other granites (Figure 4.8f). Moreover, select Erongo biotite granite samples have a significant Mn and P enrichment that is dissimilar to the other Namibian granites (Figure 4.8d). As a corollary of the high silica nature of these granites, the de La Roche et al. (1980) R_1 vs R_2 diagram, adapted by Batchelor and Bowden (1985) for the tectonic discrimination of granitoids, proves uninformative as all these granites indistinctly cluster as *Post-Orogenic*.

Trace element variations provide a better comparative approach and greater insight into the petrological differences between the unmineralised and mineralised granite suites (Figure 4.9). The Zr/Hf ratio is well demonstrated as a proxy for granitic fractionation (Bau, 1996; Dostal and Chatterjee, 2000; Zraisky et al., 2009), as a decreasing Zr/Hf ratio indicates an increasing degree of fractionation. This parameter illustrates the conventional trend of an increasing degree of fractionation from barren to mineralised granites (Figure 4.9). The El Dair granites appear to be the most primitive of the barren examples, followed by the greater Nebo granite, the GGS and the Kudaru granite complex. Comparatively, the metallogenic granites have an evolved Zr/Hf ratio, becoming more fractionated from the Nebo (at Zaaipplaats) and Kudaru, to the Bobbejaankop, Lease and Ririwai granites respectively (Figure 4.9). The Zr/Hf fractionation difference between the two Spitzkoppe stocks was discussed by Haapala et al. (2007), geochemically demonstrating that the Klein Spitzkoppe is more evolved than the Gross Spitzkoppe.

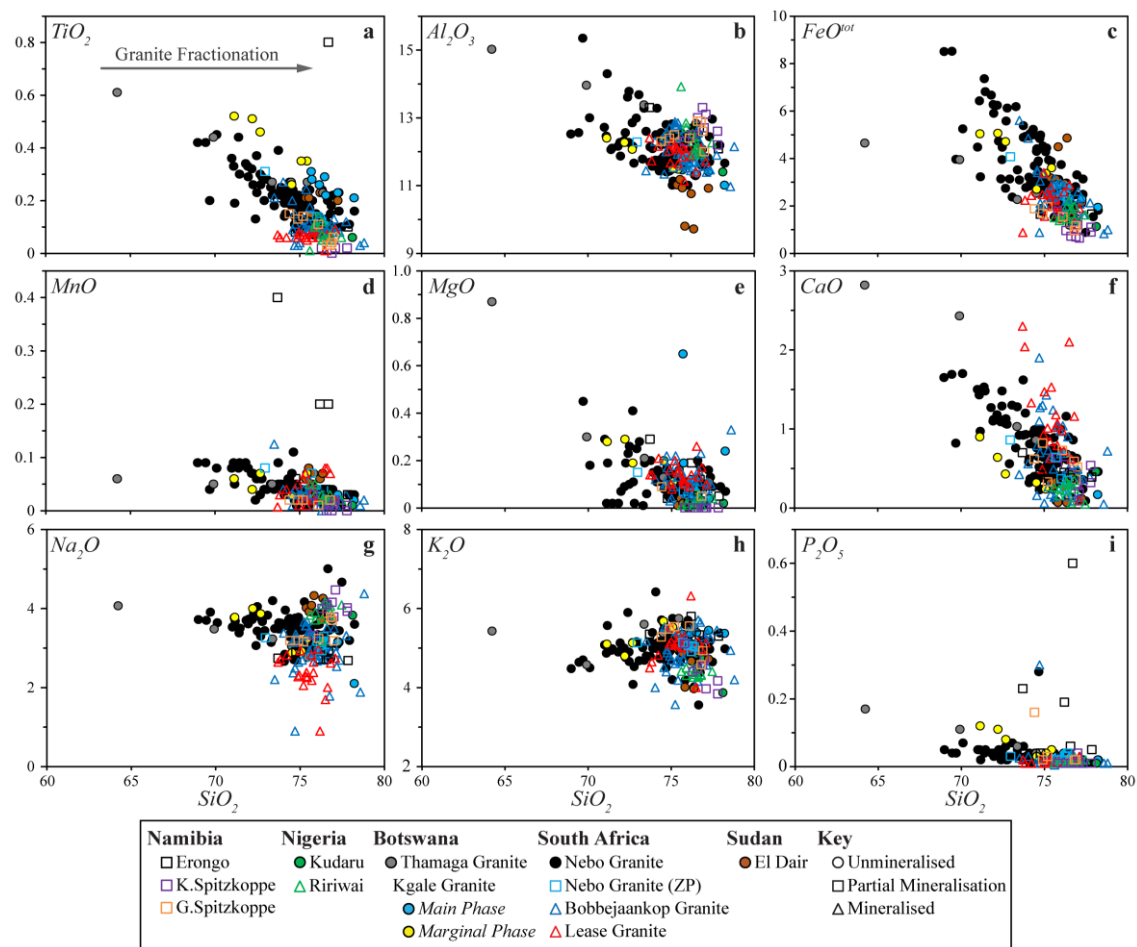


Figure 4.8. Harker style diagram displaying the major element variations between the different African granite complexes. An increasing SiO_2 content from barren to mineralised granites is associated with: (a) a sharp decreasing Ti content; (b) a general decreasing proportion of Al; (c) a strong depletion of Fe^{tot} ; (d) a slight decrease of Mn except for the anomalous enrichment of some Erongo samples; (e) a generally low Mg content; (f) A distinct depletion of Ca, although the Bobbejaankop and Lease granites become unusually enriched; (g) A generally uniform Na content apart from the depletion exhibited by the Bobbejaankop and Lease granites; (h) Little variation of K between the granite suites; and (i) an overall depletion of P, apart from the select samples from Erongo. Units in wt% oxides. Circles represent unmineralised granites, squares represent granites with minor mineralisation and triangles represent mineralised granites.

The typical enrichment of incompatible and corresponding depletion of compatible trace elements associated with granite fractionation is therefore evident, although not uniform in all of these granite complexes. For example, two distinct arrays are defined by the Li variations of the studied granites (Figure 4.9a). The Ririwai, Erongo and Spitzkoppe complexes constitute an array that is a factor of ten greater than the LGS, GGS and Sudanese granites. The former group show anomalously high Nb and Ta contents, indicating a higher degree of enrichment relative to their apparent degree of fractionation (Figure 4.9e, f and j). The El Dair granites however, exhibit a significant Sr and Ba deficiency relative to their primitive composition. This

Sr and Ba low is considered a product of their formation, which is thought to be the partial melting of Neoproterozoic tholeiitic lower crust in the zone of plagioclase stability (Ali et al., 2015; Salih et al., 2020).

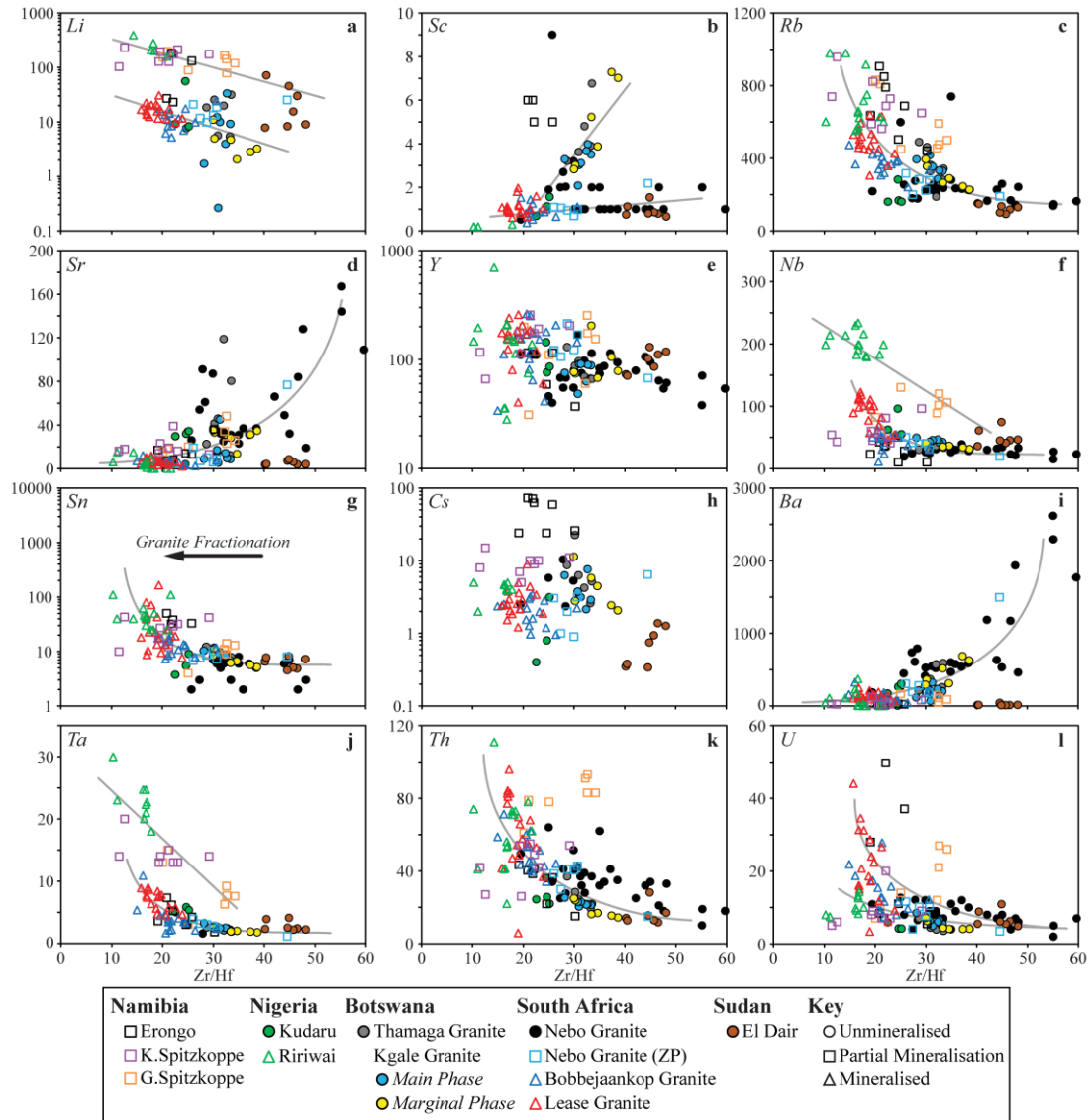


Figure 4.9. Graphs displaying selected trace element variations between the various granite complexes, plotted against Zr/Hf. A decreasing Zr/Hf ratio from barren to mineralised granites is associated with: (a) a slight enrichment of Li although, there appear to be two separate evolutionary trends; (b) a general decrease of Sc content; (c) a gradual increase of Rb content; (d) a general decrease in the Sr proportions of the granites; (e) a gradual enrichment of Y of the mineralised granites; (f) A sharp increase in Nb content, with the Ririwai granites exhibiting a distinctly enriched nature; (g) an expected enrichment in Sn with fractionation; (h) A large variation in Cs, separating the Sudanese and Namibian granites from the rest of the A-Type suites; (i) a distinct depletion of Ba with increasing fractionation; (j) an enrichment of Ta, similar to that of Nb although the Namibian and Nigerian granites are unusually enriched; (k) a general increase of Th with increasing fractionation; and (l) a similar but smaller enrichment of U compared to that of Th. Units in ppm. Circles represent unmineralised granites, squares represent granites with minor mineralisation and triangles represent mineralised granites.

The Cs content is variable, with the Sudanese and Namibian granites showing the lowest and highest values respectively, while the remaining granites plot between 1 and 10 ppm (Figure 4.9i). Thorium and U both increase with a decreasing Zr/Hf, however the atypical Th and U highs from the Erongo and Gross Spitzkoppe granites are suggestive of either a greater degree of crustal contamination or a signature of their source (Figure 4.9k, l). Tin, like other HFS elements, is fractionally concentrated, yet is only appreciably enriched in the Erongo, Gross Spitzkoppe, Ririwai, Bobbejaankop and Lease granites (Figure 4.9h).

Rare Earth Element plots exhibit characteristics that are thought to indicate an interaction with hydrothermal fluids (Bau, 1996; Jahn et al., 2001; Li et al., 2014), and are suggested as potential markers to distinguish unmineralised and mineralised granites. The more hydrothermally altered and mineralised granites display a pronounced negative Eu anomaly and a flatter, possibly even positively sloping, heavy REE gradient. Whereas, the barren granites exhibit a comparatively shallower Eu anomaly and a typical negatively sloping heavy REEs (Figure 4.10a, b).

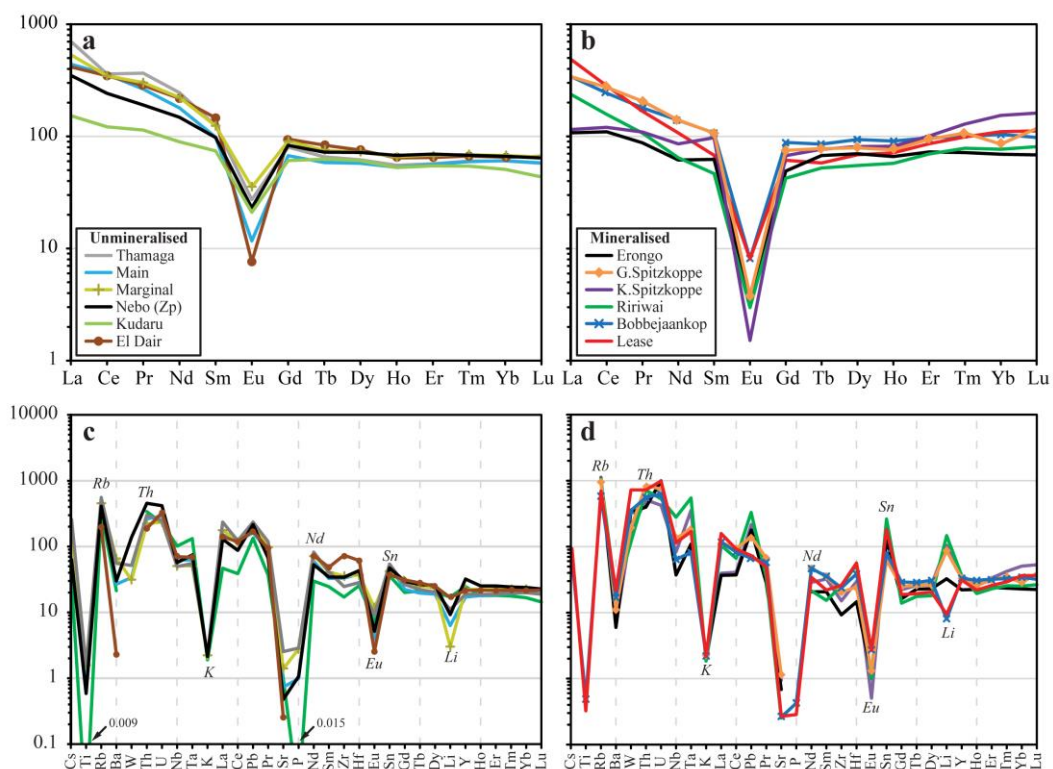


Figure 4.10. REE diagrams comparing (a) unmineralised and (b) mineralised African A-Type granites. Multielement diagrams comparing the various (c) unmineralised and (d) mineralised African A-Type granites. Several geochemical datasets have missing elements and thus have a gap in their compositional plots. Data normalised to McDonough and Sun (1995).

Multielement diagrams, highlight the contrasting enrichments and depletions between these unmineralised and mineralised granites (Figure 4.10c, d). The barren granites, apart from Kudaru, have similar Th and U abundances relative to La, indicating limited crustal contamination and hydrothermal influence (Figure 4.10c), conversely mineralised granites have a larger degree of separation between Th and U from La (Figure 4.10d) (Taylor and McLennan, 1985; Kamaunji et al., 2020). Unsurprisingly, all mineralised granites share significant HFS element enrichments, particularly W and Sn, compared to their unmineralised analogues. Moreover, the earlier mentioned Li differences are emphasised as the barren granites have negative Li anomalies, while mineralised granites, apart from the Bobbejaankop and Lease granites, exhibit positive Li anomalies (Figure 4.10c and d).

4.2.6. Discussion

A Geochemical Comparison of Mineralised and Unmineralised A-Type Granites

The anorogenic characteristics of these African granites is well established, yet slight trace elemental differences, primarily drawn from HFS and incompatible elements such as Li, Nb, Ta and REEs, provide clues to their petrogenesis. The A-Type classification implies a HFS and volatile element enrichment, although the specific elements and degree of enrichment differs between suites and metallogenic character. This hints at the various petrogenetic and external factors that influenced their mineralisation potential.

Lithium, Rb, Nb, Ta and Sn are enriched with increasing fractionation (Neiva et al., 2011; Simons et al., 2017; Wolf et al., 2018), and such fractionally-controlled enrichment should produce a positive correlation between these geochemically similar elements (Dostal and Chatterjee, 2000; Clemens and Stevens, 2012). Lithium however, shows an apparent decoupling with other elements such as Rb is particularly exhibited by some of the younger granitic complexes (Figure 4.11a). The Li enrichment, and to a lesser degree Nb and Ta, appear to have an age connotation, as the younger granites of Nigeria and Namibia (<184 Ma) tend to be more enriched in these elements than the older magmatic events. However, whether these “temporal” variations are a reflection of mantle or crustal evolution is beyond the scope of this review.

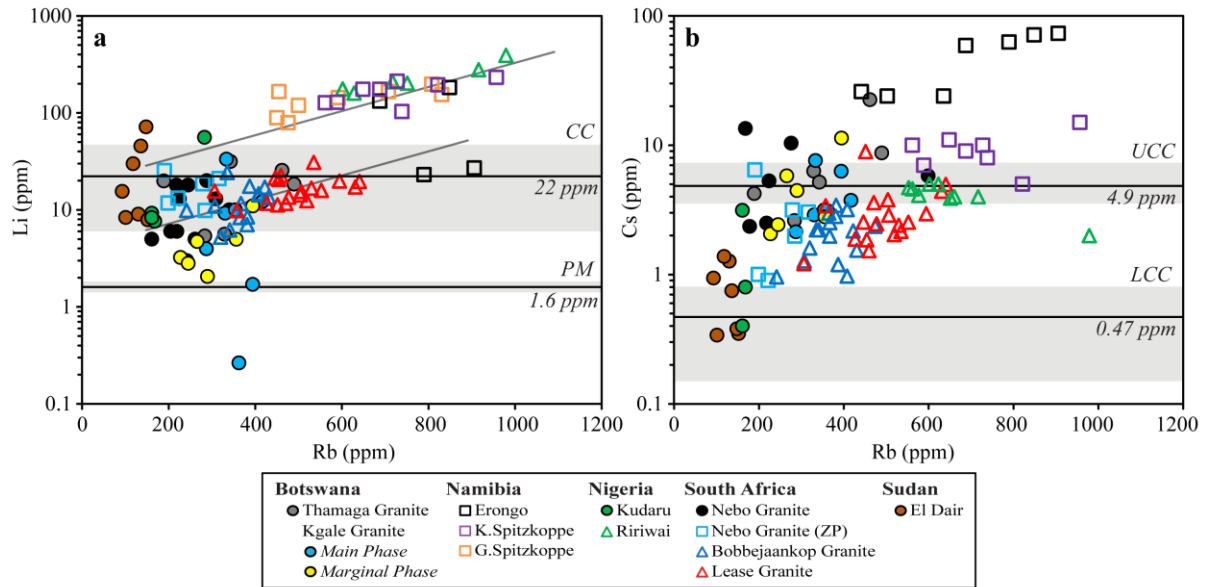


Figure 4.11. Comparison of the Li and Cs content of African A-Type granites with continental crust and primitive mantle. (a) Graph showing the Li content of the A-type granite suites compared to the estimated Li range (grey shading) of the continental crust (CC) and primitive mantle (PM). (b) Comparison of the Cs content with the estimated Cs content of the upper continental crust (UCC) and lower continental crust (LCC). Crustal and mantle compositions after Palme and O'Neill (2003) and Rudnick and Gao (2003). Circles represent unmineralised granites, squares represent granites with minor mineralisation and triangles represent mineralised granites.

Comparing Li contents of these suites with the estimated Li composition of the average continental crust and primitive mantle, indicates that the LGS, GGS, Kudu and Sudanese granites retain a continental Li signature, whereas the younger Ririwai, Erongo and Spitzkoppe granites define a fractionating array with a higher Li content than the average continental crust (Figure 4.11a). Interestingly, despite the prominent Li content of some granites, there is a distinct lack of Li-bearing minerals and Li mineralisation in African A-Type systems. A comparable Li enrichment is described from the Cornubian Batholith and is explained by biotite-dominated melting at granulitic conditions of the lower crust, resulting in the preferential liberation of Li, Nb, Ta, Sn, W and F (Cuney and Barbey, 2014; Simons et al., 2017). The unmineralised and considerably less fractionated Kudu granites exhibit a dominantly crustal Li signature, which is dissimilar to the Li-enriched, mineralised and evolved Ririwai granites (Figure 4.11a). It can therefore be argued that sufficient fractionation of the Kudu suite could reproduce a similar Li and HFS enrichment as the Ririwai granites as evidently, the single most fractionated Kudu sample is substantially more Li-rich than the lesser fractionated samples (Figure 4.11a).

In contrast to the other African A-type granites, the GGS from Botswana and particularly the Kgale granites are Li poor (Figure 4.11a). The Li depletion may be accounted for by the exsolution and subsequent loss of a magmatic-hydrothermal fluid (Manning et al., 1996; Simons et al., 2017), removing incompatible elements from the late-stage granite system and reducing the likelihood of endogranitic mineralisation. The exsolution and escape of a HFS element- and Li-enriched fluid, does have the potential for exogranitic mineralisation. Grobler (1996) highlighted and described various hydrothermal characteristics and breccia pipes within the Gaborone-Kanye Igneous Terrane, which he likened to the St. Francois Igneous Terrane and Olympic Dam. Fluid loss from the late-stages of the GGS, may therefore suggest a possibility of exogranitic mineralisation, similar to other rapakivi granite associated examples, such as the Rondônia tin field from Brazil (Debowski et al., 2019) and the Eurajoki batholith in Finland (Haapala, 1997) among others.

The geochemical similarity of Cs and Rb implies that both are influenced by the relative abundances of alkali-feldspar and mica (Hall et al., 1993; Rickers et al., 2006). Together with Li, Rb and Sn, a Cs enrichment is linked to both the fractionation of a granitic body as well as the formation and mobilisation by late-stage hydrothermal fluids (Hall et al., 1993; Rickers et al., 2006). The relatively lower Cs content of the mineralised Ririwai, Bobbejaankop and Lease granites compared to the GGS could be explained by the relative mineralogical proportions of alkali-feldspar and mica. As Cs is principally hosted in alkali-feldspar and biotite (Hall et al., 1993; Jackson et al., 1995; Rickers et al., 2006), the chloritisation and greisenisation of the Bobbejaankop, Lease and Ririwai granites would consequently decrease the proportion of magmatic Cs-bearing phases (Figure 4.11b). Conversely the lesser altered, feldspar- and biotite-dominant granites, such as the GGS, Sudan and Kudaru complexes, would retain their original Cs signature. The Cs enrichment of the Namibian granites however, particularly notable in the Erongo samples, may be attributed to extensive metasedimentary assimilation (Figure 4.11b) (Haapala et al., 2007; Trumbull et al. (2008)).

Crustal Contamination and Assimilation

The prolific assimilation of the Damara metasediments by the Erongo granite resulted in the enrichment of trace elements, including significant amounts of boron (Pirajno, 1990; Pirajno et al., 2000; Trumbull et al., 2008; Boudreaux, 2014; Falster et al., 2018). Tourmaline is an unusual phase in A-Type granites and, within the context of this study, is only present in the

Namibian and South African examples. The effect of crustal contamination on an intruding magma is empirically demonstrated by the difference in both tourmalinisation and mineralisation between the Erongo and Spitzkoppe granites, as their age, proximity, mineralogy and major elemental compositions argues against distinct sources. Even though the Spitzkoppe hosts minor tourmaline, it is restricted to late-stage manifestations in fluid-associated pegmatites, implying that a high degree of fractionation was required to concentrate sufficient boron. In contrast, the similarly fractionated Erongo granite, hosts significantly more endogranitic tourmaline, which Trumbull et al. (2008) demonstrated using B isotopes to be sourced from the assimilation of Damaran metasediments.

The broader effect of crustal contamination is demonstrated by the tectonic discrimination of these granites. Coexisting anorogenic granites exhibiting A1 and A2 signatures are uncommon, although are documented and explained by various magmatic and metasomatic processes, rather than having originated from separate sources (Jiang et al., 2018). For the Niger-Nigerian granites, a single hot-spot trace was responsible for the younging of the complexes, from Ordovician in northern Niger to Triassic in northern Nigeria, Jurassic in central Nigeria and Early Cretaceous at Afu (Figure 4.4) (Van Breemen et al., 1975). However, some of the Kudara biotite granites reflect an A2 signature, which is ascribed to trace element enrichment by extensive crustal contamination (Kamaunji et al., 2020). This phenomenon may also be applicable to the Namibian granites with A2 signatures, as the hot-spot relationship as well as extensive crustal contamination of the Namibian granites is well established (Pirajno, 1994; Frindt et al., 2004a; Haapala et al., 2007; Trumbull et al., 2008). Therefore, as the Spitzkoppe granites show a lower degree of crustal assimilation (Haapala et al., 2007) and partially display an A1 signature, it is likely that, like the Younger Granites of Nigeria, the anorogenic Namibian magmatism was originally A1 and the A2 signature of the Erongo is truly the result of assimilation.

The A1 magmatic sources are generally boron-poor (Chaussidon and Marty, 1995; Ryan et al., 1996), explaining the absence of tourmaline in the Nigerian Younger Granites, whereas assimilation accounts for tourmaline in Namibia (Trumbull et al., 2008; Boudreaux, 2014). The lack of orbicular or granitic tourmaline within the Spitzkoppe and other Namibian complexes supports the notion that B is not inherited but rather externally sourced. Furthermore, the effect of crustal assimilation extends beyond tourmalinisation, as the Erongo Complex hosts

minor HFS element mineralisation, whereas the Spitzkoppe stocks, although exhibiting elevated HFS element abundances, are unmineralised. This indicates the ability of localised crustal assimilation to enhance mineralisation potential within a granitoid.

Continental Emplacement and Magmatic Origin

Individual Archean cratons and younger crustal terranes are shown by de Wit and Thiar (2005) to have unique metallogenic signatures. Consequently such crustal variability will be reflected in the composition of the magmas generated, their evolution and their metallogenic potential. Archean cratons are significantly more metal-enriched, compared to younger (<2.4 Ga) crustal terranes, with elements such as Sn, W, Au, Cu, Zn and Pb steadily decreasing in abundance from old to young respectively (de Wit and Thiar, 2005). Moreover, the LGS and Nigerian granites are sourced and hosted in Archean cratons, and arguably are the most mineralised examples of African A-Type magmatism, whereas the Archean hosted GGS is completely unmineralised (Figure 4.1). Therefore, although influential, the crustal setting does not solely define metallogenic potential.

The hot-spot/plume related Namibian and Nigerian complexes are both associated with continental breakup, yet were initiated beneath different crustal terranes (Figure 4.1, 12) (Bowden et al., 1976; Rahaman et al., 1984; Kinnaid, 1985; Kinnaid, 1987). The Namibian hot-spot was positioned beneath a Neoproterozoic orogenic melange, in which numerous predefined structural lineaments provided magmatic passageways and access to a greater lithological variety (Figure 4.12). The Nigerian hot-spot was pinned beneath more homogeneous Archean basement, predominantly of granites and gneisses, which did not offer the same lithological variety, although the older craton did provide a greater metalliferous enrichment at the initial stages of magmatism (de Wit and Thiar, 2005).

Unlike the hot-spot generated complexes, the GGS and Sudanese granites are not associated with an underpinning plume (Figure 4.12). The GGS is thought to have developed in an extensional sag-basin from the collisional rebound that formed the Limpopo orogenic belt (Grobler, 1996), while the Sudanese granites formed from post-orogenic magmatism caused by the collision of Gondwana and the Arabian-Nubian Shield (Salih et al., 2020). These decompressive melting and magmatic regimes would intrinsically have developed at shallower crustal levels than the former examples. Granulitic conditions facilitated the liberation of HFS elements and Li from the melting of biotite (Cuney and Barbey, 2014; Simons

et al., 2017), the lack of which would limit economic potential. Additionally, these suites would be sourced from the depleted mantle below the craton. Vasyukova and Williams-Jones (2020) discounted the depleted mantle as a viable source for HFS element mineralisation in A-Type alkaline-granites, as it requires a remarkably low degree of partial melting and high degree of fractional crystallisation (>96%) to accumulate significant HFS elements.

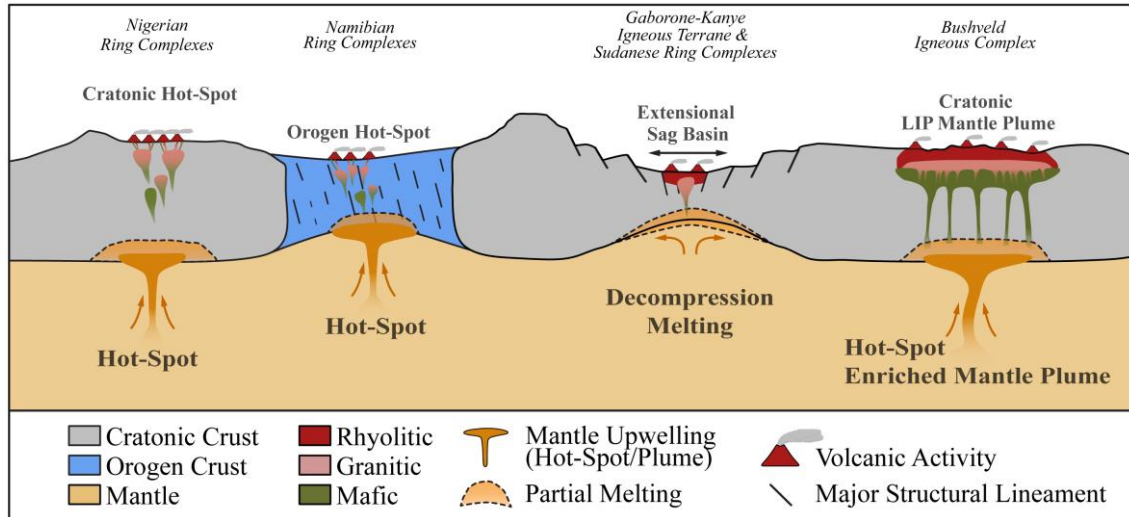


Figure 4.12. Schematic cross-section illustrating the various crustal environments and sources of magmatism for the African A-Type granite suites.

The current consensus on the formation of the Bushveld Igneous Complex is linked to a large mantle plume, which initiated magmatism beneath the Archean Kaapvaal Craton (Figure 4.12) (Zeh et al., 2015; Zeh et al., 2019). The LGS is likely to have resulted from the partial melting of the Archean basement by the influx and transient heat levels from an underpinning plume and the generation of the vast mafic Rustenburg Layered Suite. During emplacement, the LGS was enclosed between the underlying Rustenburg Layered Suite and overlying Rooiberg Group Volcanics (Figure 4.12) (Hill et al., 1996; Skursch et al., 2020). This unique situation insulated the granites, limiting their ability to assimilate metasedimentary material, in contrast to the RLS which displays various crustal signatures (Zeh et al., 2019). Insulation would have reduced the amount of assimilated Li from the continental crust, resulting in an unusually low Li content of the Bushveld Granites (Figure 4.11c and d). Therefore, another explanation for the previously mentioned Li discrepancy is that crustal assimilation in the Nigerian and Namibian granites would have provided an additional Li-source, whereas the LGS was insulated. However, this insulation hypothesis is inconsistent with the assimilation

model invoked for the source of B in the Erongo Complex, as endogranitic tourmaline is present in various LGS phases.

Three concurrently plausible explanations to account for B in the Bobbejaankop and Lease granites are presented: (i) The A2 affinity of the Nebo granite implies partial melting of the lower continental crust, which was caused by an uncommonly large mantle plume that is arguably of an enriched mantle source (Zirakparvar et al., 2014). The enriched source of the Bushveld is thus inherently dissimilar to the inferred smaller hot-spots of the Namibian and Nigerian granites, providing an initial B, LIL and HFS element enrichment (Chaussidon and Libourel, 1993; Chaussidon and Marty, 1995; Ryan et al., 1996); (ii) the assimilation of B from the Transvaal Supergroup sediments (Eriksson et al., 1996) by the RLS could have increased its B content, although quantifying the degree of crustal assimilation has plagued researchers (Zirakparvar et al. (2014) and references therein). As the LGS was emplaced before the complete crystallisation of the underlying mafic RLS, exsolved fluids emanating from the crystallising mafics (Kleemann and Twist, 1989; Skursch et al., 2020) could have introduced B into the overlying Nebo. Despite a noted B content of the Pretoria group of the Transvaal Supergroup in which the RLS intruded (Eriksson et al., 1996), evidence of a B enrichment at the base of the Nebo is lacking, thus this scenario is unlikely; and (iii) the simplest explanation postulates that as B is highly incompatible it was concentrated towards the roof during crystallisation. This is evident as tourmalinisation in the Lebowa Granite Suite is restricted to a few localities in the fringes of the Nebo granite, such as in the upper Bobbejaankop, Lease and Klipkloof granites (Kleemann and Twist, 1989; Vonopartis et al., 2020a). Furthermore, the well documented fractionation of the Nebo granite (Kleemann and Twist, 1989; Hill et al., 1996; Skursch et al., 2020) would have eventually accumulated sufficient quantities of B, F, Cl, H₂O, HFS and incompatible elements into the margins and cupolas, enabling the development of late-stage magmatic-hydrothermal alteration and tourmalinisation. Thus, it is likely that any minor B content, from such a monumental accumulation of magma, would have gradually become enriched by the prolonged fractionation of the 100 000 km³ Nebo intrusion (Fourie and Harris, 2011).

Influence of Fractionation

Fractionation has long been considered the key mechanism of HFS and incompatible element enrichment in granitoids (Zaraisky et al., 2009; Neiva et al., 2011; Ballouard et al., 2016;

Simons et al., 2017; Vasyukova and Williams-Jones, 2020). This is exemplified by the relative degree of fractionation exhibited by the mineralised and unmineralised granite suites in this study and their potential for economically viable mineralisation (Figure 4.13). Zarausky et al. (2009) utilised the HFS elemental ratio of Zr/Hf as a granitic fractionation proxy and proposed the SiO₂ vs Zr/Hf plot for the discrimination of barren and mineralised granites. Thus, the unmineralised granites have a Zr/Hf ratio above 30, while the more fractionated and mineralised granites plot below 30, within the field of Sn-W-Mo-Be greisen related granitic mineralisation (Figure 4.13). The granites with disseminated mineralisation such as the Ririwai, Bobbejaankop and Lease granites plot closer to a Zr/Hf of 15 (Dostal and Chatterjee, 2000; Zarausky et al., 2009), emphasising the importance of fractionation as an indicator of mineralisation potential.

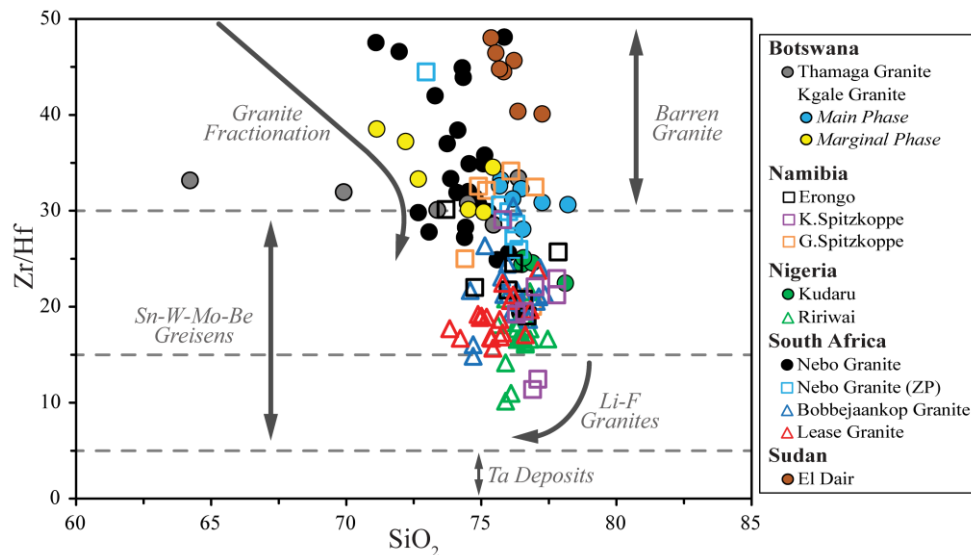


Figure 4.13. The plot of SiO₂ vs Zr/Hf after Zarausky et al. (2009), highlighting the relationship of fractionation, HFS element enrichment and style of granitic mineralisation. Circles represent unmineralised granites, squares represent granites with minor mineralisation and triangles represent mineralised granites.

The distinct differences in fractionation of the evolved and fertile Ririwai compared to the less evolved and barren Kudaru granites in the same province, demonstrates that fractionation is one of the main factors in the mineralisation of Nigerian complexes (Figure 4.13). Yet, the role that F-rich magmatic-hydrothermal fluid exsolution plays is equally as imperative in endogranitic mineralisation as is fractionation. The comparable importance of a F-rich magmatic-hydrothermal fluid is emphasised in the mineralisation of various tin granites, including the Zaaiplaats example (Vonopartis et al., 2020a), Furong tin mine in China

(Zhao et al., 2005) and the Heemskirk granite of Tasmania (Hong et al., 2017). This supports the idea that fractionation-controlled enrichment is commonly augmented by a secondary enrichment factor, such as late-stage fluid saturation, that promotes and facilitates HFS element mineralisation.

Importance of Hydrothermal Fluid

The presence of magmatic-hydrothermal fluids within many of these granites is petrographically evident from the various styles of hydrothermal alteration, formation of hydrothermal phases, the development of miarolitic cavities and occurrence of late-stage pegmatites. Geochemical evidence includes a correlated increase of HFS and incompatible elements, which indicates an interaction with magmatically derived fluid (Halter et al., 1998; Dostal and Chatterjee, 2000). Mineralised granites exhibit a sharper increase of Ta compared to Rb, therefore decoupling the linear, fractionation-related, enrichment of these elements (Figure 4.14a), to which Dostal and Chatterjee (2000) ascribe to an increased involvement of F-rich internally derived hydrothermal fluids prior to greisenisation.

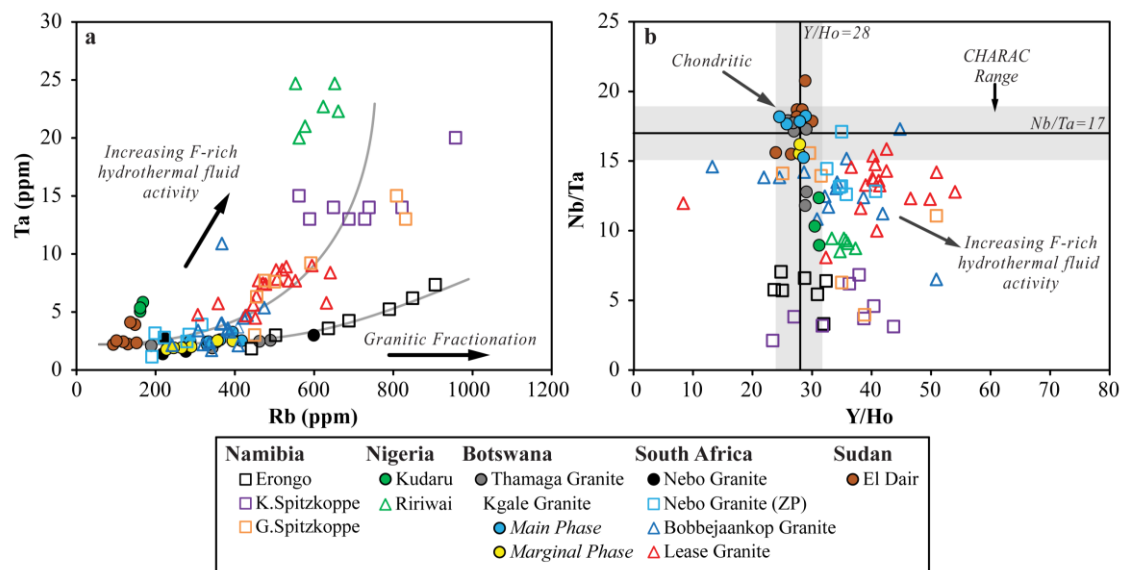


Figure 4.14. Trace element ratios indicating the influence of fractionation and hydrothermal fluids on these African A-Type granites. (a) Graph of Rb vs Ta indicating the influence of F-rich greisenising hydrothermal fluids (HTF). (b) Graph of Y/Ho vs Nb/Ta distinguishing highlighting HFS elemental deviations from a chondritic composition. CHARAC trace element behaviour ranges after Bau (1996) and Green and Pearson (1987). Circles represent unmineralised granites, squares represent granites with minor mineralisation and triangles represent mineralised granites.

Highly incompatible trace element pairs, such as Nb/Ta and Y/Ho, are thought to maintain a chondritic ratio in purely magmatic systems, although they are shown to be independently

hydrothermally modified (Figure 4.14) (Green and Pearson, 1987; Green, 1995; Bau, 1996; Dostal and Chatterjee, 2000; Aseri et al., 2015; Ballouard et al., 2016). An increase in Y/Ho and a decrease in Nb/Ta are both linked to interactions with F-rich magmatic-hydrothermal fluids, which would enhance the complexation and transportation of metals (Green and Pearson, 1987; Green, 1995; Bau, 1996; Dostal and Chatterjee, 2000; Aseri et al., 2015; Ballouard et al., 2016). The Gaborone, Sudanese, Kudaru, Erongo and some of the Spitzkoppe granites, all plot within the chondritic CHARGE and Radius Controlled (CHARAC) trace element range of the Y/Ho ratio (Figure 4.14b). In contrast, the Ririwai, Bobbejaankop, Lease and select Spitzkoppe granites which all host disseminated fluorite, display higher, non-chondritic, Y/Ho values (Figure 4.14b). The Y/Ho deviation of the latter indicates a greater degree of F-rich magmatically derived hydrothermal fluid interaction (Bau and Dulski, 1995; Bau, 1996).

The differences in the Nb/Ta ratio are not as distinct. Unmineralised granite suites preserve a chondritic Nb/Ta ratio while the mineralised Ririwai, Bobbejaankop and Lease granites do not deviate as significantly from the chondritic Nb/Ta value as the partially mineralised Namibian examples (Figure 4.14b and c). As the Nb/Ta ratio is shown to be modified by F-rich magmatically-derived hydrothermal fluids (Green and Pearson, 1987; Green, 1995; Bau, 1996; Dostal and Chatterjee, 2000; Aseri et al., 2015; Ballouard et al., 2016), it is likely that the larger Nb/Ta deviation of the Namibian granites is linked to the escape of hydrothermal fluids, resulting in a strongly altered Nb/Ta ratio (Figure 4.15). Furthermore, Sn among other incompatible elements would also have been lost with these fluids. As some Namibian granites display a more chondritic ratio than others, it is likely that the Nb/Ta deviation is not source related. Therefore, the lower Nb/Ta ratio together with the lower Sn content of select Namibian granites, could be the result of escaping F- and incompatible element bearing magmatic-hydrothermal fluids. These fluids would have had the potential to have mineralised the surrounding lithologies as is evident from the exogranitic Erongo Sn-W greisens (Pirajno et al., 2000). In contrast, the endogranitic mineralisation of the Ririwai, Bobbejaankop and Lease granites lack a direct exogranitic event, thus the fluids circulating within the cupola, would have homogenised and ultimately preserved a smaller Nb/Ta variation and concomitant tin enrichment, not reflected in the barren granites (Figure 4.15). Furthermore, despite the possibility of fluid escape from the GGS, as the chondritic ratio of Nb/Ta and Y/Ho and absence of fluorite implies a lack of a F-rich hydrothermal fluid, mineralisation is unlikely.

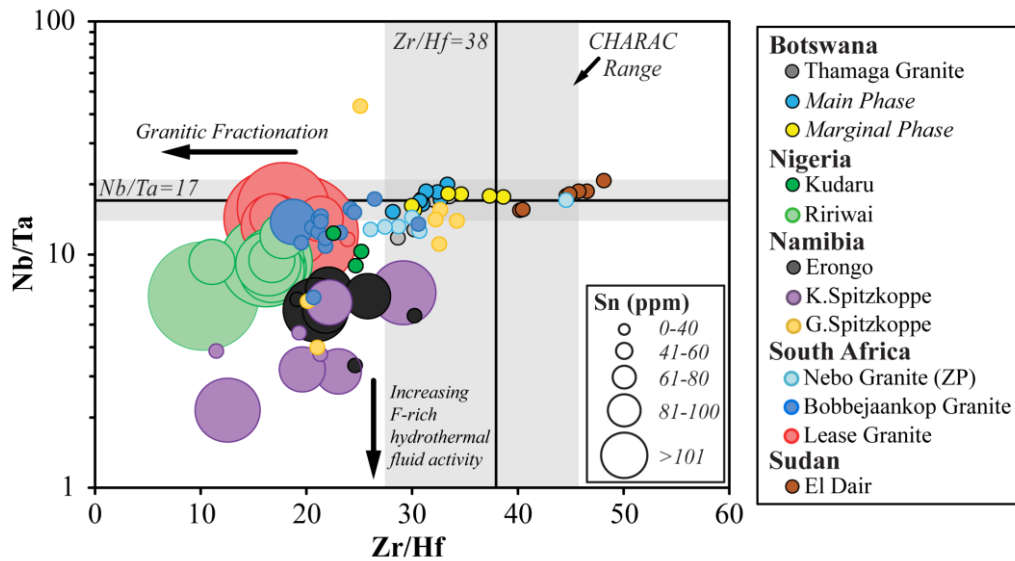


Figure 4.15. Graph of Zr/Hf vs Nb/Ta with Sn content, highlighting the correlation of HFS element enrichment with increasing fractionation and F-rich hydrothermal fluid interaction. Bubble-size corresponds with Sn content in ppm. CHARAC trace element behaviour ranges after Bau (1996) and Green and Pearson (1987).

The concentration and complexation of F⁻ to form HF within the hydrothermal fluids, plays a vital role in both fluid acidity and eventual greisenisation, which is important for SnO₂ precipitation (Burt, 1981; Taylor and Wall, 1993; Heinrich, 2007; Sherman, 2010; Lehmann, 2020). Although not always analysed, the abundance of fluorite in mineralised A-type granites, suggests a moderate to high F concentration within the mineralising system (Price et al., 1999). Such F enrichments within A-Type granites is thought to be an intrinsic characteristic of A-Type magmas (Collins et al., 1982; Price et al., 1999), although most fluorite is late magmatic-hydrothermal to hydrothermal rather than purely magmatic. Moreover, despite an intrinsic F enrichment of A-Types, both the barren Botswanan and Sudanese suites are fluorite poor, whereas the other mineralised complexes are host to disseminated fluorite. This highlights the need of substantial F in the late-stage mineralisation of A-Type granites.

Fluorine and boron are critical components in the development of A-Type mineralisation as their ability to depress the magmatic solidus, potentially below 600°C, prolongs magmatic fractionation (Chorlton and Martin, 1978; Pollard et al., 1987; Thomas et al., 2003; Migdisov and Williams-Jones, 2014; Finch and Tomkins, 2017). This prolonged fractionation enhances the likelihood of an evolving magma to achieve Sn, or other HFS element, saturation and ultimately improves mineralisation potential.

The presence of Cl^- in the system drastically improves the ability to transport elements such as Sn, W and REEs as metal chlorine complexes (Taylor and Wall, 1993; Wolf and London, 1997; Sherman, 2010; Migdisov and Williams-Jones, 2014). A high Cl content can explain the increased heavy REE signatures of the mineralised granites (Figure 4.10), as heavy REE-Cl complexation is preferred in acidic hydrothermal fluids (Migdisov and Williams-Jones, 2014; Tillberg et al., 2019). The hypersaline nature of the hydrothermal fluids within the Zaaiplaats tin granites containing KCl, NaCl and FeCl, highlight their alkali, Fe and Cl enrichment (Pollard et al., 1991a). The Gross Spitzkoppe granites contrastingly exhibit evidence of magmatic degassing and preferential loss of Cl relative to F during crystallisation of the magma (Frindt et al., 2004a), consequently precluding metal complexation and late-stage mineralisation.

The correlation of Sn mineralisation with Cl content of the fluid is not novel (Taylor and Wall, 1993; Zhao et al., 2005; Migdisov and Williams-Jones, 2014) and together with F, emphasises the importance of the halogen composition of the exsolved magmatic-hydrothermal fluid. Furthermore, F and Cl directly influence the metal transportation potential of the fluids in the final, and arguable most crucial, stage of granitic HFS element mineralisation. The complexation of SnCl_2 hinges on maintaining a reduced and acidic fluid (Taylor and Wall, 1993; Halter et al., 1998; Sherman, 2010). Therefore, a physiochemical change of these acidic, F- and Cl-rich fluids, such as fluid escape or neutralisation-induced greisenisation (Taylor and Wall, 1993; Heinrich, 2007) resulted in the precipitation of cassiterite and other economically significant minerals, as demonstrated by the Ririwai, Bobbejaankop, Lease and Erongo granites.

Synthesis

The features of these African examples (Table 4.2) highlight the intrinsic and variable factors involved in the evolution of A-Type HFS element mineralisation. The main controls on the metallogenic potential of granite systems are partial melting, mineralogical evolution, fractionation and evolution of a hydrothermal fluid (Wolf et al., 2018; Lehmann, 2020; Vasyukova and Williams-Jones, 2020). Each of these factors contribute to HFS element accumulation, yet the importance of crustal assimilation has only recently been reintroduced (Vasyukova and Williams-Jones, 2020).

Table 4.2. Summary of the various characteristics and features of the African A-Type granite suites

Lithology/ Complex	Min.	Fl.	Tur.	F-HTF	Deg. of Fract.	Crustal conta.	Form.	Source Material	A- Type	Complex Age
Gaborone Granite Suite										
Thamaga Granite	Barren	-	-	-	Low	Low	Ext.	Arch.	A2	2.78 Ga
Kgale Granite	Barren	-	-	-	Low	Low	Sag-Basin	Craton		
Namibian Ring Complexes										
Erongo Complex	Minor	Yes	Yes	Yes	High	High	Plume	Neoprot. Orogenic Belt	A1	130 to 132 Ma
Gross Spitzkoppe	Barren	Yes	Minor	Yes	Mod.	Mod.				125 ± 1 Ma
Klein Spitzkoppe	Barren	Yes	Minor	Yes	High	Mod.				
Nigerian Ring Complexes										
Kudaru Complex	Barren	Yes	-	Yes	Low	Mod. to High	Plume	Arch. Craton	A1	179 to 184 Ma
Ririwai Complex	Miner.	Yes	-	Yes	High	Mod.				169 to 172 Ma
Lebowa Granite Suite										
Nebo Granite	Barren	-	-	-	Low	Low	Enriched Plume	Arch. Craton	A2	2.056 Ga
Nebo Granite (ZP)	Minor	Minor	-	Yes	Mod.	Low				
Bjk Granite	Miner.	Yes	Yes	Yes	High	Low				
Lease Granite	Miner.	Yes	Yes	Yes	High	Low				
Sudanese Ring Complexes										
El Dair Complex	Barren	-	-	-	Low	Low	Post-orog. magmatism	Neoprot. Crust	A2	560 to 600 Ma

Abbreviations: Zaaipplaats (ZP); Bobbejaankop (Bjk.); Mineralisation (Min.); Mineralised (Miner.); Fluorite (Fl.); Tourmaline (Tur.); Fluorine-Rich Hydrothermal Fluids (F-HTF); Moderate (Mod.); Degree of Fractionation (Deg. of Fract.); Contamination (Conta.); Formation (Form.); Extensional (Ext.); Post-orogenic (Post-orog.); Archean (Arch.); Neoproterozoic (Neoprot.).

The melting and emplacement of these granites within an Archean craton enhanced the potential HFS element reservoir of the granite system. However, despite an Archean setting, the reduced thermal activity and lower metamorphic facies, inferred from the proposed decompressional regime of the GGS (Grobler, 1996), inhibited the initial liberation of volatiles and economically significant metals. Moreover, the lack of an associated plume further reduced the potential elemental enrichment that benefited other hot-spot/plume related examples (Table 4.2). Plume-related melting at high temperature granulitic conditions facilitated the liberation of F ± Cl from biotite, which subsequently prolonged fractionation and enhanced complexation of REE and HFS elements (Pollard et al., 1987; Finch and Tomkins, 2017). Therefore, plume-induced melting of the lower continental crust is ideally suited to enhance the likelihood of late-stage mineralisation in A-Type granites. Moreover, as the primitive mantle is more F-rich than the depleted mantle and is considered a viable hot-spot source, decompressive melting of the depleted mantle inherently reduces available F, hindering the achievable degree of fractionation and HFS element transportation in examples such as the GGS and El Dair.

The degree of fractionation is a useful indicator of potential mineralisation, as demonstrated by these mineralised and unmineralised African examples (Figure 4.13). Reducing the required degree of fractionation for HFS element saturation would then increase the likelihood of developing a deposit (Wolf et al., 2018; Vasyukova and Williams-Jones, 2020). This is achievable by the assimilation of the upper crust which is shown to reduce the required fractionation of an A-Type granite, derived from a depleted mantle source, to reach appropriate HFS element contents (Vasyukova and Williams-Jones, 2020). Such a modification of an inauspicious granite, from an unfavourable magmatic source, could result in a potentially viable candidate for economic mineralisation. This is demonstrated by the Erongo granite, which despite being less fractionated than the Bobbejaankop, Lease or Ririwai granites, developed minor Sn-W mineralisation (Pirajno, 1990, 1994). In contrast, the neighbouring, less contaminated and marginally more fractionated Spitzkoppe granites are sourced from the same hot-spot and yet are uneconomic. This contradiction to the conventional fractionation-mineralisation correlation, is explained by the extensive and fortuitous assimilation of B and HFS element-enriched metasedimentary lithologies by the Erongo granites.

The most significant events in the evolution of an endogranitic mineralised granite is the formation of a compositionally suitable hydrothermal fluid and the transition from a magmatic to magmatic-hydrothermal regime. The subsequent hydrothermal alteration of metal-bearing phases such as chloritisation of biotite and other HFS element-bearing minerals are able to liberate sequestered metals, further enriching the circulating fluids in the cupolas (Zhao et al., 2005; Finch and Tomkins, 2017; Lehmann, 2020). However, even though almost all of the granites discussed, experienced some level of hydrothermal alteration in their latter stages, not all host HFS elemental mineralisation. Furthermore fluorite and greisenisation is commonly associated with both endo- and exogranitic Sn mineralisation, implying that mineralisation is triggered during the magmatic-hydrothermal and hydrothermal stages of an A-Type granite from an acidic F- and Cl-rich hydrothermal fluid. Thus, despite a late-stage fluid presence, the suitability of the hydrothermal phase and likelihood of economically viable deposition is determined long before the magmatic-hydrothermal transition.

An uninterrupted evolution of a granitic magma, and the eventual exsolution of a suitable magmatic-hydrothermal fluid will, if sufficient HFS and incompatible elements are

accumulated, develop mineralisation. This process can be aided by HFS element enrichment from the source or opportunistic assimilation, reducing the required degree of fractionation for phase separation and metal saturation. Alternatively, achieving late-stage magmatic-hydrothermal mineralisation with appropriate metal contents may be accomplished by the prolonging of granitic fractionation, by either an external influx of F $\pm$ B or volatile concentration from the progressive fractionation of a massive magmatic body.

4.2.7. Conclusions

The factors that positively influence the metallogenic potential of African A-Type granites are condensed into five stages: (i) magma generation from an enriched source, be it a hot-spot/mantle plume or the partial melting of an enriched lithology; (ii) melt occurring at high temperature granulite facies, beneath an Archean craton, facilitating the liberation of HFS, incompatible and volatile elements from metal- and volatile-bearing phases; (iii) a high degree of fractionation, which may vary depending on initial HFS element composition, the scale of the fractionating magma and the F $\pm$ B composition of the evolving granite; (iv) the exsolution and accumulation of a magmatically derived F- and Cl-rich hydrothermal fluid in the cupola of the granite; and (v) a mineralising precipitation event, due either to a change in the physiochemical conditions of the late stage fluid or fluid escape into the overlying lithologies.

External factors such as crustal assimilation can improve the potential to develop late-stage mineralisation, regardless of magmatic source and degree of fractionation, and may be accomplished by a combination of direct and indirect enrichment mechanisms. While fractionating and rising through the crust, the assimilation of beneficial lithologies can directly enrich the magma with incompatible and HFS elements, or with F, Cl and B which would indirectly improve the capacity to transport and concentrate metals. This would increase the likelihood that sufficient quantities of incompatible and HFS elements have been accumulated to precipitate appreciable levels of mineralisation. Ultimately, the development of A-Type HFS element mineralisation requires a series of sequential enrichment stages, during the magmatic evolution of the granite, which can be augmented by external and situationally variable enrichment events.

Declaration of Competing Interest: The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work presented in this paper.

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Chapter 5

Tourmaline and Cassiterite Mineral Chemistry of the Zaaipplaats Tin Granites

5.1. Preamble

This chapter includes a manuscript submitted to **The Canadian Mineralogist**, on the composition of tourmalines and cassiterite from the Zaaipplaats tin field. Previous published data for tourmalines from various settings around the world has been collated and their ability to record the hydrothermal history from an evolving granite to a pegmatite has been evaluated (Slack, 1996; Mlynarczyk and Williams-Jones, 2006; Marks et al., 2013). Using this tourmaline compositional data together with the mineral compositions of cassiterite, the magmatic-hydrothermal evolution and mineralisation of the stanniferous granites of the Zaaipplaats tin field can be unravelled. The aim of this manuscript is to provide the first comprehensive set of mineral descriptions and compositions of the various tourmalinised features from the Zaaipplaats tin field. This data is used to describe the evolution and eventual mineralisation of the mineralised granites.

5.1.1. Author Contributions

Leonidas Vonopartis was the main contributor for this paper and did most of the field work, sample collection, sample preparation, data compilation and write-up of the manuscript. Deon Van Niekerk set up the methodology and calibrations for the electron probe micro-analyser at Rhodes University. Moreover, he provided the spreadsheet for the tourmaline recalculations, valuable insight, guidance and scientific review of the manuscript. The co-authors, Paul Nex, Judith Kinnaird and Laurence Robb supervised and provided guidance in the development of the manuscript. Furthermore, these co-authors assisted with the field work, editorial review and the interpretation of the data.

Contribution percentage per author:

- | | |
|-------------------|-----|
| 1. L. Vonopartis | 70% |
| 2. D. Van Niekerk | 10% |
| 3. J. Kinnaird | 10% |
| 4. P. Nex | 5% |
| 5. L. Robb | 5% |

5.2. Tourmaline and cassiterite compositions from the A-Type Lebowa Granite Suite, South Africa: A case study from the Zaaiplaats Tin Field

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5.2.1. Abstract

The A-type Lebowa Granite Suite includes the Bobbejaankop and Lease granites at the Zaaiplaats and Groenfontein tin mines. Cassiterite occurs as disseminated low-grade ore within the granites, and within a network of higher-grade tourmalinized and greisenized hydrothermal pipes. In this paper, we provide the first set of tourmaline and cassiterite mineral compositions from the Bushveld Granites. The mineral chemistry is used to further understand the mineralization in these stanniferous granites. We infer that tourmaline, which occurs within cluster, large pegmatitic vugs, miarolitic cavities, orbicules and large pipes, formed from two distinct compositional stages in an evolving magmatic-hydrothermal system. The initial separation of a B-, Fe- and alkali-rich magmatic-hydrothermal fluid formed schorl – foitite tourmaline orbicules within the upper facies of the Bobbejaankop granite. The later more acidic, Fe³⁺ and incompatible-rich composition of the magmatic-hydrothermal fluid resulted in the formation of Fe³⁺-rich schorl – schorl – foitite tourmalines in the Lease granite. The apparent ferric-enrichment is explained as a combination of two factors: 1) the subsolidus dissolution of alkali-feldspar resulted in the liberation of tetrahedrally incorporated Fe³⁺; and 2) the prolonged and possibly reactivated hydrothermal systems of the Bushveld Complex allowed the potential interaction of Fe³⁺-bearing formational fluids with magmatic-hydrothermal fluids. The later stage B-, Fe³⁺- and F-rich fluid tourmalinized the Lease granite and coalesced into large buoyant anastomosing swarms of greisen-tourmaline pipes. The ferric-influx permitted the incorporation of Fe³⁺ into the mineral structure allowing the precipitation of Fe³⁺-rich schorl tourmaline. Subsequent greisenization and alkali-feldspar dissolution reduced the stability of SnCl₂ complexes. This caused the precipitation of Fe-rich cassiterite alongside Fe³⁺-rich schorl tourmaline. We conclude that the tin mineralization in the Zaaiplaats tin field is associated with late-stage Fe³⁺-rich schorl tourmalinization and greisenization. The presence of Fe³⁺-bearing tourmaline and associated greisenization shows promise as an exploration vector for endogranitic tin mineralization.

Keywords: Lebowa Granite Suite, Tourmaline, Cassiterite, Tin Mineralization, A-Type Granites.

5.2.2. Introduction

The petrogenesis and mineralization of the A-Type granites in the Zaaiplaats tin field, has been the focus of multiple petrological, geochemical and fluid inclusion studies (Kynaston et al., 1909; Söhnge, 1944; Strauss and Truter, 1944; Strauss, 1954; De Waal, 1972; Lenthall and Hunter, 1977; Coetzee, 1984; Pollard and Taylor, 1986; Pollard et al., 1991a; Pollard et al., 1991b; McNaughton et al., 1993; Crocker et al., 2001; Vonopartis et al., 2020a). However, a mineral chemistry approach to understanding the evolution of the Zaaiplaats tin field has not yet been attempted.

Tourmaline is commonly associated with metasedimentary rocks and S-Type granites, which host various styles of polymetallic hydrothermal deposits (Slack, 1996; Mlynarczyk and Williams-Jones, 2006; Marks et al., 2013). The environmental diversity of tourmaline is attributed to a robust physiochemical stability, across a wide range of pressures, temperatures and compositions (Mlynarczyk and Williams-Jones, 2006; Dutrow and Henry, 2011; Slack and Trumbull, 2011; van Hinsberg et al., 2011a; van Hinsberg et al., 2011b; Dutrow and Henry, 2018). Therefore, tourmaline compositions provide an excellent record of hydrothermal fluid evolution. A-Type granites are typically tourmaline-poor, although notable tourmaline occurrences include: the Seagull Batholith in Canada (Samson and Sinclair, 1992; Sinclair and Richardson, 1992); the Pikes Peak Batholith of Colorado (Foord et al., 1995); the Inychek Complex, Kyrgyzstan (Konopelko et al., 2007; Konopelko et al., 2009); the Erongo Granites in Namibia (Bowden et al., 1990; Henry et al., 2008; Trumbull et al., 2008); and the Los Riojanos and El Portezuelo granites from Argentina (Henry and de Brodtkorb, 2009). However, none of these examples are associated with significant tin mineralization. Therefore, the presence of both tourmaline and cassiterite, within the Bobbejaankop and Lease granites is unusual.

Tourmaline is the most common borosilicate mineral, with a general formula of $XY_3Z_6(T_6O_{18})(BO_3)_3V_3W$ (Table 5.1). The cyclosilicate structure allows the incorporation of many minor and trace elements within its crystal lattice (Hawthorne and Henry, 1999; Clark, 2007; Dutrow and Henry, 2011; Henry et al., 2011; Slack and Trumbull, 2011; van Hinsberg et al., 2011a; van Hinsberg et al., 2011b; Marks et al., 2013). The International Mineralogical

Association (IMA) lists 18 accepted tourmaline species (Table 5.2). Schorl (Fe), elbaite (Al+Li) and dravite (Mg) tourmalines are considered the most common species and are associated with granitic magmatic-hydrothermal systems (Pirajno and Smithies, 1992; Hawthorne and Dirlam, 2011; van Hinsberg et al., 2011a).

Table 5.1. General outline of the structural formula of tourmaline and its elemental occupancies (Hawthorne and Henry, 1999; Clark, 2007; Henry et al., 2011; van Hinsberg et al., 2011b; Dutrow and Henry, 2018).

Site	Possible ions	Occupancy
X	Ca ²⁺ , Na ¹⁺ , K ¹⁺ or □ ^X (vacancy)	1
Y	Li ¹⁺ , Fe ²⁺ , Mg ²⁺ , Mn ³⁺ , Al ³⁺ , Cr ³⁺ , Fe ³⁺ , V ³⁺ , Ti ⁴⁺	3
Z	Mg ²⁺ , Al ³⁺ , Fe ³⁺ , V ³⁺ , Cr ³⁺	6
T	Si ⁴⁺ , Al ³⁺ , B ³⁺	6
B	B ³⁺	3
V	OH ⁻ , O ²⁻	3
W	OH ⁻ , F ⁻ , O ²⁻	1

Compositional variation and zonation of cassiterite reveals chemical changes in their associated magmatic-hydrothermal fluids (Cerny et al., 1985; Möller et al., 1988; Haapala, 1997; Costi et al., 2000; Chicharro et al., 2015; Bennett et al., 2020). These compositional differences are used to discriminate magmatic, pegmatitic and greisen related cassiterite (Haapala, 1997; Costi et al., 2000). Endogranitic tin mineralization in the Zaaipplaats tin field occurs as zones of low-grade disseminated cassiterite and as high-grade tourmalinized hydrothermal pipes and greisenized lenticular ore-bodies (Söhnge, 1944; Strauss and Truter, 1944; Coetzee, 1984; Coetzee and Twist, 1989; Pollard et al., 1991b; Vonopartis et al., 2020a).

This research aims to provide novel mineral chemistry from the granites in the Zaaipplaats tin field, particularly from the lesser studied Groenfontein tin mine (Figure 5.1). The combination of tourmaline and cassiterite compositions is therefore expected to provide new insights into the evolution of the mineralizing magmatic-hydrothermal fluids in the Zaaipplaats tin field.

Table 5.2. Summarized list of IMA-accepted tourmaline species and their ideal end-member compositions (Henry et al., 2011).

General formula	(X)	(Y ₃)	(Z ₆)	T ₆ O ₁₈	(BO ₃) ₃	V ₃	W
Alkali Group							
Dravite	Na	Mg ₃	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	(OH)
Schorl	Na	Fe ²⁺ ₃	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	(OH)
Fluor-dravite	Na	Mg ₃	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	F
Fluor-schorl	Na	Fe ²⁺ ₃	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	F
Elbaite	Na	Li _{1.5} Al _{1.5}	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	(OH)
Povondraite	Na	Fe ³⁺ ₃	Mg ₂ Fe ³⁺ ₄	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	O
Buergerite	Na	Fe ²⁺ ₃	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(O) ₃	(OH)
Fluor-buergerite	Na	Fe ³⁺ ₃	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(O) ₃	F
Calcic Group							
Fluor-uvite	Ca	Mg ₃	MgAl ₅	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	F
Feruvite	Ca	Fe ²⁺ ₃	MgAl ₅	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	(OH)
Uvite	Ca	Mg ₃	MgAl ₅	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	(OH)
Liddicoatite	Ca	Li ₂ Al	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	F
Vacancy Group							
Foitite	□ ^x	Fe ²⁺ ₂ Al	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	(OH)
Magnesio-foitite	□ ^x	Mg ₂ Al	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	(OH)
Rossmannite	□ ^x	LiAl ₂	Al ₆	Si ₆ O ₁₈	(BO ₃) ₃	(OH) ₃	(OH)

5.2.3. Regional Geology

The Lebowa Granite Suite is the largest known A-type granite intrusion on Earth. It is renowned for its associated endo- and exogranitic polymetallic mineralization, including Sn, F, Mo, Ag, Pb and Cu-sulfides (Crocker et al., 2001; Bailie and Robb, 2004). The Paleoproterozoic Lebowa Granite Suite is subdivided into five main granitic facies including the coarse-grained Nebo, Makhutso and Bobbejaankop granites, and the fine-grained Klipkloof and Lease granites (Robb et al., 2000; Kinnaird et al., 2004).

The northern limb of the Bushveld Igneous Complex, along the Makapansberg escarpment, is host to endogranitic cassiterite mineralization. The Zaaipplaats tin field comprises the Zaaipplaats and Groenfontein tin mines, on the farms Zaaipplaats 223 KR and Groenfontein 227 KR respectively (Figure 5.1) (Lenthall and Hunter, 1977; Robb et al., 2000; Crocker et al., 2001). The area consists of a sequence of granites: the Nebo granite; the Bobbejaankop; and Lease

granites. In the northwest, the Rashoop Granophyre Suite overlies the granitic sequence (Figures 5.1 and 5.2) (Strauss and Truter, 1944; Strauss, 1954; McNaughton et al., 1993; Crocker et al., 2001; Vonopartis et al., 2020a). Tin mineralization in the Zaaipplaats tin field is primarily hosted within the Bobbejaankop granite, Lease granite and hydrothermal pipes. Cassiterite was the focus of mining although, it is occasionally associated with minor scheelite, chalcopyrite and molybdenite and was mined from 1908 until 1989 (Strauss and Truter, 1944; Coetzee, 1984; Pollard et al., 1991b; Crocker et al., 2001).

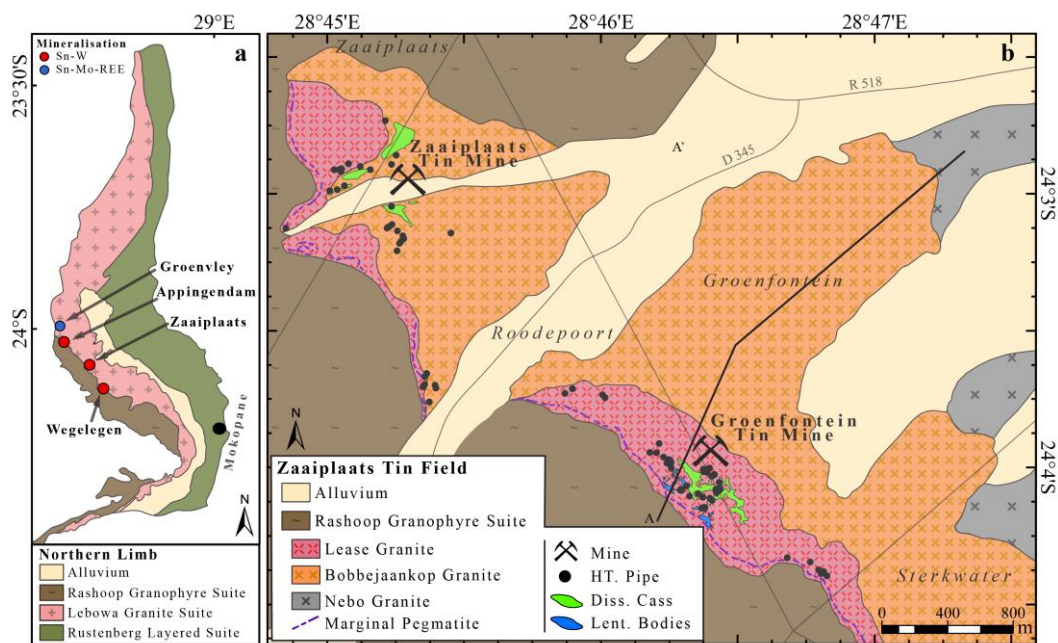


Figure 5.1. Geological map of the Northern Limb and Zaaipplaats tin field. (a) Geological map of the Northern Limb of the Bushveld Igneous Complex and occurrences of Sn mineralization, after Hunter (1975). (b) Geological map of the Zaaipplaats tin field after Vonopartis et al. (2020a). A schematic cross section of the granites across the Groenfontein tin mine along A-A' is shown in Figure 5.2.

The brick-red coarse-grained Bobbejaankop granite is composed of alkali-feldspar, ¹synneusis-textured quartz and chloritized biotite. Disseminated miarolitic cavities, typically (0.5 to 5 cm) in size, are filled with fluorite, sericite and occasionally cassiterite and tourmaline (McCarthy and Fripp, 1980; Pollard et al., 1989; Pollard et al., 1991b; McNaughton et al., 1993; Hill et al., 1996; Kinnaird et al., 2004; Vonopartis et al., 2020a). The Bobbejaankop granite, although homogeneous, becomes increasingly miarolitic towards the Lease contact (Strauss, 1954; Crocker et al., 2001; Vonopartis et al., 2020a). The lenticular, concordant Lease granite is restricted to the roof of the Bobbejaankop granite, along the contact with the Rashoop

¹ A texture describing the aggregation of crystals, forming multi-grain chains of linked quartz crystals.

Granophyre Suite (Figures 5.1 and 5.2) (Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1984; Coetzee, 1986; Crocker et al., 2001; Vonopartis et al., 2020a).

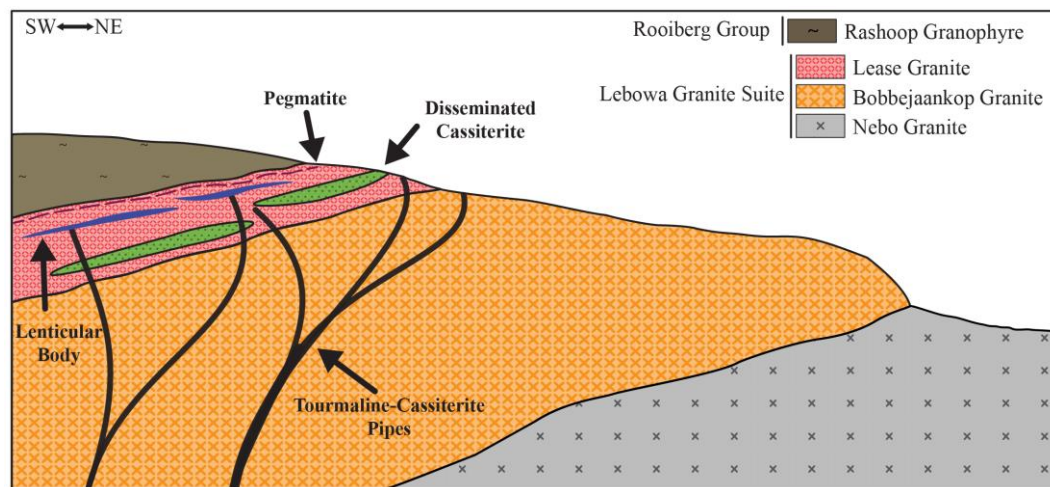


Figure 5.2 Schematic geological cross section across the Groenfontein Tin Mine from the Rashoop Granophyre Suite towards the Nebo Granite (SW to NE) along line A-A' in Figure 5.1. Modified from Coetzee (1984).

The red metasomatically altered Lease microgranite exhibits pervasive sericitic alteration of feldspar, chloritization of biotite, patches of epidotization, abundant fluorite and zones of low-grade disseminated cassiterite (Strauss and Truter, 1944; Coetzee, 1984; Crocker et al., 2001; Kinnaird et al., 2004; Vonopartis et al., 2020a). Large greisenized and tourmalinized hydrothermal pipes (1 to 25 m in diameter) radiate upwards from the center of the Bobbejaankop facies, into the overlying Lease granite. These pipes terminate and pond in high-grade lenticular greisenized lenses, that are devoid of tourmaline (Strauss and Truter, 1944; Lenthall and Hunter, 1977; Coetzee, 1984; Pollard et al., 1991b; Crocker et al., 2001).

5.2.4. Petrography

Tourmaline features

There are various styles of tourmalinization within the Bobbejaankop and Lease granites (Figure 5.3). Some features, such as the hydrothermal pipes and lenticular ore-bodies, are no longer accessible due to extensive mining and were sampled from waste piles. Detailed and comprehensive descriptions of these features are published in Strauss & Truter (1944) and Strauss (1954). The dominant styles of tourmalinization within the Bobbejaankop granite differ from those in the Lease granite. In the Bobbejaankop granite, tourmaline primarily occurs in quartz-tourmaline orbicules (approximately 5 to 20 cm in diameter) and occasionally within centimetric sized miarolitic cavities. All tourmaline occurrences in the Bobbejaankop

granite are restricted to the upper facies of the intrusion (Figure 5.3). In contrast, tourmaline is more ubiquitous in the Lease granite. It occurs as orbicules and forms clusters of tourmaline (approximately 1 to 5 cm across) that are predominantly intergrown tourmaline are disseminated throughout the granite. Additionally, larger irregularly shaped tourmaline ± cassiterite-bearing pegmatitic quartz-tourmaline pods are found towards the roof of the Lease granite (Figure 5.3).

Anastomosing swarms of tourmaline-rich greisenized hydrothermal pipes, radiate upwards from the center of the Bobbejaankop granite. These pipes intrude the Lease granite before terminating beneath the Rashoop Granophyre Suite contact (Figure 5.3) (Strauss and Truter, 1944; Coetzee, 1984; Pollard et al., 1991b; Crocker et al., 2001). These hydrothermal pipes are thickest within the Bobbejaankop granite (10 to 20 m in diameter) and diminish in size within the Lease granite (1 to 5 m in diameter) (Strauss and Truter, 1944; Lenthall and Hunter, 1977; Coetzee, 1984; Pollard et al., 1991b; Crocker et al., 2001).

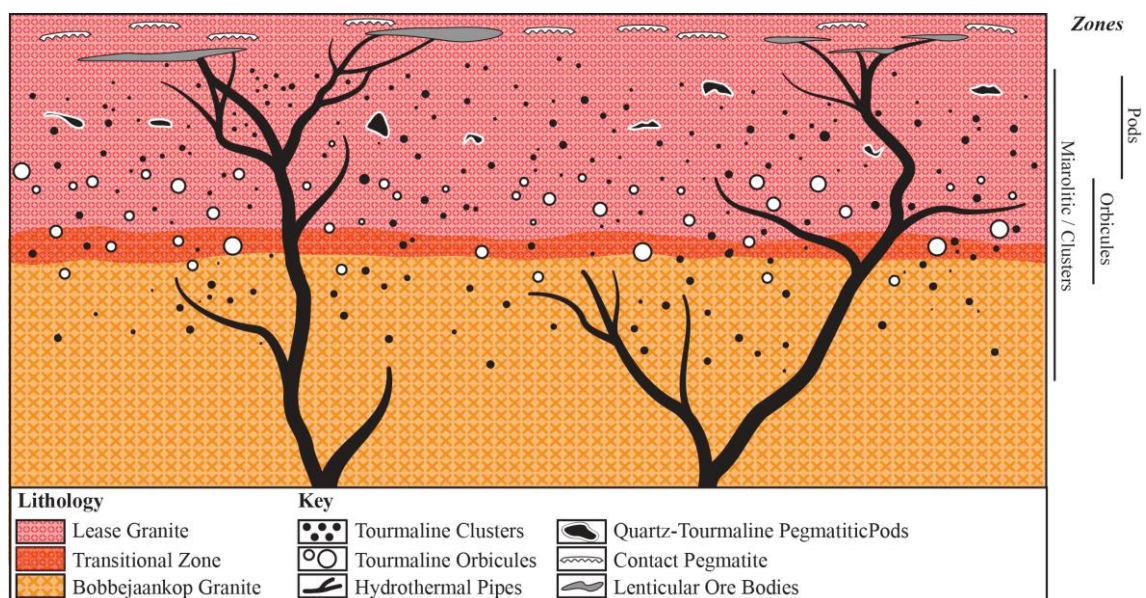


Figure 5.3. Schematic representation of a vertical cross section (NW to SE) of the Bobbejaankop and Lease granites from the Zaaipplaats tin field. The contact between the Bobbejaankop and Lease granites is suggested to represent a transitional zone rather than a sharp boundary (Vonopartis et al., 2020a). The zones in which the various types of tourmaline occur are represented by the bars to the right of the diagram.

Tourmaline clusters and pods

Irregularly shaped tourmaline-filled miarolitic cavities range from 0.5 to 5 cm in diameter. These miarolitic cavities increase in size and abundance upwards within the Lease granite (Figure 5.4a, b). The quartz (~49 %, 0.2 to 5 mm) is intergrown with fine- to coarse-grained,

interstitial, radial and dendritic tourmalines (~49 %, 0.1 to 0.5 mm). The miarolitic tourmalines within the Bobbejaankop granite are elongated, sub- to euhedral and display a green-brown pleochroism (Figure 5.4c).

The zones of disseminated tourmaline clusters occur in the upper facies of the Bobbejaankop granite. These clusters radiate from a central nucleation point, progressively replacing alkali-feldspar of the host granite to form a network of interstitial acicular tourmaline fans. These fans surround and occasionally replace quartz and host small relict digested feldspar and quartz (Figure 5.4c). Pleochroic blue-green clusters of fine-grained and granular tourmaline in the Lease granite, radiate from a nucleation point as in the Bobbejaankop granite. This tourmalinization selectively replaces alkali-feldspar, biotite and chlorite. These interstitial fans have a blue-green core with edges of brown pleochroic tourmaline (Figure 5.4e). Euhedral quartz crystals hosted in the tourmaline clusters and miarolitic cavities contain many small (<1 mm) fluorite, tourmaline and fluid inclusions. Miarolitic cavities are a common feature inside tourmaline clusters and are lined by a rim of brown, euhedral, coarse-grained, inward-projecting tourmaline crystals (Figure 5.4f). Accessory minerals (~2 %) within these clusters include calcite, fluorite, cassiterite and zircon.

Large, elongated and irregularly shaped pods of tourmaline (0.05 to 1 m across) occur sporadically within the upper facies of the Lease granite (Figures 5.3 and 5.4e). These pegmatitic tourmaline-quartz pods consist of a radial and specular tourmaline core, similar to those described in the miarolitic cavities. However, the pods are surrounded by a rim (1 to 2 cm thick) of a coarse-grained pegmatitic intergrowth with inward projecting quartz and red alkali-feldspar (Figure 5.4g). The pegmatitic pods are typically larger than the tourmaline clusters, and are occasionally interconnected by channels that are lined by pegmatitic quartz and alkali-feldspar (Figure 5.4g).

Accessory fluorite, calcite and cassiterite are common phases and range from 0.1 to 1 cm in grain-size. The thickness of the tourmaline cores of the pods varies and hosts large euhedral quartz crystals (Figure 5.4g). The presence of tourmaline and cassiterite within these pegmatitic pods decreases with stratigraphic height. Towards the roof of the Lease granite, these pegmatitic pods become purely pegmatitic quartz and alkali feldspar.

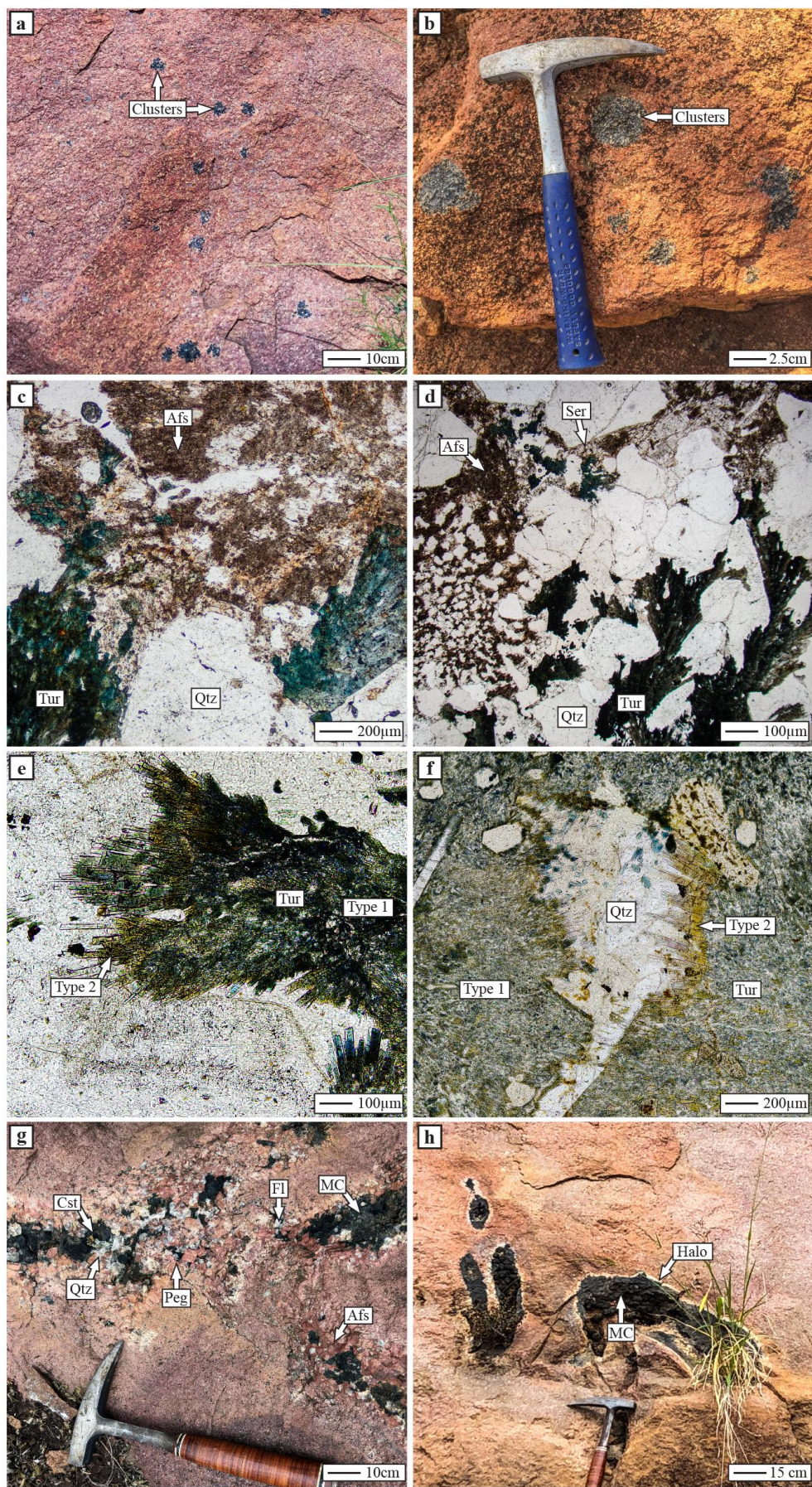


Figure 5.4. Field and thin-section photomicrographs of tourmaline clusters and pods from the Bobbejaankop and Lease granites. (a) Clusters of tourmaline scattered within the Bobbejaankop granite. (b) Rounded and irregular tourmaline clusters within the Lease granite. (c) Photomicrograph in plane-polarized light exhibiting the tourmalinization of red alkali-feldspar by blue green tourmaline. (d) Photomicrograph in plane-polarized light displaying the tourmalinization of the Lease granite by the selective replacement of alkali-feldspar, with subsequent digestion of quartz by tourmaline and sericite. (e) Photomicrograph in plane-polarized light of a tourmaline cluster from the Lease granite. Brown (Type 2) sub- to euhedral tourmaline is shown growing along the rim of the main mass of a blue (Type 1) fine-grained granular tourmaline. (f) Photomicrograph in plane-polarized light showing patch tourmaline from the Lease granite showing brown (Type 2) euhedral, inward projecting tourmaline crystals. These crystals line the walls of a quartz filled miarolitic cavity within the main mass of blue (Type 1) granular tourmaline. (g) Network of pegmatitic tourmaline quartz pods in the Lease granite, composed of a melanocratic core of tourmaline with cassiterite, rimmed by coarse-grained euhedral quartz, red alkali-feldspar and fluorite. (h) Irregularly shaped, elongated vugs in the Lease granite, with melanocratic tourmaline cores rimmed by a halo of bleached granite. Abbreviations: melanocratic (MC); alkali-feldspars (Afs); sericite (Ser); cassiterite (Cst); tourmaline (Tur); quartz (Qtz); fluorite (Fl).

Tourmaline Orbicules

Orbicules from the Bobbejaankop granite are similar to features described from the Seagull Batholith in Canada (Samson and Sinclair, 1992; Sinclair and Richardson, 1992), the Los Rios pluton of Argentina (Lira and Poklepovic, 2017), the Heemskerk granite of Tasmania (Hong et al., 2017), the Moslavačka Gora granite in Croatia (Balen and Petrinec, 2011) and the Erongo granite of Namibia (Bowden et al., 1990; Henry et al., 2008; Trumbull et al., 2008). Tourmaline orbicules are concentrically zoned spheroids, which are considerably larger than the tourmaline patches. These orbicules range from 5 to 60 cm in diameter (Figure 5.5a). They comprise a melanocratic core that is primarily composed of tourmaline with lesser quartz and are surrounded by a leucocratic zone of quartz with lesser tourmaline (Figure 5.5).

These spherical features are surrounded by a biotite-free halo of euhedral, graphically intergrown, quartz and reddened alkali-feldspar (Figure 5.5a). The melanocratic core typically comprises tourmaline with >60 % of the volume, with the tourmaline-quartz and halo each comprising approximately ~20 %. A few orbicules have a central cavity that is lined by inward projecting quartz and rarely cassiterite. The melanocratic components constitute a mosaic of radial, blue-green to brown tourmaline (0.5 to 2 cm in diameter) that are intergrown with sub- to euhedral quartz grains (0.1 to 0.8 mm). The leucocratic layer consist of quartz and tourmaline, with minor fluorite and resorbed red alkali-feldspar. The outermost halo is solely composed of coarse-grained quartz and reddened alkali-feldspar that is texturally similar to the host granite, although is completely void of biotite.

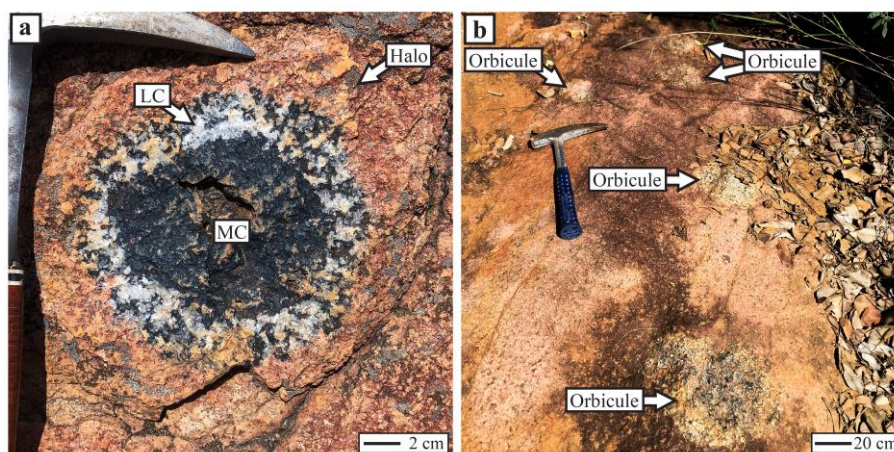


Figure 5.5. Field photographs of tourmaline orbicules from the Zaaipplaats tin field granites. **(a)** Tourmaline orbicule in the roof of the Bobbejaankop granite composed of a melanocratic tourmaline-quartz core, leucocratic quartz-tourmaline zone surrounded by a biotite free halo. **(b)** Multiple aligned tourmaline orbicules within the Lease granite along the Bobbejaankop – Lease contact. Abbreviations: melanocratic (MC); leucocratic (LC).

Orbicules occur in both the Bobbejaankop and Lease granites, although they are more abundant within the latter lithology. Along the Bobbejaankop – Lease contact, tourmaline orbicules occur in a 10 to 15 m wide zone, parallel to and mostly within the Lease granite (Figures 5.3 and 5.5b). There are no obvious feeders that would suggest any channelized movement of fluids or any apparent alteration of the surrounding granite beyond the quartz-feldspar aureole (Figure 5.5).

Tourmaline in Pipes

Hydrothermal pipes, up to 900 m in length, occur in anastomosing swarms that radiate upwards from the interior of the Bobbejaankop intrusion (Strauss and Truter, 1944; Coetzee, 1984; Crocker et al., 2001; Vonopartis et al., 2020a). Although these pipes are mineralogically and texturally variable, they can be separated into major pipes (1 to 25 m across) and three varieties of minor pipes (0.1 to 2 m in diameter). For the minor pipes, Type 1 are the largest and have a predominantly tourmaline-bearing core that is surrounded by a ring of intergrown quartz-tourmaline and then rimmed by a halo of quartz and reddened feldspar (Figure 5.6a); Type 2 has a core of quartz and sericitized alkali-feldspar $\pm$ cassiterite that grades into a more tourmaline-quartz-feldspar assemblage and is rimmed by a thin white quartz margin (Figure 5.6b); and Type 3 have a highly sericitized and eroded core, which may represent a central cavity. The core is surrounded by a quartz-tourmaline zone and then a rim of intergrown quartz and red alkali-feldspar (Figure 5.6c). These pipes share a similar structure to the

tourmaline orbicules, although they are significantly larger, irregularly shaped and vertically continuous.

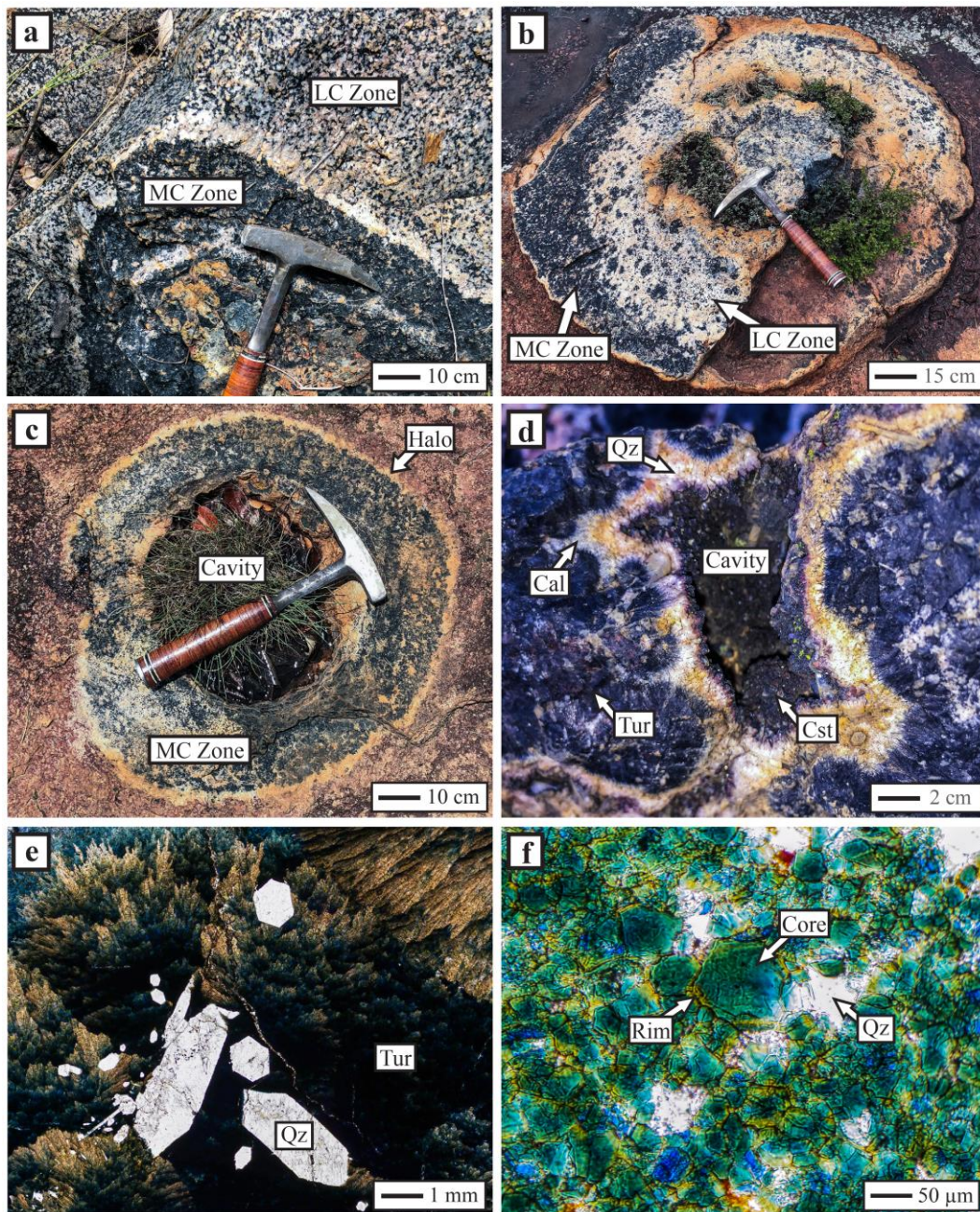


Figure 5.6. Field and thin-section photomicrographs of tourmaline from hydrothermal pipes. (a) Image of the contact between the melanocratic and leucocratic zones within a large hydrothermal pipe from the Bobbejaankop granite. (b) Circular hydrothermal pipe from the Bobbejaankop granite, exhibiting a leucocratic core and melanocratic outer rim. (c) Small hydrothermal pipe from within the Bobbejaankop granite with a large central cavity. (d) Miarolitic cavity from within a hydrothermal pipe, lined with euhedral cassiterite. (e) Microphotograph in plane-polarized light of the melanocratic hydrothermal pipe material displaying radial green-brown tourmaline intergrown with doubly terminated quartz from a hydrothermal pipe in the Lease granite. (f) Microphotograph in plane-polarized light showing the pleochroic zonation of tourmaline crystals with blue-green cores and brown rims from a hydrothermal pipe in the Lease granite. Abbreviations: melanocratic (MC); leucocratic (LC); cassiterite (Cst); tourmaline (Tur); quartz (Qtz).

Major pipes are similar to the minor pipes although less structured and range from 3 to 25 m in diameter. These major hydrothermal pipes host interstitial miarolitic cavities that contain fine- to coarse grained euhedral cassiterite (Figure 5.6d). They were mined for their remarkable Sn grades that were up to 80 % cassiterite and are mostly inaccessible in the Lease granite (Strauss and Truter, 1944; Crocker et al., 2001) (Figure 5.6d).

The melanocratic tourmaline zones of the pipes are composed of sub- to euhedral, doubly-terminated quartz grains (0.1 to 6 mm) cemented in place by large radial tourmaline fans (5 to 7 mm in radius) (Figure 5.6e). The spherical tourmaline fans form acute angles with coarse-grained inward projecting quartz. Tourmaline fans radiate from a central nucleation point, terminating along individual crystal faces, forming a herringbone textured contact between fans. These tourmalines are coarser grained (0.1 to 0.5 mm) and exhibit a distinct pleochroism, from dark brown to a blue-green (Figure 5.6e, f). Additionally, where visible, the tourmalines show a zonation of a blue-green core to a thin brown rim (Figure 5.6f). Miarolitic spaces between tourmaline fans are infilled by interlocking quartz grains, sub- to euhedral fluorite, calcite, cassiterite and occasionally pyrite with minor chalcopyrite.

Cassiterite Mineralization

At the Groenfontein tin mine, mineralization is restricted to the upper facies of the Lease granite. In contrast, both the Bobbejaankop and Lease granites host disseminated mineralization at the Zaaipplaats tin mine (Figure 5.2). There are three primary styles of cassiterite mineralization at the Groenfontein tin mine: (1) low-grade disseminated mineralization; (2) large tourmalinized and greisenized hydrothermal pipes; and (3) highly greisenized lenticular ore-bodies. Due to extensive mining and back-filling, no mineralized material remains from the high-grade lenticular ore bodies. Therefore, this study compares cassiterite from the various styles of disseminated cassiterite (interstitial disseminations and pegmatitic vugs) with the greisen-related cassiterite from hydrothermal pipes.

Disseminated cassiterite is restricted to a 600 m by 30 m wide zone in the upper facies of the Lease granite. This zone follows the upper contact with the overlying Rashoop Granophyre Suite (Figure 5.2). Red-brown subhedral cassiterites (0.5 to 0.7 mm) are interstitially disseminated within these mineralized zones (Figure 5.7). The homogeneous cassiterites lack any visible zonation or inclusions and are closely associated with the chloritized and subsequent greisenization of biotite and alkali-feldspar (Figure 5.7a, b). Exsolutions of small

(10 to 100 μm) anhedral cassiterite grains are seen along the relic cleavage and mineral boundaries of the altered biotite (Figure 5.7b).

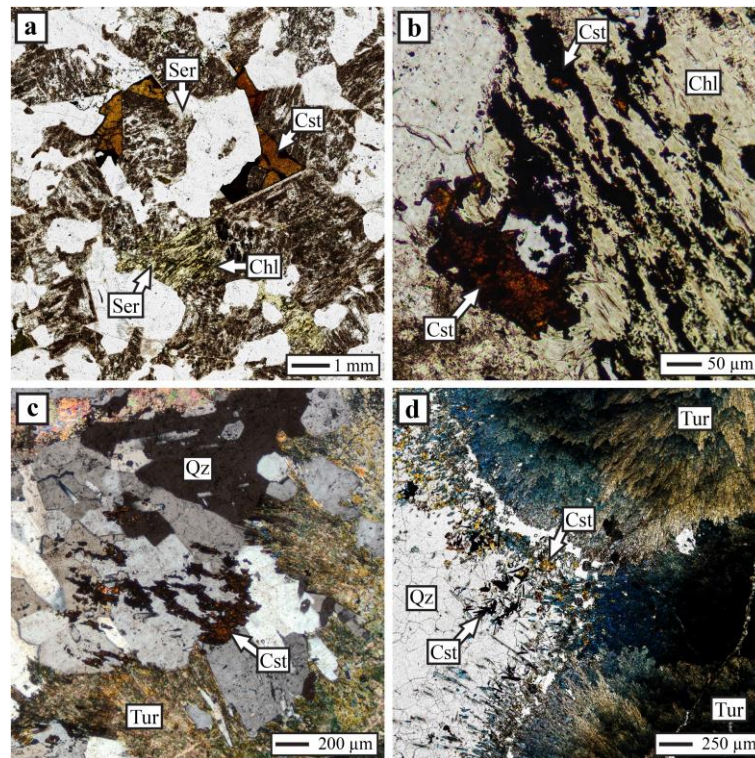


Figure 5.7. Photomicrographs of cassiterite from the Lease granite. (a) Photomicrograph in plane-polarized light of disseminated cassiterite showing euhedral red-brown cassiterites growing interstitially between quartz and alkali-feldspar with proximal chloritization and sericitization. (b) Photomicrograph in plane-polarized light of cassiterite exsolution from within the chloritized biotite. (c) Photomicrograph of a pegmatitic vug in cross-polarized light containing a large cassiterite grain intergrown with quartz. (d) Photomicrograph in plane-polarized light of small round cassiterite granules precipitating along the margin of radial tourmaline fans in a hydrothermal pipe. Abbreviations: sericite (Ser), chlorite (Chl), cassiterite (Cst); tourmaline (Tur); quartz (Qtz).

The occasional cassiterite within the pegmatitic tourmaline vugs are typically large (0.1 to 1.5 mm) and sometimes exhibit a light-brown and red-brown sector zonation. These pegmatitic cassiterites are subhedral and intergrown with quartz along the margins of the new blue-green tourmaline (Figure 5.7c). The cassiterite within the tourmalinized hydrothermal pipes is a lighter brown, anhedral and with a large range in grain-sizes (10 to 500 μm). These red-brown cassiterite grains are either intergrown with quartz along the rims of radial tourmalines, occur as inclusions within the tourmaline fans or formed within miarolitic cavities (Figure 5.7d). Occasionally, cassiterite exhibits two distinct non-concentric zones of a deep-red to brown core and a light-brown rim. This resembles sector zonation and is more prominent within the cassiterites from the pegmatitic vugs and greisenized pipes. The disseminated variety is more homogenous and displays a dark-red to brown pleochroism.

5.2.5. Analytical Methods

Tourmaline-bearing samples from the Bobbejaankop granite, Lease granite and hydrothermal pipes, in addition to cassiterite-bearing samples from the Lease granite and hydrothermal pipes were collected *in situ* or from waste piles. The samples were crushed, milled and sieved to less than 500 µm before being processed on a Wilfley table. These samples were then magnetically separated using a Franz magnetic separator. The extracted minerals were separated into heavy and light density populations. Tourmaline and cassiterite were subsequently picked and mounted in resin blocks for microprobe analysis. Tourmaline and cassiterite epoxy mineral mounts were polished to between 1 and 2 microns and vacuum carbon coated to approximately 25 nm thickness. In total, 251 tourmaline grains were analyzed from the Lease granite (165) and the Bobbejaankop granite (86). Where any zonation was observed, the different zones were analyzed. A total of 231 analyzes were made on cassiterite grains from three styles of mineralization within the Lease granite, including greisen-related (94), disseminated (41) and pegmatitic pods and veins (96).

The tourmaline and cassiterite from Groenfontein tin mine were analyzed at Rhodes University, Grahamstown, South Africa. Quantitative mineral chemical compositions of tourmaline and cassiterite were obtained by using four wavelength dispersive spectrometers on a JEOL JXA-8230 electron probe micro-analyzer (EPMA). The complete sets of tourmaline and cassiterite compositions are provided in Supplementary Tables 1 and 2 respectively. The beam was generated by a tungsten cathode, and excited with 20 and 15 kV accelerating potential at 30 and 20 nA current. Beam sizes of 1 to 10 µm were used. All elements were measured on K-alpha peaks, except for Sn and Nb on L-alpha, and W and Ta on M-alpha with a peak counting time of 10s and 10s total on background. Commercial "SPI" standards were used for intensity calibration. The standards were Sn-metal (Sn), Ta-metal (Ta), Nb-metal (Nb), Rhodonite (Mn), Rutile (Ti), W-metal (W), Magnetite/Pyrope (Fe), Kaersutite (Al), Plagioclase (Ca), Albite (Na), Pyrope (Mg, and Si), Orthoclase (K), and MgF₂ (F). Fluorine was measured on TAPL. The data was collected with JEOL software (PC EPMA 1.9.2.0) and its ZAF algorithm (Heinrich/Duncumb-Reed with FFAST-2005 MACs) was applied to correct for differential matrix effects. Oxygen was stoichiometrically calculated and nominal boron and water included in the matrix correction.

Recalculation of tourmaline compositions was accomplished by using a similar process to Tindle et al. (2002). Tourmaline compositions were normalized to 31 anions including 15 cations at the tetrahedral and octahedral sites (T+Z+Y). Recalculation was based on the tourmaline structural formula $XY_3Z_6(T_6O_{18})(BO_3)_3V_3W$. Boron and (OH+O) were not measured, thus were stoichiometrically calculated. Assuming 3 B atoms per formula unit (*apfu*) (complete saturation of B with none occupying the tetrahedral site) and 4 *apfu* for OH (Tindle et al., 2002; Clark, 2007; Henry and Dutrow, 2012; Morgan, 2016). Cassiterite compositions were normalized to 2 anions based on the structural formula SnO_2 . All Fe was assumed to be divalent and is reported as FeO^{tot} and Fe^{tot} . The stoichiometric recalculation of tourmaline data was accomplished using the online spreadsheet available from http://www.open.ac.uk/earth-research/tindle/AGT/AGT_Home_2010/Microprobe-2.html. (For the spreadsheet or more information please contact the corresponding author).

5.2.6. Results

Tourmaline Mineral Chemistry

Representative analyzes from the various styles of tourmalinization in the Bobbejaankop granite, Lease granite and hydrothermal pipes, are shown in Table 5.3. The use of Li, B and H_2O in the direct classification and categorization of these tourmalines was excluded as these values were stoichiometrically calculated. Consequently, the *W-site* anion classification of fluor-, oxy- and hydroxyl-subgroups based on Hawthorne and Henry (1999) and Henry *et al.* (2011), was not attempted. The exchange vectors relating to the aforementioned elements are not directly discussed, although their influence is inferred from the use of elemental proxies, as discussed by Tindle et al. (2002) and Fuchsloch (2018). There is no significant compositional difference between the varieties of tourmaline within the Lease and Bobbejaankop granite. Therefore, in order to present the data, the tourmalines are lithologically grouped as follows: Bobbejaankop granite tourmalines; Lease granite tourmalines; Bobbejaankop-pipe tourmalines; and Lease-pipe tourmalines.

Table 5.3. Representative tourmaline compositions from the Bobbejaankop granite, Lease granite and hydrothermal pipes.

Style	Lease Granite					Lease Granite					Lease Granite				
	Patch Tourmaline					Patch Tourmaline					Orbicule Tourmaline				
	Srl	Srl	Srl	Srl	Foi	Srl	Srl	Srl	Foi	Foi	Srl	Srl	Srl	Foi	Foi
#	1a	2	34	27b	2b	15	48	31b	19	39	31b	9	12	12b	39
SiO ₂	34.04	33.52	33.20	33.91	34.70	33.61	34.06	34.54	35.03	35.55	34.54	34.80	33.69	35.37	35.55
TiO ₂	0.06	-	-	0.50	0.02	-	-	-	-	-	-	0.11	0.04	0.01	-
Al ₂ O ₃	26.71	25.14	24.51	25.46	31.62	24.48	26.14	26.27	32.05	31.83	26.27	28.83	24.28	31.35	31.83
FeO	21.67	23.05	24.05	22.17	16.50	23.48	22.05	22.38	15.57	16.19	22.38	18.04	23.76	15.97	16.19
MgO	0.03	0.02	-	0.06	0.02	0.02	0.03	0.03	0.08	0.05	0.03	0.02	-	0.02	0.05
CaO	0.09	0.07	0.04	0.01	0.02	0.04	0.20	0.20	0.02	0.05	0.20	0.28	0.04	0.01	0.05
MnO	-	0.03	0.01	0.03	0.04	0.04	0.04	0.02	0.02	0.01	0.02	0.01	0.01	0.02	0.01
Na ₂ O	2.51	2.68	2.55	2.78	0.72	2.62	2.66	2.50	0.62	1.00	2.50	1.88	2.54	0.80	1.00
K ₂ O	0.07	0.09	0.06	0.10	0.04	0.07	0.07	0.08	0.03	0.03	0.08	0.04	0.06	0.02	0.03
F	0.62	-	0.01	0.79	0.10	-	0.45	0.01	0.10	0.15	0.01	0.08	0.03	0.02	0.15
H ₂ O*	3.05	3.27	3.24	2.94	3.38	3.25	3.12	3.36	3.40	3.42	3.36	3.36	3.24	3.45	3.42
B ₂ O ₃ *	9.67	9.48	9.39	9.60	9.94	9.43	9.65	9.74	10.00	10.12	9.74	9.85	9.43	10.01	10.12
Li ₂ O*	0.10	0.03	-	0.17	0.08	0.07	0.16	0.18	0.21	0.32	0.18	0.46	0.08	0.37	0.32
Total	98.61	97.38	97.05	98.53	97.16	97.13	98.62	99.32	97.11	98.72	99.32	97.75	97.18	97.41	98.72
O=F	0.26			0.33	0.04		0.19	0.01	0.04	0.06	0.01	0.03	0.01	0.01	0.06
Total	98.35	97.38	97.05	98.20	97.12	97.13	98.44	99.31	97.06	98.66	99.31	97.72	97.17	97.40	98.66
Cations based on 31 anions															
T:Si	6.12	6.15	6.14	6.14	6.07	6.19	6.14	6.16	6.09	6.10	6.16	6.14	6.21	6.14	6.10
Al	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Z:Al	5.66	5.43	5.35	5.43	6.00	5.32	5.55	5.52	6.00	6.00	5.52	5.99	5.27	6.00	6.00
Mg	0.01	0.01	-	0.02	-	0.01	0.01	0.01	-	-	0.01	0.01	-	-	-
Y:Al	-	-	-	-	0.52	-	-	-	0.57	0.44	-	-	-	0.41	0.44
Ti	0.01	-	-	0.07	-	-	-	-	-	-	-	0.01	0.01	-	-
Mg	-	-	-	-	-	-	-	-	0.02	0.01	-	-	-	-	0.01
Mn	-	-	-	0.01	0.01	0.01	0.01	-	-	-	-	-	-	-	-
Fe ²⁺	3.26	3.53	3.72	3.36	2.41	3.62	3.32	3.34	2.26	2.33	3.34	2.66	3.66	2.32	2.33
Li*	0.07	0.02	-	0.12	0.06	0.05	0.11	0.13	0.15	0.22	0.13	0.33	0.06	0.26	0.22
ΣY	3.33	3.56	3.72	3.55	3.00	3.68	3.44	3.47	3.00	3.00	3.47	3.00	3.73	3.00	3.00
X:Ca	0.02	0.01	0.01	-	-	0.01	0.04	0.04	-	0.01	0.04	0.05	0.01	-	0.01
Na	0.88	0.95	0.91	0.98	0.24	0.93	0.93	0.86	0.21	0.33	0.86	0.64	0.91	0.27	0.33
K	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.01	-	0.01
[□]	0.09	0.01	0.06	-	0.74	0.04	0.02	0.08	0.78	0.65	0.08	0.30	0.07	0.72	0.65
OH	3.65	4.00	4.00	3.55	3.95	4.00	3.74	3.99	3.94	3.92	3.99	3.96	3.98	3.99	3.92
F	0.35	-	-	0.45	0.05	-	0.26	0.01	0.06	0.08	0.01	0.04	0.02	0.01	0.08
Endmember Mole Fraction															
Srl	0.90	0.97	0.94	0.99	0.29	0.96	0.95	0.90	0.22	0.30	0.90	0.59	0.94	0.24	0.30
Foi	0.08	0.02	0.05	0.01	0.68	0.03	0.02	0.07	0.70	0.57	0.07	0.25	0.05	0.62	0.57
Lid	0.02	0.01	0.01			0.01	0.03	0.03		0.01	0.03	0.04	0.01		0.01
Elb					0.03				0.08	0.12		0.12		0.14	0.12
Drv															

Table 3 (cont.):

Style	Lease Granite					Bobbejaankop Granite					Bobbejaankop Granite				
	Pipe Tourmaline					Pipe Tourmaline					Orbicule Tourmaline				
#	Srl	Srl	Srl	Srl	Foi	Srl	Srl	Srl	Srl	Foi	Srl	Srl	Srl	Foi	Foi
8	19	34	47	5	14	17	39	42	16	12	50	52	43	53	
SiO ₂	34.45	34.46	35.66	33.51	34.94	33.56	33.94	34.11	34.74	34.50	34.79	35.83	33.93	34.50	35.53
TiO ₂	-	0.34	-	0.03	0.09	-	0.09	0.08	0.06	-	0.13	0.06	-	0.07	0.09
Al ₂ O ₃	26.05	26.56	30.17	23.10	31.38	26.70	27.26	27.36	27.24	31.25	29.01	30.63	29.15	30.08	30.68
FeO	22.63	21.22	18.29	25.55	16.36	21.32	21.00	20.91	21.25	17.28	18.80	18.58	19.32	17.75	18.28
MgO	-	0.01	-	0.01	0.03	0.01	-	-	0.01	0.02	0.13	0.15	0.06	0.07	0.13
CaO	0.18	0.20	0.09	0.39	-	0.02	0.02	0.03	0.04	0.17	0.01	0.01	0.02	0.01	0.02
MnO	0.04	0.05	0.06	0.03	-	0.06	0.01	0.05	0.02	0.01	-	0.01	-	-	-
Na ₂ O	2.45	2.40	2.06	2.66	0.89	2.45	2.22	2.27	2.24	1.35	1.66	1.64	1.54	1.32	1.47
K ₂ O	0.11	0.04	0.05	0.07	0.01	0.06	0.04	0.05	0.08	0.04	0.05	0.05	0.05	0.04	0.04
F	0.23	0.55	0.01	0.04	-	-	0.04	-	0.01	-	-	-	-	-	-
H ₂ O*	3.24	3.10	3.49	3.22	3.44	3.30	3.31	3.35	3.38	3.43	3.40	3.52	3.36	3.40	3.49
B ₂ O ₃ *	9.71	9.74	10.14	9.39	9.97	9.56	9.65	9.70	9.80	9.96	9.87	10.20	9.73	9.85	10.13
Li ₂ O*	0.15	0.27	0.40	-	0.21	0.03	0.06	0.10	0.20	0.06	0.22	0.22	-	0.14	0.18
Total	99.22	98.93	100.42	97.99	97.31	97.06	97.64	98.00	99.06	98.08	98.07	100.88	97.17	97.23	100.05
O=F	0.10	0.23		0.02			0.02								
Total	99.12	98.70	100.42	97.97	97.31	97.06	97.62	98.00	99.06	98.07	98.07	100.88	97.17	97.23	100.04
Cations based on 31 anions															
T:Si	6.17	6.15	6.11	6.20	6.09	6.10	6.11	6.11	6.16	6.02	6.13	6.11	6.06	6.09	6.10
Al	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Z:Al	5.50	5.59	6.00	5.04	6.00	5.72	5.78	5.78	5.69	6.00	6.00	6.00	6.00	6.00	6.00
Mg	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Y:Al	-	-	0.10	-	0.45	-	-	-	-	0.43	0.02	0.15	0.14	0.26	0.20
Ti	-	0.05	-	-	0.01	-	0.01	0.01	0.01	-	0.02	0.01	-	0.01	0.01
Mg	-	-	-	-	0.01	-	-	-	-	-	0.03	0.04	0.02	0.02	0.03
Mn	0.01	0.01	0.01	0.01	-	0.01	-	0.01	-	-	-	-	-	-	-
Fe ²⁺	3.39	3.17	2.62	3.96	2.39	3.24	3.16	3.13	3.15	2.52	2.77	2.65	2.89	2.62	2.62
Li*	0.11	0.19	0.27	-	0.15	0.02	0.04	0.07	0.14	0.04	0.16	0.15	-	0.10	0.13
ΣY	3.50	3.41	3.00	3.96	3.00	3.27	3.22	3.22	3.31	3.00	3.00	3.00	3.04	3.00	3.00
X:Ca	0.03	0.04	0.02	0.08	-	-	-	0.01	0.01	0.03	-	-	-	-	-
Na	0.85	0.83	0.68	0.96	0.30	0.87	0.77	0.79	0.77	0.46	0.57	0.54	0.53	0.45	0.49
K	0.02	0.01	0.01	0.02	-	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01
[□]	0.09	0.12	0.29	-	0.70	0.12	0.21	0.19	0.21	0.50	0.42	0.45	0.45	0.54	0.50
OH	3.87	3.69	4.00	3.97	4.00	4.00	3.98	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
F	0.13	0.31	-	0.03	-	-	0.02	-	-	-	-	-	-	-	-
Endmember Mole Fraction															
Srl	0.90	0.86	0.59	0.94	0.30	0.89	0.81	0.82	0.81	0.49	0.56	0.51	0.59	0.46	0.48
Foi	0.08	0.11	0.25		0.62	0.11	0.19	0.17	0.18	0.48	0.36	0.39	0.41	0.48	0.44
Lid		0.03	0.02	0.06				0.01	0.01	0.03					
Elb	0.02		0.14		0.08						0.08	0.09		0.05	0.07
Drv												0.01		0.01	0.01

Stoichiometrically calculated values denoted by ()

*Abbreviations: Bobbejaankop Granite (BG); Bobbejaankop hydrothermal pipe (BP); Lease Granite (LG); Lease hydrothermal pipe (LP); Schorl (Srl); Foitite (Foi); Liddicoatite (Lid); Elbaite (Elb); Dravite (Drv); and Below Detection Limit (-).

The tourmalines range in composition from 32.71 to 35.97 % SiO₂, 22.43 to 33.11 % Al₂O₃, 12.42 to 25.55 % FeO^{tot} and 0.62 to 2.79 % Na₂O. Other structurally significant components, such as TiO₂, MgO, CaO and F contribute up to 0.50 %, 0.17 %, 1.02 % and 0.86 % respectively.

All the Zaaiplaats tin field tourmalines plot within the “Li-poor granitic rocks” subdivision of the Al-Fe-Mg tourmaline classification diagram of Henry and Guidotti (1985) (Figure 5.8a). The principle classification of tourmalines predominantly places them as part of the “Alkali Group”, mainly involving Na+K and X -site vacancy ($\square^X$) substitutions with little Ca contribution (Figure 5.8b).

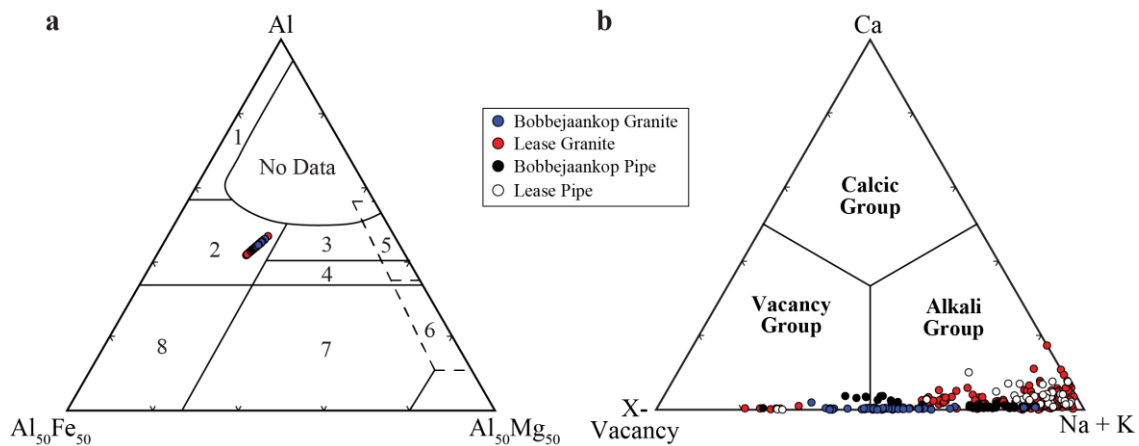


Figure 5.8. Ternary tourmaline classification diagrams. (a) Al-Fe-Mg tourmaline classification diagram adapted from Henry and Guidotti (1985) placing all the Zaaiplaats tin field tourmalines within the Li-poor granitic rock field. Numbered fields within the diagram correspond to various regimes of tourmaline occurrences; (1) Li-rich granitic rocks (2) Li-poor granitic rocks (3) Al-rich metapelites and metapsammities (4) Al-poor metapelites and metapsammities (5) Low-Ca ultramafics (6) Metacarbonates (7) Fe^{3+} -rich rocks (8) Fe^{3+} -rich granitic rocks. (b) The principal tourmaline subgroup classification diagram, modified after Hawthorne and Henry (1999). Most tourmalines fall within the Alkali Group, however several are scattered along the bottom boundary of the X -site vacancy group.

Bobbejaankop granite tourmalines

The Bobbejaankop granite tourmalines are very alkali- and Fe-rich and have little to no Mg content. They exhibit a slightly higher $\square^X$ than the other tourmalines and follow the schorl-foitite solid solution (Figure 5.9a). Bobbejaankop granite tourmalines are dominantly schorl with little foitite and evolve along the exchange vectors $(Al, Mg)(Fe^{2+})_{-1}$, $(Al, \square^X)((Ca, Na, K)(Fe))_{-1}$ (Figure 5.9a, b). The Bobbejaankop tourmalines are Ca-, Li-, F- and Ti-poor, although are comparatively Al- and Mg-rich compared to the Lease granite and both hydrothermal pipe populations. Due to the homogeneity of the Bobbejaankop granite tourmalines in backscattered electron imagery (Figure 5.10a), their compositional range is not attributed to an apparent chemical zonation.

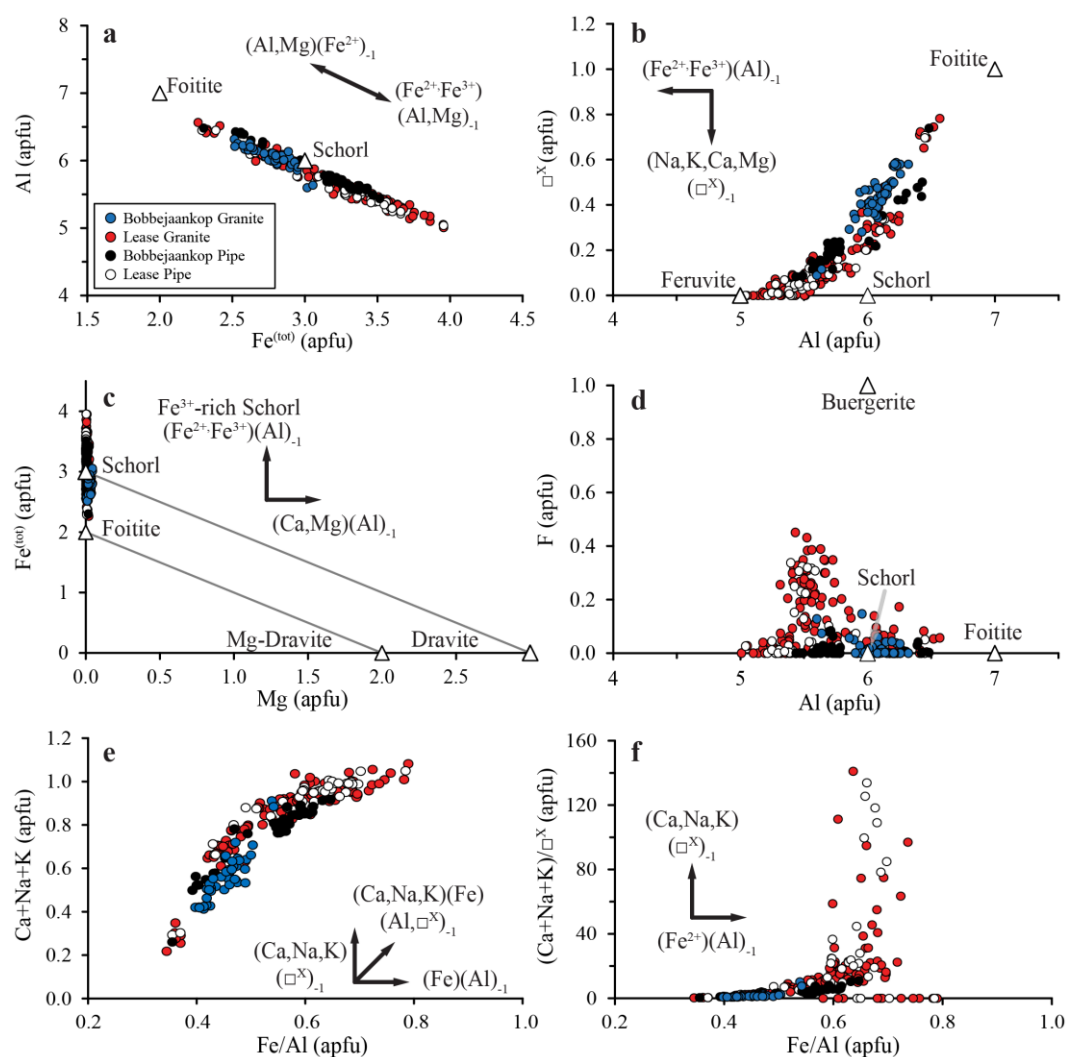


Figure 5.9. Graphs displaying the various cationic substitutions of the analyzed tourmalines. **(a)** Graph of Fe^{tot} vs Al displaying the schorl – foitite solid solution. **(b)** Graph of X-site vacancy ($\square^x$) vs total variation in Al. **(c)** Graph displaying the variation in Fe^{tot} and Mg of the tourmalines with respect to the schorl – dravite and foitite – Mg-foitite solid solution tie lines. **(d)** Graph displaying the variation in F content between the various lithologies. **(e)** Graph highlighting the enrichment of alkali-elements compared to variations in the Fe/Al ratio. **(f)** Graph displaying the relationship between alkali-elements and X-site vacancy compared to an increasing Fe/Al ratio. White triangles represent ideal tourmaline end-member compositions after Henry and Guidotti (1985) and Hawthorne and Dirlam (2011).

The Ca and Na content of all the tourmalines are positively correlated, yet Ca and Na exhibit a negative correlation with $\square^x$. Furthermore, all the tourmaline populations exhibit a distinct negative correlation between Fe and Al (Figure 5.9a, b, e and f). Therefore, the controlling cationic substitution within these tourmalines occurs primarily through Al – Fe and (Na, K, Ca) – $\square^x$ variations. This restricts their compositional range to the foitite–schorl– Fe^{3+} -rich schorl solid solution (Figure 5.9a, c) (London and Manning, 1995; Williamson et al., 2000; Buriánek and Novák, 2007).

Lease granite tourmalines

In contrast to the tourmalines from the Bobbejaankop granite, backscatter imaging of the tourmalines from the Lease granite highlights their considerably finer-grained, subhedral and more compositionally variable nature (Figure 5.10a, b). Consequently, combining backscatter images and major elemental differences, these compositional variations are separated into two distinct types, an Fe-rich *Type 1* and an Al-rich *Type 2* (Figure 5.10b).

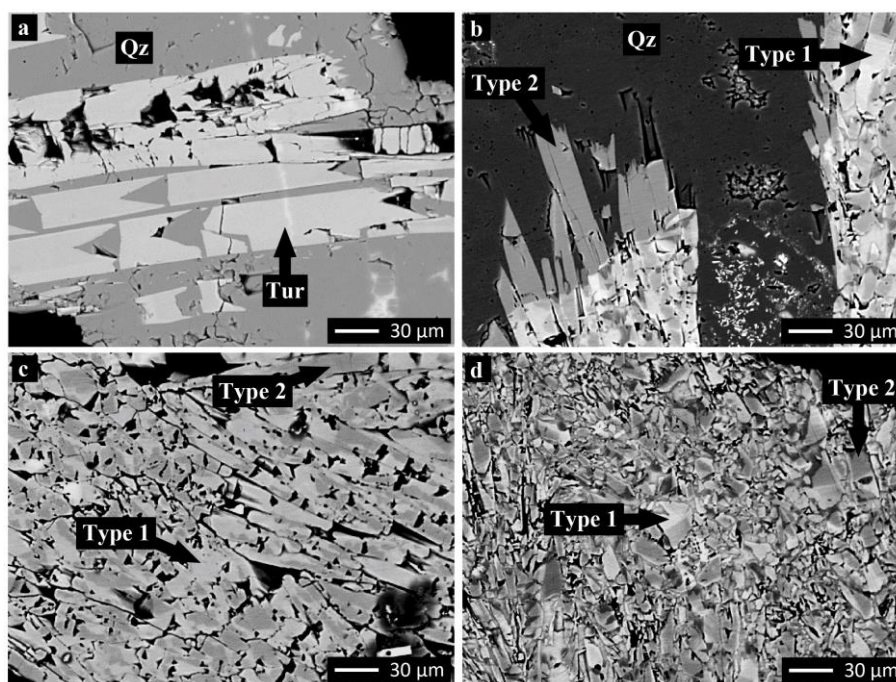


Figure 5.10. Backscattered electron images of tourmaline mineral separates from the Bobbejaankop granite, Lease granite, Bobbejaankop pipes and Lease pipes. (a) Backscattered electron image of euhedral, homogeneous tourmaline of the Bobbejaankop granite hosted within a quartz groundmass. (b) Backscattered electron image of zoned tourmaline from the Lease granite displaying euhedral tourmaline crystals (Type 1) and fine-grained granular tourmaline (Type 2). (c) Backscattered electron image of granular and chemically variable tourmaline (Type 1 and Type 2) from a hydrothermal pipe within the Bobbejaankop granite. (d). Backscattered electron image of fine-grained, granular and chemically variable (Type 1 and Type 2) tourmaline from a hydrothermal pipe in the Lease granite. Abbreviation: tourmaline (Tur) and quartz (Qtz)

The granular centers of the Lease granite tourmaline are of a *Type 1* composition. These *Type 1* tourmalines are Fe-rich and associated with a higher Na, Ca, K and F with a lower Al, Mg and $\square^x$ content (Figure 5.11a, d, g, j). This elevated Fe is strongly correlated with an Al depletion and defined by the exchange vectors $(\text{Fe}^{2+}, \text{Fe}^{3+})(\square^x)_-$ and $(\text{Al}, \text{Mg})(\text{Fe}^{2+}\text{Fe}^{3+})_-$ (Figure 5.9a, b). These granular centers of the Lease granite tourmalines exhibit an excess of Fe, beyond the stoichiometrically ideal composition of schorl. The Fe content of these

tourmalines approaches the composition of feruvite, yet they possess insufficient Ca and Mg to be considered feruvitic (Table 5.2, Figure 5.9b).

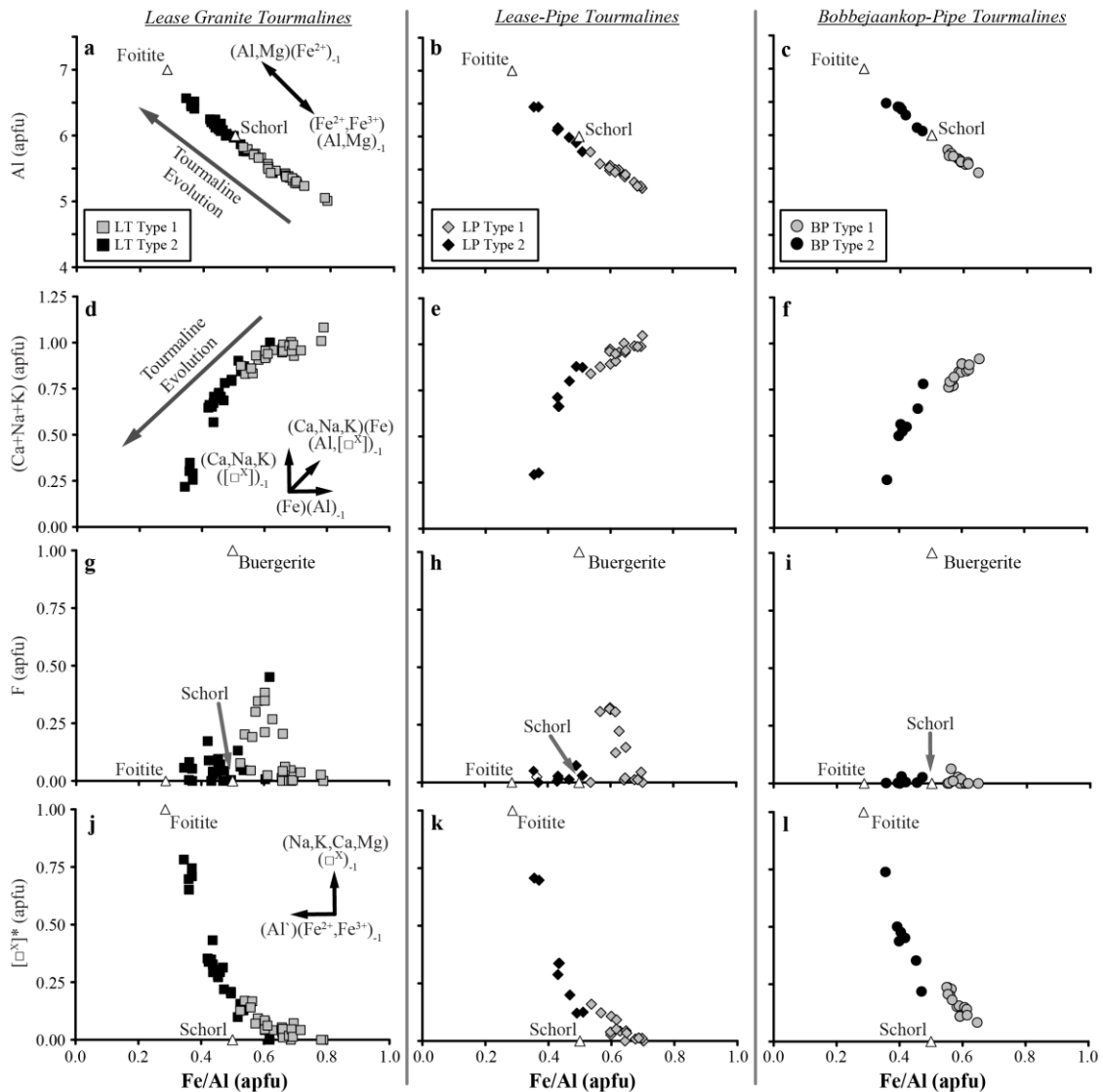


Figure 5.11. Graphs displaying chemical variability of the lithologies that exhibit the two compositional types. Type 1 represented in black, Type 2 represented in grey. The relationship of $\text{Fe}^{\text{tot}}/\text{Al}$ vs Al from the tourmaline within the Lease granite (LG, squares), Lease pipe (LP, diamonds) and Bobbejaankop pipe (BP, circles) is displayed in (a), (b) and (c) respectively. The graphs (d), (e) and (f) displays alkali differences in content against the Fe/Al ratio between Type 1 and Type 2 from the LG, LP and BP respectively. The variability of F within the zones of the LG, LP and BP is highlighted in graphs (g), (h) and (i). The calculated X-site vacancy ($\square^{\text{X}}$) from the LG, LP and BP in the different zones is displayed in (j), (k) and (l). White triangles represent ideal tourmaline endmember compositions after Henry and Guidotti (1985) and Hawthorne and Dirlam (2011).

The Type 2 tourmalines from the Lease granite typically occur along the periphery of the cluster. These tourmalines occasionally form inwards projecting euhedral crystals, which line the rims of quartz-filled miarolitic cavities within these tourmaline clusters (Figure 5.4f). They

share a similar composition with the Fe-poor Bobbejaankop granite tourmalines, exhibiting a higher Al, Mg, and $\square^X$ content than the Lease granite *Type 1* (Fe-rich schorl) tourmalines (Figure 5.11a, d, g and j). They follow the schorl – foitite substitution along the exchange vector $(\text{Al, Mg})(\text{Fe}^{2+})_{-1}$ and show a slightly greater foitite composition than the Bobbejaankop granite tourmalines. The *Type 1* Lease granite tourmalines are more Na-, Ca- and K-rich in the *X-site* than the *Type 2* variety, increasing from 0.20 to 0.98, 0 to 0.11 and 0.0 to 0.02 *apfu* respectively. This increased Na, Ca and K content has a corresponding $\square^X$ decrease from 0.78 to 0 *apfu* (Figure 5.11). *Type 1* tourmalines have a notably higher F content between 0.45 and 0.39 *apfu* and a Li component reaching 0.33 *apfu*.

Hydrothermal-pipe tourmalines

Unlike the homogeneous unzoned Bobbejaankop granite tourmaline, backscatter imagery reveals that the Bobbejaankop-pipe tourmalines are more compositionally variable. This variability is less concentric and less defined than in the Lease granite tourmalines, occurring as distinct irregular patches in backscatter imagery (Figure 5.10b, c). However, compositionally, these variations are similar to the Lease granite tourmalines, resembling the already defined Fe-rich (*Type 1*) and Al-rich (*Type 2*) varieties. The Bobbejaankop-pipe tourmalines are predominantly Fe-rich *Type 1*, hosting smaller irregularly shaped and distributed patches of Fe-poor *Type 2* (Figure 5.10b). The *Type 2* patches are $\square^X$ -, Al- and Mg-rich and follow the exchange vectors $(\text{Al, Mg})(\text{Fe}^{2+})_{-1}$ and $(\text{Al}, [\square^X])((\text{Ca, Na, K})(\text{Fe}))_{-1}$ (Figure 5.11b, e, h, k). The more ubiquitous *Type 1* tourmaline has a greater Fe, Na, and K content than the patches. The Bobbejaankop-pipe *Type 1* tourmaline mirrors the compositional range and exchange vectors of the *Type 1* tourmalines described in the Lease granite, although are notably F-poor (Table 3 and Figure 5.11i).

The Lease-pipe tourmalines display a similar granular texture and heterogeneity to the Bobbejaankop-pipe tourmalines (Figure 5.10d). However, they display a larger compositional range and are significantly finer-grained. The Lease-pipe tourmalines also exhibit both Fe-rich (*Type 1*) and Al-rich (*Type 2*) varieties. The distinction between the two types of tourmaline is less clear on backscatter imagery (Figure 5.10d). The Lease-pipe tourmalines exhibit a similar compositional range and abundance to the tourmalines of the Lease granite (Figure 5.11c, f, i, l). The decrease in F content from *Type-1* to *Type-2* tourmalines in the Lease granite is replicated by the Lease-pipe tourmalines (Figure 5.11g, h). In addition, the volumetrically

dominant *Type 1* composition are significantly more alkali- and Fe-rich compared to the lesser *Type 2* patches (Figure 5.11c, f, i, l).

Cassiterite Mineral Chemistry

The cassiterites from the different mineralized environments are grouped into three categories: disseminated cassiterite; greisen-related (hydrothermal pipes); and pegmatitic cassiterite. Representative cassiterite compositions from each occurrence are provided in Table 5.4. The compositional differences between the cassiterites from the samples of the Lease granite and mineralized hydrothermal pipes are small. This is attributed to their >98 % SnO₂ and very low Ti- and Ta content (Table 5.4).

Table 5.4. Representative cassiterite compositions from the various styles of mineralization in the Lease granite at the Groenfontein tin mine.

Style	Disseminated					Greisen Related (pipe)					Pegmatitic Vugs				
Type	1	1	1	2	2	1	1	1	2	2	1	1	1	2	2
Point #	94/1	94/36	94/20	94/40	94/15	69/22	69/31	72/11	72/24	72/25	67/19	67/40	67/2	67/26	85/17
SnO ₂	99.50	100.17	99.59	100.12	98.98	100.40	100.21	98.65	93.92	96.43	99.53	100.30	99.51	98.81	100.69
Nb ₂ O ₅	0.51	0.17	0.65	0.34	0.24	-	-	0.85	3.69	0.91	0.06	-	0.01	0.18	0.06
FeO	0.95	1.31	1.28	0.45	0.50	1.02	0.93	1.87	1.43	0.93	0.97	0.27	0.51	0.33	0.23
MnO	-	-	-	-	0.01	-	0.01	-	0.01	-	-	-	0.01	-	-
Ta ₂ O ₅	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
WO ₃	-	-	0.11	0.76	0.65	-	-	-	0.85	1.53	-	0.10	-	0.89	0.71
TiO ₂	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	100.96	101.65	101.63	101.66	100.38	101.42	101.14	101.37	99.90	99.81	100.56	100.67	100.03	100.22	101.69
Cations based on 2 anions															
Sn	0.98	0.99	0.98	0.99	0.97	0.99	0.99	0.97	0.92	0.95	0.98	0.99	0.98	0.97	0.99
Nb	0.01	-	0.01	-	-	-	-	0.01	0.04	0.01	-	-	-	-	-
Fe ²⁺	0.02	0.03	0.03	0.01	0.01	0.02	0.02	0.04	0.03	0.02	0.02	0.01	0.01	0.01	-
Mn	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ta	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
W	-	-	-	-	-	-	-	-	0.01	0.01	-	-	-	0.01	-
Ti	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	1.00	1.01	1.01	1.00	0.99	1.01	1.01	1.01	0.98	0.98	1.00	0.99	0.99	0.99	1.00

Abbreviation: Below Detection Limit (-)

However, many of the individual cassiterites are shown to be heterogeneous under backscatter imagery (Figure 5.12). Compositional variability arises primarily from differences in minor element abundances, specifically from fluctuations in the Fe, Mn, Nb and W content. Due to the very low abundances of Ta, Ti and the minor Nb contents of all cassiterites, cationic substitution is principally controlled by Sn, (Fe+Mn) and W variations (Figure 5.13). The ratio of (Nb+Ta)/Sn of these cassiterites variable whereas the Fe/Sn ratio remains relatively constant (Figure 5.13a, b). This implies that substitution does not follow the typical stoichiometric proportions of either 1:1 or 2:1 of (Nb+Ta):Fe as suggested by Möller et al., 1988 and Costi et al., 2000.

The composition of the cassiterite from pegmatitic vugs remains relatively constant across the area and backscatter imaging reveals light and dark zonations (Figure 5.12c). These cassiterites are predominantly SnO_2 and incorporate only 0.17 to 1.26 % FeO^{tot} and up to 1.06 % WO_3 , 0.77 % Nb_2O_5 and 0.05 % MnO . There is an apparent correlation between backscatter signal response and the purity of the cassiterite. This allows the classification of these cassiterites into two types. Type 1 cassiterite has a lower backscatter electron signal and a slightly higher SnO_2 content. These types are texturally associated with the lighter brown zonations (Figures 5.12c, 5.13). Type 2 cassiterite displays a higher backscatter electron signal and shows a significant increase in WO_3 with a lower SnO_2 content. These types are texturally associated with the darker brown zonations (Figures 5.12c, 5.13).

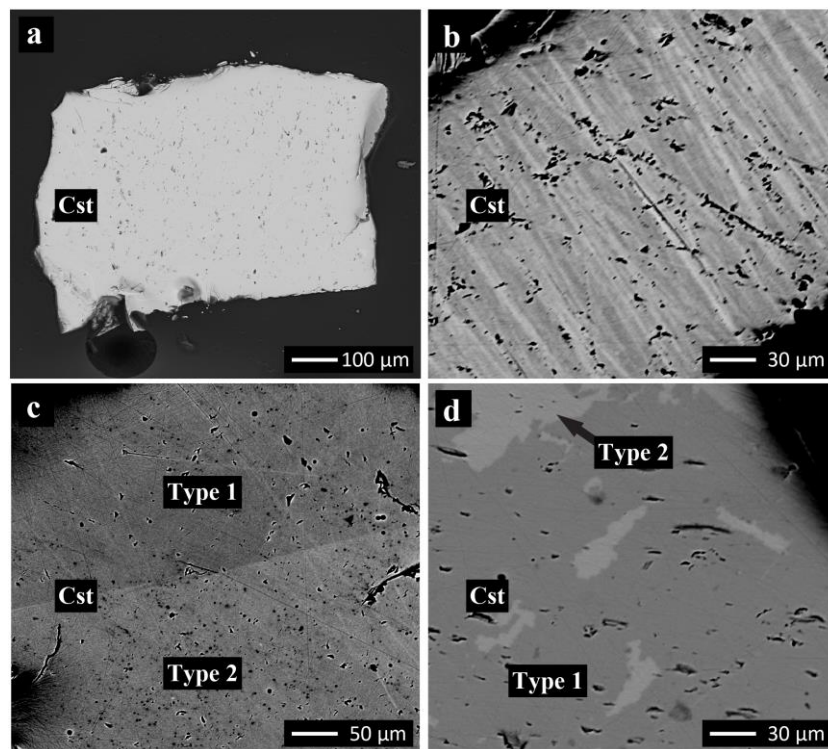


Figure 5.12. Backscattered electron (BE) images of cassiterites from the Lease granite. (a) Backscattered electron image of a homogeneous cassiterite from the low-grade disseminated mineralization. (b) Backscattered electron image of very-fine exsolution lamellae within a cassiterite from the disseminated mineralization. (c) Backscattered electron image of a cassiterite from the pegmatitic vugs, displaying two sectors. (d) Backscattered electron image of a greisen-hosted cassiterite grain exhibiting patches of Type 2 exsolution. Type 1 cassiterite has a low BE response and Type 2 cassiterite has a high BE response.

Type 1 cassiterite appears to be the dominant variety within all these cassiterite populations. *Type 1* cassiterite displays a compositional evolution from disseminated through greisen to pegmatitic cassiterites, involving a decrease in Fe and an increase in Sn. The

compositions of the *Type 2* cassiterite are Sn- and Fe- depleted but comparatively W-enriched (Figure 5.13c, d). The size and abundance of these *Type 2* exsolutions and zonations increases from the disseminated to the greisen-hosted and pegmatitic cassiterite populations respectively (Figure 5.13d).

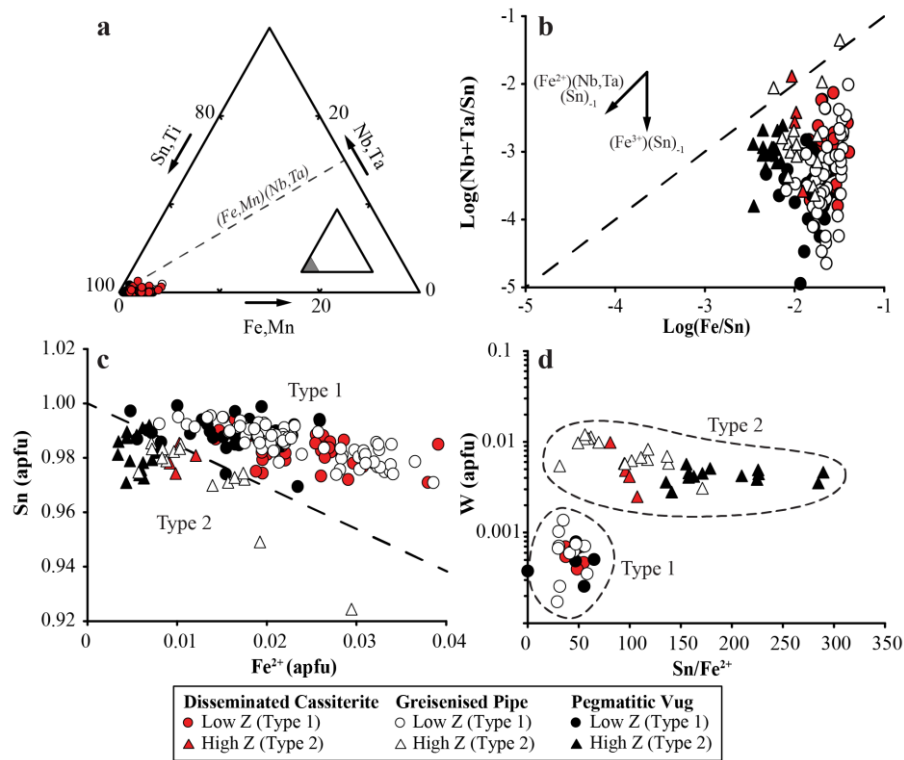


Figure 5.13. Diagrams displaying the compositional differences of cassiterite between Type 1 (circle) and Type 2 (triangle) zonation within each style of cassiterite occurrence. **(a)** Ternary (Fe, Mn)-(Nb, Ta)-(Sn, Ti) diagram after Cerny et al. (1985) defining the substitution line of (Fe, Mn)(Nb, Ta). The negligible Nb and Ta and high Sn content of these oxides is displayed by the grouping of the cassiterites in the Sn field of the diagram. **(b)** Diagram of $\text{log}[(\text{Nb}+\text{Ta})/\text{Sn}]$ vs $\text{log}[\text{Fe}/\text{Sn}]$ after Möller et al. (1988). The diagram shows the geochemical behavior of cassiterite, and the deviation from the ideal 1:1 stoichiometric substitution ratio of $(\text{Fe}^{2+})(\text{Nb, Ta})(\text{Sn})_{1-1}$. **(c)** Comparison of Fe^{2+} vs. Sn, showing a decreasing Fe content from disseminated to greisen-hosted to pegmatitic cassiterite. Type 1 cassiterite has a lower Fe than Type 2 cassiterite. **(d)** Graph of Sn/Fe^{2+} vs W highlighting the W enrichment of Type 2 cassiterite.

This correlated decrease of Fe and increase of W in the *Type 2* cassiterites is indicative of sector-zonation. The preferential incorporation of W over Fe is based on protosite coordination, as described by Bennett et al. (2020). They ascribe the formation of these W sectors within cassiterite crystals to the asymmetric favoring and enrichment of W in one crystallographic face. The sectoral preference is controlled by the coupled substitution of either $\text{W}^{6+}+\text{W}^{4+}+\text{Fe}^{2+} \leftrightarrow \text{Sn}^{4+}$ or $2\text{W}^{5+}+\text{Fe}^{2+} \leftrightarrow \text{Sn}^{4+}$ (Bennett et al., 2020).

The disseminated cassiterites are mostly SnO_2 , with minor elements ranging from 0.45 to 1.90 % FeO^{tot} , and up to 1.54 % WO_3 , 1.14 % Nb_2O_5 and 0.03 % MnO and negligible Ta_2O_5 . These cassiterites lack any apparent compositional zonation, although occasionally they exhibit very fine ($<5 \mu\text{m}$) exsolution (Figure 5.12b). Cassiterite from the greisenized hydrothermal pipes has a high WO_3 content with comparable FeO and Nb_2O_5 contents to the disseminated and pegmatitic cassiterite varieties. Zonation/exsolution within the disseminated cassiterite variety is non-concentric and occurs primarily as a patchy exsolution texture (Figure 5.12d). These patches of exsolution display a high backscatter response, a low Fe and high W content, making them *Type 2* cassiterites (Figures 5.12d, 5.13d).

Cassiterite from the greisenized hydrothermal pipes is compositionally intermediate between the pegmatitic and the disseminated varieties. These cassiterites have the highest W content, with , up to 1.88 % WO_3 . Zonation within these cassiterites is nonconcentric and appears as a patchy exsolution texture (Figure 5.12d). The Sn-rich *Type 1* variety is the volumetrically dominant (Figure 5.12d), whereas the *Type 2* exsolutions display a high backscatter response and are notably W-rich (Figures 5.12d, 5.13d).

5.2.7. Discussion

Classification of Tourmalines

Based on *X-site* occupancy, the principal subgroup classification of the studied tourmalines lies dominantly within the alkali-group, slightly overlapping the vacancy-group (Figure 5.8b). The tourmalines from the Groenfontein tin granites are classified as Fe^{3+} -rich schorl – schorl with lesser foitite (Figure 5.9). The end-member compositions in the Lease granite range from $\text{Schorl}_{0.22-0.99}\text{Foitite}_{0.01-0.7}\text{Liddicoatite}_{0-0.04}\text{Elbaite}_{0-0.14}$ and the Bobbejaankop granite tourmalines range from $\text{Schorl}_{0.3-0.94}\text{Foitite}_{0-0.62}\text{Liddicoatite}_{0-0.06}\text{Elbaite}_{0-0.14}$. Additionally, the range in end-member compositions from the Lease-pipe tourmaline is $\text{Schorl}_{0.49-0.89}\text{Foitite}_{0.11-0.48}\text{Liddicoatite}_{0-0.03}$, and the Bobbejaankop-pipe tourmaline is $\text{Schorl}_{0.46-0.59}\text{Foitite}_{0.36-0.48}\text{Elbaite}_{0-0.09}\text{Dravite}_{0-0.01}$.

Tourmaline compositions have been used as a proxy for hydrothermal fluid properties, provenance, temperature and distance travelled from a magmatic source (Dutrow and Henry, 2011; Slack and Trumbull, 2011; van Hinsberg et al., 2011a; van Hinsberg et al., 2011b). Pirajno and Smithies (1992) described an increase in Mg content of tourmaline with distance travelled

by the hydrothermal fluids from the parental magma. They propose that Mg-poor tourmalines indicate the fluids did not migrate from their magmatic source and are considered a magmatic-hydrothermal product of the hosting granite (Pirajno and Smithies, 1992; London and Manning, 1995; Balen and Broska, 2011). Therefore, the Mg-poor and Fe-rich tourmalines from the Zaaipiaats tin field granites imply that they originated from their host granitoids (Figure 5.14).

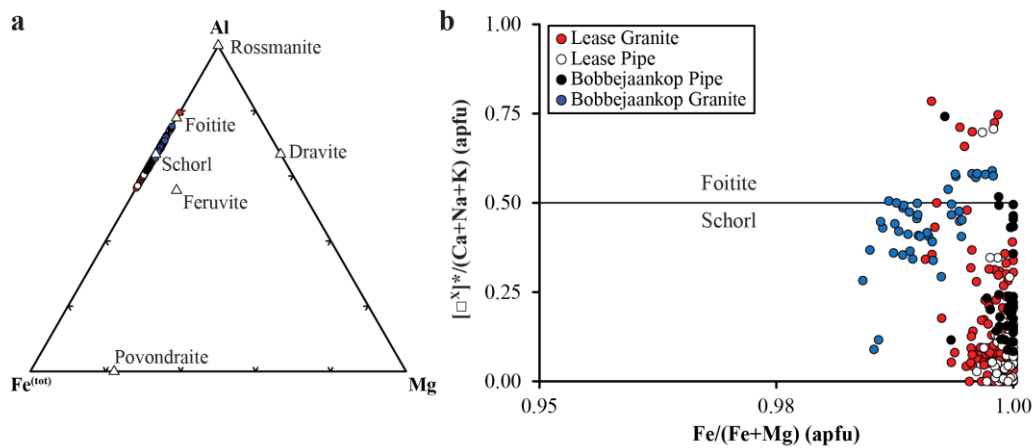


Figure 5.14. Graphs indicating the species of tourmaline from the Zaaipiaats tin field granites and hydrothermal pipes. (a) Al-Fe-Mg tourmaline classification diagram displaying the compositional range of the tourmaline. The tourmalines of the study area follow the schorl – foitite compositional range and exceed the ideal composition of schorl. White triangles represent ideal tourmaline endmember compositions after Hawthorne and Henry (1999) and Hawthorne and Dirlam (2011). (b) Comparison of the X-site compositional variability using Fe/(Fe+Mg) against $\square^x/(Ca+Na+K)$ of the tourmalines, emphasizing the schorl composition of the Lease granite, Bobbejaankop-pipe and Lease-pipe tourmalines. The Bobbejaankop granite tourmalines exhibit a slightly greater foitite composition.

The Bobbejaankop granite tourmalines are mostly schorl with lesser foitite. These tourmalines exhibit a lower Fe and a smaller compositional range than the Lease granite and hydrothermal pipe tourmalines (Figure 5.14). The Bobbejaankop granite tourmalines follow the exchange vector (Al,Mg)(Fe)₋₁, representing a decrease in Fe and increase in Mg and Al of the fluid composition (Figure 5.9a, b, c). This compositional shift is an expected evolutionary trend within closed granitic systems (London and Manning, 1995; London, 1999; Williamson et al., 2000; Drivenes et al., 2015). Compositions of the Lease granite and hydrothermal pipe tourmalines are not as predictable. The Lease granite is considered to be a facies that resulted from of hydrothermal alteration in the Bobbejaankop granite cupola (Vonopartis et al., 2020a). The composition of the tourmalines from the Lease granite would therefore be expected to display a continuation of the tourmaline evolution exhibited in the Bobbejaankop granite. However, the Lease granite tourmalines, together with the hydrothermal pipe

tourmalines, display a more Fe-rich or Fe³⁺-rich schorl composition. This contradicts the typical tourmaline evolution, from an initial Fe-rich tourmaline towards a more evolved Mg- and Al-rich tourmaline *i.e.*, from schorl–foitite towards dravite (Figure 5.9a, b).

The *Type 1* compositions of the Lease granite and hydrothermal pipe tourmalines have an unusually high proportion of Fe incorporated within their structure. The incorporated Fe is in excess of the ideal Fe *Y-site* occupancy for schorl, indicating a Fe³⁺-rich schorl composition (Figures 5.9c, 5.15a) (London and Manning, 1995; Williamson et al., 2000; Taewoo, 2017). Furthermore, there is a depletion of Al that indicates the Lease and pipe tourmalines are incorporating Fe in lieu of Al. This unusual increase in Fe is only recorded by the tourmalines in the Lease granite and hydrothermal pipes. Thus, they did not form from the same magmatic-hydrothermal fluid with the same composition that tourmalinized the Bobbejaankop granite, but rather a fluid with a more Fe-rich composition.

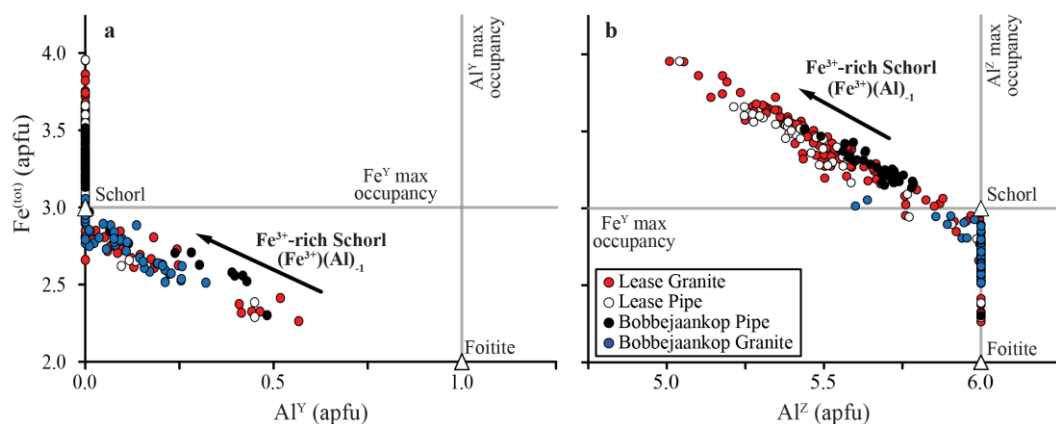


Figure 5.15. Graphs demonstrating the decrease of Al and increase of Fe in the various tourmalines. **(a)** The relationship of Fe^{tot} with the amount of Al at the *Y-site* (Al^Y). **(b)** Relationship of Fe^{tot} and the amount of Al at the *Z-site* (Al^Z). Grey lines delineate the maximum *Y*- and *Z*-site occupancies. White triangles represent ideal tourmaline endmember compositions after Hawthorne and Henry (1999) and Hawthorne and Dirlam (2011).

The surplus of Fe²⁺ for the *Y-site* (>3 *apfu*) is associated with a proportional depletion of Al at both the *Y*- and *Z*-sites (Figure 5.15). Experimentally, Dyar et al. (1998) revealed no obvious chemical or structural control on the substitution of Fe³⁺ into tourmalines, apart from its presence within the system. As no Fe²⁺:Fe³⁺ ratios were obtained from these tourmalines, the incorporation of Fe³⁺ is proxied by the behavior of Fe^{tot}, Al and □^x. The Al depletion from 0.2 to 0 *apfu* at the *Y-site* is reflected in the *Z-site*, where Al decreases from 6 to 5 *apfu* (Figure 5.15). Moreover, this systematic Al depletion is associated with a proportional increase in Fe^{tot} from 2.0 to 3.9 *apfu* (Figure 5.15). The Fe³⁺ cation is the only Fe valency permitted in the *Z*-

site. This indicates a substitution of both Fe^{2+} for Al^{4+} at the Y-site and Fe^{3+} for Al^{3+} in the Z-site. The necessary charge balance is evidently achieved by the proportionate $\square^x$ decrease of the tourmalines, further supporting the incorporation of Fe^{3+} (Figures 5.9b, 5.15) (London and Manning, 1995; Williamson et al., 2000).

The compositional continuity of the tourmaline populations, together with the similar whole-rock compositions of the Bobbejaankop and Lease granites (Vonopartis et al., 2020a), is suggestive of a single hydrothermal fluid. The evolution of this hydrothermal fluid resulted in two distinct types of tourmalines: (1) an initial magmatic-hydrothermal tourmaline with a schorl – foitite composition. This variety is typified by the unzoned, euhedral, coarse-grained tourmalines in the Bobbejaankop granite (Figure 5.16a); and (2) a later magmatic-hydrothermal tourmaline seen in the Lease granite and hydrothermal pipes. This later tourmaline formed from a more Fe^{3+} and F-rich magmatic-hydrothermal fluid (Figure 5.16b). The tourmaline from the Lease granite is texturally and geochemically similar to the tourmaline from the hydrothermal pipes. Therefore, it is likely that the Lease granite and hydrothermal pipe tourmaline populations formed from the same Fe^{3+} -bearing magmatic-hydrothermal fluid composition, rather than the initial composition that tourmalinized the Bobbejaankop granite.

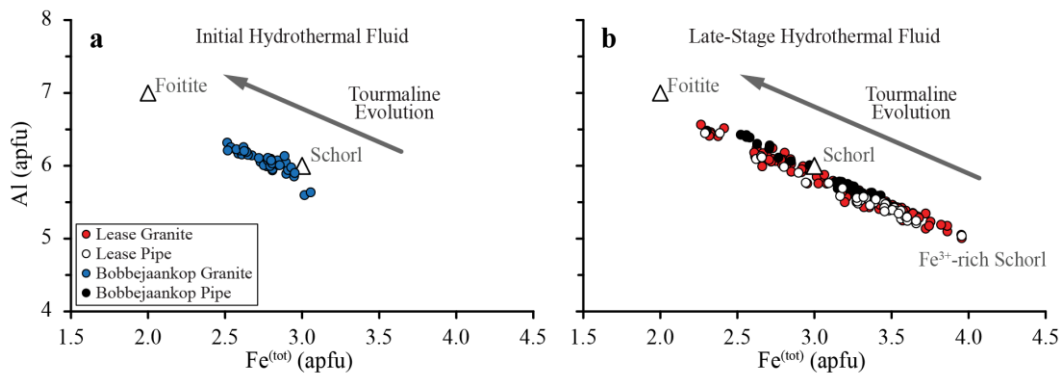


Figure 5.16. Graphs of $\text{Fe}^{(\text{tot})}$ vs Al illustrating the two stages of tourmalinization and their respective compositional evolutions. **(a)** The first stage of tourmalinization, recorded by the tourmalines in the Bobbejaankop granite from schorl to foitite. **(b)** The second stage of tourmalinization, recorded from the tourmalines in the Lease granite and hydrothermal pipes, from Fe^{3+} -rich schorl to schorl then foitite.

Formation of Tourmaline Features

The presence of tourmaline orbicules is uncommon within evolved granitic rocks and is considered even rarer in A-type granitic suites (Balén and Petrinec, 2011; Lira and Poklepovic,

2017). Regardless of their scarcity, tourmaline orbicules are consistently characterized by a melanocratic tourmaline-rich core with a leucocratic quartz-tourmaline rim (Bowden et al., 1990; Samson and Sinclair, 1992; Sinclair and Richardson, 1992; Foord et al., 1995; Bonin, 2007; Konopelko et al., 2007; Henry et al., 2008; Trumbull et al., 2008; Konopelko et al., 2009; Balen and Broska, 2011; Drivenes et al., 2015; Lira and Poklepovic, 2017). The mechanism of orbicule formation remains equivocal and a comprehensive summary of the various models is discussed in Balen and Broska (2011). However, tourmaline orbicules are commonly interpreted to be magmatic-hydrothermal features within a granite. They have been considered the result of the phase separation of a B-, Fe- and alkali-rich magmatic-hydrothermal fluid from a crystallizing silicic magma (London and Manning, 1995; Williamson et al., 2000; Veksler et al., 2002; Thomas et al., 2003; Veksler, 2004; Drivenes et al., 2015; Hong et al., 2017).

The tourmaline orbicules in the Zaaiplaats tin field show no evidence of post-magmatic alteration or associated fluid conduits. Therefore, they are likely to have formed by the proposed mechanism of fluid phase separation during magmatic crystallization. The Seagull batholith, Erongo granite and Heemskirk granite all host comparable tourmaline orbicules that are likewise thought to have formed from the separation of such a Fe- and B-rich fluid phase (Samson and Sinclair, 1992; Sinclair and Richardson, 1992; Drivenes et al., 2015). Boron and H₂O decreases the density of these fluid bubbles, assisting their ascent through a semi-crystalline magma, while maintaining their spherical shape to reduce surface energy (Candela, 1991; Jiang et al., 2003; Hong et al., 2017; Lira and Poklepovic, 2017). Therefore, the initial occurrence of orbicules below and along the Bobbejaankop – Lease contact, may delineate the magmatic to magmatic-hydrothermal transition within the Bobbejaankop pluton (Samson and Sinclair, 1992; Balen and Broska, 2011; Hong et al., 2017; Vonopartis et al., 2020a).

The tourmaline from the clusters in the Lease granite are Fe-rich, although they are not spherical and do not have the concentric melanocratic and leucocratic layers that characterize the orbicules (Figure 5.4a, b). They are therefore likely to have formed via a different mechanism. The tourmaline clusters within the Bobbejaankop granite are concentrated along the upper contact, becoming more abundant within the overlying Lease granite. This upward concentration is suggestive of an accumulation of the B-rich fluid within the granite cupola. These small tourmaline clusters lack a bleached halo, are interstitial and typically filled with

fine-grained tourmaline, calcite, fluorite and relict alkali-feldspar. The lack of fluid conduits and the selective tourmalinization of alkali-feldspar and other minerals implies their formation by incipient tourmalinization (Figure 5.4c). Larger tourmaline clusters display a meshing of the radially expanding tourmaline fans, incorporating partially digested alkali-feldspar and quartz. The incipient tourmalinization of the clusters require a degree of magmatic crystallization, whereas orbicular formation and migration is reliant on a much less solidified environment. Therefore, the upwards percolation of fluids through the partially crystalline cupola resulted in the incipient tourmalinization of alkali-feldspar and the formation of tourmaline clusters.

This process of devolatilization and fluid migration was proposed by Candela (1991). The model describes the formation of B-, Fe-, alkali- and metal-rich bubbles that migrate up through a crystallizing granitic magma and accumulate in the cupola. The reddening of the feldspar in the Bobbejaankop and Lease granites is caused by the hydrothermally induced structural re-ordering of the lattice, and the precipitation of hematite within the resulting micro-cavities (Putnis et al., 2007; Vonopartis et al., 2020a). This structural reordering of feldspar is discussed by Putnis et al. (2007) and is shown to increase permeability, and thus facilitate pervasive fluid migration. At lower degrees of crystallization the fluid coalesced and formed large channels or “bubble-laden plumes” (Candela, 1991). These plumes are analogous to the swarms of hydrothermal pipes radiating upwards from the center of the Bobbejaankop granite. As the viscosity of the magma increased via crystallization, the cohesion of these bubbles would correspondingly decrease (Candela, 1991). Thus, would favor the formation of larger and irregularly-shaped tourmaline pods, clusters and miarolitic cavities. During the final stages of crystallization, larger bubbles would have crystallized irregularly-shaped pegmatitic tourmaline- and cassiterite-bearing vugs, as they expanded from a decrease in pressure. The smaller, interstitial bubbles formed the disseminated tourmaline ± cassiterite filled interstitial miarolitic cavities of the Lease granite.

It is reasonable to suggest, from the ubiquitous tourmaline and fluorite, an abundance of B and F within the circulating magmatic-hydrothermal fluids. Boron- and F-rich granitic systems have a higher diffusivity, greater H₂O solubility, lower viscosity and enhanced ability of their resulting fluids to digest the surrounding granite (Pollard et al., 1987; London et al., 1989; Candela, 1991; London, 1999). Therefore, as proposed by Candela (1991), the

coalescence and channelization of these acidic B- and F-rich fluids resulted in the large hydrothermal pipes. These pipes rose through the semi-crystalline Bobbejaankop mush into a more competent Lease facies. The porosity of the reordered feldspars permitted the pervasive hydrothermal alteration and selective incipient tourmalinization of alkali-feldspar within the Lease granite.

The Lease granite tourmalines, with an inferred Fe^{3+} enrichment, are associated with a proportional increase in F at the *W-site*. This is expected in tourmaline that formed from an acidic, Fe- and F-rich magmatic-hydrothermal fluid (Buriánek and Novák, 2007). The high F as well as the increased Na and Ca content of the tourmaline in the Lease granite indicate a formation from an evolved incompatible element-rich magmatic-hydrothermal fluid. Fluid inclusion research by Pollard et al. (1991a) describes their composition to be hypersaline (containing NaCl, KCl and FeCl), and the coexistence of liquid- and vapor-bearing fluid inclusions within the Bobbejaankop and Lease granites (Pollard et al., 1991a). These acidic hypersaline and Cl-rich autometasomatic fluids can transport significant amounts of Fe, Al, Na and other metals such as Sn and W (Pollard et al., 1991a; London and Manning, 1995; London, 1999; Williamson et al., 2000; Robb, 2005; Hong et al., 2017). Unlike the other fluid components, the source of the Fe^{3+} is enigmatic and cannot be attributed to fractionation-controlled incompatible element enrichment. The Fe^{3+} is suggested to be introduced through a combination of three possible mechanisms.

The first hypothesis suggests boiling and the loss of H^+ into the vapor phase as a potential mechanism for the oxidation of the hydrothermal fluids. However, this is unlikely as textural evidence of a “boiling event” is lacking and the substantial F content of the Lease granite and pipe tourmalines is contradictory (Figure 5.9d). As a result of boiling, HF is preferentially partitioned into the vapor phase (Williamson et al., 2000). This would result in a low F content of the tourmaline, whereas the Fe^{3+} -rich schorl tourmalines of the Lease and Hydrothermal pipes have notable F contents (Figure 5.9d).

The second mechanism proposes the interaction of circulating magmatic-hydrothermal fluids with Fe^{3+} -bearing formational fluids. Williamson et al. (2000) proposed the interaction of the granitic system with external oxidized fluids for the formation of Fe^{3+} -rich blue tourmalines in the Cornubian batholith. It is likely that during the long-lived (~100 Ma) hydrothermal system at Zaaiplaats and the Bushveld Complex (McNaughton et al., 1993; Robb

et al., 2000; Kinnaird et al., 2004), the interaction with external fluids is possible. Moreover, the source and extent of the ~1,950 Ma overprinting event (Robb et al., 2000; Kinnaird et al., 2004) in the Bushveld Complex remains unresolved. This event is recorded throughout the Bushveld Complex and is suggested to potentially generate and reactivate hydrothermal systems (Robb et al., 2000; Kinnaird et al., 2004). Therefore, as the age of secondary hydrothermal features at Zaaipplaats is unknown, the interaction of magmatic-hydrothermal and formational fluids cannot be easily disregarded.

The third potential explanation suggests an internal ferric-enrichment of the evolving hydrothermal fluid. This is proposed to have been achieved by the liberation of Fe^{3+} through the alteration of alkali-feldspar. The tetrahedral diadochy of Fe^{3+} in lieu of Al^{4+} in alkali-feldspar is discussed in Putnis et al. (2007) and is suggested as the Fe source for the hematite in red alkali-feldspar micro-cavities. The Fe^{3+} -rich schorl tourmaline in the Lease granite and the hydrothermal pipes are formed during the incipient tourmalinization of red alkali-feldspar (Figure 5.4c). The sub-solidus alteration of alkali-feldspar by acidic B-rich hydrothermal fluids in the semi-crystallized Lease granite, introduced the required Fe^{3+} into the hydrothermal system (Putnis et al., 2007; Norberg et al., 2014). A similar occurrence of Fe^{3+} -rich endogranitic tourmalines are recorded in the A-Type Qitianling batholith in China (Yang et al., 2015). These tourmalines are thought to have formed within a closed granitic system. They demonstrate the ability to develop Fe^{3+} tourmaline compositions without a boiling event or external fluid interaction (Yang et al., 2015). However, at Zaaipplaats the involvement of formational waters is difficult to disprove. Thus, it is possible that the increased Fe^{3+} is a combination of alkali-feldspar dissolution and the interaction with ferric formational fluids.

The later blue tourmalines of the Lease granite and hydrothermal pipes formed during the introduction of Fe^{3+} into the magmatic-hydrothermal fluid. Thus, the modified fluid composition permitted the precipitation of Fe^{3+} -rich schorl tourmaline. The Fe^{3+} tourmalines of the Lease granite and hydrothermal pipes then exhibit an evolution along an expected trend, from Fe^{3+} -rich schorl (Fe^{3+}) to schorl (Fe^{2+}) towards foitite (Mg) (Figure 5.16b). This is illustrated at a smaller scale by the brown euhedral tourmalines that line the rims of the miarolitic cavities within the blue-green tourmaline clusters in the Lease granite (Figure 5.4f). During the progressive crystallization of the blue/green Fe^{3+} -rich schorl – schorl tourmaline clusters, the fluids were concentrated and trapped in cavities. The depletion of Fe within the

trapped fluid by tourmaline formation resulted in the growth of euhedral brown foitites into the cavity (Figure 5.4f).

In summary, the formation of the various tourmaline features is proposed as a result of the evolution and ferric-enrichment of a magmatic-hydrothermal fluid. During the crystallization of the Bobbejaankop granite, the separation of a B-, Fe- and alkali-rich fluid resulted in the precipitation of schorl – foitite tourmaline within orbicules. These orbicules rose through the crystallizing Bobbejaankop magma and were concentrated along and above the Bobbejaankop – Lease contact. The continued fractional crystallization of the granite resulted in the concentration of B-, F- and metal-rich magmatic hydrothermal fluids towards the cupola. These acidic fluids caused the incipient alteration of alkali-feldspar, liberating Fe^{3+} and allowing the growth of Fe^{3+} -rich schorl tourmaline in the Lease granite. The potential interaction of the magmatic-hydrothermal fluids with formational waters may have also introduced Fe^{3+} into the system. The coalescence and channelization of these acidic B-rich hydrothermal fluids resulted in swarms of buoyant hydrothermal pipes (bubble-laden plumes). These large ascending pipes digested and greisenized vast quantities of granite. The dissolution of mica, chlorite and alkali-feldspar would provide the required Sn, Fe^{3+} and Al for the cassiterite, Fe^{3+} -rich schorl tourmalines and aluminosilicates formation (London and Manning, 1995; London, 1999; Williamson et al., 2000; Hong et al., 2017). This later-stage, Fe^{3+} -bearing hydrothermal fluid initially precipitated tourmaline with a Fe^{3+} -rich schorl composition. The late-stage tourmaline then evolved along the typical tourmaline exchange vector $(\text{Al})(\text{Fe}^{2+}, \text{Fe}^{3+})_{-1}$. This resulted in a Fe^{3+} -rich schorl – schorl – foitite tourmaline evolution exhibited by the tourmaline in the Lease granite and hydrothermal pipes.

Implications for Mineralization

Tourmaline and cassiterite are characteristic features of the Zaaipplaats tin field, although not all tourmaline occurrences are associated with cassiterite (Strauss and Truter, 1944; Coetzee, 1986; Crocker et al., 2001; Vonopartis et al., 2020a). Low-grade disseminated cassiterite within miarolitic cavities without tourmaline is well-documented (Strauss and Truter, 1944; Coetzee, 1986; Crocker et al., 2001; Vonopartis et al., 2020a). At Groenfontein, cassiterite is rarely found within the schorl – foitite tourmaline orbicules of the Bobbejaankop granite. It is more commonly associated with Fe^{3+} -rich schorl tourmaline clusters and pegmatitic pods in the Lease granite and the hydrothermal pipes.

Cassiterite from the various styles of mineralization exhibits a dominantly hydrothermal and greisenization-related origin. Costi et al. (2000) successfully used Nb+Ta, Ti and Sn to differentiate between magmatic and hydrothermal cassiterite. Cassiterite with a low-Ti content is proposed to have a magmatic origin (Costi et al., 2000). The cassiterites analyzed in this study are all Ti-poor and are inferred to have been sourced from their hosting granite (Figure 5.17). The (Nb+Ta) – Ti – Sn/10 diagram indicates that the disseminated cassiterite has a magmatic signature, although the majority compositionally plot within the magmatic-hydrothermal overlap (Figure 5.17). There is an observable increase in Sn and a decrease in Nb from disseminated through greisen-related to pegmatitic cassiterite on Figure 5.17. This compositional evolution corresponds with an increasing hydrothermal signature of the cassiterite. This suggests that the disseminated variety may have initially begun as purely magmatic. The cassiterite then became dominantly controlled by greisenizing magmatic-hydrothermal fluids through progressive fluid saturation (Figure 5.17).

The deviation from the 1:1 or 2:1 stoichiometric substitution of (Nb+Ta):Fe indicates an increased incorporation of Fe into the cassiterites, without the involvement of Nb or Ta. Therefore, cassiterites that have high Fe and low Sn contents are explained by the coupled substitution of Fe^{3+} and OH^- for Sn^{4+} (Möller et al., 1988; Costi et al., 2000; Bennett et al., 2020). Möller et al. (1988) accounts for a high Fe content in cassiterite without the involvement of Nb, Ta or Ti via the substitution of Fe^{3+} for Sn^{4+} , described in equation [1] (Figure 5.13b). The bonding of a H^+ ion on an available O^{2-} , facilitates the necessary charge balance for the coupled substitution of Fe^{3+} and OH^- in cassiterite [1] (Möller et al., 1988; Costi et al., 2000; Bennett et al., 2020).



Together with the inferred Fe^{3+} of the Fe^{3+} -rich schorl tourmalines, the cassiterites are proposed to have precipitated from the same magmatically-derived and Fe^{3+} -enriched hydrothermal fluid stage. The implication being that the majority of the cassiterite mineralization is linked to the later ferric and greisenizing stage of the hydrothermal fluid.

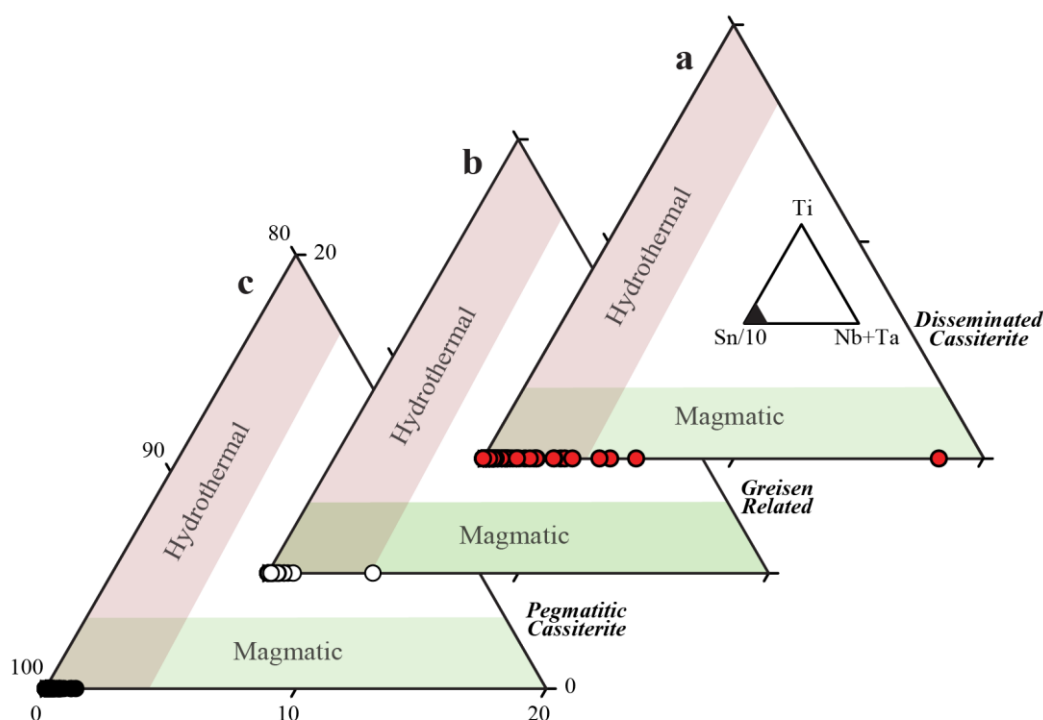


Figure 5.17. Ternary diagram of (Nb+Ta) – Ti – Sn/10 displaying the compositional differences between the styles of mineralization in the Lease granite. Magmatic and hydrothermal (greisen) related fields after Costi et al. (2000). (a) Disseminated cassiterite plotting within the magmatic field. (b) Greisen-related cassiterite plotting within the magmatic and hydrothermal region, towards the Sn apex of the ternary diagram. (c) Pegmatitic cassiterite showing an almost pure Sn composition within the overlapping hydrothermal and magmatic fields. Circle colors represent: Disseminated cassiterite (red); greisen related cassiterite (white); and pegmatitic cassiterite (black).

A physiochemical change destabilized the metal-, F- and Cl-bearing acidic fluids and resulted in cassiterite crystallization. The solubility of Sn within a hydrothermal fluid is strongly influenced by the presence of Cl^- in an acidic and reduced brine (Heinrich, 1990; Taylor and Wall, 1993; Duchoslav et al., 2017). Tin precipitation was initiated by neutralization induced greisenization, through the formation of sheet silicates during the hydrolysis of feldspars (Heinrich, 1990; Taylor and Wall, 1993; Duchoslav et al., 2017; Vonopartis et al., 2020a). Thus, the dissolution of mica, chlorite and feldspar provided the required Sn, Fe^{3+} and Al for the cassiterite, Fe^{3+} -rich schorl tourmalines and aluminosilicates formation (London and Manning, 1995; London, 1999; Williamson et al., 2000; Hong et al., 2017).

In the Zaaipplaats tin field, tourmalinization alone is not an indication of mineralization. The cassiterite mineralization at Groenfontein is associated with the Fe^{3+} -rich schorl that formed from the later-stage greisenizing, Fe^{3+} -bearing and F-rich magmatic-hydrothermal fluid. Duchoslav et al. (2017) also identified a correlation of high Fe^{3+} in tourmalines with cassiterite

mineralization in the Cornubian Batholith. Therefore, the identification of Fe³⁺-rich schorl tourmaline composition in an A-Type granite can potentially be used to vector tin mineralization.

5.2.8. Conclusion

The tourmaline compositions in the Bobbejaankop granite, Lease granite and hydrothermal pipes suggest at least two distinct stages of tourmalinization from an evolving fluid. Initially, the crystallization of the Bobbejaankop magma caused the separation of a buoyant B-, Fe- and alkali-rich fluid. This initial stage formed the tourmaline orbicules that record a typical magmatic-hydrothermal schorl – foitite tourmaline evolution. These fluids percolated towards the roof of the intrusion, ultimately saturating the upper facies of the Bobbejaankop and Lease granites. This magmatic-hydrothermal fluid liberated Fe³⁺, Al, Sn and alkali elements via the alteration of alkali-feldspar, mica and chlorite. The potential interaction with formational fluids may be an additional source of Fe³⁺ in the hydrothermal system of the Zaaiplaats tin field. This ferric-influx allowed the formation of Fe³⁺-rich schorl tourmaline together with Fe-rich cassiterite. The incipient sub-solidus tourmalinization of the alkali-feldspar resulted in the development of Fe³⁺-rich schorl tourmaline clusters in the Lease granite. The coalescences and channelization of these fluids formed large swarms of Fe³⁺-rich schorl tourmaline-bearing and greisenizing hydrothermal pipes. These acidic brines digested the granite through which they rose, scavenging metals and forming high-grade hydrothermal pipes. Pockets of fluid that were trapped at later stages of crystallization formed Fe³⁺-rich schorl tourmaline-cassiterite bearing vugs and larger clusters within the granite cupola. It is apparent that the cassiterite mineralization is primarily associated with the later-stage Fe³⁺ hydrothermal fluids. The composition of the tourmaline can therefore be used to vector regions of potential Sn mineralization within granites.

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Chapter 6

Compositional Comparison of Mica and Chlorite from the Lebowa and Gaborone Granite Suites

6.1. Introduction

Considering the number of geological studies on the Lebowa Granite Suite, there is a marked lack of research relating to its mineral chemistry. Therefore, together with the tourmaline and cassiterite data presented in Chapter 5, this chapter provides the first mica and chlorite compositions from the Bushveld Granites. These mineral compositions from the Zaaipplaats tin granites are compared to those from the barren granites of the Gaborone Granite Suite. The compositional comparison of mica and chlorite from these suites will contribute towards a better understanding of A-Type granite petrogenesis and mineralisation. These results will be used to evaluate the potential of mica and chlorite compositions to vector towards endogranitic Sn-mineralisation.

The composition of micas is the focus of this investigation, although most have been chloritised. Therefore, chlorite was also analysed to better understand the petrogenesis and alteration of these granites. The formation of chlorite in the Gaborone and Lebowa granite suites are primarily due to the alteration of biotite. This alteration involves the removal of K^+ from the interlayer site, and the introduction of Fe, Mg and Ti into the restructured lattice (Eggleton and Banfield, 1985; Abdel-Rahman, 1995; Shabani, 2009; Beaufort et al., 2015). For the purposes of this study, the K content of chloritised micas is used to measure the degree of chloritisation. Mineral compositions with $<5.5\%$ K_2O are regarded as chlorite, whereas those with $>6\%$ K_2O are considered to be mica. Detailed petrographic descriptions of the Zaaipplaats tin field and Gaborone Granite Suite granitoids are presented in Chapters 2 and 4 respectively.

6.1.1. Mica

Mica minerals are the most common OH-bearing silicates and are stable across a wide range of physiochemical conditions, occurring in igneous, metamorphic and hydrothermal assemblages (Bailey, 1984; Howie et al., 1992; Tischendorf et al., 2001; Mottana et al., 2018). This environmental and compositional range allows mica minerals to record the petrogenetic, hydrothermal and metallogenic evolution of a system. Micas are commonly the only hydrous

component within fractionated granitoids. Therefore, their chemistry and alteration products are used in investigations of late-stage granitic and pegmatitic magmatic-hydrothermal mineralisation (Bailey, 1984; Jolliff et al., 1987; Peacor et al., 1988; Stepanov et al., 2014; Legros et al., 2018; Mottana et al., 2018; Uribe-Mogollon and Maher, 2020).

This physiochemical range stems from the variability of their crystal chemistry and the structure of the phyllosilicate framework. Mica compositions vary depending on a number of factors including: temperature; pressure; the magma/fluid composition at the time of their formation; the coexisting mineral assemblages; pH; and the O-, F- and Cl-fugacity of the system (Bailey, 1984; Howie et al., 1992; Tischendorf et al., 2001; Mottana et al., 2018). Therefore, compositional variations provide insight into their formation, and the magmatic-hydrothermal evolution of both mineralised and barren granitic systems (Jolliff et al., 1987; Stone et al., 1997; Sakoma et al., 2000; Shabani et al., 2003; Nachit et al., 2005; Zhao et al., 2005; Legros et al., 2018; Soltani Dehnavi et al., 2019; Yin et al., 2019; Uribe-Mogollon and Maher, 2020).

Mica mineral chemistry and classification

The general mica structural formula, $I_1M_{2-3}\square_{1-0}T_4O_{10}A_2$, permits an assortment of cationic substitutions (Table 6.1), and results in a diverse and extensive mineral group. A summary of endmembers, synonyms, discredited and official mica names is published in Rieder et al. (1999), with an update in IMA (2020).

The crystallographic structure of micas consists of repeating layer packages, composed of two opposing sheets of tetrahedral (T) molecules (Figure 6.1). Sandwiched between these two tetrahedral sheets is a sheet of hydrated (A) and octahedral (M) cations. These superimposed layer packages are separated by interlayer (I) cation sites (Table 6.1) (Bailey, 1984; Rieder et al., 1999; Brigatti and Guggenheim, 2002; Mottana et al., 2018). Micas are structurally subdivided into two principal groupings, trioctahedral and dioctahedral micas, based on their M-site occupancy (Figure 6.1). They are further characterised as true, brittle or interlayer-deficient micas based on their I-site occupancy (Table 6.2) (Bailey, 1984; Rieder et al., 1999; Mottana et al., 2018).

The differences between trioctahedral and dioctahedral micas are not limited to their crystal chemistry. Trioctahedral micas of the annite–phlogopite series are typically associated

with mafic and felsic igneous rocks, whereas magmatic dioctahedral micas of the muscovite–celadonite series are limited to peraluminous granitoids (Zane and Rizzo, 1999; Brigatti et al., 2000; Benincasa et al., 2003; Mottana et al., 2018). Dioctahedral micas are also a common product of hydrothermal alteration, and are frequently associated with mineralisation (Hall, 1971; Higashi, 1980; Štemprok, 1987; Witt, 1988).

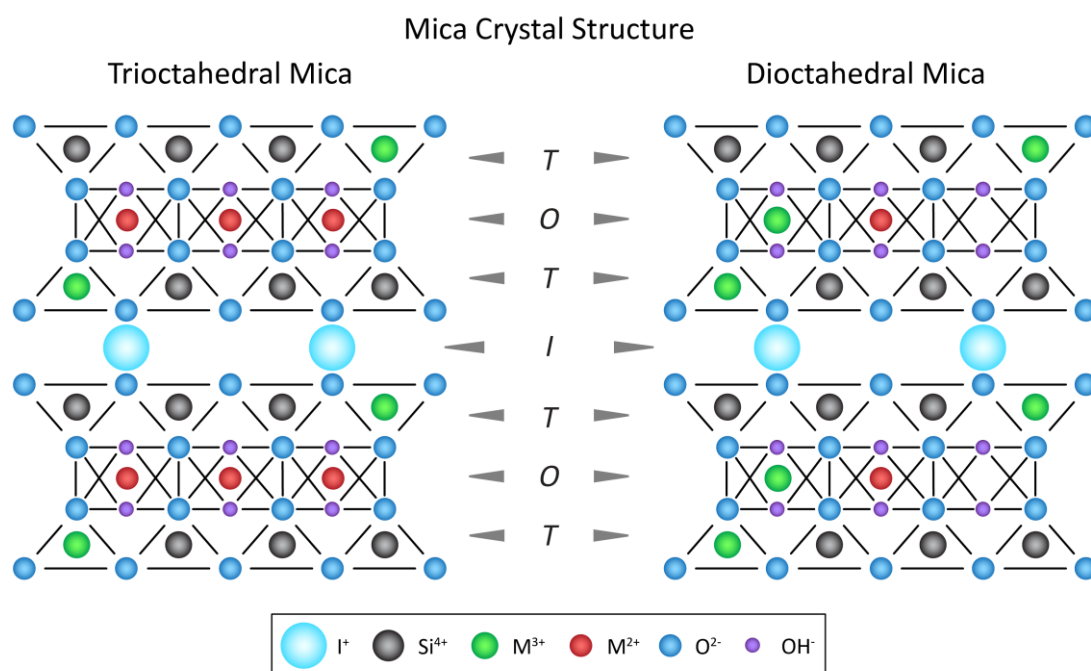


Figure 6.1. Schematic illustration of the crystal structure of trioctahedral and dioctahedral micas, modified after Nelson (2015). Abbreviations: tetrahedral (T); octahedral (O); interlayer (I); divalent cations (M²⁺); and trivalent cations (M³⁺).

Table 6.1. General outline of mica structural formula and site occupancies (Bailey, 1984; Rieder et al., 1999; Mottana et al., 2018). Most common ions are shown in bold font.

Site	Possible ions	Occupancy
I	K⁺, Na⁺, Ca²⁺ , NH ₄ ⁺ , Rb ⁺ , Ba ²⁺ and Cs ¹⁺	1
M	Al⁴⁺, Fe²⁺, Fe³⁺, Li⁺, Ti⁴⁺ , Mg ²⁺ , Mn ²⁺ , Zn ²⁺ , Cr ²⁺ and V ²⁺	2 to 3
□	Site Vacancy	0 to 1
T	Si⁴⁺, Al⁴⁺, Fe³⁺ and B ²⁺	4
A	OH⁻, F⁻, Cl⁻, O²⁻ and S ²⁻	2

A comprehensive review of micas was published by Bailey (1984) and was subsequently revised by Mottana et al. (2018). This revision incorporated the new classification scheme suggested by the International Mineralogical Association (IMA), which was published in Rieder et al. (1999). This simplified more than 300 names of micas into 6 series and 37 IMA approved species (as of 2018).

Table 6.2. Summarised table of mica endmember formulae and subgroupings (Bailey, 1984; Rieder et al., 1999; Mottana et al., 2018). Interlayer cationic site (I); bi- or trivalent cationic site (M); cationic vacancy ($\square$); tetrahedrally coordinated cation (T); and hydrated cationic site (A).

Species	I ₁	M ₂₋₃	$\square_{0-1}$	T ₄ O ₁₀	A ₂
Trioctahedral Micas					
True Micas					
Annite	K	Fe ²⁺ ₃	-	AlSi ₃ O ₁₀	(OH) ₂
Phlogopite	K	Mg ₃	-	AlSi ₃ O ₁₀	(OH) ₂
Siderophyllite	K	Fe ²⁺ ₂ Al	-	Al ₂ Si ₂ O ₁₀	(OH) ₂
Eastonite	K	Mg ₂ Al	-	Al ₂ Si ₂ O ₁₀	(OH) ₂
Hendricksite	K	Zn ₃	-	AlSi ₃ O ₁₀	(OH) ₂
Polyolithionite	K	Li ₂ Al	-	Si ₄ O ₁₀	F ₂
Trilithionite*	K	Li _{1.5} Al _{1.5}	-	AlSi ₄ O ₁₀	F ₂
Aspidolite	Na	Mg ₂ Al	-	AlSi ₃ O ₁₀	(OH) ₂
Ephesite	Na	LiAl ₂	-	Al ₂ Si ₂ O ₁₀	(OH) ₂
Brittle Micas					
Clintonite	Ca	Mg ₂ Al	-	Al ₃ SiO ₁₀	(OH) ₂
Bityite	Ca	LiAl ₂	-	BeAlSi ₂ O ₁₀	(OH) ₂
Anandite	Ba	Fe ²⁺ ₃	-	Fe ³⁺ AlSi ₂ O ₁₀	S(OH)
Kinoshitallite	Ba	Mg ₃	-	Al ₂ Si ₂ O ₁₀	(OH) ₂
Interval-Deficient Micas					
Wonesite*	Na _{0.5}	Mg _{2.5} Al _{0.5}	$\square_{0.5}$	AlSi ₃ O ₁₀	(OH) ₂
Diocahedral Micas					
True Micas					
Muscovite	K	Al ₂	$\square$	AlSi ₃ O ₁₀	(OH) ₂
Celadonite	K	Fe ³⁺ (Mg, Fe ²⁺)	$\square$	Si ₄ O ₁₀	(OH) ₂
Roscoelite	K	V ₂	$\square$	AlSi ₃ O ₁₀	(OH) ₂
Chromophyllite	K	Cr ₂	$\square$	AlSi ₃ O ₁₀	(OH) ₂
Boromuscovite	K	Al ₂	$\square$	BSi ₃ O ₁₀	(OH) ₂
Paragonite	Na	Al ₂	$\square$	AlSi ₃ O ₁₀	(OH) ₂
Nanpingite	Cs	Al ₂	$\square$	AlSi ₃ O ₁₀	(OH) ₂
Tobelite	(NH ₄)	Al ₂	$\square$	AlSi ₃ O ₁₀	(OH) ₂
Brittle Micas					
Margarite	Ca	Al ₂	$\square$	Al ₂ Si ₂ O ₁₀	(OH) ₂
Chernykhite	Ba	V ₂	$\square$	Al ₂ Si ₂ O ₁₀	(OH) ₂
Interval-Deficient Micas					
Illite	K _{0.65}	Al ₂	$\square$	Al _{0.65} Si _{3.35} O ₁₀	(OH) ₂
Glauconite	K _{0.8}	R ³⁺ _{1.33} R ²⁺ _{0.67}	$\square$	Al _{0.13} Si _{3.87} O ₁₀	(OH) ₂
Brammalite	Na _{0.65}	Al ₂	$\square$	Al _{0.65} Si _{3.35} O ₁₀	(OH) ₂

*Not true endmember compositions

Numerous compositional diagrams and schemes have been developed to provide a graphical representation for the classification of mica species (Foster, 1960b; Foster, 1960a; Rieder et al., 1970; Bailey, 1984; Cerny and Burt, 1984; Monier and Robert, 1986; Jolliff et al., 1987; Burt and Perchuk, 1991; Tischendorf et al., 1997; Rieder et al., 1998; Shihua and Jie, 2000; Tischendorf et al., 2004; Tischendorf et al., 2007; Mottana et al., 2018). Lithium however, is not incorporated by most proposed mica classification schemes, as it is not readily detectable by electron microprobe. Tischendorf et al. (1997) addressed this issue by considering the correlations of Li with other measurable elements, and developed multiple regressions that accurately calculate Li content (Table 6.3).

Table 6.3. Table of regression equations for lithium in mica calculations and conditions for use, after Tischendorf et al. (1997). Oxide values in wt%.

Equation No.	LiO ₂ Regressions	R ²	Conditions of Validity
Tri 1*	$\text{Li}_2\text{O} = (0.289 \times \text{SiO}_2) - 9.658$	0.912	$\text{SiO}_2 > 34$; $\text{MgO} < 6$
Tri 2*	$\text{Li}_2\text{O} = (2.7 / (0.35 + \text{MgO})) - 0.13$	0.880	$\text{MgO} = 0.01$ to 20
Tri 3**	$\text{Li}_2\text{O} = 1.55 \times \text{MgO}^{-3.1}$	0.580	$\text{SiO}_2 > 34$; $\text{MgO} > 6$
Tri 4	$\text{Li}_2\text{O} = 0.237 \times \text{F}^{1.544}$	0.852	$\text{F} = 0.1$ to 9
Tri 4a	$\text{Li}_2\text{O} = (0.697 \times \text{F}) + 1.026$	0.700	Aplites, pegmatites
Tri 4b	$\text{Li}_2\text{O} = 0.177 \times \text{F}^{1.326}$	0.906	Granitoids
Tri 5	$\text{Li}_2\text{O} = 3.5 \times \text{Rb}_2\text{O}^{1.55}$	0.865	$\text{Rb}_2\text{O} = 0.01$ to 1.7
Di 1*	$\text{Li}_2\text{O} = 0.3935 \times \text{F}^{1.326}$	0.843	$\text{F} = 0.01$ to 8
Di 2	$\text{Li}_2\text{O} = 1.579 \times \text{Rb}_2\text{O}^{1.45}$	0.710	$\text{Rb}_2\text{O} = 0.01$ to 2

*Recommended Regression; **Recommended in conjunction with regression Tri 1

Tri = Trioctahedral Micas; Di = Dioctahedral Micas.

Tischendorf et al. (1997) proposed a Mg-Li (*MgLi*) vs $\text{Fe}^{\text{tot}} + \text{Mn} + \text{Ti} - \text{Al}^{\text{VI}}$ (*FeAl*) diagram based on absolute abundance of octahedral cations and chemical compositions. The *MgLi* vs *FeAl* diagram, shown in Figure 6.2, provides a comprehensive and robust mica classification scheme. Subsequent modifications were made to the *MgLi* vs *FeAl* diagram in adherence to the modified IMA nomenclature (Tischendorf et al., 1997; Tischendorf et al., 2001; Tischendorf et al., 2007). The Tischendorf et al. (1997) mica classification diagram has been widely used to describe micas from various geological settings and styles of mineralisation (Förster et al., 1999; Kirkland et al., 2007; Colombo et al., 2010; Afshooni et al., 2013; Berni et al., 2017; Falster et al., 2018; Guarino and Brigatti, 2018; Mészárosóvá et al., 2018; René, 2018; Ballouard et al., 2020; Nie et al., 2020).

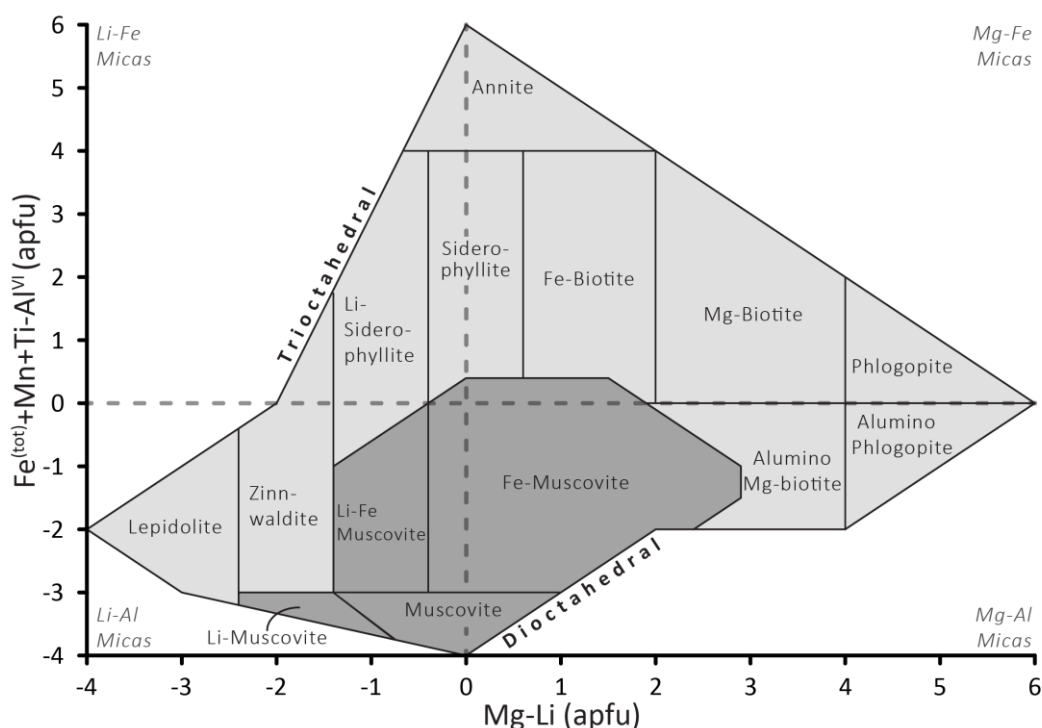


Figure 6.2. Compositional classification diagram Mg-Li vs $\text{Fe}^{\text{tot}} + \text{Mn} + \text{Ti} - \text{Al}^{\text{VI}}$ for trioctahedral and dioctahedral micas (Tischendorf et al., 1997; Tischendorf et al., 2001). The light grey field delineates trioctahedral mica compositions and the dark grey field represents dioctahedral mica compositions.

6.1.2. Chlorite

Chlorite is the most common phyllosilicate formed during low- to medium-grade greenschist facies metamorphism, and is intimately associated with hydrothermal systems and mineralisation (Hey, 1954; Bayliss, 1975; Walshe, 1986; Bailey and Lister, 1989; Howie et al., 1992; De Caritat et al., 1993; Shabani et al., 2003; Beaufort et al., 2015; Wu et al., 2019).

In igneous assemblages, chlorite is attributed to the hydrothermal alteration of pre-existing mineral phases, particularly pyroxene, amphibole, mica and feldspar. This chloritisation process ranges from low- to moderately high-temperature environments, 40 to 600°C (Walshe, 1986; Howie et al., 1992; Shabani et al., 2003; Beaufort et al., 2015). This range in formational temperatures has led to the development of many compositional geothermometers (De Caritat et al., 1993; Ciesielczuk, 2012; Yavuz et al., 2015). The reliability of chlorite geothermometers remains controversial, despite many revisions, and some have even been discredited (Jiang et al., 1994).

Particular attention has been paid to chlorite formation in granites, as it is a common alteration product of biotite from the interaction with hydrothermal fluids (Bailey and Lister, 1989; Howie et al., 1992; Abdel-Rahman, 1995; Shabani et al., 2003; Ciesielczuk, 2012; Wu et al., 2019). Chlorite compositions have been successfully used in the investigation of various styles of hydrothermal mineral deposits. The chemical variations of chlorite can provide information on hydrothermal fluid compositions, and the conditions of ore precipitation (Eggleton and Banfield, 1985; Abdel-Rahman, 1995; Beaufort et al., 2015; Soltani Dehnavi et al., 2019; Wu et al., 2019).

Chlorite mineral chemistry and classification

Most chlorite compositions are represented by the general structural formula $(M^{2+}_x, M^{3+}_y, \square_{12-x-y})_{12}^{VI}(T_z M_{8-z})^{IV}O_{20}A_{16}$, with common elemental occupancies given in Table 6.4 (Wiewióra and Weiss, 1990; Howie et al., 1992; Zane and Weiss, 1998; Ciesielczuk, 2012; Yavuz et al., 2015). The crystal chemistry of chlorites comprises alternating, 2:1, negatively charged tetrahedral-octahedral-tetrahedral (T-O-T) layers. These T-O-T layers are separated by a positively charged hydrated interlayer sheet (Figure 6.3) (Wiewióra and Weiss, 1990; Howie et al., 1992; Zane and Weiss, 1998; Ciesielczuk, 2012; Yavuz et al., 2015).

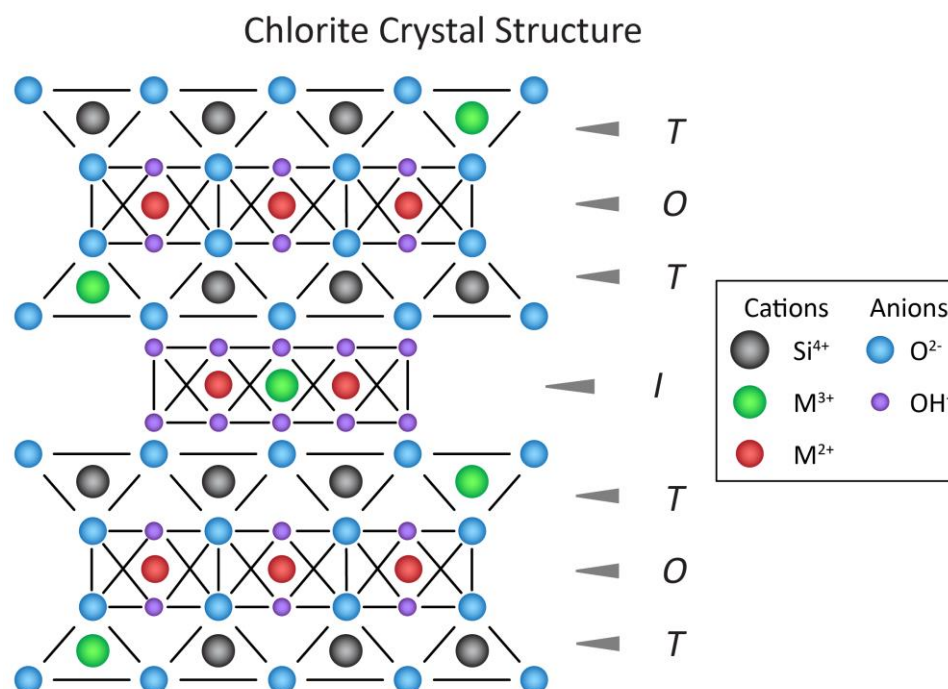


Figure 6.3. Schematic illustration of the crystal structure of chlorite, modified after Nelson (2015). Abbreviations: tetrahedral (T); octahedral (O); interlayer (I); divalent cations (M²⁺); and trivalent cations (M³⁺).

It is typical for an octahedral site to have an occupancy of 12 and these chlorites are referred to as trioctahedral chlorites. It is less common for a chlorite to have an octahedral occupancy of <10, although these varieties are known as dioctahedral chlorites. Dioctahedral chlorites are further subdivided into di-trioctahedral and di-dioctahedral chlorites. They are either composed of 2:1 dioctahedral and trioctahedral layers, or two dioctahedral layers respectively (Wiewióra and Weiss, 1990; Howie et al., 1992; Zane and Weiss, 1998; Ciesielczuk, 2012; Yavuz et al., 2015).

Table 6.4. General outline of chlorite structural formula and common elemental occupancies (Wiewióra and Weiss, 1990; Howie et al., 1992; Zane and Weiss, 1998; Ciesielczuk, 2012; Yavuz et al., 2015). Most common ions in bold.

Site	Possible ions	Occupancy
M^{2+}_x	Fe²⁺ , Mg²⁺ , Mn²⁺ , Ni ²⁺ , Co ²⁺ , Cu ²⁺ and Zn ²⁺	x
M^{3+}_y	Al³⁺ , Fe³⁺ , Ti ³⁺ and Cr ³⁺	y
□	Vacancy	12-x-y
T	Si⁴⁺ and Al⁴⁺	8-z
M^{3+}_z	Al³⁺ , Fe ³⁺ and B ³⁺	2-3
A	OH⁻	16

Both the octahedral and tetrahedral sites within the chlorite structure permit extensive cationic substitution. There have been numerous classification schemes proposed for the large compositional range of chlorite (Foster, 1962; Bailey, 1980; Bailey and Lister, 1989; Wiewióra and Weiss, 1990; Howie et al., 1992; Zane and Weiss, 1998; Ciesielczuk, 2012; Yavuz et al., 2015). These classification schemes are based on different chemical or physical characteristics and produced many chlorite species and endmember names (Table 6.5).

An attempt by Bayliss (1975) to organise and provide a reliable trioctahedral chlorite classification was accepted by the Association Internationale Pour l'Étude des Argiles (AIPEA) Nomenclature Commission. Subsequently, a similar classification method was developed that incorporated the composition and octahedral occupancy of chlorite (Wiewióra and Weiss, 1990; Yavuz et al., 2015). This latter scheme established a more robust and consistent classification, which defines three chlorite subgroups: Tri-trioctahedral; Tri-dioctahedral; and Di-dioctahedral (first prefix refers to 2:1 octahedral layer, second prefix refers to interlayer) (Wiewióra and Weiss, 1990; Weiss, 1991; Zane and Weiss, 1998; Yavuz et al., 2015).

Table 6.5. IMA approved endmember compositions for chlorite. Mineral compositions taken from various publications (Fron del, 1955; De Waal, 1970; Bailey, 1980; Bayliss, 1983; Peacor et al., 1988; Bailey and Lister, 1989; Vidal and Goffé, 1991; Zagorsky et al., 2003; Krivovichev et al., 2004; Villanova-de-Benavent et al., 2014).

Species	(	M_{2+x}	M_{3+y}	$\square_{12-x-y}$	) ₁₂	$(T_zM_{8-z})_8$	O ₂₀	A ₁₆
Chamosite	(	Fe ²⁺ ₁₀	Al ₂	-	) ₁₂	(Si ₄ Al ₄) ₈	O ₂₀	(OH) ₁₆
Clinochlore	(	Mg ₁₀	Al ₂	-	) ₁₂	(Al ₂ Si ₆) ₈	O ₂₀	(OH) ₁₆
Sudoite	(	Mg ₄	Al ₆	$\square_2$	) ₁₂	(Al ₂ Si ₆) ₈	O ₂₀	(OH) ₁₆
Pennantite	(	Mn ₁₀	Al ₂	-	) ₁₂	(Al ₂ Si ₆) ₈	O ₂₀	(OH) ₁₆
Baileychlore	(	Zn ₃ Fe ²⁺ ₃ Mg ₃	Al ₃	-	) ₁₂	(Si ₄ Al ₄) ₈	O ₂₀	(OH) ₁₆
Cookeite	(	Li ₂ Al ₄	Al ₄	$\square_2$	) ₁₂	(Al ₂ Si ₆) ₈	O ₂₀	(OH) ₁₆
Borocookeite	(	Li _{2-6x}	Al _{8-x}	$\square$	) ₁₂	(B ₂ Si ₆) ₈	O ₂₀	(OH) ₁₆
Donbassite	(	-	Al _{8.66}	$\square_{3.33}$	) ₁₂	(Al ₂ Si ₆) ₈	O ₂₀	(OH) ₁₆
Franklinfurnaceite	(	Ca ₄ Mn ²⁺ ₆	Fe ³⁺ Mn ⁺³	-	) ₁₂	(Zn ₄ Si ₄) ₈	O ₂₀	(OH) ₁₆
Glagolevite	(	Na ₂ Mg ₅	Al ₅	-	) ₁₂	(Al ₂ Si ₆) ₈	O ₂₀	(OH) ₁₆
Gonyerite	(	Mn ²⁺ ₅ Mg ₅	Fe ³⁺ ₂	-	) ₁₂	(Fe ³⁺ ₂ Si ₆) ₈	O ₂₀	(OH) ₁₆
Nimite	(	Ni ₄ Mg ₄	Al ₄	-	) ₁₂	(Si ₄ Al ₄) ₈	O ₂₀	(OH) ₁₆

Zane and Weiss (1998) then developed a two-stage stepwise procedure in the classification of chlorites using electron microprobe data, recalculated based on 28 oxygens. This technique is used in this study. This method first classifies chlorites as either Type 1 or 2 (Table 6.6), and then applies an adjective modifier, either Mg-, Fe- or Al- (Figure 6.4). Step 1 discriminates Type 1 and Type 2 chlorites based on the main octahedral cations (M), and cationic vacancy ($\square$) using the equation $\square = 12 - (M^{2+} + M^{3+} + M^{4+})^{VI}$ (Table 6.6) (Zane and Weiss, 1998; Yavuz et al., 2015). Step 2 defines the dominant cation in the octahedral site and suggests an appropriate adjective modifier: Mg-chlorite; Fe-chlorite; or Al-chlorite (Figure 6.4) (Zane and Weiss, 1998). This classification does not introduce any new chlorite species and can be modified to reflect currently accepted chlorite endmember compositions (Table 6.2).

Table 6.6: Table showing the first stage conditions for the classification of Type 1 or Type 2 chlorites after Zane and Weiss (1998).

Stage 1	Conditions
Type 1	$Mg + Fe^{tot} \geq Al + \square$
Type 2	$Mg + Fe^{tot} < Al + \square$

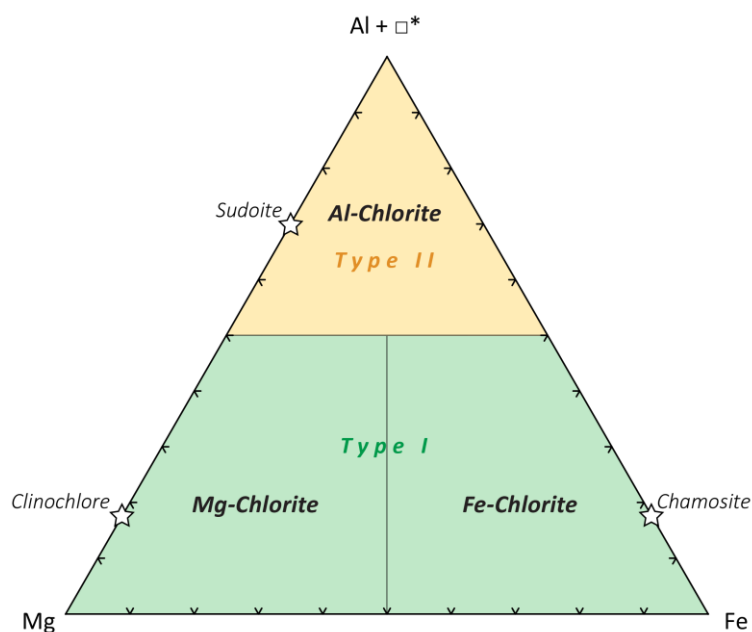


Figure 6.4. Chlorite compositional classification diagram using Fe-Mg-(Al+□) after Zane and Weiss (1998). Chlorite endmember compositions shown by white stars, see Table 6.5.

6.2. Analytical Techniques

6.2.1. Electron Probe Microanalyses of Mica and Chlorite

The analysis of mica and chlorite from the Lebowa Granite Suite and Gaborone Granite Suite was done at the University of the Witwatersrand, Johannesburg, South Africa. Quantitative mineral chemical analyses were obtained using five wavelength dispersive spectrometers on a CAMECA SX5-FE electron probe micro-analyser (EPMA). The complete sets of analyses are provided in Appendix F. Standard 30 μm thin-sections, were polished to 1 to 2 μm and then vacuum carbon coated. The electron beam was generated by a field emission gun, and excited with a 15 kV accelerating potential at approximately 20 nA current. A beam diameter of 1 to 10 μm was used. All elements were measured on K-alpha peaks with a peak counting time of 20s, and a total of 10s on background. Commercial “SPI” mineral standards were used for intensity calibration: Jadeite (Al); Diopside (Mg, Ca); Almandine (Fe); Biotite (K, Si); Albite (Na); Rhodonite (Mn); Rutile (Ti); Fluorite (F); and Tugtupite (Cl). Data collection and matrix effect was corrected for by the software provided with the CAMECA SX5-FE electron microprobe.

For the Zaaiplaats granites, the confirmed analyses of micas included a total of two hundred and thirty nine points from thin-sections with forty two from the Nebo granite, one hundred and eight from the Bobbejaankop granite and eighty nine from the Lease granite. For the Gaborone Granite Suite, a total of one hundred and seventy two analyses from thin-

sections, included one hundred and twenty two from the Thamaga, forty three from the Main Phase and seven from the Marginal Phase. Mica recalculations were accomplished by normalising to 22 oxygens. Fluorine and (OH+O) were stoichiometrically calculated assuming 4 OH⁻ atoms per formula unit (*apfu*). Recalculations were based on the mica structural formula $X_2(\square^X)_{1-0}Y_6Z_8O_{22}(OH, F, Cl)_4$. All Fe values obtained are assumed to be divalent and are reported as FeO^{tot}. Lithium was calculated using the Li₂O regression equations proposed by Tischendorf et al. (1997) (Table 6.3). A similar approach has been successfully used in numerous mica compositional investigations and classifications (Förster et al., 2005; Kirkland et al., 2007; Colombo et al., 2010; Fournier et al., 2014; Charles et al., 2018; Falster et al., 2018; Pathak and Kumar, 2019; Ballouard et al., 2020).

Chlorite was analysed on the same thin-sections and grains as the mica analyses. For the Zaaiplaats granites, they included a total of one hundred and twenty three points, with seventy nine from the Nebo granite, thirty one from the Bobbejaankop granite and thirteen from the Lease granite. For the Gaborone Granite Suite, a total of seventy eight analyses included twenty six from the Thamaga granite, sixteen from the Kgale Main Phase and thirty six from the Kgale Marginal Phase. Chlorite recalculations were accomplished by normalising to 28 oxygens and assuming 16 (OH)⁻ atoms per formula unit (*apfu*) (Zane and Weiss, 1998). The chlorite octahedral vacancy is calculated using $\square^* = (12 - (R^{2+} + R^{3+} + R^{4+})^{VI})$, based on Zane and Weiss (1998). All Fe values obtained are assumed to be divalent and are reported as FeO^{tot}. A similar approach to chlorite mineral chemistry was taken by Shabani (2009) and Wu et al. (2019).

6.3. Results

6.3.1. Mica and Chlorite Back Scattered Electron Imagery

Gaborone Granite Suite

The micas from the Thamaga granite form irregular clusters of multiple subhedral interlocking grains. They occur both interstitially and within the large plagioclase feldspar phenocrysts (Figure 6.5). The biotite and chlorite do not show a significant difference in their backscatter intensities. These minerals are therefore texturally discriminated based on their cleavage, as it is visible in mica but destroyed by chloritisation. Moreover, there is a visible increase in the exsolution of Fe- and Ti-oxides within regions of chloritisation. Many inclusions of feldspar

within the biotite-chlorite clusters exhibit variable degrees of resorption and have become partially chloritised (Figure 6.5b).

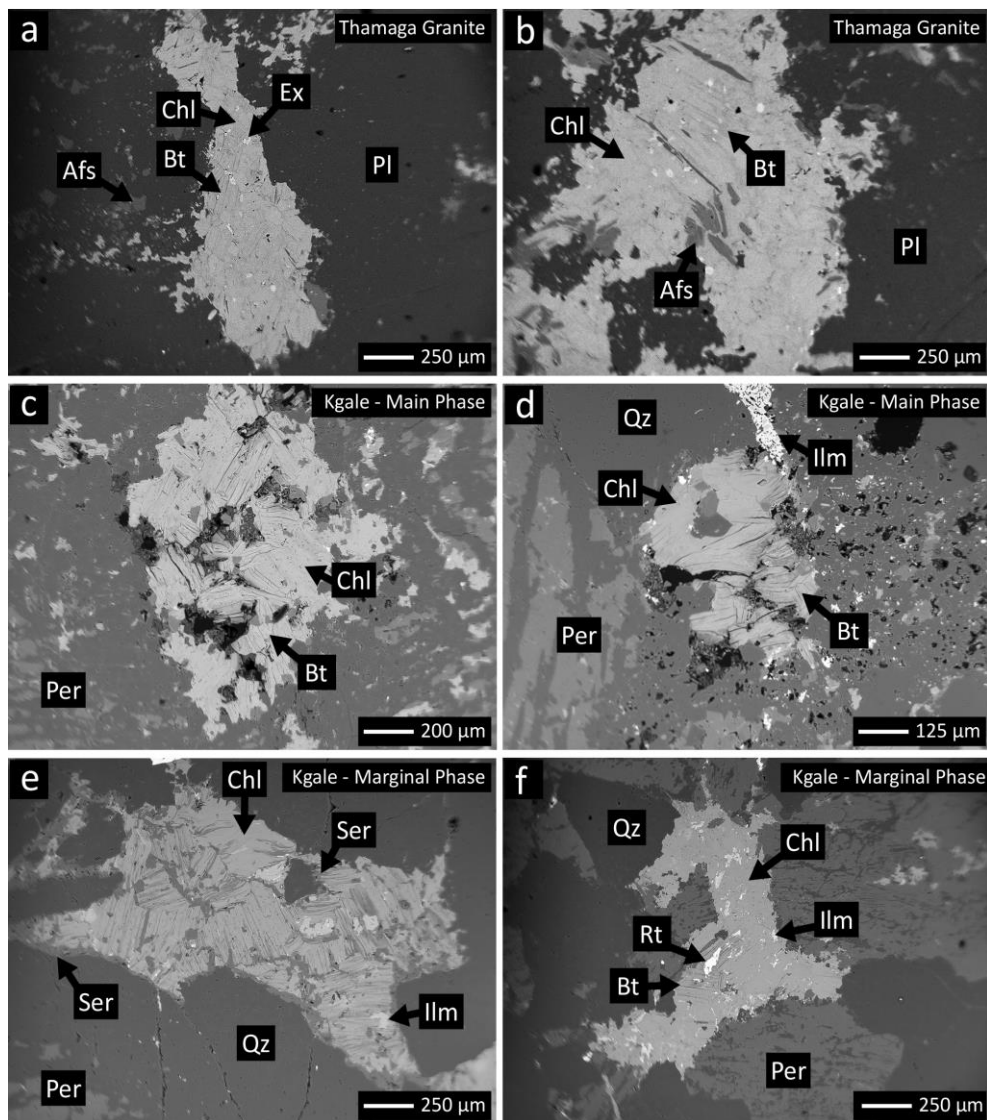


Figure 6.5. Backscatter images of the mica and chlorite from the granites of the Gaborone Granite Suite. (a) Backscatter electron image from the Thamaga granite, showing an elongate interstitial biotite cluster that is partially chloritised, with the exsolution of Fe- and Ti-oxides. The biotite cluster is hosted within a plagioclase phenocryst that shows minor patches of alkali-feldspar exsolution. (b) Backscatter electron image from the Thamaga granite showing, extensive chloritisation of biotite between plagioclase phenocrysts. (c) Backscatter electron image from the Kgale granite Main Phase showing an interstitial cluster of interlocking partially chloritised biotite grains, between larger perthite and quartz grains. (d) Backscatter electron image from the Kgale granite Main Phase, displaying an extensively chloritised biotite cluster associated with an elongated ilmenite grain. (e) Backscatter electron image from the Marginal Phase of the Kgale granite, showing the complete chloritisation and subsequent sericitisation of a biotite. (f) Backscatter electron image from the Marginal Phase of the Kgale granite, exhibiting the complete chloritisation of an interstitial biotite aggregate and the exsolution of Fe- and Ti-oxides. Abbreviations: biotite (Bt); chlorite (Chl); exsolution (Ex); plagioclase (Pl); alkali-feldspar (Afs); perthite (Per); quartz (Qz); ilmenite (Ilm); sericite (Ser); and rutile (Rt).

Micas within the Kgale granite Main Phase are typically finer-grained than the micas in the Thamaga granite. They occur interstitially, between the phenocrysts of perthite and quartz (Figure 6.5c). Backscatter imaging reveals little distinction between quartz and feldspar, and therefore are texturally discriminated by the exsolution of alkali-feldspar in the latter (Figure 6.5c, d). Micas in the Main Phase form clusters of interlocking biotite crystals, but exhibit variable but greater degrees of chloritisation (Figure 6.5c, d). This chloritisation of the micas resulted in a loss of cleavage and the increased exsolution of oxides. These characteristics enable chlorite to be distinguished from mica on backscatter imagery.

The micas from the Marginal Phase of the Kgale granite are coarser-grained and almost completely chloritised, compared to the mica from the Main Phase granite. The feldspar from the Marginal Phase is more perthitic than the feldspar from the Thamaga and Main Phase and are visibly distinct from the surrounding mineral grains in backscatter imagery (Figure 6.5e). The relic micas within the chlorite aggregate are identifiable due to a contrast in backscatter signal intensity. These micas within the chlorite have identifiable cleavage planes and exhibit a lower backscatter response than the surrounding chlorite (Figure 6.5e). Sericitisation occurs along the margins of the chlorite and cleavages of the chloritised biotite. This sericitisation displays a decreased backscatter response than that of the original micas (Figure 6.5e). Regions that show an increased degree of chloritisation and sericitisation exhibit more alteration of the surrounding feldspar and quartz grains. These regions have a greater exsolution of Fe- and Ti-oxides, both within and outside the mica-chlorite clusters. This results in the crystallisation of small (50 to 200 μm) anhedral and interstitial ilmenite and rutile grains (Figure 6.5e and f).

Lebowa Granite Suite

The micas in the Nebo granite form clusters of interlocking sub- to anhedral biotite grains (100 to 500 μm). The micas are moderately intergrown with surrounding feldspars, but exhibit sharp contacts with quartz grains (Figure 6.6a). The cleavage of the micas is clearly visible under backscatter imagery and exhibit an observable alignment of Fe- and Ti-oxides, parallel to the crystallographic faces (Figure 6.6a, b). The mica appear to be compositionally unzoned and the majority are unaltered. However, chloritisation increases in samples closer to the overlying Bobbejaankop granite. Typically, there are no distinct differences in the backscatter intensity between the micas and chlorites of the Nebo granite, although there is an increased

oxide exsolution and the destruction of mica cleavage associated with the latter (Figure 6.6a, b). Chloritisation appears to have been initiated along the margins of the micas, propagating along crystallographic structures and boundaries between the individual neighbouring mica grains (Figure 6.6a, b).

The sub- to anhedral micas in the Bobbejaankop granite (<100 to 1,000 μm) are significantly larger than the micas in the Nebo granite and are almost completely chloritised. The biotite and chlorite in the Bobbejaankop granite do not display any apparent compositional zonation in backscatter imagery. The original micas are, more often than not, completely replaced by a fine-grained chlorite aggregate. The relict micas are typically visible towards the centre of the chloritised grains, and are identifiable by their slightly lower backscatter response and remnant cleavage (Figure 6.6c). The surrounding alkali-feldspars display partial chloritisation along their margins, while the quartz grains remain largely unaltered. The exsolution of Fe- and Ti-oxides along relict mica cleavages appear to have accumulated and formed larger, anhedral grains of secondary rutile and ilmenite (Figure 6.6c, d).

In samples collected from the top of the Bobbejaankop facies, towards the Lease granite, the chloritisation intensifies and the chloritised biotites are increasingly sericitised. This has resulted in a fine-grained white micaceous growth along relict cleavages and grain boundaries of the chloritised biotite (Figure 6.6c, d). The sericitised regions have a more muted backscatter signal response than the chlorite, and a slightly brighter backscatter signal compared to the alkali-feldspar (Figure 6.6c, d).

Sericitisation within the Lease granite has replaced most of the chlorite and has altered many of the surrounding alkali-feldspars (Figure 6.6e, f). There are no visible relict micas within the chlorite aggregates, as seen in the Bobbejaankop granite. All the present micas appear to have formed from the subsequent sericitisation of the chlorite. This new sericite growth is visually homogeneous and does not show any apparent compositional zonation under backscatter imagery. The extensively sericitised areas of the Lease granite have developed coarser-grained patches of these new subhedral interlocking dioctahedral micas. These coarse-grained patches host many relict and incompletely digested grains of alkali-feldspar (Figure 6.6e, f).

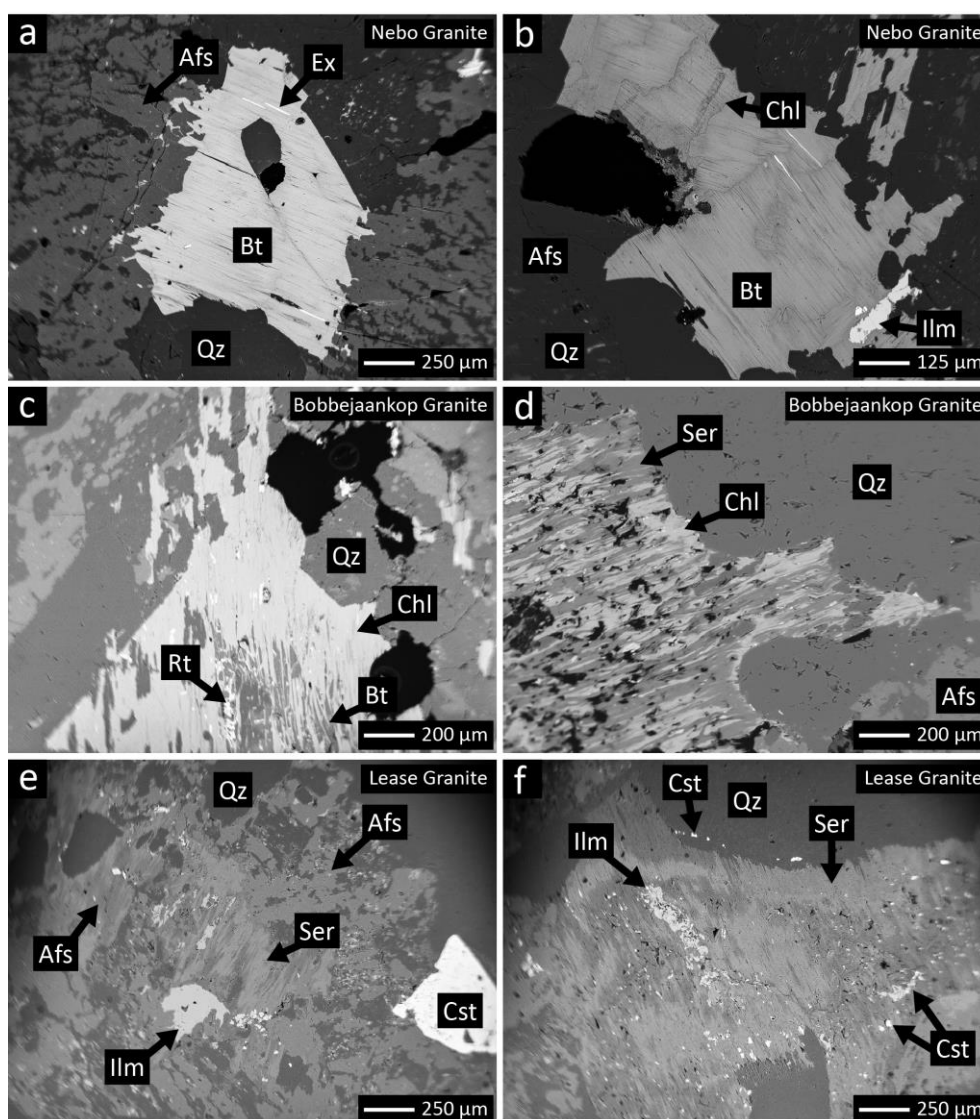


Figure 6.6. Backscatter electron images of mica and chlorite from granites of the Zaaipplaats tin field. (a) Backscatter electron image of a sub- to anhedral biotite from the Nebo granite, surrounded by alkali-feldspar and quartz. The partial exsolution of Fe- and Ti-oxides are visible along cleavage planes. (b) Backscatter electron image of partially chloritised interlocking biotite crystals from the Nebo granite, hosting anhedral ilmenite granules along the mica cleavage and margins. (c) Backscatter electron image from the Bobbejaankop granite, showing an extensively chloritised biotite and the exsolution of rutile along the relict biotite cleavage. (d) Backscatter electron image from the Bobbejaankop granite showing a completely chloritised biotite that has been subsequently sericitised along the mineral cleavages and margins. (e) Backscatter electron image from the Lease granite showing the extensive sericitisation of a chloritised biotite. Ilmenite and cassiterite grains are visible along the boundaries of the altered minerals. (f) Backscatter electron image from the Lease granite showing the formation of cassiterite and ilmenite in a sericitised mica. Small cassiterite inclusions are seen along and within the margins of surrounding quartz grains. Abbreviations: biotite (Bt); chlorite (Chl); exsolution (Ex); plagioclase (Pl); alkali-feldspar (Afs); perthite (Per); quartz (Qz); ilmenite (Ilm); sericite (Ser); cassiterite (Cst); and rutile (Rt).

There is a visible increase of the Fe- and Ti- oxide exsolution associated within regions of increased sericitisation within the Lease granite. This is accompanied by the formation of

discrete granules of sub- to anhedral cassiterite (Figure 6.6e, f). Within these extensively sericitised regions, smaller inclusions of cassiterite (<10 μm) are present along and within the margins of the surrounding quartz grains (Figure 6.6f). In general, the Lease granite is more sericitised and exhibits a higher proportion of Fe-, Ti- and Sn-oxide phases compared to the Nebo and Bobbejaankop granite (Figure 6.6e, f).

6.3.2. Mica Mineral Chemistry

Gaborone Granite Suite Mica Compositions

The micas from the Gaborone Granite Suite are predominantly trioctahedral and show a wide range in composition (Figure 6.7). On the MgLi vs FeAl classification diagram, the mica from the Thamaga granite display a compositional evolution from annite towards Fe-biotite, from the centre to the periphery of the intrusion respectively (Figure 6.7). The micas with the lower Fe content from the Thamaga granite partially overlap the Fe-biotite compositions of the Kgale granite Main Phase, along the annite–Fe-biotite boundary (Figure 6.7).

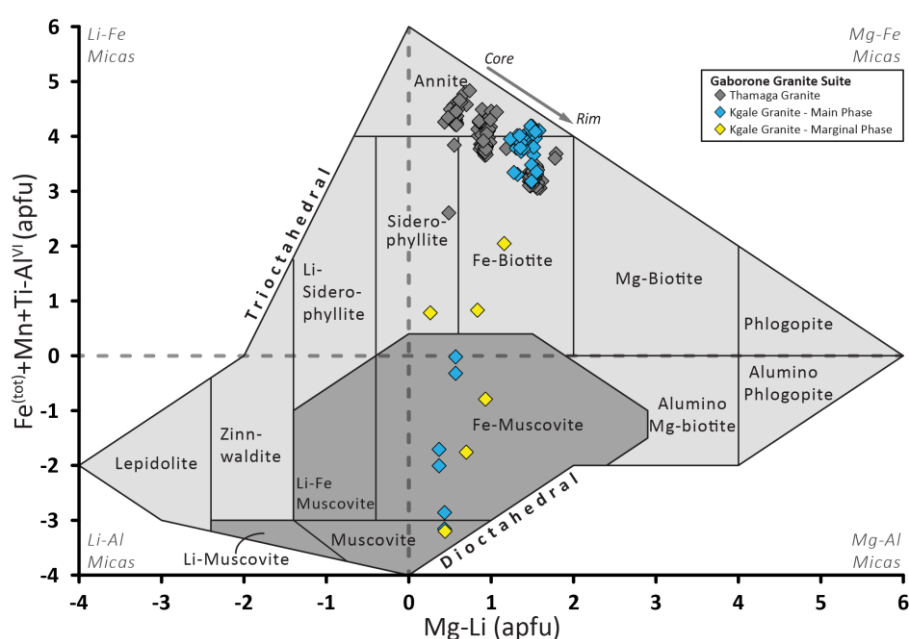


Figure 6.7. Mg-Li vs. $\text{Fe}^{(\text{tot})} + \text{Mn} + \text{Ti} - \text{Al}^{\text{VI}}$ (apfu) mica classification diagram (Tischendorf et al., 1997; Tischendorf et al., 2001) showing the composition of micas from the granites of the Gaborone Granite Suite. The field for the trioctahedral micas is shown by the light grey shading. The dioctahedral mica field is shown in dark grey. Arrow indicates evolution from the core to the rim of the Thamaga granite.

The Si and Al content of the Thamaga and Main phase micas range from 31.2 to 42.7 % and 29.7 to 45.5 % respectively (Appendix F-3). The range in Thamaga mica composition is primarily due to the wide range in ferromagnesian content with FeO^{tot} varying from 19.7 to 35.2 %, MnO from 0.4 to 0.7 % and MgO from 1.9 to 7.4 % (Appendix F-3). In comparison, the

ferromagnesian content of the micas from the Main phase is considerably less variable than the Thamaga micas. The micas from the Main phase have 7.8 to 32.2 % FeO^{tot} and MnO that is <0.2%. The Thamaga micas show an increase in Mg content from the plutonic centre towards the margin of the intrusion (Figure 6.8c).

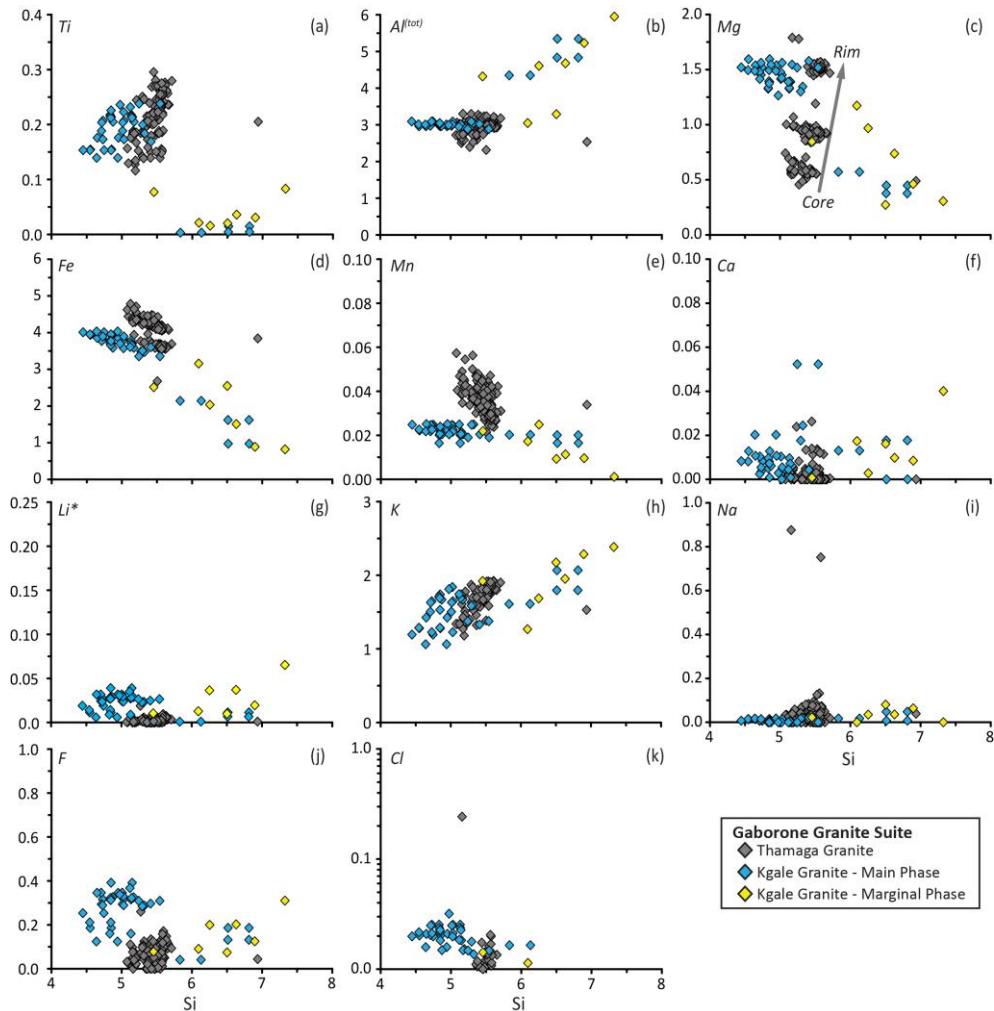


Figure 6.8. Major elemental graphs of mica from the granites of the Gaborone Granite Suite, plotted against Si. The trioctahedral micas from the Thamaga and Main phase have a lower Si compared to the dioctahedral Main and Marginal phase micas. The Si value of 6 *apfu* is used as an approximate value to separate the trioctahedral (<6) and dioctahedral (>6) micas. (a) Ti shows a depletion in the dioctahedral micas compared to the trioctahedral micas. (b) Al^{tot} shows a correlated increase with an increasing Si content, separating tri- and dioctahedral micas. (c) Mg displays a stepwise increase in the trioctahedral micas, from the core of the Thamaga granite towards the peripheral Main phase micas. (d) Trioctahedral micas show a higher Fe content than the dioctahedral micas. (e) The Thamaga micas are more Mn-rich compared to the Main phase and Marginal Phase micas. (f) Ca shows little variation between lithologies with an increase in Si. (g) Li generally decreases with an increased Si. (h) K exhibits a slight increase with an increase in Si. (i) Na is generally low albeit micas from the Thamaga granite are marginally more sodic. (j) F is generally constant in the micas although those from the Main phase are slightly F-enriched. (k) Cl content is low however, mica from the Main Phase show slightly higher Cl values. Element compositions in *apfu*. Arrow indicates evolution of the micas from the core to the margin of the Thamaga granite intrusion.

The micas from the Main Phase have a MgO content between 1.7 and 7.1 %. However, a few micas from the Main phase exhibit considerably lower Fe and Mg contents than the majority of the analyses, and plot within the dioctahedral Fe-muscovite field (Figure 6.7). The micas from the Marginal phase are considerably more variable and display both trioctahedral and dioctahedral compositions. The limited mica data from the Marginal Phase is due to the complete chloritisation of most of the original trioctahedral micas. Most micas that have been analysed from the Marginal phase formed at a late-stage by sericitisation of the chlorite. These late muscovites are generally more Si- and Al-rich, and have a lower Ti, Mg, Fe and F content. In comparison to the Main Phase, they display little variation in their Mn, Ca, K, Na and Cl content (Figure 6.8).

The micas of the Marginal Phase are not distinctly tri- or dioctahedral, as half plot as dioctahedral Fe-muscovite field, and the other half exhibit trioctahedral Fe-biotite and siderophyllite compositions (Figure 6.7). Despite the care taken to focus on mica during analysis, the extensively altered and fine-grained nature of the Marginal phase mica and chlorite intergrowth proved problematic. This intergrowth may have resulted in a spurious trioctahedral composition of the Marginal Phase micas. This is attributed to the accidental contamination by partially chloritised material or by the unintentional excitement of atoms proximal to the electron beam spot during analysis.

Lebowa Granite Suite Mica Compositions

The micas from the Lebowa Granite Suite cluster into two distinct trioctahedral and dioctahedral mica populations (Figures 6.9 and 6.10). The micas from the Nebo granite are trioctahedral and plot within the annite compositional field on the *MgLi* vs *FeAl* classification diagram (Figure 6.10). Compositions for these micas are tightly clustered, with the largest variations being 0.02 to 2.9 % TiO₂, 0 to 0.4 % CaO and the calculated Li content of between 0 and 0.3 % (Appendix F-3). The Ti content of the Nebo micas shows the largest variation of all the micas from the Zaaiplaats granites (Figure 6.10a). These annitic micas are also the most ferromagnesian (Figure 6.10c-e) and have a significantly higher Cl content, which ranges from 1.0 to 2.1 % (Figure 6.10k) (Appendix F-3).

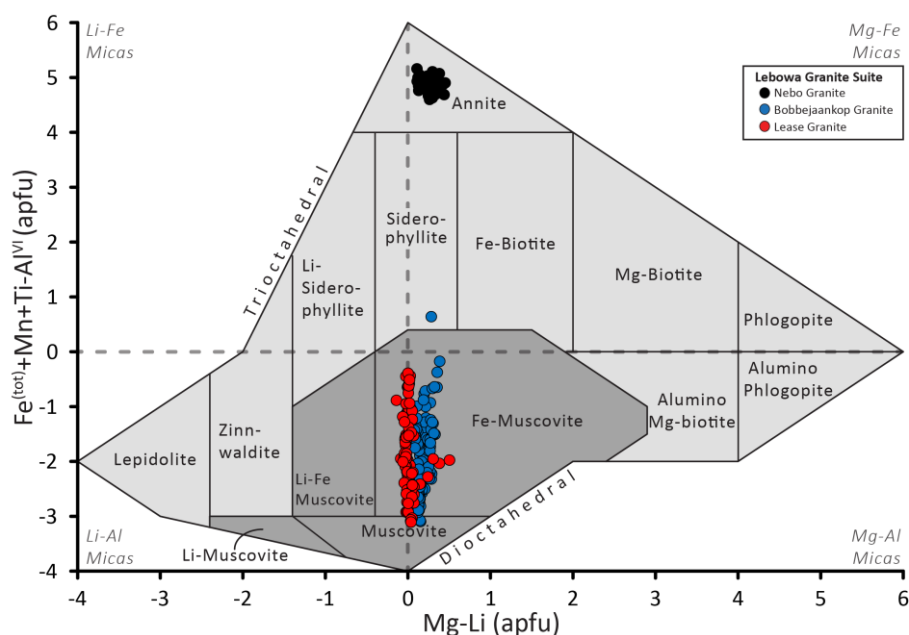


Figure 6.9. Mg-Li vs. $\text{Fe}^{\text{(tot)}} + \text{Mn} + \text{Ti} - \text{Al}^{\text{VI}}$ (apfu) mica classification diagram (Tischendorf et al., 1997; Tischendorf et al., 2001) showing the composition of micas from the granites of the Lebowa Granite Suite. The field for the trioctahedral micas is shown by the light grey shading and for dioctahedral micas in the dark grey.

The micas from the Bobbejaankop and Lease granites are dioctahedral and have a lower ferromagnesian content, compared to the trioctahedral annites of the Nebo granite (Figure 6.10c-e). As would be expected, these dioctahedral micas display a high Si content, between 40.8 % and 51.4 %, and an Al^{tot} content that ranges from 24.3 % to 30.7 % (Appendix F-3). However, the dioctahedral mica populations from the Bobbejaankop and Lease granites are not identical (Figure 6.10).

The micas from the Bobbejaankop and Lease granites primarily plot within the compositional field of Fe-muscovite, although the Lease micas slightly overlap the muscovite compositional field (Figure 6.9). The Bobbejaankop micas are slightly more Si-, Mg-, Fe-, Mn-, Ca- and K-rich, and are F- and Li-poor compared to the Lease micas (Figure 6.10). The Lease micas are the most Mg, Mn and Ca depleted of the two dioctahedral mica populations. In contrast the micas from the Bobbejaankop granite contain up to 2.5 % MgO, 0.5 % MnO, and 0.5 % CaO (Appendix F-3). The F content of the mica increases from the trioctahedral micas of the Nebo to the dioctahedral Bobbejaankop to the Lease micas respectively (Figure 6.10l). In addition, the Lease mica are marginally more Cl-rich than the mica from the Bobbejaankop granite, although they both are remarkably Cl-poor compared to the trioctahedral Nebo micas (Figure 6.10k).

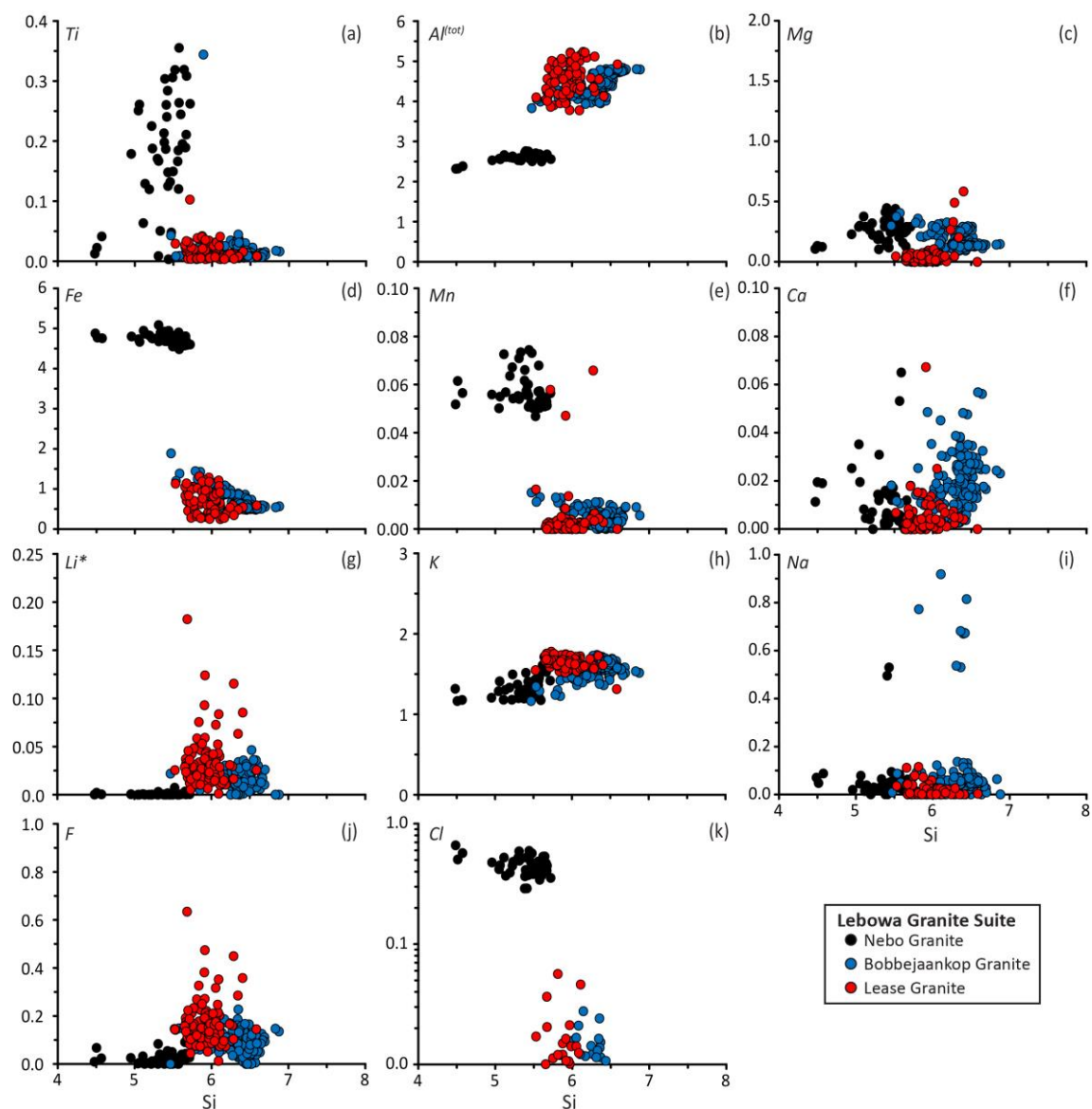


Figure 6.10. Major elemental graphs of mica from the granites of the Zaaipplaats tin field. The trioctahedral micas from the Nebo granites have a lower Si compared to the dioctahedral Bobbejaankop and Lease micas. The Si value of 6 *apfu* is used as an approximated separation of trioctahedral (<6) and dioctahedral (>6) micas. (a) Ti shows a depletion in the dioctahedral micas compared to the trioctahedral micas. (b) Al^{tot} shows a correlated increase with an increased Si content. This effectively separates the tri-octahedral micas of the Nebo granite and dioctahedral micas of Bobbejaankop and Lease granites (c) There is a low Mg content in all the micas. (d) The trioctahedral Nebo micas are Fe-rich compared to the dioctahedral Bobbejaankop and Lease micas. (e) Mn is higher in the trioctahedral Nebo micas than in the dioctahedral Bobbejaankop and Lease micas. (f) Ca shows little variation with an increase in Si. (g) Li is slightly higher in the dioctahedral micas compared to the trioctahedral micas (h) K is higher in the dioctahedral micas. (i) Na is generally low albeit several Nebo and Bobbejaankop analyses have higher values. (j) F displays a gradual enrichment from the Nebo through the Bobbejaankop to the Lease micas. (k) Cl in the Nebo micas is more abundant than in the micas of the Bobbejaankop and Lease granites. Element compositions in *apfu*.

6.3.3. Chlorite Mineral Chemistry

Gaborone Granite Suite Chlorite Compositions

The chlorites from each of the granite lithologies in the Gaborone Granite Suite are compositionally distinct, although there is a considerable degree of overlap (Figure 6.11). The Thamaga chlorites have a similar range in composition to the Main Phase chlorites, whereas the Marginal Phase chlorites are much more variable. The composition of the Thamaga chlorites range from 23.9 to 30.3 % SiO₂, 0.1 to 2.2 % TiO₂, 14.4 to 18.1 % Al₂O₃, 30 to 41.6 % FeO^{tot}, 2.8 to 9.1 % MgO, 0.1 to 4.92 % K₂O and negligible amounts of MnO, Na₂O, F and Cl (Appendix F-4). The chlorites from the Main Phase granite are less variable than the Thamaga chlorites, and range from 22.5 to 32.4 % SiO₂, 0 to 1.2 % TiO₂, 12 to 17.6 % Al₂O₃, 30.4 to 39.3 % FeO^{tot}, 3.5 to 8.4 % MgO and 0.2 to 5.5 % K₂O with a minor contribution of MnO, Na₂O, F and Cl (Appendix F-4).

The chlorites from the Marginal Phase are more compositionally varied than those of the Thamaga and Main Phase granites. They exhibit a slight bimodal distribution, clustering at a higher (6.5 to 7.5 *apfu*) and a lower (5.5 to 6 *apfu*) Si composition (Figure 6.11). These Marginal Phase chlorites range from 23.4 to 32.1 % SiO₂, 0.1 to 1.7 % TiO₂, 13.2 to 18.3 % Al₂O₃, 26.4 to 40 % FeO^{tot}, 5.2 to 9.3 % MgO and up to 3.8 % K₂O with insignificant MnO, Na₂O, F and Cl (Appendix F-4). There is a general increase in Fe, Mg, Al and Mn with Si content of the chlorites (Figure 6.11). The Ti, Ca and F content of these chlorites do not show any obvious enrichment or depletion trends when plotted against Si.

The chlorite classification system proposed by Zane and Weiss (1998), categorises the chlorites from the Thamaga, Main and Marginal Phase granites as Type 1, Fe-chlorite (Figure 6.12a). The chlorites from the Thamaga and Main Phase granites display a compositional overlap in the centre of the Fe-chlorite field (Figure 6.12). The Marginal Phase chlorites exhibit a greater range in (Al+□) and little change in Mg or Fe content (Figure 6.12). The chlorite classification diagram after Hey (1954), is modified to reflect current chlorite nomenclature (Figure 6.12b). On this Si^{IV} vs (Fe+Mn)/(Fe+Mn+Mg) classification diagram, the Thamaga and Main Phase chlorites plot across the chamosite–Fe-chamosite compositional boundary. They show a relatively small range in ferromagnesian components, between 0.79 and 0.88 (Fe+Mn)/(Fe+Mn+Mg) (Figure 6.12c).

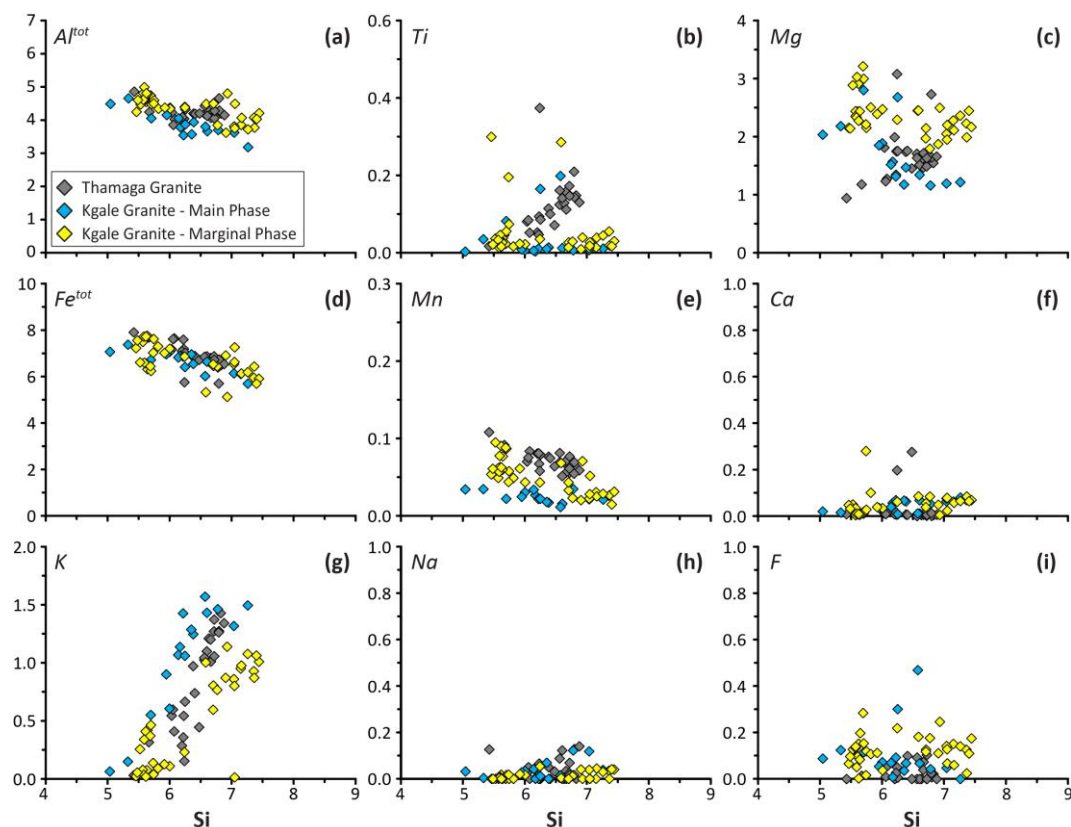


Figure 6.11. Major elemental graphs of chlorites from the Gaborone Granite Suite plotted against Si *apfu*. (a) Si vs Al^{tot} shows a slight negative correlation. (b) Si vs Ti does not show much variation between the Main and Marginal Phase chlorites, although chlorite from the Thamaga granite is slightly more enriched in Ti. (c) Si vs Mg indicates an increasing Mg content from the Thamaga through the Main Phase to the Marginal Phase. (d) Si vs Fe^{tot} displays a strong negative correlation. (e) Si vs Mn exhibits a negative correlation and notably low abundances. (f) Si vs Ca does not show any obvious compositional trends, although exhibits a marginally higher Ca content in the Kgale granite chlorites. (g) Si vs K displays a positive correlation with a decreasing K content from the Thamaga and Main Phase to the Marginal Phase. (h) Si vs Na shows little compositional variation. (i) Si vs F indicates a minor presence of F, with a slight enrichment in the Marginal Phase compared to the Main Phase and Thamaga granites. Element compositions in *apfu*.

The bimodal distribution of the Marginal Phase, on the modified chlorite classification diagram of Hey (1954) (Figure 6.12a), places the low Si chlorites within the chamosite field and the higher Si chlorites within the Fe-chamosite field (Figure 6.12c). These chlorites have a tightly constrained ferromagnesian content, between 0.70 and 0.78 $(Fe+Mn)/(Fe+Mn+Mg)$ (Figure 6.12c). This ferromagnesian range defines a slightly lower compositional array than the chlorites of the Thamaga and Main Phase granites (Figure 6.12c). The chlorites are mostly separated into two compositional fields, the ferromagnesian Thamaga and Main Phase chlorite array and the less ferromagnesian Marginal Phase chlorite array (Figure 6.12). However, a few of the Main Phase and Thamaga chlorites plot within the Marginal Phase chlorite compositional range (Figure 6.12c).

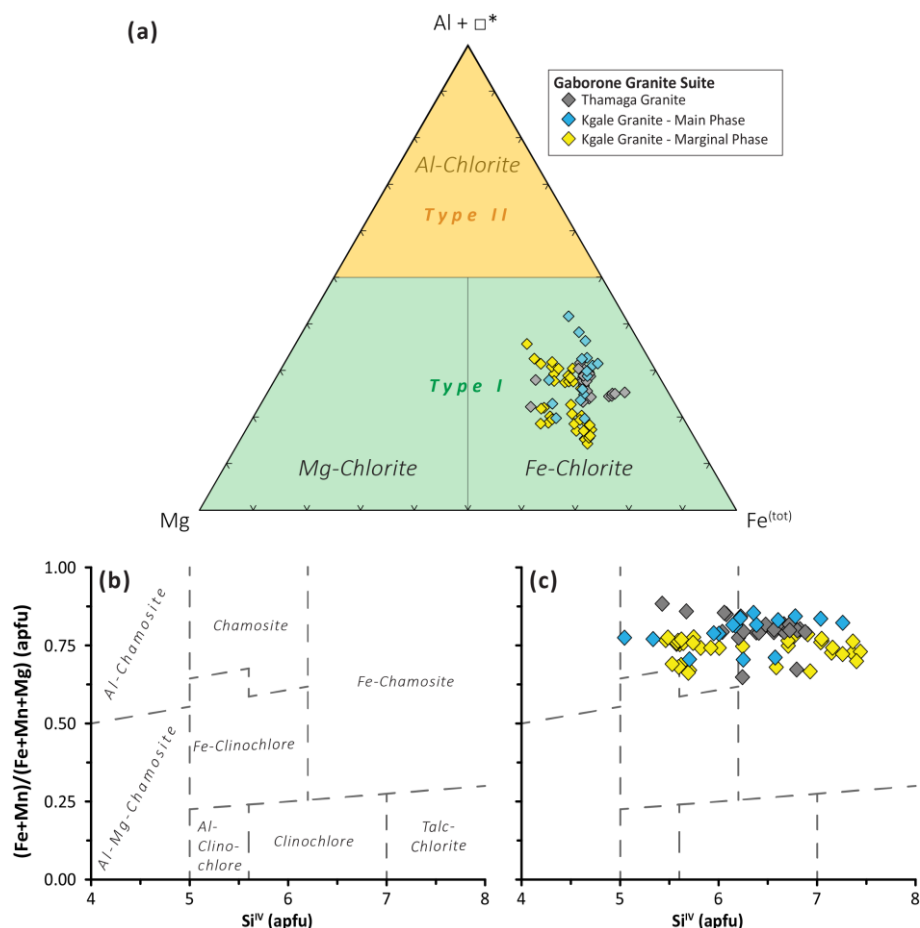


Figure 6.12. Chlorites from the granites of the Gaborone Granite Suite are plotted on various chlorite classification diagrams. (a) $Al + \square - Fe^{(tot)} - Mg$ classification system proposed by Zane and Weiss (1998), classifying chlorites into Type 1 or Type 2 based on their Al and calculated octahedral site vacancy. (b) Si^{IV} vs $(Fe+Mn)/(Fe+Mn+Mg)$ classification diagram with field boundaries after Hey (1954), with updated chlorite nomenclature based on the list of IMA accepted minerals (IMA, 2020). (c) Classification of chlorites from the various granites in the Gaborone Granite Suite on the Si^{IV} vs $(Fe+Mn)/(Fe+Mn+Mg)$ plot.

The mechanisms and types of cationic substitution in chlorite, between the tetrahedral and octahedral sites are described using variations in Al^{IV} and Al^{VI} compositions (Xie et al., 1997; Parra et al., 2005; Wu et al., 2019). Cationic substitution in chlorites is dominated by one of three substitution mechanisms: i) The tschermakite-type substitution $[Si^{IV}(Mg, Fe^{2+})^{VI} = (Al^{IV}, Al^{VI})]$; ii) a di/trioctahedral-type substitution $[\square^{VI} 2Al^{VI} = 3(Mg, Fe^{2+})^{VI}]$; iii) or a ferromagnesian type substitution (Fe, Mg_{-1}) (Xie et al., 1997; Parra et al., 2005; Wu et al., 2019). The characteristic linear 1:1 relationship of $Al^{IV} : Al^{VI}$ in tschermakite-type substitution is lacking in the chlorites from all granites in the Gaborone Granite Suite (Figure 6.13a-c).

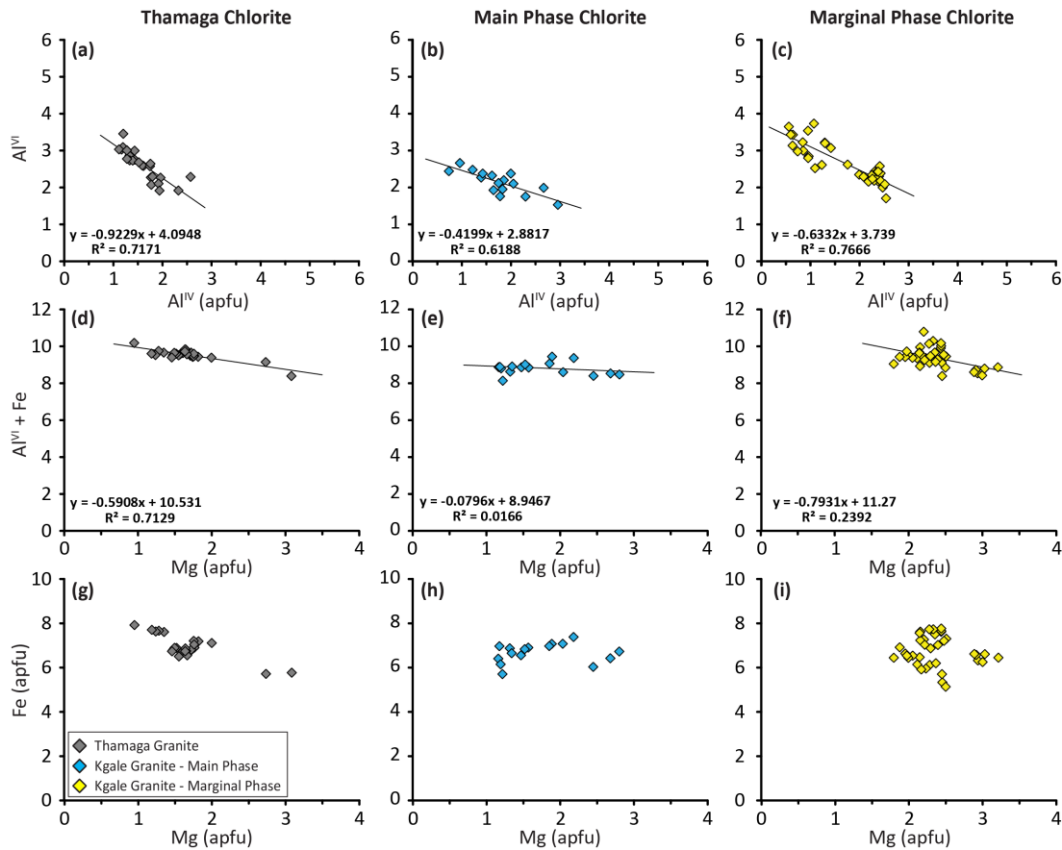


Figure 6.13. Graphs showing the cationic substitution in chlorites from granites of the Gaborone Granite Suite: Graphs (a), (b) and (c) show the Al^{IV} vs Al^{VI} tschermakite-type substitution; graphs (d), (e) and (f) display the main cationic substitution of the octahedral position; and graphs (g), (h) and (i) show the relationship of Fe vs Mg in the octahedral site. Linear regression and R² values are displayed on respective graphs.

Overall, the chlorites from the Gaborone Granite Suite show significant variation in their Fe and Mg content. This implies a ferromagnesian dominant cationic substitution, and is corroborated by the negative relationship exhibited by the Mg vs Al^{VI}+Fe diagrams (Figure 6.13 e-f). The chlorites from the Kgale granite display a larger Al^{IV} variation than the chlorites from the Thamaga granite. The increasing Mg content correlated with a decreasing Al^{VI} highlights the preferential incorporation of Mg, rather than Fe, within the octahedral site (Figure 6.13g-i). This suggests that di/trioctahedral cationic substitution, defined by $\square^{\text{VI}}2\text{Al}^{\text{VI}} = 3(\text{Mg}, \text{Fe}^{2+})^{\text{VI}}$, is the dominant substitution in the octahedral site of the Gaborone Granite Suite chlorites.

Lebowa Granite Suite Chlorite Compositions

The chlorite compositions from each of the granites of the Zaaipplaats tin field are compositionally distinct and typically well constrained. The chlorites from the Nebo granite generally show little compositional variation, apart from a gradual decrease in Al^{tot} and Fe^{tot}

with an increasing Si content. They have a compositional range from 24.7 to 37.5 % SiO₂, 0 to 2.6 % TiO₂, 10.6 to 16.1 % Al₂O₃, 27 to 37.5 % FeO^{tot}, 0.6 to 3.9 % MgO and 0.6 to 5.5 % K₂O with minor MnO, Na₂O, F and Cl (Appendix F-4). There is considerable fluctuation in their Ti and K content that can be attributed to the varying degree of mica chloritisation (Figure 6.14). The chlorites from the Bobbejaankop granite show a similar compositional variability to the Nebo chlorites, however they are comparatively Fe-richer and K-poorer (Figure 6.14). The chlorites range from 21.4 to 31.1 % SiO₂, 0 to 2.4 % TiO₂, 16.8 to 21.8 % Al₂O₃, 28.9 to 43.5 % FeO^{tot}, 1.1 to 3.6 % MgO, 0 to 2.9% K₂O and exhibit low contents of MnO, Na₂O, F and Cl (Appendix F-4). There is a correlated increase in Al and Fe with a decrease in Si from the Nebo to the Bobbejaankop chlorites (Figure 6.14a, d). It appears that there is a progressive increase in the Fe content from chlorites in the Nebo to the chlorites in the Bobbejaankop granite.

In contrast, chlorites from the Lease granite are considerably more Mg-, K- and F-rich, with less Fe and Ti than chlorites from the Nebo and Bobbejaankop granites (Figure 6.14). The compositions of the Lease chlorites, although different to the chlorite from the Nebo and Bobbejaankop granites, are more tightly constrained (Figure 6.14). The Lease chlorites range in compositions from 26.1 to 32.6 % SiO₂, 0 to 0.1 % TiO₂, 15.7 to 18.7 % Al₂O₃, 24.2 to 33.1 % FeO^{tot}, 3.7 to 7.3 % MgO, 3.7 to 5.4 % K₂O and 0.1 to 0.4 % F with negligible amounts of MnO, Na₂O and Cl (Appendix F-4).

On the (Al+□) – Fe^{tot} – Mg classification diagram, the chlorites from the Zaaiplaats tin granites plot within the Type 1, Fe-chlorite classification (Figure 6.15a). The chlorites from the Nebo granite plot between 50% and 60% Fe and with less than 10% Mg (Figure 6.15a). Compositions of the chlorites from the Bobbejaankop granite trend towards the Fe apex with 70% Fe and exhibit a similar low Mg content to the chlorites from the Nebo granite.

On the modified chlorite classification diagram of Hey (1954), the chlorites from both the Nebo and Bobbejaankop granites exhibit high and well-constrained compositions, with regard to (Fe+Mn)/(Fe+Mn+Mg). The chlorites from the Nebo and Bobbejaankop granites should plot with similar Fe-chamosite compositions. However, the compositional classification scheme proposed by Hey (1954) (Figure 6.15b) cannot account for the high Fe content within the Bobbejaankop chlorites. This is due to the Fe enrichment being charge balanced by an increase in Al rather than of Si (Figure 6.14a, d). Because of the diadochy of Al for Si, the ferrous chlorites of the Bobbejaankop granite plot in the chamosite compositional field,

rather than in the Fe-chamosite compositional field together with most of the Nebo and Lease granite chlorites.

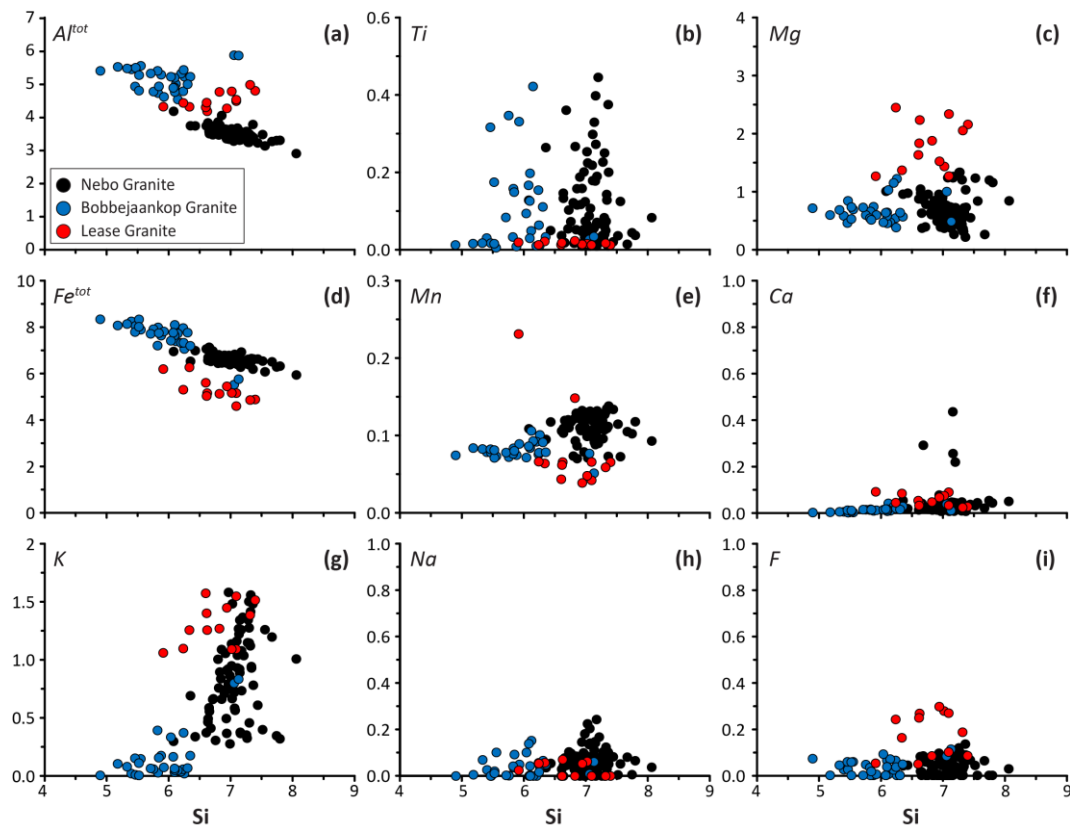


Figure 6.14. Major elemental graphs of chlorites from the Lebowa Granite Suite plotted against Si *apfu*. (a) Si vs Al^{tot} shows a strong negative correlation, with Al increasing from the Nebo to the Bobbejaankop then the Lease granites respectively. (b) Si vs Ti shows similar compositional ranges between the Nebo and Bobbejaankop chlorites, although the Lease chlorite is Ti-depleted. (c) Si vs Mg shows similar Mg contents in the Nebo and Bobbejaankop chlorites, whereas the Lease micas are Mg-rich. (d) Si vs Fe^{tot} displays a strong negative correlation from the Bobbejaankop to Nebo chlorites, however the Lease granite appears depleted in Fe^{tot} . (e) Si vs Mn displays a slightly higher Mn content in the Nebo compared to the Bobbejaankop chlorites, while chlorites from the Lease granite are Mn-poor. (f) Si vs Ca does not show any obvious compositional trends, although chlorite from the Lease granite is slightly Ca-enriched. (g) Si vs K shows a large range of K content in the chlorites from the Nebo granite. The chlorite from the Bobbejaankop facies is K-poor. The Lease chlorites are K-enriched compared to the Nebo and Bobbejaankop chlorites. (h) Si vs Na shows little compositional variation between the chlorite from these granites. (i) Si vs F indicates the minor presence of fluorine in Bobbejaankop and Nebo chlorites, with a slight enrichment in the Lease chlorites. Element compositions in *apfu*.

The ferromagnesian contents on the classification diagram of Hey (1954) range between 0.82 to 0.92 for the Nebo and 0.81 and 0.93 for the Bobbejaankop granite. The Lease chlorites have a lower Fe content and a larger range of $(Fe+Mn)/(Fe+Mn+Mg)$ between 0.66 and 0.81 (Figure 6.15c). The chlorite compositions from the Lease granite cluster within the Type 1 Fe-chlorite field in Figure 6.15a and within the Fe-chamosite compositional field of Figure 6.15c.

These chlorites are notably more Mg-rich and display an increased Al+□ component compared to the Nebo and Bobbejaankop chlorites (Figure 6.15c).

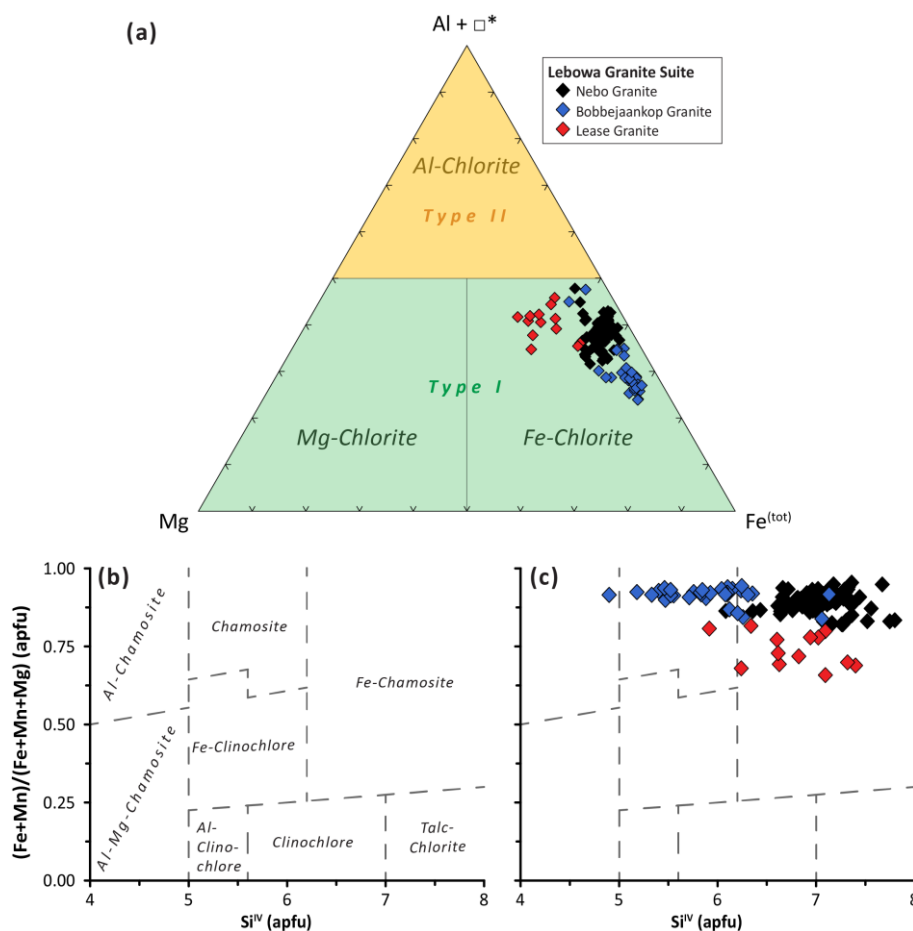


Figure 6.15. Chlorites from the granites of the Lebowa Granite Suite are plotted on various chlorite classification diagrams. (a) On the Al+□ – Fe^(tot) – Mg classification system proposed by Zane and Weiss (1998), the chlorites plot in the field of Type 1 Fe-chlorite based on their Al and calculated octahedral site vacancy. (b) Si^{IV} vs (Fe+Mn)/(Fe+Mn+Mg) classification diagram with field boundaries after Hey (1954), and updated chlorite nomenclature based on list of IMA accepted minerals (IMA, 2020). (c) Classification of chlorites from the various granites in the Lebowa Granite Suite based on the plot of Si^{IV} vs (Fe+Mn) / (Fe+Mn+Mg).

The chlorites from the granites in the Lebowa Granite Suite show steep negatively sloping Al^{IV} vs Al^{VI} substitution, implying a lack of tschermakite-type cationic substitution (Figure 6.16a-c). The Nebo and Bobbejaankop chlorites are the most similar although the chlorite from the Bobbejaankop granite is more Fe-rich than the chlorite from the Nebo granite. These chlorite populations exhibit a marginally negative gradient on the Mg vs Al^{VI}+Fe diagram (Figure 6.16d-f). This suggests that the substitution in the chlorites from the Lebowa Granite Suite is primarily controlled by di/trioctahedral-type substitution and the replacement of Al^{VI} by Mg (Figure 6.16e-f).

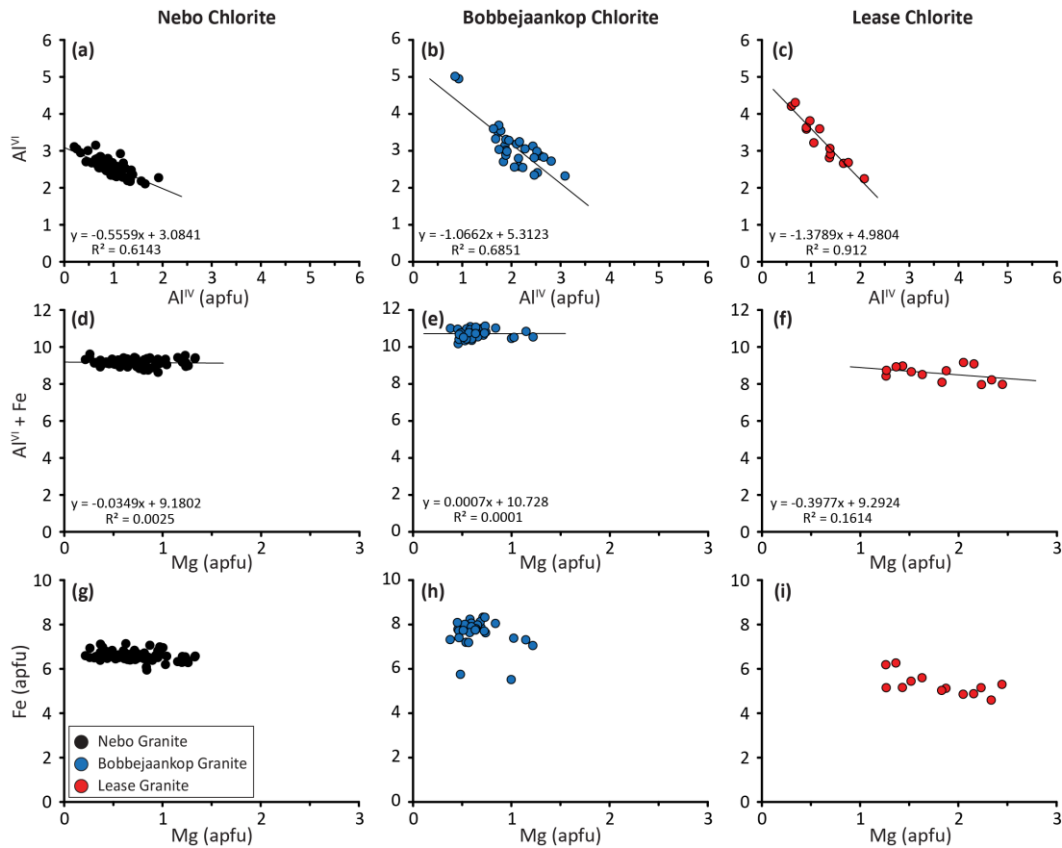


Figure 6.16. Graphs showing cationic substitutions in chlorite from granites of the Lebowa Granite Suite: Graphs (a), (b), and (c) show the Al^{IV} vs Al^{VI} tschermakite-type substitution. Graphs (d), (e) and (f) display the main cationic substitution of the octahedral position. Graphs (g), (h) and (i) shows the relationship of Fe vs Mg in the octahedral site. Linear regression and R^2 values are displayed on respective graphs.

The Lease chlorites exhibit a steeper negative gradient on the Mg vs ($Al^{VI} + Fe$) graph and have a correlated depletion of Fe and Al^{VI} . This indicates a substitution of both Al^{VI} and Fe by Mg within the octahedral site of these chlorites. Therefore, the cationic substitution within the Lease chlorites is primarily controlled by both ferromagnesian and di/trioctahedral-type substitutions at the octahedral site (Figure 6.16g-i).

6.4. Discussion

6.4.1. Mica Evolution

Trioctahedral Mica

The micas from the Gaborone Granite Suite are predominantly trioctahedral and ferromagnesian, whereas only the Nebo micas from the Lebowa Granite Suite samples are trioctahedral and ferromagnesian (Figure 6.17). However, the trioctahedral micas, from both suites, are not primary magmatic phases. This is petrographically evident from the replacement of hornblende by biotite in the Nebo granite (Figure 6.18a). The alteration from

hornblende to biotite was not observed in thin-section from the samples of the Thamaga granite. However, this alteration has been recorded by previous petrographic studies on the Thamaga and Kgale granites (Lowe, 1995; Grobler, 1996).

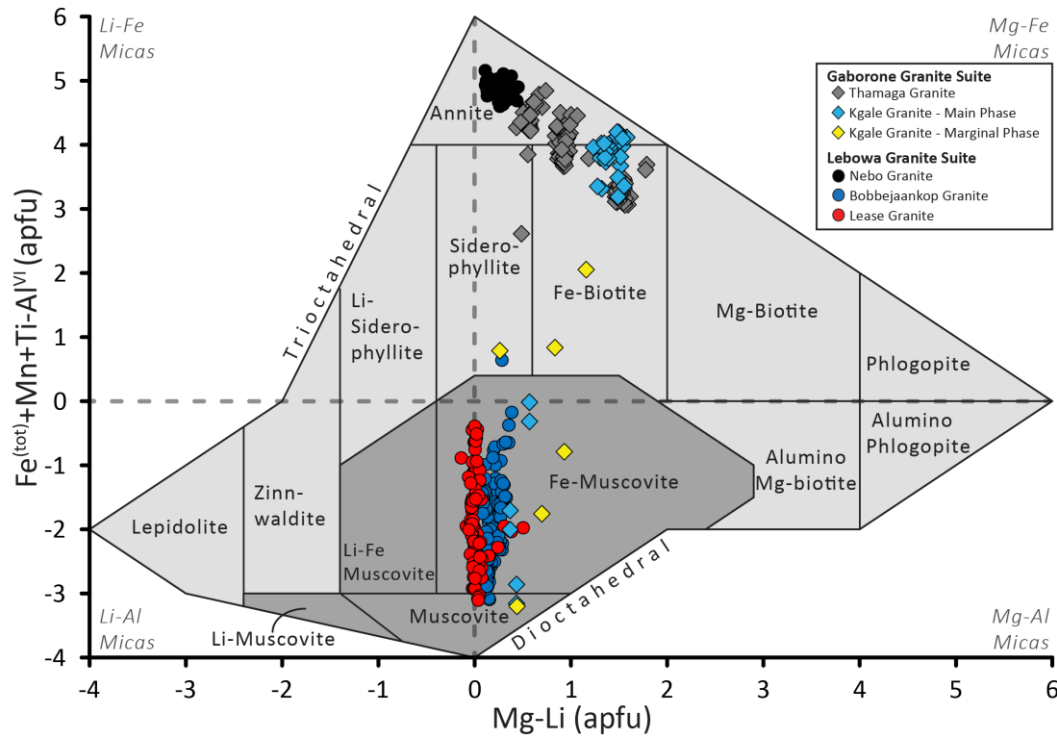


Figure 6.17. Composition of micas from the granites of the Lebowa and Gaborone granite suites on the Mg-Li vs. $\text{Fe}^{(\text{tot})} + \text{Mn} + \text{Ti} - \text{Al}^{\text{VI}}$ (apfu) mica classification diagram (Tischendorf et al., 1997; Tischendorf et al., 2001). The field for the trioctahedral micas is shown by the light grey shading and for dioctahedral micas in the dark grey.

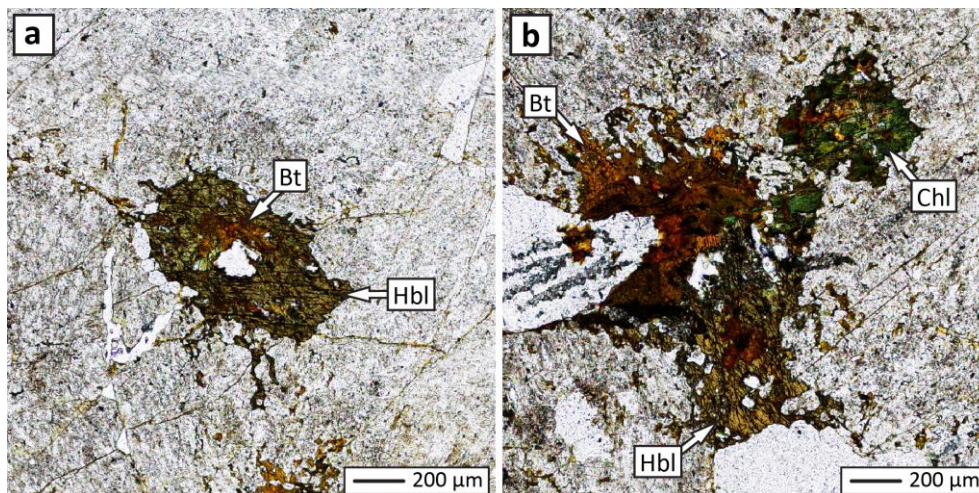


Figure 6.18. Photomicrographs of the alteration of hornblende and biotite in the Nebo granite. (a) Photomicrograph in plane polarised light of hornblende being altered to biotite. (b) Photomicrograph in plane polarised light of a hornblende being altered to biotite then being altered to a dark green chlorite. Abbreviations: hornblende (Hbl); biotite (Bt); and chlorite (Chl).

In addition, the low TiO_2 content of these trioctahedral micas is suggested by Nachit et al. (2005) to indicate that they are not primary magmatic phases. Rather, low Ti micas are considered to be re-equilibrated and/or neoformed from pre-existing minerals, by the alteration from magmatically derived hydrothermal fluids (Figure 6.19). The trioctahedral mica diagram of $(\text{FeO}+\text{MnO}) - \text{MgO} - (10\times\text{TiO}_2)$ (Nachit et al., 2005), classifies most of the Nebo, Thamaga and Main phase micas to be re-equilibrated from pre-existing ferrous amphiboles (Figure 6.19) (Walraven, 1986; Grobler, 1996; Hill et al., 1996; Vonopartis et al., 2020a). This indicates a concentration of magmatic-hydrothermal fluids towards the roof of the crystallising Nebo granite. The high Cl content of the Nebo annites may indicate a saline nature of the early magmatic-hydrothermal fluids. There are some mica compositions from the Nebo and Thamaga granite that plot within the primary-magmatic field on Figure 6.19. Therefore, it is reasonable to suggest that despite most of the mica being re-equilibrated, some of the micas may be primary magmatic phases.

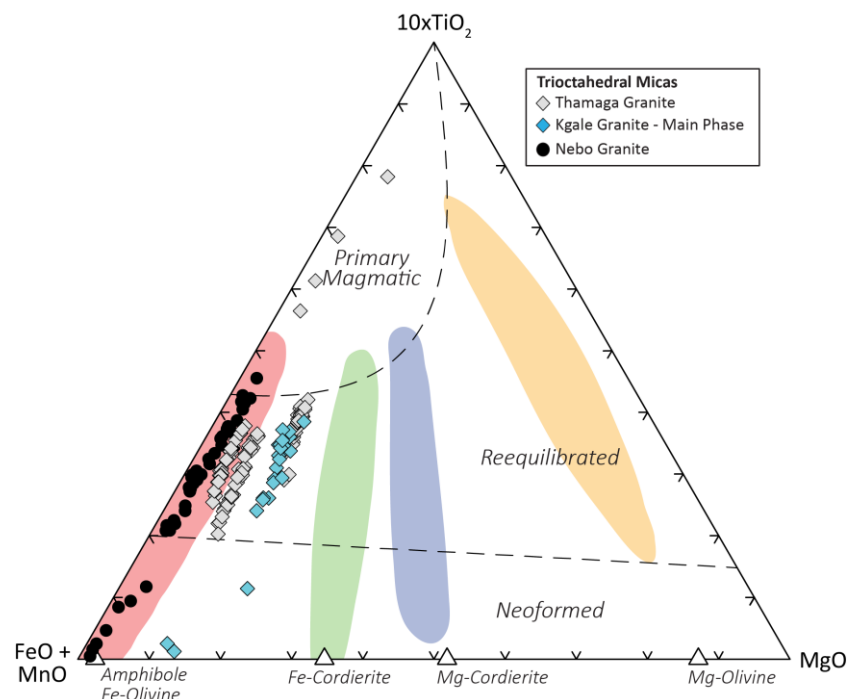


Figure 6.19. Fields of magmatic, re-equilibrated and neoformed trioctahedral micas on the ternary diagram $(\text{FeO}+\text{MnO}) - \text{MgO} - (10\times\text{TiO}_2)$. Trioctahedral micas from the Gaborone and Lebowa granite suites primarily plot as re-equilibrated micas. White triangles represent coexisting Fe-Mg minerals. Diagram and compositional fields after Nachit et al. (2005). Areas shaded in colour represent compositional fields for the dominant pre-existing mafic minerals before mica formation: amphibole–Fe-olivine (red); Fe-Cordierite (green); Mg-Cordierite (blue); and Mg- Olivine (orange).

The evolution of the Thamaga micas, from annite to Fe-biotite, represents a typical evolution, exhibiting a proportional decrease in Fe and increase in Mg of the system (Figure

6.17) (Abdel-Rahman, 1994; Stussi and Cuney, 1996; Colombo et al., 2010). The Thamaga micas exhibit a distinct increase in Mg and decrease in Fe with the outwards evolution towards the Main Phase micas (Figure 6.8c, d). The general Fe decrease during the evolution of a magmatic system is well understood, and is represented in the evolution of various minerals such as pyroxene, olivine and tourmaline (Cerny and Burt, 1984; Henderson et al., 1989; Stone et al., 1997; Nachit et al., 2005; Colombo et al., 2010). The Main Phase Fe-biotites display a relative enrichment in Mg, Li and F, with a depletion in Mn and Fe compared to the Thamaga annites. On the *MgLi* vs *FeAl* diagram, the micas from the Gaborone Granite Suite show a linear evolution that is suggestive of magmatic differentiation along a single liquid-line-of-descent (Figure 6.17). This is consistent with the “one-event” formational model that was proposed for the Gaborone Granite Suite (Grobler and Walraven, 1993; Moore et al., 1993; Grobler, 1996).

The micas from the peripheral Marginal phase of the Kgale granite are predominantly chloritised and lack any relict mica compositions. This extensive chloritisation of mica in the Marginal Phase indicates a concentration of hydrothermal fluids within the late-stages of the Kgale granite. This allowed the pervasive alteration of micas to Fe-chlorite, with minor subsequent greisenisation. Although scarce, this later greisenisation resulted in the formation of fine-grained micas with a Fe-muscovite composition (Figure 6.17).

The Lebowa Granite Suite is characterised by a high-Fe signature that is expressed mineralogically in multiple ways: i) the ubiquitous feldspathic haematisation towards the roof of the Nebo granite and the pink/red alkali-feldspars of the Bobbejaankop and Lease granites (Strauss and Truter, 1944; Coetzee, 1984; Coetzee and Twist, 1989; Hill et al., 1996; Crocker et al., 2001; Vonopartis et al., 2020a); ii) the presence of schorl and Fe³⁺-rich schorl tourmaline within the Bobbejaankop granite, Lease granites and hydrothermal pipes of the Zaaipplaats tin field (Vonopartis et al., 2021b); and iii) the annitic composition of the micas in the Nebo granite (Figures 6.9 and 6.10d).

This Fe-rich characteristic is considered common for differentiated A-Type granites (Eby, 1992; Bonin, 2007). The Fe-rich nature of the re-equilibrated micas in the Nebo granite, is mirrored by comparable mica compositions from the stanniferous alkali-granites of the Younger Granite Complex of Central Nigeria (Imeokparia, 1981; Imeokparia, 1982; Nachit et al., 2005). However, this ferrous signature appears to be absent in the Gaborone Granite

Suite, as the micas become considerably more magnesian with evolution (Figures 6.7 and 6.8c). In contrast, the micas of the Nebo and the Nigerian granites maintain or even increase in Fe content with progressive differentiation (Imeokparia, 1981; Imeokparia, 1982; Nachit et al., 2005).

In addition, the trioctahedral annites from the Nebo granite contain considerably more Cl than any of the micas from the Gaborone Granite Suite (Figure 6.10k). Chlorine within a magmatic system enhances the mobility and complexation of incompatible elements in the fluid phase, such as Sn, W and REEs (Heinrich, 1990; Taylor and Wall, 1993; Wolf and London, 1997; Sherman, 2010; Duchoslav et al., 2017). Metal complexation with Cl⁻ ligands in acidic and reduced granitic hydrothermal fluids facilitates the mass transportation of tin (Heinrich, 1990; Taylor and Wall, 1993; Wolf and London, 1997; Sherman, 2010; Duchoslav et al., 2017). The tin content of trioctahedral micas is shown to exponentially increase from magnesian to ferrous then lithian-ferrous micas (Tischendorf et al., 2001).

The sequestered chlorine, together with Sn and other incompatible elements, could have been later liberated during the chloritisation of the Nebo annites, enhancing the Cl and Sn content of the fluids. The presence and liberation of Sn from biotite during alteration was similarly suggested to enhance the Sn content of the fluids in the Sn mineralised Qitianling granites of South China (Zhao et al., 2005). The preferential partitioning of Sn and Cl into the present magmatic-hydrothermal fluids would have allowed and improved metal transportation (Imeokparia, 1982; Stone et al., 1997; Tischendorf et al., 2001; Soltani Dehnavi et al., 2019). The high Cl content in the annites in the Nebo granites suggests an early abundance of chlorine within the magmatic-hydrothermal fluids, allowing early transportation of metals and an increased likelihood of later saturation. Whereas the lack of a notable Cl signature in the micas of the Gaborone Granite Suite suggests that this critical metallogenic component was lacking from the system.

Moreover, Pollard et al. (1991b) described fluid inclusions within the Bobbejaankop and Lease granites to be hypersaline. These inclusions host phases such as KCl, NaCl and FeCl, which further corroborate the Cl enrichment of the magmatic-hydrothermal fluids. It is reasonable to conclude that the magmatic-hydrothermal fluids were originally Cl rich and were further enriched during the subsequent alteration of the Cl-bearing Nebo annites. The lack of Cl in the later micas of the Bobbejaankop and Lease granites, may be due to the

preferential complexation of Cl^- with available cations within the fluid, such as Sn, Fe, K and Na. There is no compositional data on the fluid inclusions from the granites of the Gaborone Granite Suite. Therefore, it is reasonable to suggest that the intrinsic lack of Cl in the Thamaga granite micas implies a general lack of Cl in the system. This ultimately inhibited the mass mobilisation of LIL elements, and hindered the potential economic enrichment of the Main and Marginal phases.

Diocahedral Mica

The initial alteration of hornblende in the Nebo granite to form annite, was followed by chloritisation, which produced a dark-green Fe-chlorite (Figure 6.18b). The degree of chloritisation increased towards the roof of the Nebo granite, extensively chloritising the minerals of the Bobbejaankop and Lease granites (Figure 6.9). Vonopartis et al. (2020a) described the replacement of Fe-chlorite, during late-stage autometasomatic greisenising fluids by a pale-green to white mica that is now shown to be Fe-muscovite (Figure 6.17). This process can be considered as late-stage muscovitisation. These late-stage diocahedral micas in the Bobbejaankop and Lease granites are considerably more Al-rich and Fe-, Mn- and Ti-poor compared to the trioctahedral annites of the Nebo granite. Whilst these Fe-muscovites are generally fine-grained, they occasionally develop coarser-grained books of muscovite, where greisenisation was concentrated (Vonopartis et al., 2020a). Therefore, a sequence of alteration is proposed for the granites in the Zaaiplaats tin field. The re-equilibrated annites of the Nebo granite were increasingly chloritised to Fe-chlorite towards the Bobbejaankop granite. These Fe-chlorites were subsequently muscovitised to Fe-muscovite in the Bobbejaankop granite then Fe-muscovite–muscovite in the Lease granite (Figure 6.17).

The Bobbejaankop granite is proposed to be the result of extensive fractionation and fluid-saturation of the underlying Nebo granite (Kleemann, 1985; Coetzee and Twist, 1989; Kleemann and Twist, 1989; Hunt, 2005; Vonopartis et al., 2020a). Similarly, the Kgale granite is an evolved and hydrothermally saturated phase of the underlying Thamaga granite (Key and Wright, 1982; Sibiya, 1988; Grobler and Walraven, 1993; Lowe, 1995). It is interesting therefore that the micas of these A-Type granitoids are compositionally distinct, despite their similar petrogenesis.

The micas of the Kgale Main phase are trioctahedral and enriched in F compared to the diocahedral micas of the Bobbejaankop and Lease granites (Figures 6.8 and 6.10). Although

whole-rock F was not analysed, due to the prolific occurrence of fluorite, specifically within the Bobbejaankop and Lease granites (Vonopartis et al., 2020a), a moderate- to high-F concentration can be inferred (Price et al., 1999; Colombo et al., 2010). A low-F content for the Bobbejaankop and Lease micas, can be attributed to the coprecipitation of fluorite from the late-stage greisenising hydrothermal fluids. This process would have reduced the available F for mica and enhanced the formation of late-stage fluorite in the Bobbejaankop and Lease granites (Bailey, 1977; Burt, 1981; Imeokparia, 1981; Witt, 1988; Kinnaird et al., 2004). Therefore, the Fe-muscovite in the Bobbejaankop and Lease would not have recorded the abundance of F, despite the potential increased F concentration of the fluids.

Christiansen and Lee (1986) discussed a difference in the preferential partitioning of F between ferrous and magnesian trioctahedral micas. They show that the partition coefficient of F between magnesian- and ferrous-biotites and a granitic melt, is significantly higher for magnesian-biotite. Therefore, the preferential incorporation of F into Mg-biotites presents an additional explanation for the higher F content of the Main phase micas. The more magnesian micas of the Kgale granites would have sequestered F and reduced its concentration in the resulting magmatic-hydrothermal fluid whereas, the ferrous-micas of the Nebo granite would have promoted the partitioning of F into the hydrothermal fluid during crystallisation. The consequent formation of HF increased the acidity of the evolving magmatic-hydrothermal fluid. This promoted the subsequent greisenisation of the Lease granite that induced cassiterite precipitation (Burt, 1981; Heinrich, 1990; Taylor and Wall, 1993; Heinrich, 2007; Sherman, 2010; Duchoslav et al., 2017). In addition, the greater F concentration in a granitic system would depress the magmatic solidus (Manning, 1981; Pollard and Taylor, 1986; Finch and Tomkins, 2017). This would extend the degree of granitic fractionation, increase the concentration of incompatible elements and improve the likelihood of fluid- and metal-saturation (Pollard et al., 1987; Migdisov and Williams-Jones, 2014; Finch and Tomkins, 2017).

The dioctahedral micas of the Bobbejaankop and Lease granites are similar, although the Lease micas have a slightly higher Al, F, Li and K content with slightly lower Si, Fe, Mn and Mg abundances (Figure 6.10). It seems likely that these micas formed in a closed hydrothermal system, which was progressively depleted in Fe, Mn and Mg. This resulted in an increasingly incompatible element-enriched fluid. The increased Al and K of the Lease micas can be attributed to the greater degree of alteration of the alkali-feldspar. The increase in Li and F

may be attributed to both the gradual evolution of the fluids and potential liberation from any Li- and F-bearing phases through alteration.

Therefore, the F enrichment of the late-stage magmatic-hydrothermal fluids at Zaaiplaats is suggested to be a combination of three factors: i) the lack of early sequestration into fluorine-bearing phases; ii) the gradual fractionation-controlled enrichment of F; and iii) the liberation of any F from earlier trioctahedral micas. These mechanisms facilitated the accumulation of an acidic magmatic-hydrothermal fluid in the granitic cupola. This ultimately resulted in the greisenisation of the Lease granite and the formation of Fe-muscovite–muscovite micas.

Mica Evolution and A-Type Granite Fertility

Comparison of mica compositions from the Gaborone and Lebowa granite suites, with micas from different styles of mineralised and barren A-Type granitoids, revealed two distinct mica evolution trends (Figure 6.20a). Micas from mineralised A-Type granites follow a Fe-Li evolutionary trend, whereas micas from barren A-Type granites exhibit an Mg-dominant evolutionary trend (Figure 6.20).

The Fe-Li evolution from annite through siderophyllite towards zinnwaldite represents the evolution from barren to early magmatic-hydrothermal then late magmatic-hydrothermal trioctahedral mica crystallisation. These Fe-Li trioctahedral micas are associated with endogranitic mineralisation (Figure 6.20). The significance of this Fe-Li mica evolution in mineralised A-type granite suites is that Fe-Li micas have a significantly greater affinity for Sn sequestration (Tischendorf et al., 2001). Thus, their presence in the early stages of magmatic crystallisation increases the available Sn that can later be liberated during subsequent alterations. Other early Sn-bearing phases, such as rutile (Wolf et al., 2018) are absent from the Nebo granite (Vonopartis et al., 2020a), whereas magmatic rutile is present in the early Thamaga and characteristic in the Main Phase (Grobler, 1996). Rutile is not as easily altered by late-stage hydrothermal fluids as are micas. Therefore, any sequestered Sn would have remained unavailable (Wolf et al., 2018), and thus militate late-stage metal enrichment.

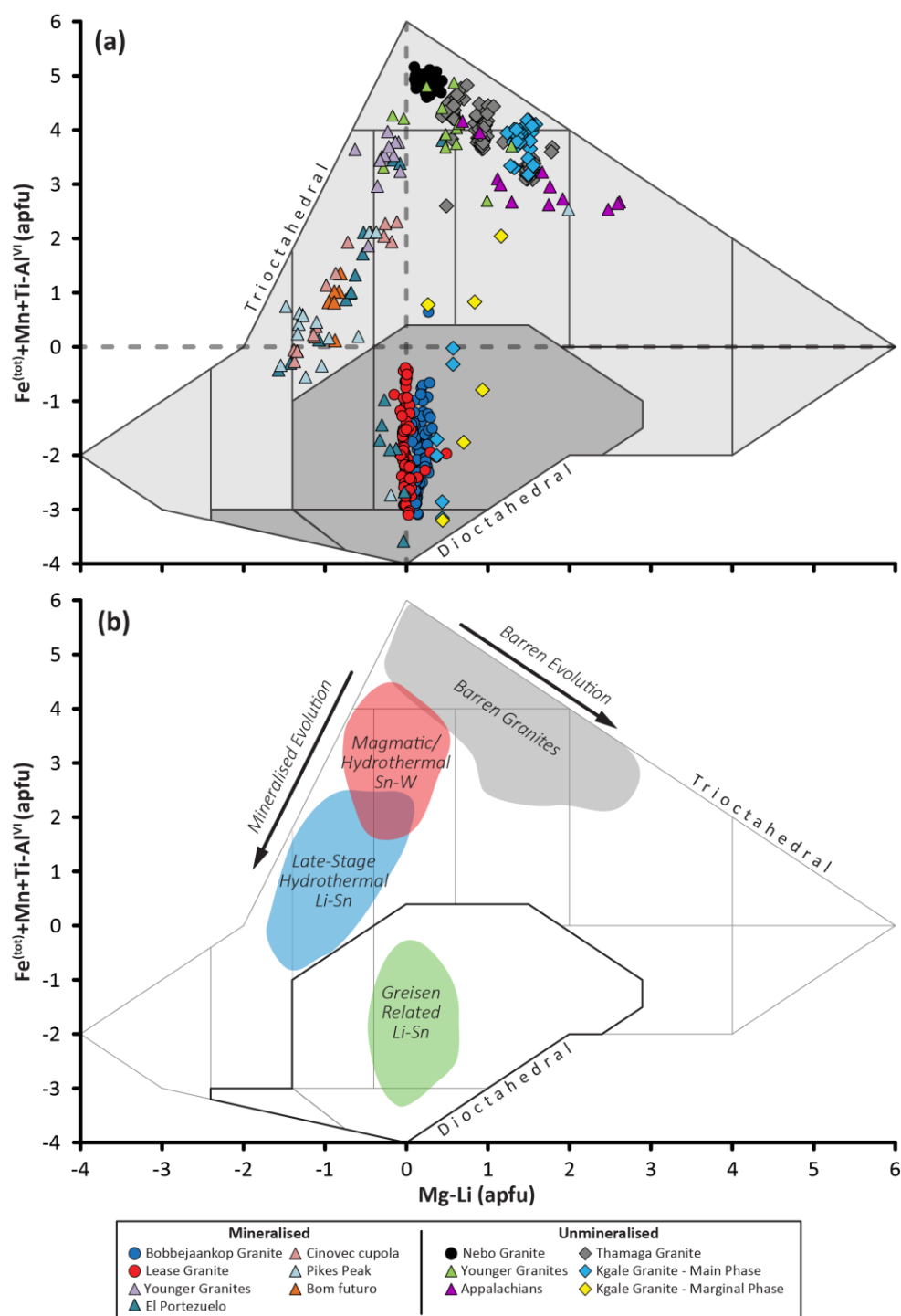


Figure 6.20. Comparison of mica compositions, from mineralised and unmineralised A-type provinces on the MgLi vs FeAl diagram, after Tischendorf et al. (1997). (a) Mica compositions from barren A-Type granites compared with mica compositions from mineralised A-Type granites from various provinces. (b) Proposed mineralisation discrimination fields, representing different styles of mineralisation associated with various A-Type mica composition. A-Type granite mica compositions are sourced from literature and include: the Younger Granites, Nigeria; the Cinovec Cupola, Czech Republic; Pikes Peak, USA; Bom Futuro, Brazil; El Portezuelo, Argentina, Appalachians, USA (Imeokparia, 1982; Foord et al., 1995; Lowell and Ahl, 2000; Shabani et al., 2003; Colombo et al., 2010; Johannes and Holtz, 2012).

Late-stage greisenisation is a well corroborated indicator of a physiochemical change in a F-rich hydrothermal fluid, such as a shift in the pH or oxidation state of the fluid. This shift in the magmatic-hydrothermal fluid conditions is necessary for the precipitation of transported Sn (Heinrich, 1990; Taylor and Wall, 1993; Duchoslav et al., 2017). The dioctahedral micas of the Bobbejaankop and Lease granite and associated cassiterite mineralisation, reinforce this association. Despite the occurrence of dioctahedral micas in the Kgale granite, their scarcity indicates a lack of a significant presence of a suitable greisenising fluid. Thus, it is evident that the lack of a notable muscovitisation event within the later-stages of an A-Type granite, as in the Kgale granite, is an indication of a barren system.

The mica compositions of the Bobbejaankop and Lease granites overlap with other mica compositions from greisen-related mineralised A-Type granites. They specifically overlap the dioctahedral micas from the Pikes Peak granite of Colorado and the El Portezuelo granites of Argentina (Figure 6.20). In contrast, trioctahedral micas dominate in the barren granites, such as in the Gaborone Granite Suite, the Appalachian granites in North America and some of the barren Younger Granites of Nigeria (Figure 6.20). In addition, these trioctahedral micas display a Mg-dominant evolution trend on the *MgLi* vs *FeAl* diagram of Tischendorf et al. (1997) (Figure 6.20). As previously discussed, it is evident that development of Mg-rich trioctahedral micas has a deleterious effect on the metallogenic potential of an A-type granite. This compositional divergence emphasises the implications that ferrous mica compositions, mica evolutionary pathways and an ultimate greisenisation event have on the mineralisation potential of an A-Type granitic system. These compositional characteristics and evolutionary pathways can be used as metallogenic indicators for the potential of an A-Type granite to host late-stage magmatic-hydrothermal mineralisation.

6.4.2. Chloritisation of Micas

The distribution of mica compositions on the *MgLi* vs *FeAl* mica classification diagram may imply a potential for trioctahedral Fe-Li micas to become dioctahedral micas, purely through magmatic-hydrothermal evolution. However, experimental work by Monier and Robert (1986) shows this to be unlikely. Chloritisation seems to be a common intermediate stage in the evolution from tri- to dioctahedral micas in these examples. Therefore, it is suggested that the muscovitisation in the later stages of these granites is required to have been preceded by the chloritisation of the initial trioctahedral micas.

The Fe/Al ratio proves effective in distinguishing trioctahedral, dioctahedral and chloritised micas. Therefore, in combination with K content, a useful mica–chlorite ternary diagram, $K_2O \times 10 - Al_2O_3 - (FeO + TiO_2 + MgO + MnO)$, is proposed to determine of the extent of mica chloritisation (Figure 6.21a). The apparent drift in mica compositions towards more ferromagnesian and less potassic compositions in Figure 6.21a, is linked to an increasing degree of chloritisation. In contrast, the migration of data points towards more potassic compositions, on Figure 6.20a, is an indication of muscovitisation.

The petrography and geochemistry of the micas from both the Gaborone Granite Suite and Lebowa Granite Suite display variable degrees of chloritisation. The micas from the Gaborone Granite Suite are concentrated around the ideal composition of annite and all compositions trend towards clinochlore (chlorite) (Figure 6.21b). As expected, the micas from the Nebo granite cluster around the annite composition and micas from the Bobbejaankop and Lease granites are concentrated around an ideal Fe-muscovite composition (Figure 6.21c). It is apparent that the micas of the Thamaga and Kgale granites exhibit differing degrees of chloritisation (Figure 6.21b). The most complete chloritisation of the micas is seen in the Thamaga granite, where data points cluster close to the ideal chlorite compositions. The chlorites from the Main and Marginal phases exhibit a larger range in K content, and are interpreted to be in various stages of chloritisation.

The chloritisation of mica is associated with a proportional increase in ferromagnesian components, H₂O content and coupled with a distinct depletion of K from the interlayer site (Shabani et al., 2003; Beaufort et al., 2015). There are distinct differences in potassium between the chlorites of the Nebo, Bobbejaankop and Lease granites. Chlorites from the Nebo granite show a progressive depletion of K from 3.1 to 0.3 *apfu*. In comparison, the chlorites from the overlying more altered Bobbejaankop granite are predominantly below 0.3 *apfu* (Figure 6.14g). This indicates a progressive but incomplete chloritisation of the Nebo micas, whereas micas from the Bobbejaankop granite are almost completely chloritised (Figure 6.16c).

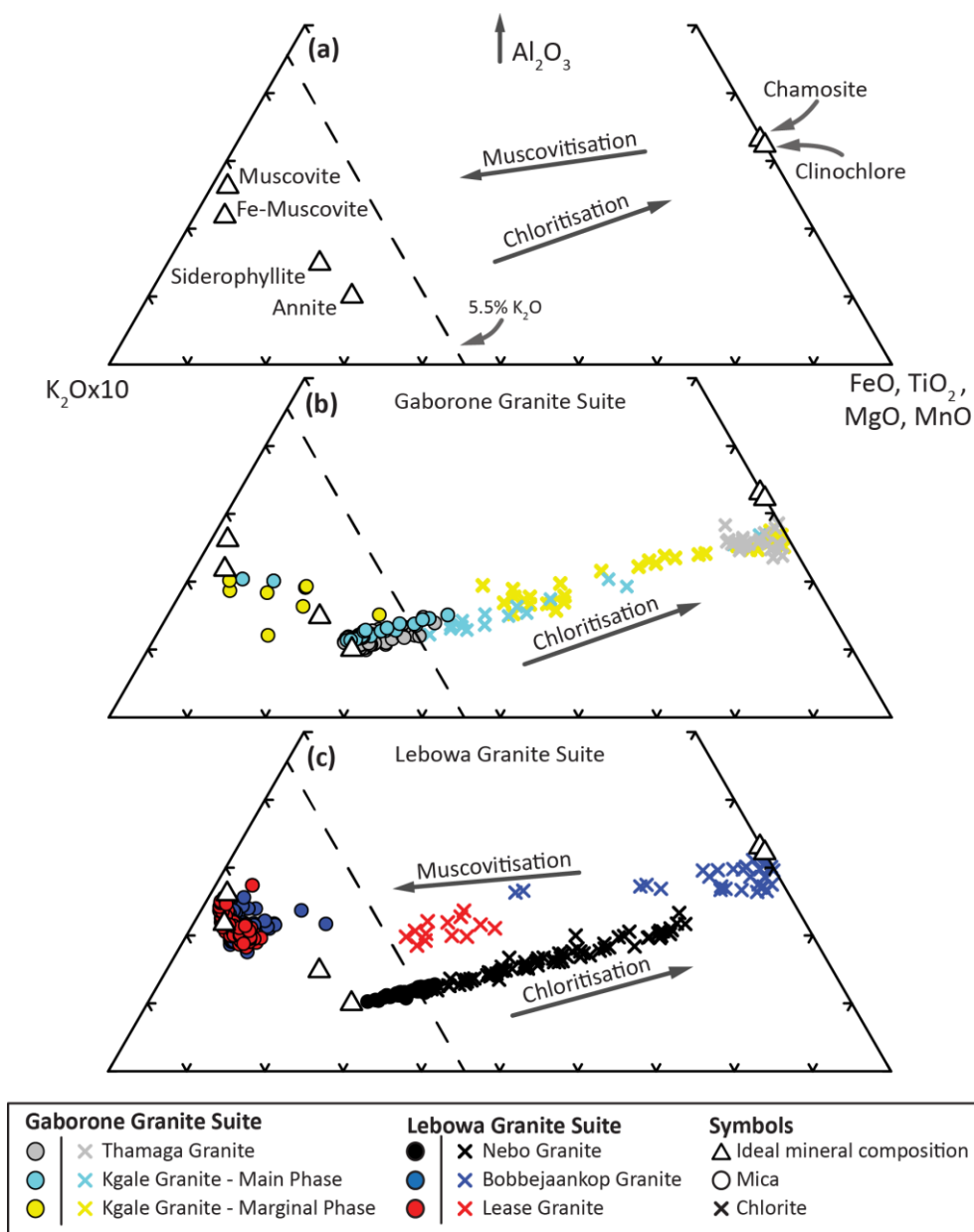


Figure 6.21. Ternary diagrams $K_2O \times 10 - Al_2O_3 - (FeO + TiO_2 + MgO + MnO)$ depicting the extent of chloritisation of the micas from the Gaborone and Lebowa granite suites. (a) Ideal mica and chlorite mineral compositions are shown by white triangles. The boundary between mica and chlorite compositions is delineated by a dashed line, representing 5.5 wt% K_2O . (b) Compositions of mica and chlorite from the Gaborone Granite Suite. (c) Compositions of mica and chlorite from the Lebowa Granite Suite. Circles represent mica compositions, crosses represent chlorite compositions.

In contrast, the Lease chlorites are notably Ti-depleted but do not exhibit the anticipated depletion of K, and range from 4 to 5.5 *apfu* (Figure 6.21c). In addition, these chlorites are Si-rich compared to those from the Bobbejaankop granite and Si-poor compared to the Nebo chlorites (Figure 6.16). Petrological observations of the Lease granite (Vonopartis et al., 2020a), show that the majority of the chloritised micas have been subsequently muscovitised. Therefore, it is suggested that these chlorites do not represent the progression of mica

chloritisation, but rather indicate the muscovitisation of chlorite (Figure 6.21c). During this process, the gradual development of dioctahedral micas (muscovitisation) reintroduced K as well as Si into the sheet silicate, with a proportionate loss of H₂O. Due to the precipitation of secondary Ti phases and other oxides during the prior chloritisation stage (Vonopartis et al., 2020a), it is possible that Ti, Fe and possibly Sn were not available to be reincorporated into the new dioctahedral mica. This resulted in the intermediate chlorite–muscovite composition of these ferromagnesian-poor and K-rich Lease chlorites (Figure 6.21c).

The granitic lithologies from the Gaborone and Lebowa granite suites have all experienced some degree of chloritisation and/or greisenisation. However, the composition of the altering fluids in the two suites are different. Compared to the Lebowa Granite Suite, the micas of the Gaborone Granite Suite appear to be altered to a slightly more magnesian chlorite composition (Figures 6.11c and 6.14c). Together with the magnesian evolution of their micas, this indicates a more magnesian and likely Sn-deficient hydrothermal fluid in the Gaborone Granite Suite. Moreover, most of the dioctahedral micas from the Kgale granite fall close to the ideal composition of Mg-muscovite (Figure 6.21b). This emphasises that even the late-stage greisenisation that produced dioctahedral micas was more magnesian. In contrast, both the tri- and dioctahedral micas as well as the chlorite of the Lebowa Granite Suite exhibit a Fe enrichment (Figures 6.11c, d and 6.14c, d). The Fe-rich mineral compositions correlate with the characteristically ferrous nature and inferred Fe-rich magmatic-hydrothermal events in the Bobbejaankop and Lease granites.

6.5. Conclusion

The mica and chlorite comparison of these mineralised and barren A-Type granite suites have highlighted differences in the evolution of the associated magmatic-hydrothermal fluids. The mica compositions of the Gaborone Granite Suite demonstrate a typical magmatic evolution from the annite of the Thamaga granite to the Fe-biotite of the Kgale granite Main phase. The mica of the Marginal phase is completely chloritised and exhibits minor late-stage muscovitisation.

In contrast, the micas of the Zaaipplaats tin field granites do not exhibit a simple linear evolution from the Nebo to the Bobbejaankop and Lease granite, as was implied from the interpretation of their whole-rock geochemistry. The mica and chlorite compositions of the

Nebo granite record the initial formation and partial chloritisation of the micas. An increased rock-fluid interaction, by the accumulated hydrothermal fluids, resulted in the complete chloritisation of annite to a Fe-chlorite. This rock-fluid interaction increased upwards, such that the complete mica chloritisation was overprinted by muscovitisation. This formed Fe-muscovite during the greisenisation in the overlying Bobbejaankop facies and later muscovite within the uppermost Bobbejaankop and mineralised Lease facies. This greisenisation stage is associated with endogranitic Sn mineralisation and is not present, to any significant extent, within the Gaborone Granite Suite.

In addition, the trioctahedral micas of the Gaborone Granite Suite and other examples of barren granites, evolved along a magnesian compositional evolution. In contrast, the Lebowa and other mineralised A-Type granite suites followed a more ferrous mica compositional trend. This divergence in mica evolution facilitated the sequestration of significantly more Sn by the ferrous micas. This provided a more appropriate Sn reservoir in the Lebowa Granite Suite to be later scavenged during subsequent alterations.

In addition, the Cl-rich annite of the Nebo granite suggest the initial fluids in the Lebowa Granite Suite to be notably saline. The later alteration of these annites would have liberated Cl and LIL elements, thus enhancing the transportation of Sn and other metals. The formation of these ferrous micas in the Nebo granite is shown to have favoured the enrichment of F into the evolving magmatic-hydrothermal fluids. In comparison, Mg-rich trioctahedral micas readily sequester F into their structure. Therefore, Mg-rich micas would decrease the partitioning of F in the fluid and reduced the potential for late-stage greisenisation in the Gaborone Granite Suite. The absence of a crucial acidic magmatic-hydrothermal fluid is ultimately reflected by the lack of dioctahedral micas in the Kgale granites. The lack of an acidic Cl- and F-rich hydrothermal fluid, and the early sequestration of Sn by rutile, reduced the potential to form a metalliferous greisenising magmatic-hydrothermal fluid. This ultimately hindered the development of tin mineralisation in the later-stages of the Gaborone Granite Suite. Thus, mica compositions show promise as an indicator for the potential of an A-type granite to host tin mineralisation.

Chapter 7

Trace Elements-in-Quartz from the Zaaipplaats Tin Field

7.1. Introduction

There are fourteen naturally occurring polymorphs of silicon dioxide (SiO_2), of which quartz is the most common (Table 7.1) (Howie et al., 1992; Götze et al., 2004; Götze, 2009). The mineral quartz accounts for approximately 12.6 wt% of the Earth's crust and is stable over a wide range in physiochemical conditions (Howie et al., 1992; Sharp et al., 1999; Götze et al., 2004; Götze, 2009). The mineral quartz was described as far back as the ancient Greeks, when it was known as *κρύσταλλο* (krystallo), which resulted in the use of the word “crystal” (Tomkeieff, 1942). The first use of the word “quartz” was published anonymously in 1505. Freiberg physician Ulrich Rühlein von Kalbe has been recognised as the author of this work, which described the terms used by Saxon miners for various minerals (Tomkeieff, 1942). Georgius Agricola is credited to have first used the word “quartz” during the 1530s, in his first book on mineralogy and mining (Tomkeieff, 1942).

Quartz exists as either: α -quartz (low-quartz), which is a trigonal-trapezohedral crystal and stable up to 573°C at 1 atm pressure; or β -quartz (high-quartz), which has a hexagonal-trapezohedral crystal structure. High-quartz is stable between 573 to 870°C and metastable above 870°C (Howie et al., 1992; Götze et al., 2004; Götze, 2009). The transition from β - to α -quartz at $\pm 573^\circ\text{C}$ involves a minor rotation of the SiO_4 tetrahedra during cooling, without breaking Si–O bonds (Howie et al., 1992; Götze, 2009; Heaney et al., 2018). The low-temperature α -quartz crystallises in the final stages of evolved magmas and is a common component in evolved granites, granodiorites, rhyolites and pegmatites (Heaney et al., 2018). Conversely, β -quartz and other varieties of high-temperature polymorphs are transient species. They form during the crystallisation of higher temperature igneous bodies and in high-grade metamorphic facies (Howie et al., 1992; Götze et al., 2004; Götze, 2009).

A study, using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) to measure the trace element compositions of quartz from the Zaaipplaats tin field was undertaken. The aim of this research was to use the trace element variations in quartz, to investigate the magmatic and magmatic-hydrothermal history of these granites, and evaluate

whether the trace element variations could indicate potential endogranitic tin mineralisation in a granite.

Table 7.1. Table of silica polymorphs, modified after Götze (2009) and common occurrences (Skinner and Appleman, 1963; Heaney and Post, 1992; Howie et al., 1992; Götze, 2009; Grapes and Müller-Sigmund, 2010; Heaney et al., 2018).

Polymorph	Crystal Structure	Occurrence
Quartz-Tridymite-Cristobalite Group (Low Pressure)		
α-quartz	Trioctahedral	Evolved igneous rocks, low temperature metamorphic facies, sedimentary rocks and hydrothermal systems
β-quartz	Hexagonal	Primitive igneous rocks, high temperature metamorphic facies, sedimentary rocks
α-tridymite	Monoclinic	Felsic volcanics, lunar rocks and meteorites, typically associated with active volcanism.
β-tridymite	Hexagonal	
α-cristobalite	Tetragonal	Felsic volcanics, olivine basalts, lunar rocks and meteorites, contact metamorphosed sandstones
β- cristobalite	Cubic	
Melanophlogite	Cubic	Rare silicate polymorph, forming overgrowths of sulphur and calcite
Fibrous SiO₂*	Orthorhombic	Synthetic form of SiO ₂
Moganite	Monoclinic	Igimbrites, chert in arid and alkaline environments
Keatite-Coesite-Stichovite Group (High to Ultra-high Pressure)		
Keatite*	Tetragonal	Synthetic form of high pressure SiO ₂
Coesite	Monoclinic	Associated with meteorite impacts and in xenoliths from kimberlite
Stichovite	Tetragonal	
Seifertite	Orthorhombic	Remarkably rare, associated with exceedingly high pressures induced by large scale meteorite impacts
Lechatelierite-Opal Group (Amorphous)		
Lechatelierite	Natural Silicate Glass	Natural silicic melt quenched glass. Lightning induced melting of silicic sediments or rocks.
Opal	Solid Hydrous SiO ₂ gel	Sedimentary and volcanic terranes where evaporation from an accumulated SiO ₂ -rich fluid may occur. Marine siliceous ooze from biogenic amorphous silica

**Synthetic silica polymorph*

7.1.1. Quartz Mineral Chemistry

The composition of quartz is typically close to 100 wt% SiO₂. Therefore, recent geochemical investigations using quartz have been focused on trace elements that are incorporated within

inclusions and in the crystal structure (Howie et al., 1992; Götze et al., 2004; Götze, 2009; Heaney et al., 2018). The silica lattice consists of $[\text{SiO}_2]^{4-}$ tetrahedra, joined by their oxygen atoms in a three-dimensional lattice (Figure 7.1) (Howie et al., 1992; Götze et al., 2004; Götze, 2009; Heaney et al., 2018). Although compositionally simple, these minerals show appreciable structural complexities that ultimately determine the physical properties of the quartz crystal.

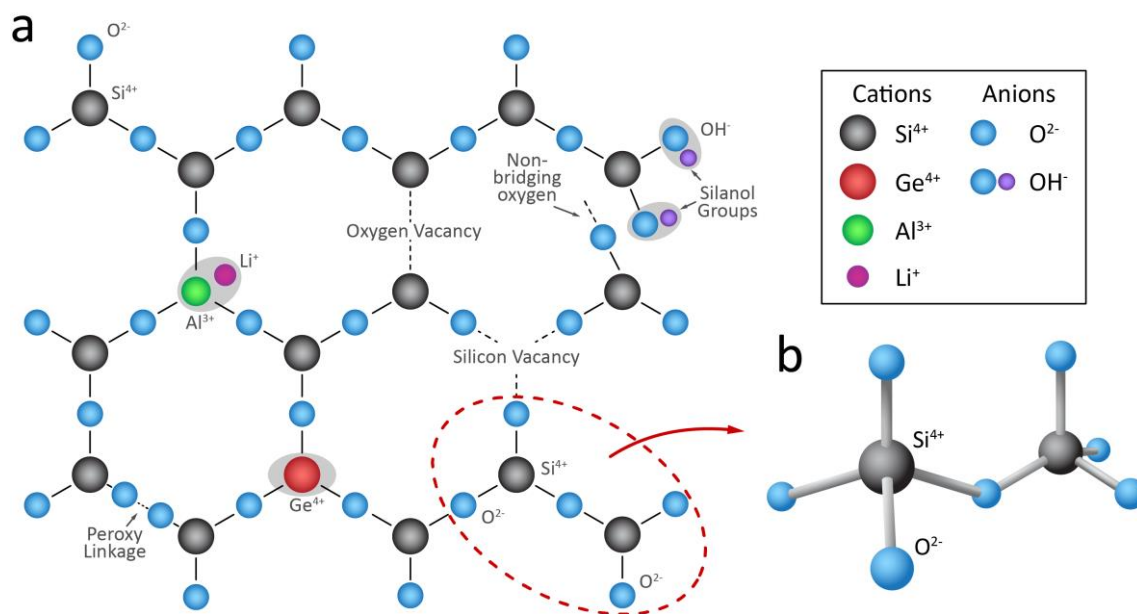


Figure 7.1. Schematic representation of the crystallographic structure of quartz. (a) Pan view of a schematic β -quartz lattice with most common types of defects, after Götze (2009). (b) Schematic structure of $[\text{SiO}_2]^{4-}$ tetrahedra joined by a common O^{2-} atom (Howie et al., 1992; Nesse, 2009; Heaney et al., 2018).

These complexities include point defects, dislocations, twinning and three-dimensional defects that are related to thermodynamic conditions during crystallisation (Howie et al., 1992; Götze et al., 2004; Götze, 2009; Heaney et al., 2018). In addition, advancements in modern analytical instruments have allowed trace element determination with significantly lower detection limits. Trace elemental variations provide novel insights on the origin and evolution of quartz. These investigations have revealed remarkable heterogeneity within single quartz crystals. These compositional differences record the magmatic or hydrothermal evolution and genetic information of both barren and mineralised systems (Howie et al., 1992; Götze et al., 2004; Götze, 2009; Heaney et al., 2018; Müller et al., 2018; Cui et al., 2019; Hong et al., 2019).

Trace element abundances in quartz provide the only compositional variability from a ubiquitous and otherwise homogeneous mineral. Numerous trace elements are incorporated

into the crystal structure and are either bound within the crystal lattice or hosted as micro-mineral or fluid-inclusions (Howie et al., 1992; Götze et al., 2004; Götze, 2009; Heaney et al., 2018). Due to the small size (0.42 Å) and charge of Si^{4+} , few elements can be directly incorporated into the SiO_2 structure. However, the incorporation of Ge^{4+} , Ti^{4+} , P^{4+} , Al^{3+} , Ti^{3+} , Ga^{3+} and Fe^{3+} through direct and coupled substitution is common (Figure 7.1a) (Howie et al., 1992; Götze et al., 2004; Götze, 2009; Heaney et al., 2018). Charge balance is maintained, during coupled substitution, by additional cations such as H^+ , K^+ , Na^+ , Li^+ , Ag^+ and Cu^+ . These cations are included along channels that run parallel to the c-axis and interstitial lattice positions (Howie et al., 1992; Götze et al., 2004; Götze, 2009; Heaney et al., 2018). Trace elements that are not structurally accepted and are detected during the analysis of quartz, are typically hosted within fluid- or mineral-inclusions (Figure 7.2) (Howie et al., 1992; Götze et al., 2004; Götze, 2009; Heaney et al., 2018).

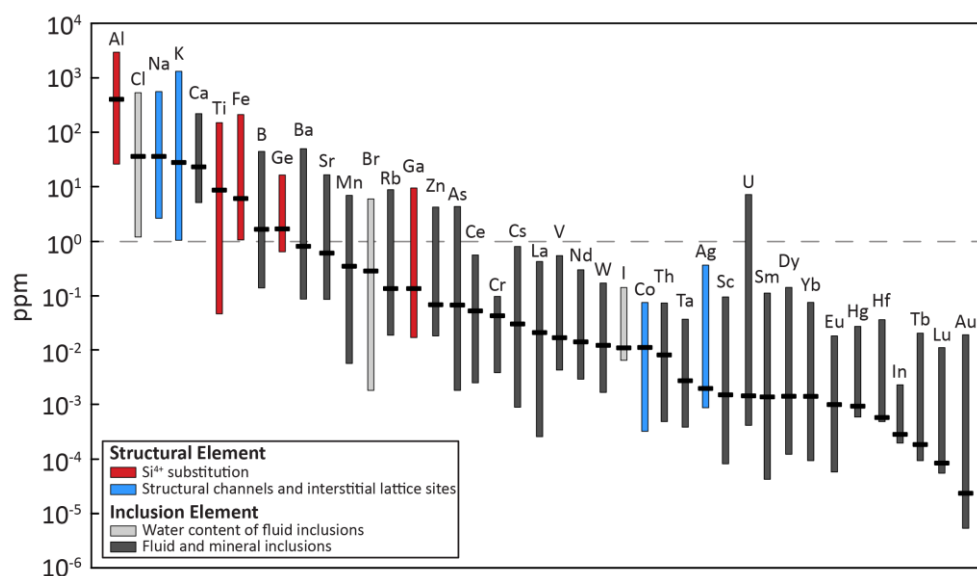


Figure 7.2. Average abundances and ranges of trace elements incorporated in quartz. Modified after Götze (2009) and references therein.

The incorporation of individual trace elements into the silica structure is influenced by the temperature and the composition of the magmatic or hydrothermal environment (Howie et al., 1992; Götze et al., 2004; Götze, 2009; Heaney et al., 2018). This is demonstrated as the degree of Si^{4+} substitution for Al, Li, Fe, Ge and Ti individually differs between syn-, late- and postorogenic pegmatites (Howie et al., 1992; Götze et al., 2004; Götze, 2009; Heaney et al., 2018; Müller et al., 2018). The preferential incorporation of Al^{3+} , Ge^{3+} or Ti^{4+} for Si^{4+} at different temperatures, has been used to distinguish magmatic from hydrothermal quartz

and provides a robust index of granitic evolution (Jacamon and Larsen, 2009; Müller et al., 2018).

The substitution of Ti^{4+} for Si^{4+} in quartz systematically decreases with decrease in temperature (Howie et al., 1992; Wark and Watson, 2006; Heaney et al., 2018). Wark and Watson (2006) used the correlations between the concentration of Ti in quartz, pressure and TiO_2 activity to develop the Ti-in-Quartz geothermometer (TitaniQ thermometer). This geothermometer proved unreliable in the temperature and pressure calculations of purely hydrothermal quartz, and was later recalibrated by Huang and Audétat (2012). However, these geothermometric calculations are strongly reliant on an accurate calculation of TiO_2 activity, and without which prove unreliable (Huang and Audétat, 2012).

The variation in the trace element geochemistry of quartz have been used to interpret the petrogenesis, evolution and mineralisation of many ore-deposits (Suttner and Leininger, 1972; Hallbauer, 1992; Heynke et al., 1992; Monecke et al., 1999; Larsen et al., 2000; Monecke et al., 2002; Müller et al., 2003; Götze et al., 2004; Larsen et al., 2004; Müller et al., 2008; Götze, 2009; Jacamon and Larsen, 2009; Larsen et al., 2009; Cui et al., 2019; Hong et al., 2019). The data presented in this chapter provides the first set of quartz trace elemental compositions for the Lebowa Granite Suite. These results help elucidate the evolution and late-stage mineralisation of the granites and hydrothermal pipes in the Zaaiplaats tin field.

7.2. Sampling and Analytical Techniques

7.2.1. Cathodoluminescence Imaging of Quartz

Cathodoluminescence (CL) images were obtained on thick-sections using a CAMECA SX5-FE electron probe micro-analyser (EPMA), at the University of the Witwatersrand. These CL images revealed various textures that are indicative of magmatic and hydrothermal growth in the development of the quartz (Rusk and Reed, 2002). These CL images were also used to map quartz grains, prior to trace element analyses by laser ablation inductively coupled plasma mass spectrometry. The CL images were used to avoid defects and inclusions, while targeting different generations of quartz.

7.2.2. Laser Ablation Inductively Coupled Plasma Mass Spectrometry of Quartz

A total of one hundred and seventy ablations were done on quartz grains from the various granitic lithologies and a hydrothermal pipe from the Zaaiplaats tin field. These included

twenty three from the Nebo granite, seventy from the Bobbejaankop granite, sixty five from the Lease granite and twelve from a tourmaline-quartz hydrothermal pipe. The samples were cut and prepared into 300 μm thick-sections at the University of the Witwatersrand, Johannesburg. The thick-sections were polished to produce a surface with less than 1 to 2 μm variation. The samples were analysed using the laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) facilities that are housed in the EarthLab, at the University of the Witwatersrand. These analyses were obtained over two runs, during October 2020 and November 2020, using identical analytical parameters and methods.

Trace elements-in-quartz were analysed employing an Australian Scientific Instruments (ASI) Resolution 193 nm ArF excimer system coupled to a Thermo Scientific Fisher sector-field inductively coupled plasma mass spectrometer (Element XR). Measurements were performed in low resolution and electrostatic scanning (E-scan) modes. The data was acquired by single spot analysis (64 μm diameter). A laser repetition rate of 10 Hz and a fluence of 3.5 Jcm^{-2} was used for ablation. The total signal acquisition time was 50 s, separated into 10 s of pre- and post-ablation (gas blank) and 30 s of ablation measurements. Laser sampling took place in a SE155 dual-volume ablation cell (Laurin Technic, Canberra, Australia) using a mixed He-Ar atmosphere with minor N_2 for an enhanced signal stability and sensitivity. The gas flow conditions were: He (350 ml/min); Ar (1000 ml/min); and N_2 (5 ml/min). Synthetic glass NIST 612 (Jochum et al., 2011) served as the primary calibration standard, with USGS natural glass NIST 614 (Gao et al., 2002) and one natural quartz (Audétat et al., 2015) as secondary standards to ensure accuracy and precision. Line scans using NIST 612 glass were used to tune maximum sensitivity for ^{59}Co , ^{115}In and ^{232}Th , while maintaining thorium oxide levels (ThO^+/Th) below 0.2 %. The isotope ^{29}Si (99.95 wt% SiO_2) was used for internal standardisation. Two analyses of the primary calibration standard were obtained at the beginning and end of an experiment. There were between ten and twenty analyses of unknowns followed by the analyses of one primary and each secondary standard as a quality control. Two laser pulses were used before each spot analysis, to ensure a clean ablation surface. Six samples per peak were measured for the following isotopes: ^7Li ; ^9Be ; ^{11}B ; ^{23}Na ; ^{27}Al ; ^{29}Si ; ^{39}K ; ^{44}Ca ; ^{49}Ti ; ^{52}Cr ; ^{54}Fe ; ^{55}Mn ; ^{57}Fe ; ^{72}Ge ; ^{85}Rb ; ^{88}Sr ; ^{89}Y ; ^{90}Zr ; ^{93}Nb ; ^{118}Sn ; ^{137}Ba ; ^{139}La ; ^{140}Ce ; ^{141}Pr ; ^{146}Nd ; ^{147}Sm ; ^{151}Eu ; ^{157}Gd ; ^{159}Tb ; ^{163}Dy ; ^{165}Ho ; ^{166}Er ; ^{169}Tm ; ^{174}Yb ; ^{175}Lu ; ^{178}Hf ; ^{181}Ta ; ^{182}W ; ^{209}Bi ; ^{232}Th ; and ^{238}U . Depending on signal strength, isotopes were measured in triple

mode, which includes pulse counting, analogue and Faraday cup. Many of the elements did not prove informative, thus only a subset is presented in this chapter. The complete set of quartz analyses, the detection limits and standards comparison are provided in Appendix G.

The trace element data reduction was accomplished using the *iolite* extension (<http://www.iolite.org.au>) of the software *Igor Pro* (<http://www.wavemetrics.com>). Specifically, the data reduction scheme (“DRS”) “X_Trace_Elements_IS”, was run in a series of sequential steps: including data import; selection of integrations; baseline subtraction; drift and down-hole fractionation; calibration; and error propagation (Paton et al., 2010; Paton et al., 2011). Due a lack of coexisting rutile and analytical time restrictions that prevented a complimentary analysis of ilmenite, the TiO_2 activity was not calculated. Therefore, Ti-in-quartz geothermometry was not attempted. References to temperature are made strictly based on the concept that the Ti abundance in quartz decreases with a decrease in temperature of crystallisation (Wark and Watson, 2006; Huang and Audétat, 2012), and are not quantified using geothermometers.

7.3. Results

7.3.1. Cathodoluminescence Textures of Quartz

In addition to guiding the LA-ICP-MS analysis of the quartz, the acquisition of more than 170 CL quartz images from the granites and hydrothermal pipe, revealed different generations, various textures, zonations and healed fractures. Detailed petrographic descriptions of these lithological units are given in Vonopartis et al. (2020a). Based on CL intensities and textures, the various generations of quartz are denoted alphabetically, beginning at the crystal core (Qz-A). The various CL distinct quartz generations are alphabetically labelled towards the rim of the quartz crystal (Qz-A, Qz-B, Qz-C, etc.). The labelling of the quartz generations is specific to each lithology.

Nebo Granite Quartz

The samples from the Nebo granite provide the stratigraphically lowest quartz population from the Zaaipplaats tin field granites. These subrounded magmatic coarse-grained (400 to 2,000 μm) quartz crystals crystallised amongst subhedral alkali-feldspars and interstitial biotite (Figure 7.3) (Vonopartis et al., 2020a). These quartz grains generally show very little to

no zonation (Figure 7.3a, b), although occasionally they exhibit a light-grey core surrounded by a less luminescent, dark-grey quartz rim (Figure 7.3c-f).

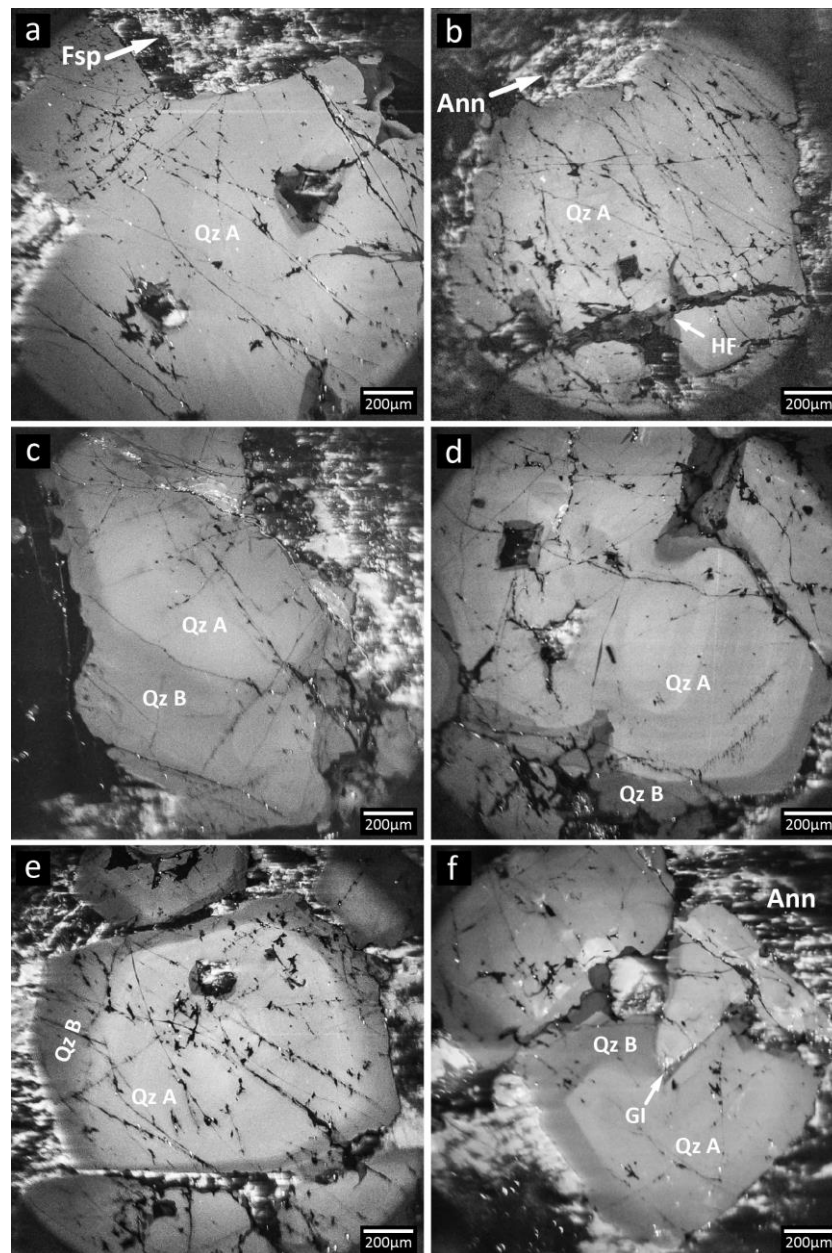


Figure 7.3. Cathodoluminescence (CL) images of quartz from the Nebo granite. (a) CL image of a large pristine and unzoned quartz grain of Nebo Qz-A generation. (b) CL image of a large quartz grain of Qz-A, with unhealed and healed fractures. (c) CL image of a slightly zoned quartz grain, showing a core of Qz-A and a darker Qz-B rim. (d) CL image of a zoned quartz grain with a core of Qz-A exhibiting oscillatory zonation, and a darker Qz-B rim. (e) CL image of a zoned quartz grain with a core of Qz-A hosting a large mineral inclusion, and darker Qz-B rim. (f) CL image of a subhedral zoned quartz grain with a core of Qz-A. The darker Qz-B rim exhibits a growth impingement caused by an adjacent mineral. Abbreviations: quartz (Qz); healed fractures (HF); growth impingement (GI); feldspar (Fsp); and annite (Ann).

Variations in the Ti content are thought to be responsible for observable difference in CL intensities in magmatic quartz (Müller et al., 2000; Müller et al., 2018). This distinct change in

luminescence (Ti content) inferred by these zonations may indicate a shift in the physiochemical conditions of the magma (Müller et al., 2000; Müller et al., 2003). Therefore, there are at least two generations of quartz described in the Nebo granite, an early light-grey core (Qz-A) and a later slightly darker-grey rim (Qz-B) (Figure 7.3c, d).

The rims of Qz-B are typically <200 µm thick and define the boundary between the quartz grain and other minerals. They grow parallel to a euhedral Qz-A core, without any growth-impingement features or visible zonation. The cores of the quartz crystals occasionally display very fine (<10 µm) concentric oscillatory zonations. The small scale oscillatory zonation in quartz is attributed to self-organisation during crystallisation (Figure 7.3d) (Müller et al., 2000). Both generations of quartz are inclusion-poor, although they host many small (<5 µm) luminescent phases along fractures. Some of the fractures are healed by a non-luminescent quartz generation (Qz-C) (Figure 7.3d, e). Although uncommon, several quartz grains display minor growth impingements, caused by the obstructive growth of an adjacent mineral (Figure 7.3f).

Bobbejaankop Granite Quartz

The medium- to coarse-grained quartz crystals (200 to 2,600 µm) from the Bobbejaankop granite are more heterogeneous than the quartz from the Nebo granite. The largest quartz grains in the Bobbejaankop granite do not show compositional zonation, although they exhibit extensive oscillatory growth (Figure 7.4a). However, the majority of the quartz crystals exhibit a similar compositional zonation to the quartz in the Nebo granite. The quartz in the Bobbejaankop granite typically hosts a light-grey (Qz-A) sub- to euhedral core with a 100 to 200 µm thick darker-grey (Qz-B) rim (Figure 7.4a, b). Both Qz-A and Qz-B generations exhibit very fine (<10 µm) oscillatory zonation, which develops parallel to the generational grain boundaries. The interior Qz-A variety has sharp edges that meet at coigns, which are somewhat rounded more often than sharp (Figure 7.4b).

The quartz from the Bobbejaankop granite does not host many large mineral inclusions, however both quartz generations are cross-cut by randomly oriented fractures. Unlike the fractures in the quartz from the Nebo granite, the fractures in the quartz from the Bobbejaankop granite are annealed by a non-luminescent variety of quartz (Qz-C). These healed fractures do not host as many luminescent phases as the quartz in the Nebo granite

(Figure 7.4). The Qz-B rims of these grains are considerably more irregular and define the final growth stage of the crystal (Figure 7.4b-d).

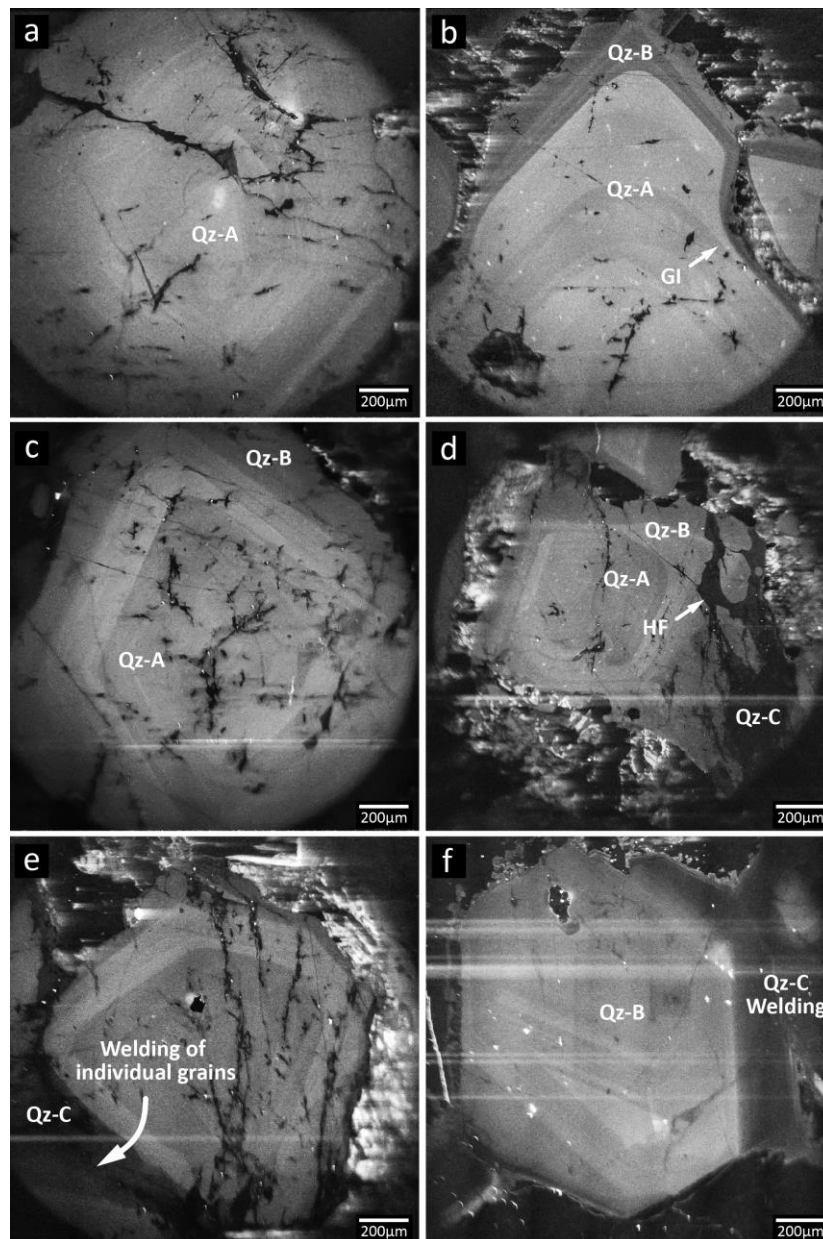


Figure 7.4. Cathodoluminescence (CL) images of quartz from the Bobbejaankop granite. (a) CL image of a large oscillatory zoned Qz-A quartz grain of the Bobbejaankop granite. (b) CL image of a coarse-grained subhedral quartz with an oscillatory zoned core of Qz-A surrounded by a darker Qz-B rim. The grain exhibits a growth impingement against an adjacent mineral. (c) CL image of a large fractured subhedral quartz with a well-developed oscillatory zoned core of Qz-A, surrounded by a darker Qz-B rim. (d) CL image of a medium-grained fractured quartz crystal exhibiting an oscillatory zoned core of Qz-A, surrounded by a darker Qz-B rim. Healed fractures are infilled by the Qz-C generation. (e) CL image of a subhedral quartz grain with well-developed oscillatory and compositional zonation. Quartz crystals are welded to adjacent quartz crystals by the Qz-C generation. (f) CL image of a subhedral oscillatory zoned Qz-B quartz welded to an adjacent grain by a Qz-C generation. Abbreviations: quartz (Qz); healed fractures (HF); and growth impingement (GI).

Many smaller (100 to 900 μm) subrounded Qz-B grains are disseminated interstitially throughout the Bobbejaankop granite. There are smaller ($<10\ \mu\text{m}$) anhedral Qz-C grains that are disseminated within the finer-grained groundmass, between the coarser-grained minerals. Adjacent quartz phenocrysts are commonly connected/welded by the non-luminescent Qz-C generation. These welded varieties of quartz form the characteristic “synneusis” textured quartz of the Bobbejaankop granite (Figure 7.4e, f) (Vonopartis et al., 2020a).

The quartz within the miarolitic cavities of the Bobbejaankop granite is more variable than the quartz in the main granitic assemblage. These miarolitic quartz crystals lack oscillatory zonation although exhibit distinct compositional zonation (Figure 7.5). These quartz grains range from 500 to 1,000 μm in diameter and occasionally exhibit double terminations. These miarolitic quartz crystals have cores of dark-grey, which correspond to the Qz-B quartz generation in the main granitic assemblage (Figure 7.4d-f). These Qz-B cores are surrounded by thin (5 to 10 μm) rims of Qz-C (Figure 7.5a). Quartz crystals, within the miarolitic cavities, that are adjacent to strongly altered mica and feldspar are usually euhedral and are outlined by a thin (5 to 10 μm) highly luminescent rim (Figure 7.5b).

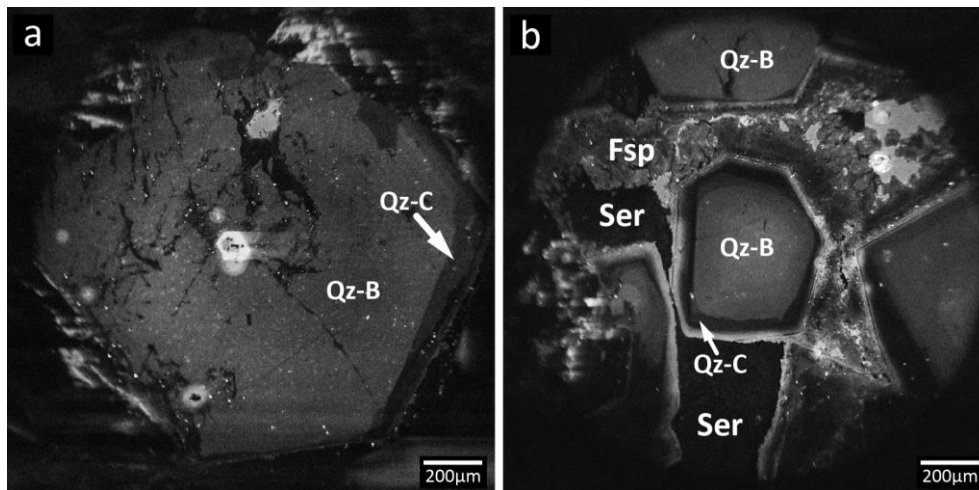


Figure 7.5. Cathodoluminescence (CL) images of euhedral quartz from miarolitic cavities in the Bobbejaankop granite. (a) CL image of a large Qz-B quartz grain with a thin Qz-C rim. (b) CL image of small quartz grains with a Qz-B core surrounded by a Qz-C zone and a bright ring of quartz. These crystals are adjacent to extensively sericitised mica and feldspars. Abbreviations: quartz (Qz); feldspar (Fsp); and sericite (Ser).

Lease Granite Quartz

The quartz from the Lease granite show the most variability from the sampled granites. These quartz crystals are typically sub- to euhedral and have the smallest grain size (100 to 1,500

µm) (Figure 7.6) (Vonopartis et al., 2020a). The larger grains contain two to three quartz generations, with a final non-luminescent quartz phase infilling the healed fractures (Figure 7.6a, b). The larger grains exhibit a moderately luminescent euhedral core (Qz-A) surrounded by a 100 to 200 µm thick, slightly more luminescent light-grey (Qz-B) zone. This second generation is enclosed by a final 100 to 300 µm thick rim of a weakly luminescent dark-grey quartz (Qz-C) phase (Figure 7.6a-d). Oscillatory zonation is common in all quartz generations in the Lease granite. The Lease quartz occasionally exhibits growth impingements, caused by neighbouring minerals and possibly the adhesion of fluid-rich melt droplets on the crystal surface (Figure 7.6d) (Müller et al., 2000).

The growth and shape of the oscillatory and compositional zonations of the Qz-A and -B generation mimic the euhedral shape of the quartz crystal. The marginal Qz-C generation terminates with a more irregular nature and results in an overall subrounded grain (Figure 7.6c-f). The majority of the quartz in the Lease granite are medium- to fine-grained (<1,000 µm) and lack a bright Qz-A core. These crystals exhibit concentric oscillatory zonation within each quartz generation. They comprise a euhedral Qz-B core and subhedral to subrounded 100 to 300 µm Qz-C rim (Figure 7.5e). The fractures within these quartz crystals are healed by a later non-luminescent generation of quartz (Qz-D). Large mineral inclusions are uncommon in the Lease quartz, although they contain many highly luminescent phases. These luminescent inclusions are concentrated primarily within the healed fractures (Figure 7.5e).

Within miarolitic cavities, quartz is usually smaller (<600 µm), sub- to euhedral having grown into the open space of the cavities. The miarolitic quartz either lacks large compositional zonation and is solely composed of Qz-B or Qz-C, or has a Qz-B core and a Qz-C rim (Figure 7.7a). These miarolitic quartz crystals terminate as euhedral grains, and are commonly welded to two or three neighbouring euhedral crystals by the non-luminescent Qz-D generation (Figure 7.7b-d). This later Qz-D generation is restricted to healed fractures in the main granitic assemblage, although it is a notable generation within miarolitic cavities. The miarolitic quartzes in the Lease granite occasionally have a euhedral Qz-B core, surrounded by a 50 to 150 µm Qz-C generation, then a later 100 to 200 µm thick non-luminescent Qz-D generation. The non-luminescent Qz-D layer is outlined by a thin highly luminescent rim (Figure 7.7b-d). This bright ring is more common in quartzes that are proximal to strongly greisenised mineralogies and adjacent to cassiterite crystals (Figure 7.7c, d).

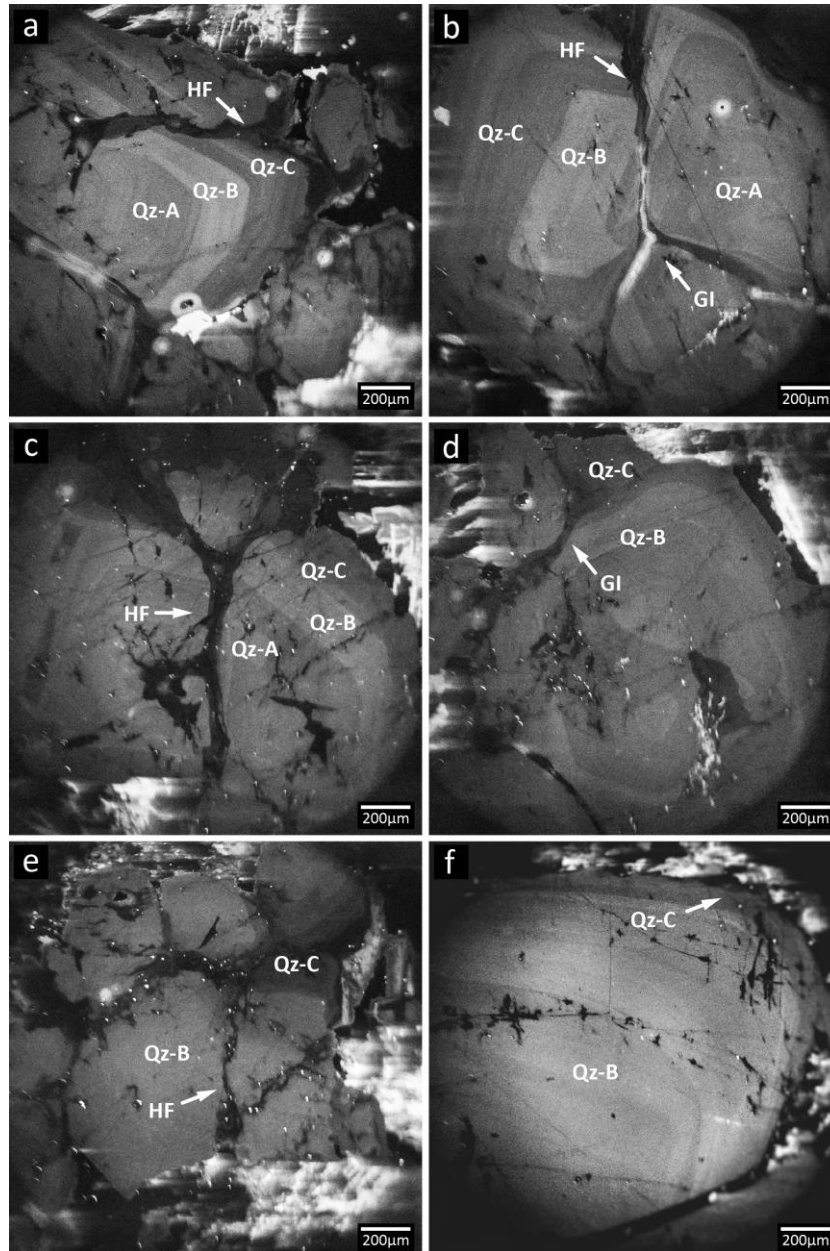


Figure 7.6. Cathodoluminescence (CL) images of quartz from the Lease granite. **(a)** CL image of a fractured coarse-grained quartz crystal, exhibiting a well-developed oscillatory Qz-A core surrounded by a Qz-B zone then a Qz-C rim and healed fractures (HF) infilled by Qz-D. **(b)** CL image of a large fractured quartz grain with a core of Qz-A then a Qz-B zone and a rim of Qz-C. Quartz crystal shows evidence of growth impingements (GI). **(c)** CL image of a large quartz grain exhibiting clear oscillatory and compositional zonation with a Qz-A core, then a Qz-B zone and Qz-C rim with healed fractures. **(d)** CL image of a quartz grain exhibiting oscillatory zoned Qz-B core, Qz-C rim and growth impingements. **(e)** CL image of a fractured quartz grain of Qz-B with sectors of Qz-C overgrowth. **(f)** CL image of a subrounded quartz grain with a large oscillatory zoned Qz-B core and thin Qz-C rim. Abbreviations: quartz (Qz); healed fractures (HF); and growth impingement (GI).

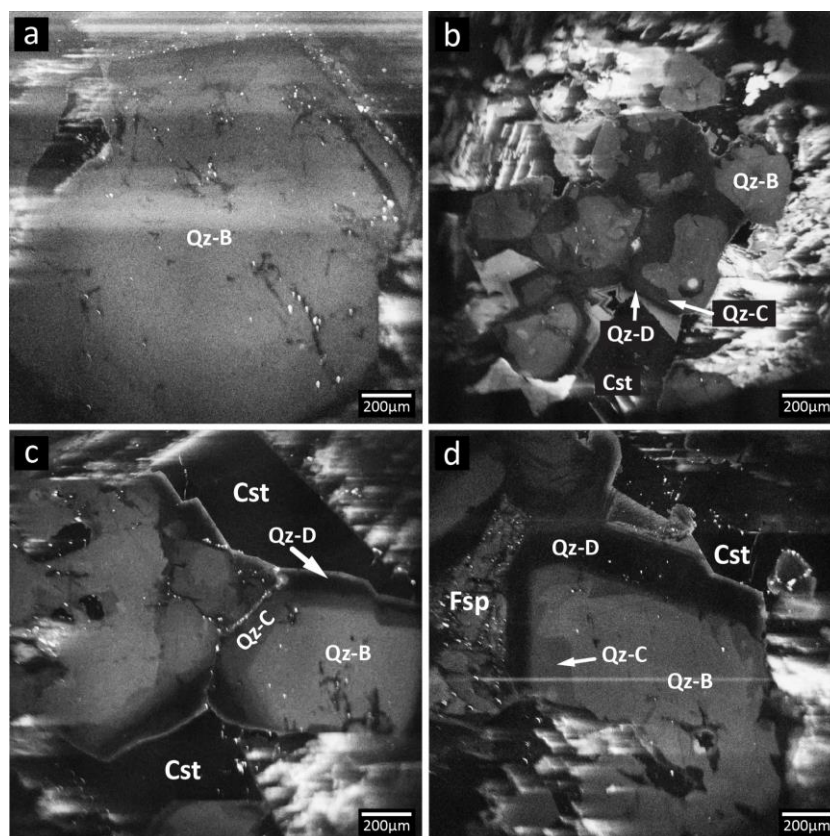


Figure 7.7. Cathodoluminescence (CL) images of miarolitic quartz from the Lease granite. (a) CL image of a homogeneous euhedral Qz-B quartz crystal. (b) CL image of several chained small Qz-B quartz crystals linked by a Qz-C generation and intergrown with euhedral cassiterite. (c) CL image of euhedral Qz-B quartz crystals surrounded by a Qz-C zone, then a Qz-D zone with a thin ring of brightly fluorescent quartz along the margin. Quartz is proximal to euhedral cassiterite. (d) CL image of a large Qz-B grain with Q-C sectors and a large Qz-D rim, lined by a bright quartz ring, adjacent to cassiterite. Abbreviations: quartz (Qz); feldspar (Fsp); and cassiterite (Cst).

Tourmaline-Quartz Hydrothermal Pipe Quartz

The quartz in the hydrothermal pipes differs considerably to the quartz from the granitic lithologies. The large grain-size (100 μm to 1 mm), euhedral and doubly terminating nature of these crystals indicate that they are distinctly hydrothermal. Some of the larger quartz crystals exhibit well defined hexagonal structures that are indicative of β -quartz. These euhedral quartz crystals have distinct sector zonation, perpendicular to the c-axis (Figure 7.8a, b). The euhedral hexagonal crystal cores are composed of a luminescent light-grey quartz (Qz-A) and lack oscillatory zonation (Figure 7.8a, b). The majority of the quartzes are medium-grained and exhibit well defined trigonal structures (Figure 7.8b, c). These trigonal crystallographic features are indicative of low-temperature α -quartz and indicate a dominantly lower temperature hydrothermal environment.

A second generation of quartz appears to have grown along the crystallographic faces of the euhedral cores. This secondary generation is differentiated into alternating luminescent Qz-A faces and less luminescent Qz-B faces (Figure 7.8c). The individual sectors within the secondary generation exhibit very-fine internal oscillatory zonations. These zonations develop parallel to the crystallographic faces of the euhedral core (Figure 7.8a, c). Most of the crystal edges are well defined, although some display a more amorphous intergrowth with the tourmaline groundmass (Figure 7.8).

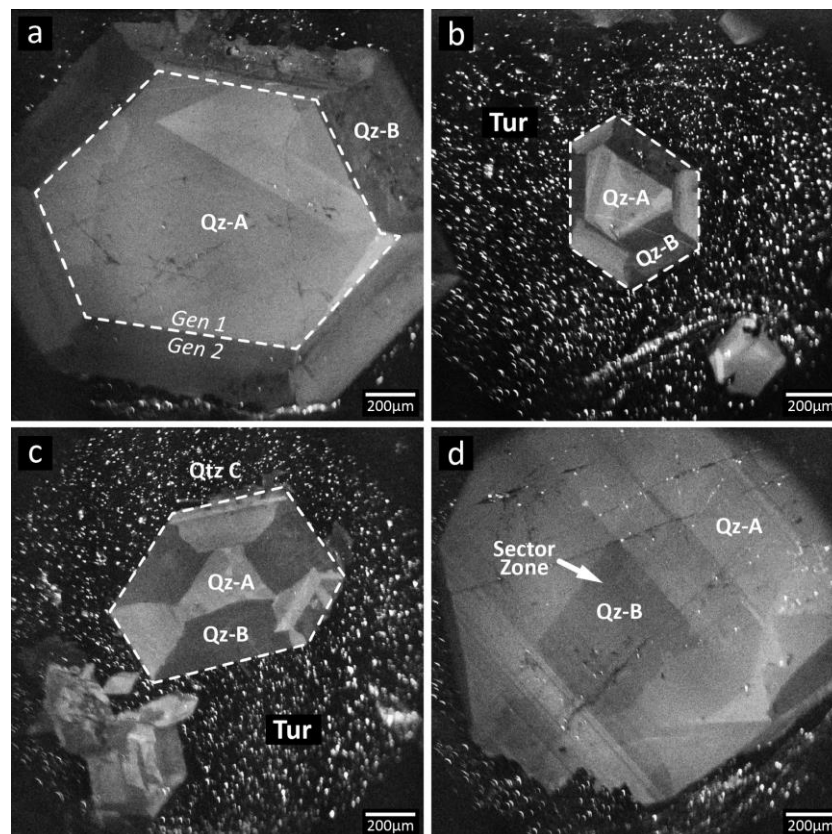


Figure 7.8. Cathodoluminescence (CL) images of quartz crystals from a tourmaline-quartz hydrothermal pipe. (a) Large hexagonal quartz crystal showing a bright Qz-A and darker Qz-B sector zonations. Quartz crystal displays two generations: generation 1 is an early hexagonal quartz core of Qz-A; and generation 2 is a rim of alternating Qz-A and Qz-B sectors. (b) Small trigonal sector-zoned quartz crystal set in a tourmaline matrix. (c) A trigonal sector-zoned quartz crystal with a deformed edge, set in a tourmaline matrix. (d) The apex of a large quartz crystal along the c-axis, exhibiting sector zonations of bright Qz-A and darker Qz-B. Abbreviations: quartz (Qz); tourmaline (Tur); and generation (Gen).

These quartz crystals from the hydrothermal pipes are heterogeneous in CL imagery and display right-angled sector zonations, when viewed parallel to the c-axis (Figure 7.8d). They are relatively pristine and inclusion-poor, although they contain highly luminescent phases along fractures and structural defects (Figure 7.8d). The quartz from the hydrothermal pipes

is set in a very fine-grained groundmass of radial tourmaline and is commonly trapped between the edges of the acicular tourmaline fans (Figure 5.6e) (Vonopartis et al., 2020a; Vonopartis et al., 2021b).

7.3.2. Trace Elements-in-Quartz

The most abundant trace element in the quartz from the granites and hydrothermal pipes is Al, which ranges from 41 to 930 ppm (Figure 7.9). The Al content of the quartz increases from the Nebo to the Bobbejaankop, Lease and then hydrothermal pipe respectively. As aluminium is the most abundant trace element in these samples and is a common structural component in quartz, it is used to discriminate the various lithologies and aid in the comparison of the other trace elements (Figure 7.9).

Light elements such as Li and B in quartz both exhibit a positive correlation with Al and generally increase from the Nebo through Bobbejaankop to the Lease granite. The quartz from the hydrothermal pipe has the highest Li and B content of the samples (Figure 7.9a, b). The Nebo quartz shows a comparable Li content to that of the Bobbejaankop quartz, whereas the Lease and Pipe quartz are considerably more Li-enriched and reach 73 and 95 ppm respectively (Figure 7.9a). The substitution of Al^{3+} for Si^{4+} in the tetrahedral site is charge balanced by a single valence cation in the interstitial lattice site, most commonly Li^+ (Figure 7.1). However, other monovalent elements, such as H^+ , Na^+ or K^+ are also incorporated during coupled substitution (Götze et al., 2004; Larsen et al., 2004; Hong et al., 2019). The Al:Li elemental ratio of 1:1 defines an ideal charge compensation for Al^{3+} by the addition of Li^+ . The magmatic quartz of the Nebo granite plots close to the ideal Al:Li ratio, while the Bobbejaankop, Lease and Pipe quartz exhibit ratios from 2:1 to >3:1 (Figure 7.10). The deviation from this ideal ratio indicates the incorporation of other single valence cations in lieu of Li^+ (Götze et al., 2004; Larsen et al., 2004; Hong et al., 2019).

The B content in the Nebo granite quartz reaches 4.1 ppm, and increases to 110 ppm in the Bobbejaankop granite quartz. The quartz in the Lease granite has the highest B content out of the sampled granites, with up to 700 ppm. The B content of the Pipe quartz is relatively indistinguishable from the Lease quartz, apart from having a more confined range from 1.84 to 11 ppm (Figure 7.9b). Analyses of quartz with anomalously high concentrations of B from the Bobbejaankop and Lease granites may be attributed to the ablation of tourmaline micro-mineral inclusions (Figure 7.9b).

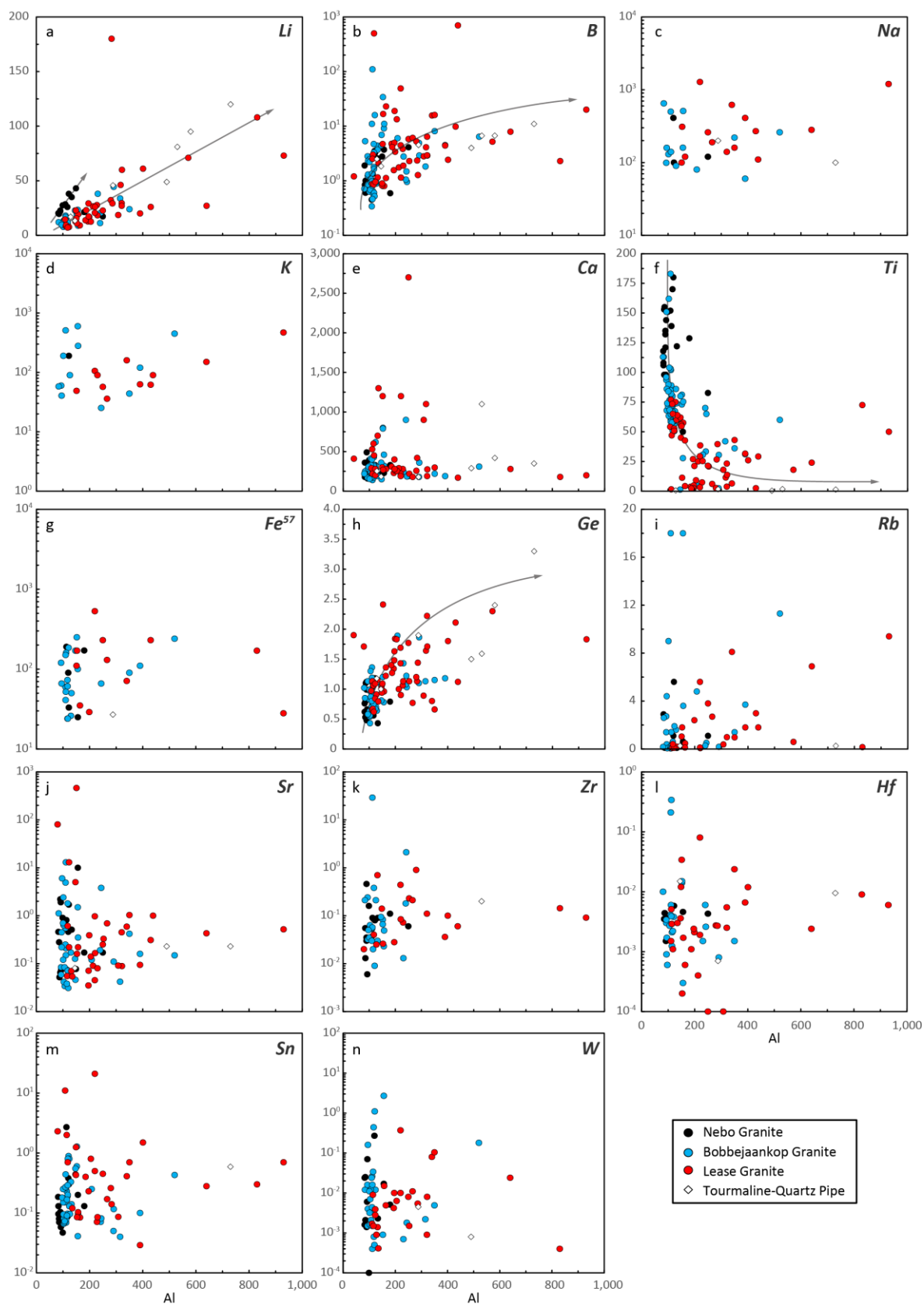


Figure 7.9. Graphs of selected trace elements-in-quartz from the Zaaipplaats tin field plotted against Al (*apfu*). (a) Li exhibits a positive correlation with Al. (b) B increases with an increase in Al content. (c) Na shows little variation with increasing Al. (d) K does not vary significantly with a change in Al. (e) Ca shows little variability, apart from several outliers from each lithology. (f) Ti exhibits a strong negative correlation with an increase in Al content, and is most apparent in the quartz from the Nebo and Bobbejaankop granites. (g) Fe does not noticeably vary with an increasing Al. (h) Ge increases with an increase in Al. (i) Rb shows a slight positive correlation with Al, although data are scattered. (j) Sr decreases with an increasing Al. (k) Zr does not vary with a change in Al. (l) Hf data are very scattered and do not show a distinct trend. (m) Sn does not vary with an increasing Al. (n) W content does not exhibit an obvious correlation with Al.

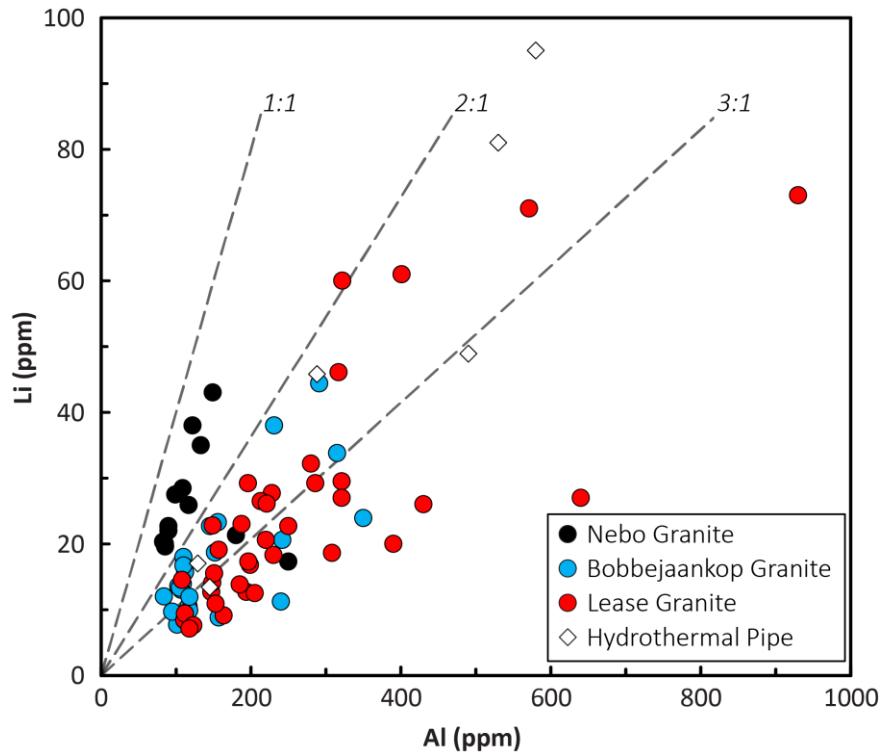


Figure 7.10. Graph of Al vs Li in quartz from the Zaaipplaats tin field. Dashed lines represent various Al:Li ratios.

There are minor variation in the Na, K and Ca content of the analysed quartz, which is generally confined below 1,000 ppm (Figure 7.9c-e), although, the Ca content of the quartz from the Lease granite does increase above 1,000 ppm in several analyses (Figure 7.9e). This is attributed to the ablation of mineral/fluid inclusions, or the edges of underlying or adjacent minerals during the analysis of the target quartz grain. The Nebo quartz has the highest Ti and lowest Al content of the quartz populations. Despite a slight discontinuity of the data, there is a visible Ti depletion and Al enrichment from the Nebo to Bobbejaankop and Lease quartz, along the “magmatic” quartz trend (Figure 7.9f) (Müller et al., 2018; Hong et al., 2019). However, some of the Bobbejaankop, Lease and all of the pipe quartz are notably Ti-deficient (Figure 7.9f).

The ^{57}Fe composition of the quartzes ranges from below detection to 530 ppm (Figure 7.9g). Despite the limited set of ^{57}Fe data points, there is a visible increase from the cluster of Nebo and Bobbejaankop quartz compositions, to a slightly more ferrous quartz in the Lease granite (Figure 7.9g). Germanium, together with Al and Ti, are central components in the cationic substitution of quartz, and allude to an increasing hydrothermal contribution (Götze et al., 2004; Larsen et al., 2004; Jacamon and Larsen, 2009; Muller and Koch-Muller, 2009; Breiter et al., 2014). The substitution of Ge in quartz is principally controlled by its presence in the crystallising environment. At lower temperatures and in increasingly hydrothermal conditions, Ge^{4+} will be preferentially incorporated into quartz substituting for Si^{4+} (Figure 7.1) (Götze et al., 2004; Larsen et al., 2004; Jacamon and Larsen, 2009; Muller and Koch-Muller, 2009; Breiter et al., 2014). The quartz from the Nebo granite is Ge-poor and compositionally overlaps many of the Bobbejaankop and Lease quartz compositions. However, the quartz from the Bobbejaankop and Lease granites become significantly more Ge-rich, reaching 2.4 ppm in the latter (Figure 7.9h). The quartz from the Nebo, Bobbejaankop and Lease granites, show a proportional increase in Ge with an increasing Al content, whereas the highest Ge content is exhibited by the quartz from the hydrothermal pipe (Figure 7.9h).

The contents of other trace elements such as Rb, Sr, Zr, Hf, Sn and W are extremely variable. This is due to these elements being hosted within mineral and fluid inclusions (Figure 7.9i-n). In spite of this, some of these elements show an increase from the Nebo through Bobbejaankop and Lease granites to hydrothermal pipe quartz. The Rb compositions of the quartz are scattered, and range from below detection to 18 ppm (Figure 7.9i). However, the Bobbejaankop and Lease granites are more Rb-rich than the Nebo quartz. The Sr, Zr and Hf compositions of the quartz from these lithologies display a relatively poor separation between the different granite facies, are scattered and have a wide compositional range. Therefore, they cannot be confidently used in the interpretation of this system, however some consistencies are apparent. At low Al contents (<175 ppm) the Nebo and Bobbejaankop quartz share similar compositional ranges and values of Sr, Zr and Hf, whereas at higher Al contents, the Lease and Pipe quartz become significantly more variable (Figure 7.9j-l).

The Sn content of the quartz displays an increase, from the Nebo (0.2 ppm) through the Bobbejaankop (0.3 ppm) and Lease (1.4 ppm) granites. Few analyses of the quartz from the hydrothermal pipe returned detectable values of Sn, with the highest value reaching 0.6 ppm.

The increase in average Sn content, from the quartz in Nebo and Bobbejaankop to the Lease granite, resembles the enrichment of Sn exhibited by the whole-rock compositions from the various granites (Figures 7.9m and 7.11) (Vonopartis et al., 2020a). The W content of the quartz from these lithologies is low and no obvious trends are apparent with respect to an increasing Al content (Figure 7.9n). However, the quartz from the Bobbejaankop and Nebo granites are the most W-rich granitic lithologies, whereas the quartz from the hydrothermal pipes are W-poor (Figure 7.9n).

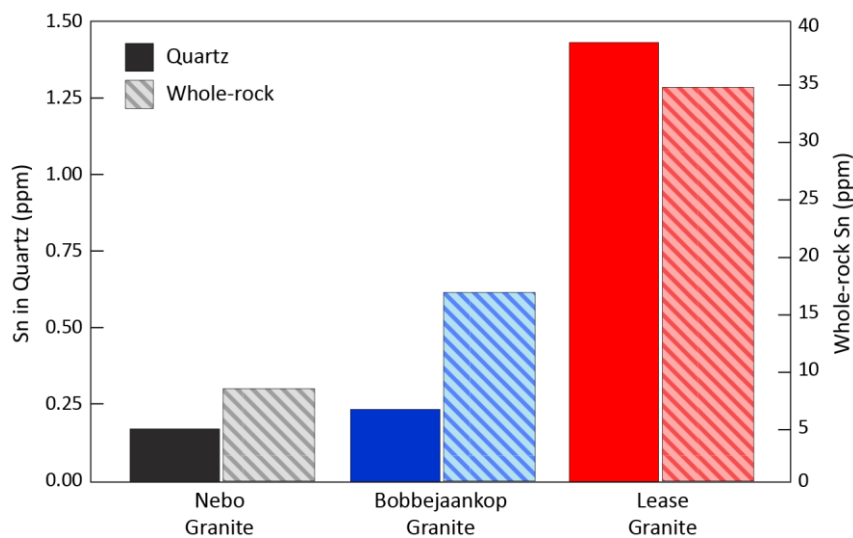


Figure 7.11. Graph showing the average Sn content of the quartz compared to the average Sn content from the whole-rock composition of the Zaaipiaats tin field granites. Whole-rock Sn compositions after Vonopartis et al. (2020a). Solid bars represent Sn-in-quartz. Striped bars represent whole-rock Sn.

7.3.3. Quartz Zonation

Multiple ablation traverses across large quartz crystals from granites and the hydrothermal pipe reveal trace elemental variations with respect to zonation. The core of the quartz grain is denoted “*point 1*” with the subsequent ablation sites sequentially numbered towards the rim (Figure 7.12). Large visible defects and inclusions were avoided wherever possible, however due to the diameter and depth of ablation this was not completely successful. These traverses analysed an identical suite of elements, to the rest of the ablations. The elements Al, Ti and Ge were selected due to their abundance and structural substitution with Si^{4+} . The comparison of these elements is used to describe the evolution of the quartz crystals. In addition, Sn was included in order to reveal any correlation with potential cassiterite mineralisation.

Nebo Quartz Zonation

The majority of the magmatic quartz grains from the Nebo granite do not show significant zonation and are relatively pristine, although, some quartz from the Nebo granite has a fluorescent quartz core (Qz-A) and a slightly less fluorescence quartz rim (Qz-B) (Figure 7.12a). A grain from the latter population was selected for the traverse. The Al content of the quartz grain decreases slightly, from 93 at *point 1* in the core to 87 ppm at *point 3* in the rim, although increases to 117 ppm at *point 2* (Figure 7.12a). Similarly, the Ti content of the Nebo quartz decreases from 144 ppm at *point 1* to 98 ppm at *point 3*, with a slight increase at *point 2* to 170 ppm. The variations in Ti reflect the fluctuations in Al content at each point in the quartz from the Nebo granite (Figure 7.12a).

The Ge content is considerably lower, and increases from below detection at *point 1*, to 0.56 at *point 2* then 0.79 ppm at *point 3* (Figure 7.12a). This increase in Ge at *points 2* and *3*, corresponds to the observable decrease of Al and Ti towards the rim of the Nebo quartz. This Ge-enrichment alludes to the cationic substitution of these structural components (Figure 7.12a). The Sn content of the quartz in the Nebo granite ranges from 0.07 to 0.08 ppm and is likely to be hosted in fluid inclusions (Figure 7.12a) (Götze, 2009; Hong, 2017). The quartz grains from the Nebo granite are relatively homogeneous. They display a slight increase in Ge and decrease in Ti content between the Qz-A and Qz-B generations (Figure 7.12a).

Bobbejaankop Quartz Zonation

The first three points from the Bobbejaankop granite quartz reflect the composition of *points 1, 2* and *3* of the Nebo quartz, whereas *point 4* from the Bobbejaankop quartz is distinct (Figure 7.12b). The first three points on the quartz in the Bobbejaankop granite are situated within the Qz-A generation, while *point 4* was positioned in the Qz-B generation (Figure 7.12b). The Al content of the Bobbejaankop Qz-A generation slightly decreases from 94 ppm at *point 1* to 81 ppm at *point 3*, with a marginal increase to 109 ppm at *point 2* (Figure 7.12b). The Ti content of the quartz mimics the variations in Al content, decreasing from 151 ppm at *point 1* to 113 ppm at *point 3*, and peaking to 183 ppm at *point 2* (Figure 7.12b).

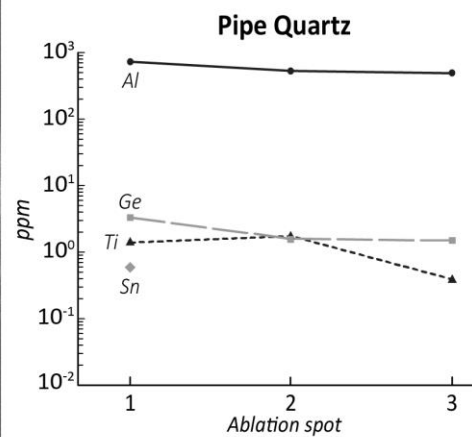
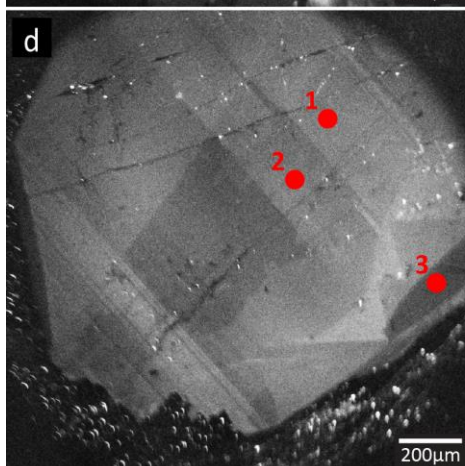
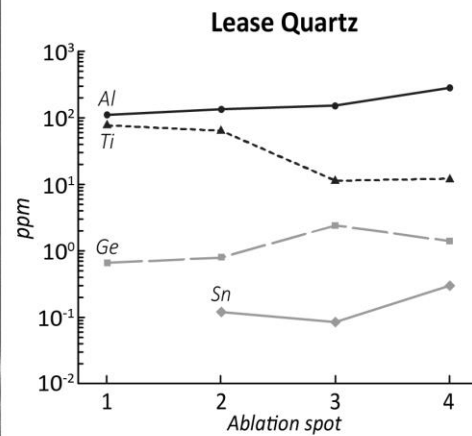
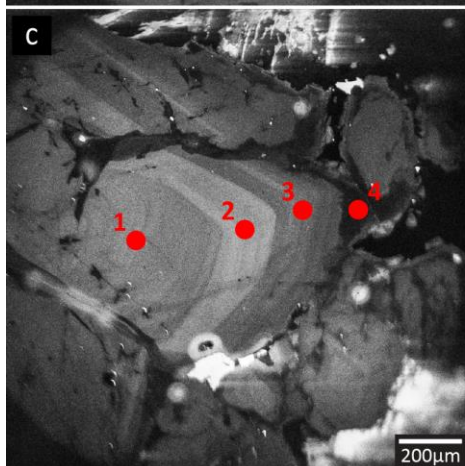
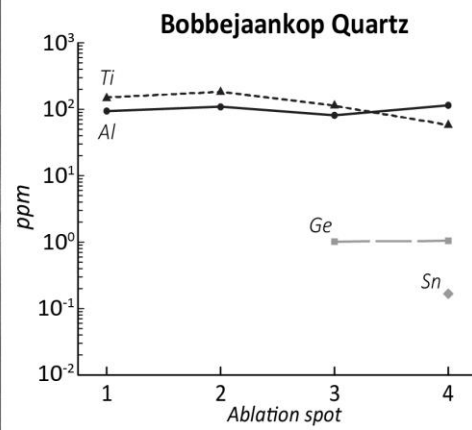
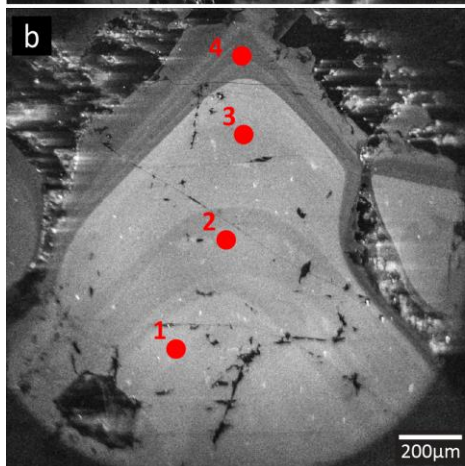
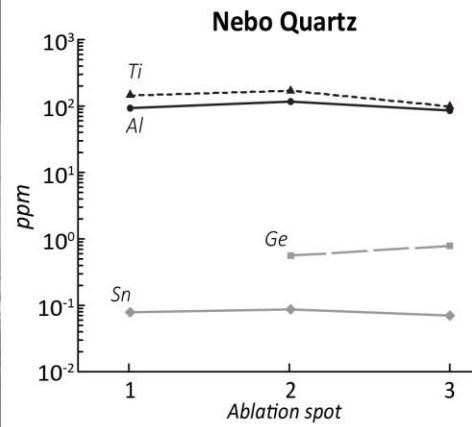
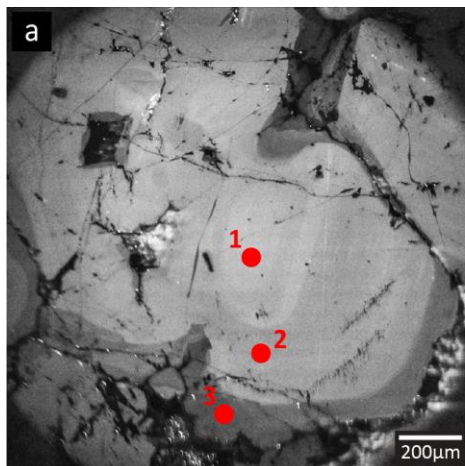


Figure 7.12. Diagrams illustrating the various ablation traverses and compositions from the Zaaiplaats tin field quartz grains. The structurally incorporated elements Ti, Al, and Ge were used for comparison. The element Sn was included as it is of economic significance in this system. CL image with ablation spots and corresponding trace element compositions of the: (a) Nebo granite quartz; (b) Bobbejaankop granite quartz; (c) Lease granite quartz; and (d) Pipe quartz. Ablation spots are numbered sequentially from the core to the rim and are represented by red circles. Trace element values that are below detection for Ge and Sn are not shown on the line graphs.

The presence of Ge in the Bobbejaankop quartz is only above the limit of detection at *points 3 and 4*, which increase from 1.02 to 1.05 ppm respectively (Figure 7.12b). Despite the early absence of Ge in Bobbejaankop quartz, the measurable Ge content is significantly higher than the Ge in the Nebo quartz. The increasing Ge content at *point 3* shows an apparent correlation with a decrease in Al and Ti content (Figure 7.12b). Tin is below detection through *points 1 to 3*, and reaches 0.17 ppm at *point 4*. The interior (*point 1 to 3*) of the Bobbejaankop quartz is compositionally similar to the magmatic quartz of the Nebo granite. However, unlike the Nebo quartz, the Qz-B generation in the Bobbejaankop quartz (*point 4*) is compositionally different to the Qz-A core. The Qz-B generation in the Bobbejaankop granite is Al-, Ge- and Sn-enriched, Ti-depleted and has a muted CL luminescence compared to the interior (Qz-A) of the quartz crystal (Figures 7.4 and 7.12b).

The Ti content is consistently greater than the Al content in the Nebo quartz and through *points 1 to 3* of the Bobbejaankop quartz (Figure 7.12a, b). However, along the rim of the Bobbejaankop quartz crystal, at *point 4*, the Al content increases to 115 ppm and the Ti content decreases to 58 ppm. This resulted in an inversion of the previous Al–Ti relationship previously described (Figure 7.12b). This compositional shift is accompanied by a marked decrease in CL fluorescence of the Bobbejaankop Qz-B generation and is attributed to the decreased Ti content of the quartz (Figure 7.12b) (Müller et al., 2000; Müller et al., 2018).

The quartz from the Bobbejaankop granite is separated into two geochemically distinct generations: 1) a core of Qz-A (*points 1 to 3*) that has a greater Ti than Al content, is Ge-poor and has a high CL luminescence; and 2) a rim of Qz-B (*point 4*) that has a greater Al than Ti content, a low CL luminescence and measurable Ge and Sn compositions.

Lease Quartz Zonation

The quartz from the Lease granite is different from the quartz in both of the Nebo and Bobbejaankop granites. However, there appears to be a continuation of the compositional evolution displayed in the Bobbejaankop quartz. The Al content is higher than the Ti content

of the Lease quartz, similar to the marginal Qz-B generation of the Bobbejaankop quartz (Figure 7.12c). There is a steady increase in Al from 111 ppm at *point 1* (Qz-A), 135 ppm at *point 2* (Qz-B), 153 ppm at *point 3* (Qz-C) and then 282 ppm at *point 4* (Qz-D) (Figure 7.12c). The decrease in Ti is partially correlated with an increase in Al, as Ti decreases from 77 ppm at *point 1* to 64 ppm at *point 2*. However, the quartz from the Lease granite displays a distinct depletion of Ti between points 2 and 3, which drops from 64 to 11 ppm, before slightly increasing to 12 ppm at *point 4* (Figure 7.12c). This depletion is not reflected by an Al enrichment, yet is still associated with a notable decrease in CL luminescence of the Lease Qz-C generation (Figure 7.12c).

The variations in Ti show an almost perfect inverse correlation with the Ge content of the Lease quartz. The Ge content increases from 0.66 ppm at *point 1* to 0.80 ppm at *point 2*. Then there is a sharp increase in Ge to 2.41 ppm at *point 3* before decreasing to 1.41 ppm at *point 4* (Figure 7.12c). Therefore, there is a greater cationic substitution relationship between Ti and Ge rather than Ti and Al in the later (Qz-B to Qz-D) generations of Lease quartz.

The Sn in the Lease quartz displays an average increase from core to rim, and is higher than the Sn in the Nebo and Bobbejaankop quartz (Figure 7.12c). At *point 1* (Qz-A), Sn is below the detection limit, although it reaches 0.12 ppm at *point 2* (Qz-B). The Sn content then decreases to 0.09 at *point 3* (Qz-C), before increasing to 0.3 ppm at *point 4* (Qz-D) (Figure 7.12c). There appears to be a minor inverse correlation of Sn with Ge at various points. The Sn content appears to increase at the expense of Ge, regardless of the relative abundance of Ti at the same point (Figure 7.12c). However, this cannot be a feature of substitution, as Sn is not incorporated into the silica tetrahedral site (Götze, 2009). Therefore, the variations between Sn and Ge reflect the fluctuating composition of the crystallisation environment.

The quartz from the Lease granite is more heterogeneous than the Nebo and Bobbejaankop samples. The Lease quartz can be separated into two geochemically different generations: 1) a core (*points 1* and *2*) of Qz-A and Qz-B with a moderate CL, and are similar to the late quartz generation of the Bobbejaankop granite; and 2) a rim of low to non-luminescent Qz-C and -D (*points 3* and *4*), which displays an Al, Ge and Sn enrichment and Ti depletion relative to the core (Figure 7.12c).

Tourmaline-Quartz Pipe Quartz Zonation

The quartz from the hydrothermal pipe is not petrographically or geochemically similar to the quartz from the granites. A notable distinction is the lack of visible concentric zonation in the quartz from the hydrothermal pipe. Thus, the largest crystal was selected for the traverse, targeting CL distinct sectors. The traverse revealed little internal variation however, the composition of the quartz is markedly different from the quartz in the granites (Figure 7.12d). The quartz from the pipe has the highest Al content of all the different quartzes from the different granites, ranging from 490 to 730 ppm. The large quartz crystal is homogeneous and does not show significant variations between the different CL sectors (Figure 7.12d). Titanium shows the most variation and is significantly depleted compared to the quartz from the granitic lithologies. The Ti content decreases from 1.4 ppm at *point 1* to 0.39 ppm at *point 3*, although *point 2* is slightly more enriched and reaches 1.74 ppm (Figure 7.12d).

The quartz from the hydrothermal pipe has the highest Ge content of the samples and slightly decreases from 3.30 to 1.59 then 1.50 ppm from points 1, 2 and 3 respectively (Figure 7.12d). There is a corresponding decrease of both Ge and Ti in the Pipe quartz, whereas Ge and Ti are usually inversely related in magmatic quartz (Götze et al., 2004; Larsen et al., 2004; Jacamon and Larsen, 2009; Muller and Koch-Muller, 2009; Breiter et al., 2014; Müller et al., 2018). There is a relative scarcity of measurable Sn in the Pipe quartz. The Sn content at *points* 2 and 3 are below detection, whereas Sn at *point 1* is 0.59 ppm. Despite the limited Sn data, the Sn content at *point 1* is higher than any value in the granitic quartz (Figure 7.12d). The Pipe quartz is the most homogeneous variety and exhibits minor geochemical variations between CL sectors. However, where measurable, the high Sn content of the quartz in the hydrothermal pipes indicates a high Sn content of the inclusions and therefore, the associated hydrothermal fluids.

7.4. Discussion

7.4.1. Quartz Trace Element Mineral Chemistry

Contamination by Fluid and Mineral Inclusions

The quartz crystals from the Zaaiplaats tin granites, particularly the Lease granite quartz, contain many inclusions. Due to the diameter of the beam and depth of the ablation process, inclusions were unavoidably analysed. Thus, various trace elements that are not structurally incorporated were analysed (Figure 7.2).

The majority of these elements are uncorrelated, thus they are likely to be hosted within mineral and fluid inclusions. Elements such as Fe, Nb, Ta, Y, Zr, Hf, Sn and W would have been sourced from both trapped saline fluids and mineral inclusions such as zircon, Sn-, W- and Fe-oxides (Figure 7.2) (Götze, 2009; Hong, 2017). The trace elements sourced from inclusions in the quartz are used to infer the composition of the coexisting minerals and magmatic/hydrothermal environment. However, these elements are considered to have large degrees of uncertainty, and any inferences based on these elements are made with caution.

Many of the measured trace elements such as Na, K, Ca, Rb, Sr, Zr, Hf, Sn and W are not present in all quartz analyses from a single lithology. Furthermore, most of these elements do not exhibit a linear correlation with Al, and are therefore not charge compensators for Al^{3+} substitution (Figure 7.9) (Götze et al., 2004; Götze, 2009). However, K and to a lesser extent Rb, do display a slight positive correlation with Al, in the quartz from the Lease and Bobbejaankop granites (Figure 7.9d). This indicates that minor amounts of K and Rb act as charge compensator for Al^{3+} , which accounts for the deviation from the ideal Al:Li ratio in the quartz from the Bobbejaankop and Lease granites. The remaining elements that were analysed but not displayed in Figure 7.9 were uninformative, and are provided in Appendix G.

Trace Element Substitution and Evolution

Cations that readily substitute for Si^{4+} in the quartz tetrahedra such as Al, Ti, Li and Ge (Götze et al., 2004; Götze, 2009; Muller and Koch-Muller, 2009), are relatively abundant and commonly correlated with each other. For instance, Li and Ge are positively correlated with Al, whereas Ti is negatively correlated with Al (Figure 7.9). The positive correlation of Al and Li is apparent across all lithologies, although the Nebo quartz exhibits a slightly different Al:Li ratio to that of the Bobbejaankop and Lease quartzes (Figure 7.10).

The linear correlation of Al^{3+} and Li^{+} can be explained by the coupled cationic substitution of $\text{Si}^{4+} \leftrightarrow \text{Al}^{3+} + \text{Li}^{+}$ (Figure 7.1a). This is required to charge-compensate Al^{3+} defects, by the incorporation of Li^{+} in the interstitial lattice site (Figure 7.1a) (Götze et al., 2001; Götze, 2009; Müller et al., 2018; Hong et al., 2019). The quartz from the Nebo granite closely aligns with the Al:Li ratio of 1:1 (Figure 7.10), indicating that the majority of the Al^{3+} charge deficit is compensated by Li^{+} (Götze et al., 2001; Götze, 2009; Müller et al., 2018; Hong et al., 2019). In

contrast, the Bobbejaankop, Lease and Pipe quartz cluster between the Al:Li ratio of 2:1 and 3:1 (Figure 7.10). This is due to the substitution of Si^{4+} by Ge, Ti, B or Fe and charge compensation being achieved with alternative trace elements such as H^+ , Rb^+ , Na^+ or K^+ as previously described (Götze et al., 2001; Götze et al., 2004; Götze, 2009; Muller and Koch-Muller, 2009; Müller et al., 2018; Hong et al., 2019).

The diadochy of Ti^{4+} substituting for Si^{4+} in the quartz lattice provides insight into both the evolution and temperature of the crystallising quartz crystal (Götze et al., 2004; Larsen et al., 2004; Muller and Koch-Muller, 2009; Breiter et al., 2014). As the structural incorporation of Ti decreases with decreasing temperature, the Ti content of quartz is a useful geothermometer and indication of quartz evolution. Higher-temperature and more magmatic quartz has a greater Ti content than the lower-temperature, evolved and hydrothermal quartz (Götze et al., 2004; Larsen et al., 2004; Muller and Koch-Muller, 2009; Breiter et al., 2014). This evolutionary trend of decreasing Ti is complemented by a relative increase in Al content with quartz evolution (Götze et al., 2004; Larsen et al., 2004; Hong et al., 2019). This is demonstrated by the quartz of the Zaaipplaats tin granites and hydrothermal pipe. The Ti content of the quartz steadily decreases from the Nebo to Bobbejaankop and then Lease granite, while Ti is mostly below detection in the quartz from the hydrothermal pipe. This apparent depletion of Ti is inversely correlated with the increase of Al. This inverse correlation indicates a gradual decrease in temperature and increase in the degree of granitic fractionation towards the hydrothermal pipes.

The relationship between the three primary, structurally incorporated, cations in quartz is demonstrated using the Al–Ti–Ge ternary diagram, proposed by Schrön et al. (1988) (Figure 7.13). Breiter et al. (2014) used the Al–Ti–Ge ternary diagram to compare quartz compositions from various I-, S- and A-Type granites and pegmatites. They showed that magmatic quartz evolves from Ti- to Al-rich compositions, while pegmatitic quartz evolves from a Ti- to a Ge-rich composition. However, both quartz evolutionary trends exhibit a depletion in Ti, as they evolve from magmatic to hydrothermal quartz (Götze et al., 2004; Götze, 2009; Larsen et al., 2009; Muller and Koch-Muller, 2009; Breiter et al., 2014; Müller et al., 2018).

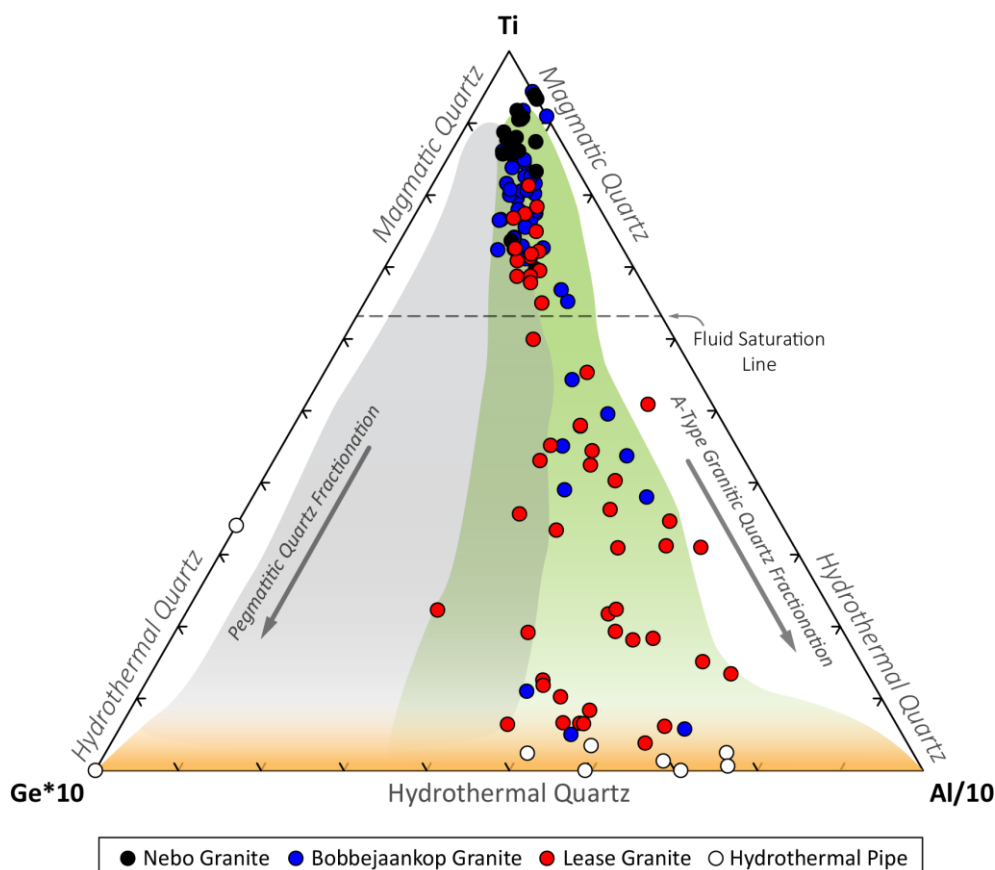


Figure 7.13. Ternary diagram of Al–Ti–Ge comparing the composition of the quartz from different granite facies in the Zaaipplaats tin field. The grey field represents the evolution of pegmatitic quartz, green field represents fractionation of A-Type granitic quartz and orange field defines hydrothermal quartz. Diagram and fields defined and modified after Breiter et al. (2014). Dashed line indicates inferred point of fluid saturation during granitic crystallisation.

The quartz from the Zaaipplaats tin granites and hydrothermal pipe follow the compositional evolution of A-Type granitic quartz (Figure 7.13). The Nebo quartz clusters towards the Ti apex of the ternary diagram (magmatic quartz) and is slightly offset towards a higher Al (Figure 7.13). The Nebo quartz compositions display a slight decrease in Ti, and slight increase in Al and Ge content. Some quartz compositions from the Bobbejaankop granite overlap the quartz from the Nebo granite (magmatic quartz), although have a greater Ti-depletion and a marginally higher Al content. Many of the Bobbejaankop quartz compositions evolve along the A-Type granite fractionation trend, steadily decreasing in Ti and increasing in Al, becoming significantly more magmatic-hydrothermal in nature (Figure 7.13).

The Lease quartz displays a greater range in composition. The Lease data is clustered at the lower Ti compositional extent of the Bobbejaankop quartz array, with a slightly higher Al content, within the magmatic sector of the ternary diagram (Figure 7.13). However, almost half of the Lease quartz plots along the A-Type granite fractionation field, towards the

hydrothermal section of the ternary diagram (magmatic-hydrothermal quartz). The quartz from the Lease granite becomes increasingly Ti-depleted and appreciably more Al- and Ge-rich than the Nebo and Bobbejaankop quartz (Figure 7.13). In contrast, the Pipe quartz is remarkably Ti-poor and plots strictly along the base of the ternary diagram (hydrothermal quartz) (Figure 7.13).

There is a distinct compositional gap on Figure 7.13, between 60 and 65 % Ti, which is interpreted to be the point of fluid saturation within these granites. The quartz compositions of the Nebo, Bobbejaankop and Lease granites above this fluid saturation line form a well constrained array. These compositions represent the magmatic evolution of the quartz towards a more magmatic-hydrothermal regime, primarily controlled by granitic fractionation. The quartz compositions of the Bobbejaankop and Lease granites below this fluid saturation line become considerably more scattered, and increasingly Ti-deficient. These compositions represent the magmatic-hydrothermal evolution of the quartz after fluid-saturation. The quartz from the hydrothermal pipes plot below 5% Ti and are considered to represent a low-temperature hydrothermal system.

This data array demonstrates that the quartz from the Nebo and the initial quartz from the Bobbejaankop and to a lesser extent in the Lease granites were magmatic. Thereafter, some of the quartz from the Bobbejaankop granite and most of the quartz in the Lease granite are magmatic-hydrothermal and precipitated in a fluid saturated environment. Therefore, Figure 7.13 provides a visual representation of the magmatic to magmatic-hydrothermal transition in an evolving granite suite, recorded by the trace elemental variations in quartz.

The use of Al, Ti and Ge and their ratios (Al/Ti and Ge/Ti) in quartz, are shown to be excellent proxies for the degree of silicate melt fractionation. These elemental ratios have been successfully utilised in understanding the petrogenetic evolution of both magmatic and pegmatitic environments (Larsen et al., 2004; Müller et al., 2010; Müller et al., 2018; Hong et al., 2019). Wark and Watson (2006) revealed the correlation between Ti and temperature in quartz, stating that Ti^{4+} – Si^{4+} cationic substitution in quartz is more compatible during the early high-temperature magmatic stages of crystallisation. In contrast, with decreasing temperature Al becomes preferentially incorporated, in lieu of Ti (Larsen et al., 2004; Wark and Watson, 2006; Müller et al., 2010; Müller et al., 2018; Hong et al., 2019). Similarly, Larsen et al. (2004) discusses the application of Ge/Ti as an additional evolutionary proxy for quartz

evolution, and this parameter is used in numerous quartz trace elemental investigations (Larsen et al., 2004; Jacamon and Larsen, 2009; Müller et al., 2010; Breiter et al., 2014; Müller et al., 2018; Hong et al., 2019). Therefore, the evolution of a granitoid corresponds to an increase in the Ge/Ti ratio of its quartz (Larsen et al., 2004; Jacamon and Larsen, 2009; Müller et al., 2010; Breiter et al., 2014; Müller et al., 2018; Hong et al., 2019). This ratio is thought to be robust, as both elements involve simple substitution for the same crystallographic site, and are immobile during sub-solidus processes (Larsen et al., 2004).

The graph of Ge/Ti vs Al/Ti ratios in quartz illustrates the evolution of the Zaaipiaats tin field granites. The plot in Figure 7.14 displays an increase in the Al/Ti and Ge/Ti ratios in quartz from the Nebo to the Bobbejaankop, the Lease and then Pipe quartz respectively. The well constrained array, large degree of overlap and sequentially plotting lithologies infers a fractionating system along a single liquid-line-of-descent. However, as discussed in Figure 7.13, there is a similar discontinuity in the geochemical evolution of the quartz compositions. Therefore, the graph of Ge/Ti vs Al/Ti, indicates the fractionation-controlled evolution and the point of fluid saturation in these granites (Figure 7.14).

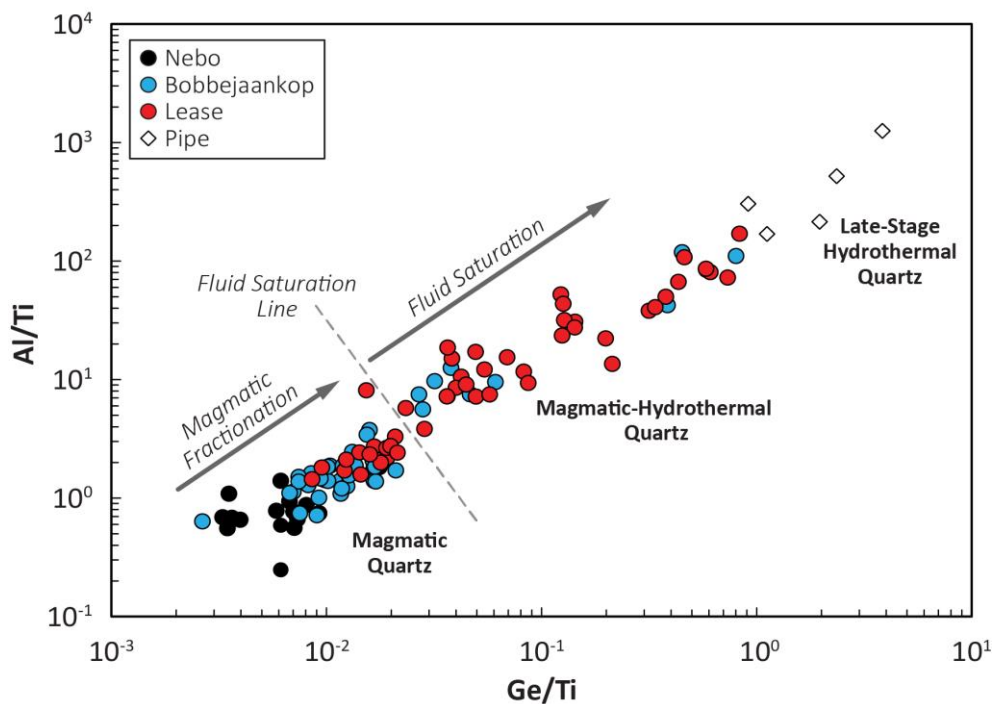


Figure 7.14. Ge/Ti vs Al/Ti graph of the quartz from the Zaaipiaats tin field highlighting the magmatic to magmatic-hydrothermal evolution of the quartz. Dashed line indicates inferred point of fluid saturation.

The quartz from the Nebo granite, together with some Bobbejaankop quartz and lesser Lease quartz plot within the magmatic fractionation portion on the Ge/Ti vs Al/Ti diagram (Figure 7.14). These early quartzes are considered to be magmatic. Some of the Bobbejaankop quartz and most of the Lease quartz plot after the inferred point of fluid saturation, and thus represent magmatic-hydrothermal quartz, whereas the quartz from the hydrothermal pipe is distinct. The Pipe quartz plot at the end of the array and are inferred to represent distinct late-stage magmatic-hydrothermal quartz. Therefore, this array is interpreted to represent the increasing concentration of magmatic-hydrothermal fluids through granitic fractionation, resulting in fluid saturation and accumulation towards the granite cupola. The evolution of the Zaaiplaats tin granites, inferred from Figures 7.13 and 7.14, corresponds with the proposed model by Vonopartis et al. (2020a).

Due to the range and abundance of Al and Ti in these quartz samples, the Al/Ti ratio is used as a discriminant, against which variations in trace elements in the different granite facies are compared (Figure 7.15). Incompatible elements in magmas, such as B^{3+} , Li^+ and Be^{2+} are incorporated into the silica structure by coupled substitution (Larsen et al., 2004; Breiter and Müller, 2009; Jacamon and Larsen, 2009). Due to the abundance of tourmaline in the Bobbejaankop and Lease granites, B is a likely component in the hydrothermal system (Vonopartis et al., 2020a; Vonopartis et al., 2021b). The B content of the Nebo quartz is relatively low, between 0.45 and 4.7 ppm and is comparable to quartz from non-tourmaline-bearing pegmatites (Breiter and Müller, 2009). The average B content in the quartz increases from the Bobbejaankop granite to the Lease granite (Figure 7.15a), and is similar to other quartz from tourmaline-bearing granitic systems (Müller et al., 2018; Hong et al., 2019). Despite the extensive tourmalinisation in the hydrothermal pipes (Vonopartis et al., 2020a; Vonopartis et al., 2021b), the B content from the Pipe quartz is similar to the Lease quartz. The lower than expected B content in the quartz from the pipes may be attributed to the depletion of B by the preferential sequestration of B during tourmaline crystallisation.

Despite the incompatible nature of Li, it does not show a simple, linear increase from the Nebo to Bobbejaankop then Lease granites and the Pipe quartzes. On average, the quartz from the Nebo granite has a higher Li content than the quartz from the Bobbejaankop facies, ranging from 14.1 to 450 ppm. This emphasises that the cationic substitution, $Si^{4+} \leftrightarrow Al^{3+} + Li^+$, to be the dominant substitution in the quartz of the Nebo granite. This Al:Li ratio of 1:1

indicates a greater incorporation of Li into the Nebo quartz than that in the Bobbejaankop quartz. The lower Al:Li ratio of the latter is therefore due to the substitution of Si by other elements and being charge balanced by different cations. The 1:1 ratio is thought to be a characteristic of magmatic quartz (Müller et al., 2018; Hong et al., 2019) and corresponds with the known magmatic nature of the Nebo granite and the magmatic characterisation of the quartz in Figures 7.13 and 7.14.

The Li content of the quartz from the Lease granite and hydrothermal pipe range from 7.1 to 1,300 ppm and 17 to 120 ppm respectively. These quartz compositions form a secondary array that increases from the average Li composition of the Bobbejaankop quartz (Figures 7.11 and 7.15b). This implies the evolution of the Lease and Pipe quartzes developed from a composition similar to the magmatic-hydrothermal Bobbejaankop quartz, rather than the magmatic Nebo quartz. Analyses with elevated B and Li compositions are attributed to the ablation of B- and Li-bearing mineral and/or fluid inclusions within the quartz.

Trace elements such as Ge, Al, Li and Be are favourably substituted for Si^{4+} in quartz within lower temperature and evolved granitic systems. These elements are not easily modified by sub-solidus processes, with the exception of Be (Breiter and Müller, 2009; Jacamon and Larsen, 2009). This late-stage preferential incorporation is evident from the linear increase of Ge exhibited by the granitic and pipe quartz, and is associated with an increasing degree of fractionation and fluid saturation (Figure 7.15c). Compared to the continental crust, the majority of the Ge content in the quartz from the Nebo, Bobbejaankop and some of the Lease granite, plots below the estimated crustal Ge composition. The remainder of the quartz from the Lease granite and almost all of the hydrothermal pipe quartz plot above the crustal composition (Figure 7.15c).

This range in Ge content in the quartz from the Zaaiplaats tin field is within the range of magmatic quartz described by Jacamon and Larsen (2009) and Müller et al. (2018). This general magmatic signature is not uncommon in hydrothermal quartz (akin to the Pipe quartz). Quartz from other fractionated and similarly tourmalinised granites, such as the Heemskirk granite in Tasmania (Hong et al., 2019), exhibit an almost identical range in Ge content, in both magmatic and hydrothermal quartz populations. Therefore, the magmatic Ge signature and linear correlation of quartz composition from the pipes and the granites, suggests their formation from internally-derived magmatic-hydrothermal fluids.

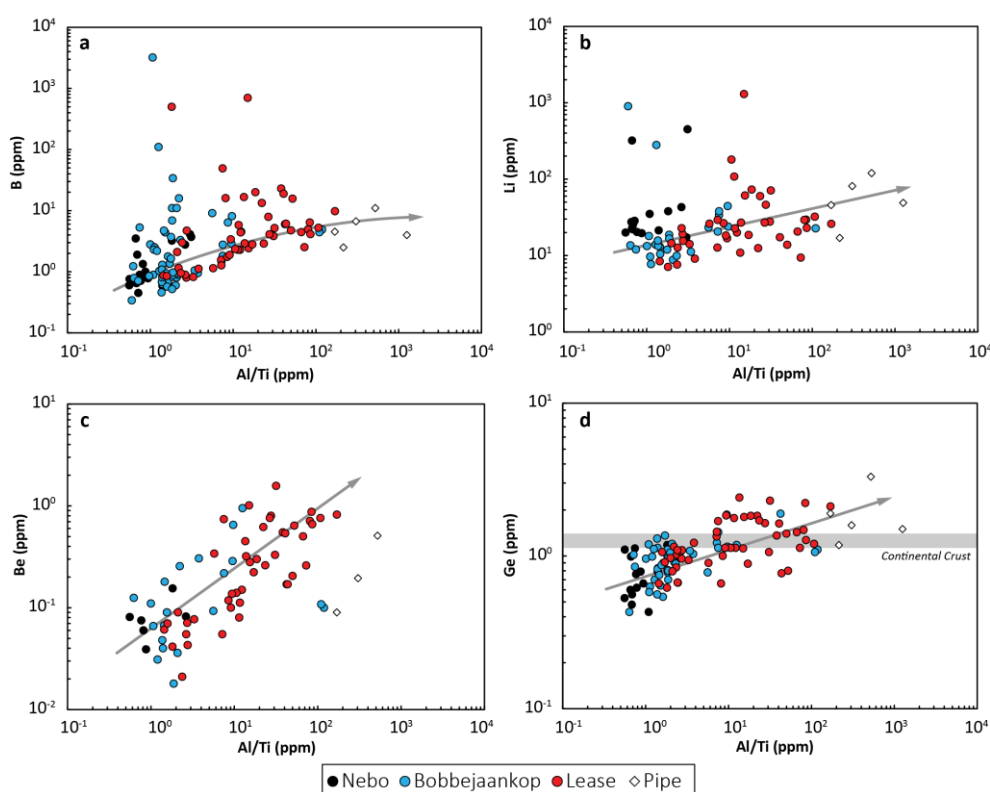


Figure 7.15. Plots illustrating the trace element variation in quartz with respect to Al/Ti fractionation proxy. Arrow indicates granitic fractionation. (a) There is an observable increase in B with an increase in fractionation of the quartz. (b) Li increases slightly with an increasing fractionation. (c) Be exhibits a sharp increase from the Nebo to Bobbejaankop then Lease and Pipe quartz. (d) The Ge content of the quartz in comparison to the estimated Ge range of the continental crust (grey area). Compositional estimates of the continental crust after Rudnick and Gao (2003).

Beryllium exhibits a linear increase with fractionation in the quartz, similar to Li and B. However, the quartz compositions from the hydrothermal pipes do not follow the enrichment trend defined by the granites (Figure 7.15d). The noticeable depletion in Be can be attributed to the subsolidus remobilisation of Be during the formation of the hydrothermal pipes. The quartz from the pipes are euhedral and show double-terminations (Figure 7.8) (Vonopartis et al., 2020a), indicating their growth in an open space. It is plausible to consider that during pipe formation, Be was subsequently stripped from the quartz through fluid interaction. This ultimately resulted in a comparable Be content to the Lease quartz, despite their late-stage hydrothermal origin (Figure 7.15d). Breiter and Müller (2009) describe the sequential enrichment of incompatible elements, such as Ge and Be, in the later-stages of A-Type granitic quartz from the Erzgebirge/Krušné Hory Mountains. They highlight a similar loss of Be in the most evolved samples. The depletion of Be is ascribed to the partitioning of Be into a very late-stage vapour, which formed beryl-bearing fissures (Breiter and Müller, 2009). Despite the

rarity of beryl in the Zaaiplaats tin field, this demonstrates that the sub-solidus remobilisation of Be may be a plausible explanation for the Be depletion in the Pipe quartz.

Elements such as Na, K and Rb, which are utilised for charge balance during coupled substitution, are not particularly definitive as they lack any correlations with Al, Ti or Ge (Figure 7.16). Sodium is primarily below detection in the Nebo and Pipe quartz, whereas in the Bobbejaankop and Lease quartz Na ranges from 60 to 650 ppm and 100 to 1280 ppm respectively (Figure 7.16a).

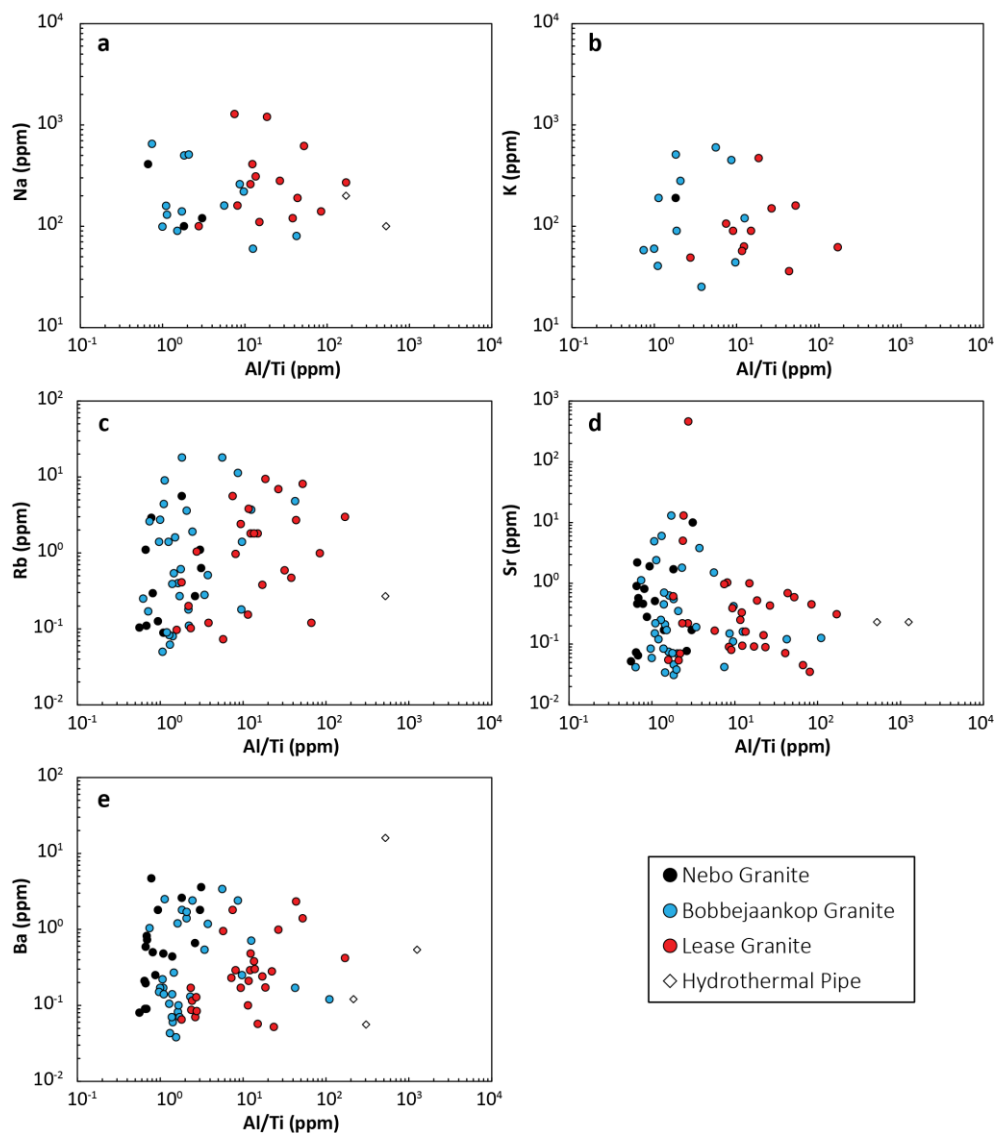


Figure 7.16. Graphs of elements commonly used for charge compensation, compared to an increasing Al/Ti ratio. **(a)** There is little variation in Na with an increase in Al/Ti; **(b)** There is little difference in the K content of the quartz compared to an increase in Al/Ti. **(c)** There is a slight increase in Rb with respect to an increase in Al/Ti. **(d)** Sr exhibits a gradual decrease from the Nebo to Lease and Pipe quartz with an increase in Al/Ti. **(e)** There is little distinction between the Ba content in quartz from each lithology with an increasing Al/Ti ratio.

The K content of the quartz from the Nebo granite and Pipes is similarly below detection, while the Bobbejaankop and Lease quartz have K values between 25 to 600 ppm (Figure 7.16b). Thus, the Al:Li ratios together with their greater Na and K abundance in the Bobbejaankop and Lease quartz, corresponds with incorporation of Na⁺ and K⁺ rather than Li⁺ as charge compensators. The Rb, Sr and Ba contents in the granitic quartzes are above detection, however they do not reveal any significant insight (Figure 7.16c-e). These elements do not correlate with any structurally incorporated components and have almost identical ranges. Therefore, these elements are attributed to the ablation of inclusions (Hong et al., 2019).

7.4.2. Petrogenetic Insight

The trace element analyses of quartz from the granites in the Zaaipplaats tin field supports the hypothesis that the Nebo, Bobbejaankop and Lease granites are all magmatically related. The Bobbejaankop and Lease granites are the result of progressive fractionation, fluid saturation and alteration during increasing magmatic-hydrothermal fluid interaction (Vonopartis et al., 2020a). This is shown by the correlated and progressive geochemical evolution of the quartz grains. The compositional variations in the quartz from the Nebo, Bobbejaankop and Lease granites define an array of increasing fractionation and fluid saturation, from magmatic to magmatic-hydrothermal quartz compositions (Figure 7.14). The trace element evolution of the quartz indicates that the Bobbejaankop granite is the evolved and hydrothermally altered cupola of the magmatic Nebo granite. The Lease microgranite is shown to be the evolved and altered roof facies of the Bobbejaankop granite, from the concentration of hydrothermal fluids. The magmatic to magmatic-hydrothermal evolution described above is evident in the quartz traverses. The trace element variations observed from these traverses define ten generations and are grouped into four different stages of quartz formation (Figure 7.17 and Table 7.2). This interpretation and grouping of the quartz analyses is based on common trace elemental abundances and characteristics that are observed between the various quartz populations (Figure 7.17).

The first stage is represented by the compositions of the Nebo quartz and cores of the Bobbejaankop quartz. Compositional comparisons of the quartz in Figure 7.17 show that the core of the Bobbejaankop quartz (*generations 1 to 3*) has nearly identical Al and Ti abundances to the Nebo quartz and similar CL luminescence and textures (Figure 7.10a, b).

Therefore, the core of the Bobbejaankop quartz are interpreted to have formed within a magmatic environment, as did the Nebo quartz.

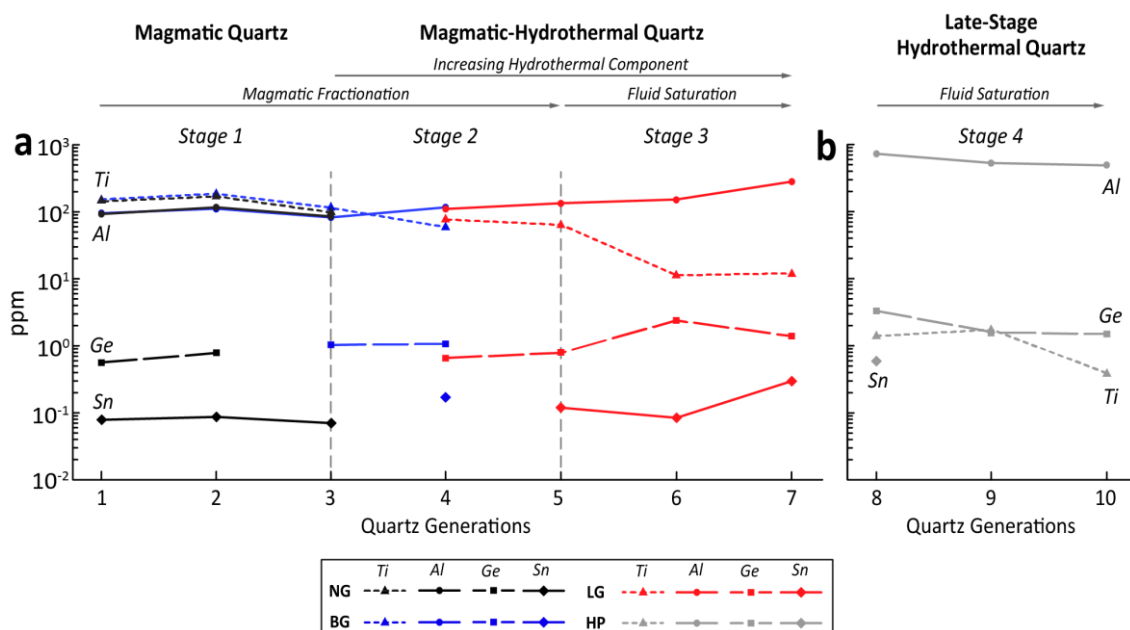


Figure 7.17. A compilation of the quartz traverses in Figure 7.10. The interpreted sequence of the geochemical data is ordered based on the abundances of Ti, Al, Ge and Sn, with respect to the defined evolution of the Zaaipplaats tin field (Vonopartis et al., 2020a). **(a)** The Nebo, Bobbejaankop and Lease quartz represent the evolution of magmatic to magmatic-hydrothermal quartz. **(b)** The Tourmaline-Quartz Pipe represents a distinct late-stage hydrothermal quartz population. Black represents the Nebo granite (NG), blue represents the Bobbejaankop granite (BG), red represents the Lease granite (LG) and grey represents the hydrothermal pipe (HP).

The second stage in the evolution of the system is reflected by the rim compositions of the Bobbejaankop quartz and cores of the Lease quartz (*generations 4 and 5*). These generations shows a muted CL luminescence, a decrease in Ti and an increase in Al and Ge content (Figure 7.17a and Table 7.2). The transition from stage 1 to 2 is characterised by the preferential substitution of Ge rather than Al for Si. The incorporation of Ge into the silicate structure is controlled by the availability of Ge in the system (Müller et al., 2018) and infers that Ge was enriched in the system from fractionation through to fluid accumulation. In addition, the Ti depletion in the margin of the Bobbejaankop quartz and cores of the Lease quartz indicates a decrease in temperature (Wark and Watson, 2006; Breiter and Müller, 2009; Jacamon and Larsen, 2009). Therefore, it is likely that Stage 2 (*generations 4 and 5*) of the Bobbejaankop quartz and early Lease quartz formed in an increasingly magmatic-hydrothermal environment.

The Sn content in the Nebo granite remains constant, whereas Sn is only measurable in the final generation of the Bobbejaankop quartz (*Stage 2*) (Figure 7.17a and Table 7.2). The variations in Sn content are attributed to how it is hosted in each lithology. As there is no cassiterite mineralisation in the Nebo granite, all the Sn would hypothetically be hosted in other Sn-bearing minerals or within saline fluids. The early Bobbejaankop quartz is considered to be magmatic (*Stage 1*), from the evolution of the Nebo granite. Therefore, the available Sn within this magmatic system would have been sequestered by early Sn-bearing phases during crystallisation of the Nebo granite. The subsequent introduction of Sn-bearing hydrothermal fluids is recorded by the final Sn-bearing generation of the Bobbejaankop granite quartz (*Stage 2*) (Figure 7.17a and Table 7.2). Therefore, it is likely that the Sn content in the rims of the Bobbejaankop quartz, represents an increase in Sn-bearing magmatic-hydrothermal fluid within the later stages of the Bobbejaankop granite.

Table 7.2. Stages of quartz and their trace element characteristics from the Zaaiplaats tin field granites and hydrothermal pipes

Gen.	Lithology	Trace Elements	Petrogenetic Insight
Magmatic Quartz			
1	Nebo Quartz	– Al < Ti	Formation within a granitic magma
	Bobbejaankop Quartz (Core)	– Low Ge	
		– Low Sn*	
Early Magmatic-Hydrothermal Quartz			
2	Bobbejaankop Quartz (Rim)	– Al > Ti	Magmatic-hydrothermal fluid component in crystallising magma
	Early-Lease Quartz (Core)	– Moderate Ge	
		– Moderate Sn*	
Fluid Saturation – Magmatic-Hydrothermal Transition			
3	Lease Quartz (Rim)	– High Al	Saturation of a magmatic-hydrothermal fluid in the granite cupola
		– Low Ti	
		– Moderate Ge	
		– Moderate to high Sn*	
Late-Stage Hydrothermal Fluid			
4	Hydrothermal Pipe	– Very High Al	Formation from a very acidic, metal-bearing magmatic-hydrothermal fluid
		– Very Low Ti	
		– Moderate Ge	
		– High Sn*	

*Non-structural element in quartz. Abbreviation: Generation (Gen.)

The interior of the Lease quartz has greater Al than Ti content, with a relatively high Sn concentration (*generations 4 and 5*). These early generations of Lease quartz share a greater resemblance to the magmatic-hydrothermal generations of the Bobbejaankop quartz

(*generation 4*) (Figure 7.17a and Table 7.2). Thus, it is reasonable to suggest that the Lease quartz crystallised from a similar magmatic-hydrothermal composition to the final stages of the Bobbejaankop granite (*Stage 2*).

The third stage is characterised by a sudden Ti depletion and simultaneous Al and Ge enrichment in the latter generations of the Lease quartz (*generations 6 and 7*) (Figure 7.17a). This sudden and distinct shift in composition is considered to signify the point of fluid-saturation during the final formation of the Lease granite (*Stage 3*). The notably greater fluid content increased the available Ge and lowered the granitic solidus of the Lease granite. This reduced the incorporation of Ti into the quartz lattice, which resulted in the marked decrease in Ti content (Figure 7.17a).

There is a noticeable increase in Al with a slight Ge depletion towards the rim of the Lease quartz (*Stage 3*) (Figure 7.17a and Table 7.2). This minor Ge depletion may be caused by either the gradual depletion of Ge in the magmatic-hydrothermal system, or by the increased uptake of Al into the quartz structure. An increase in the acidity of the fluid favours the incorporation of Al rather than Ge in quartz (Pokrovskii and Helgeson, 1997; Salvi et al., 1998; Götze, 2018). An inferred increase in acidity corresponds with the documented increase of late-stage greisenisation in the Lease granite. This would have enhanced the dissolution of feldspar, chlorite and mica, resulting in the liberation of Al, Ti and possibly Sn (Zhao et al., 2005; Vonopartis et al., 2020a; Vonopartis et al., 2021b).

Titanium has been documented, and evidently demonstrated, to effect CL luminescence in quartz (Müller et al., 2003). Therefore, the liberation of Ti during the alteration of proximal mica and chlorite in miarolitic cavities, explains the thin, highly luminescent rims on the miarolitic quartz (Figures 7.5b and 7.7c, d). In addition, the chloritisation and subsequent greisenisation of mica is shown by Vonopartis et al. (2020a) to form exsolutions of Ti- and Sn-oxides. This liberation of metals would allow Ti incorporated into the rims of the crystallising quartz proximal to alteration, producing the observed “Ti-induced” increase in CL luminescence (Figures 7.5b and 7.7c, d).

The fourth and final stage comprises the quartz from the hydrothermal pipe and is characterised by the lowest Ti and the highest Al, Ge and Sn contents from the quartz populations (*generations 8 to 10*) (Figures 7.13, 7.17b and Table 7.2). The high Ge and very

high Al content is characteristic of a highly acidic, fractionated and hydrothermal system. Whereas, the very low Ti content indicates a significantly lower crystallisation temperature than that of the granitic quartz (Figure 7.17b). Therefore, the Pipe quartz is distinct and formed in a very late-stage acidic hydrothermal fluid, during the final stages in the evolution of the Zaaipplaats tin field (*Stage 4*). This is corroborated by the petrological evidence of extensive greisenisation (Strauss, 1954; Pollard et al., 1989; Crocker et al., 2001; Vonopartis et al., 2020a; Vonopartis et al., 2021b) and low temperature α -quartz observed within the hydrothermal pipes (Figure 7.8b, c).

These hydrothermal pipes are host to the highest Sn grades in the Zaaipplaats tin field (Crocker et al., 2001; Vonopartis et al., 2020a), therefore a high Sn content was to be expected. However, the cores of the quartz exhibit the highest Sn content and drop below detection towards the rims (Figure 7.17b). The absence of Sn towards the rims of the quartz crystals may indicate the precipitation of cassiterite, thus resulting in the depletion of the Sn content in the hydrothermal fluid.

7.4.3. Insight into Sn-Mineralisation

Tin is a highly incompatible and fluid mobile element, allowing it to be readily concentrated via granitic fractionation and hydrothermal mobilisation (Wolf et al., 2018; Lehmann, 2020; Vasyukova and Williams-Jones, 2020). The Lease granite is the most fractionated, hydrothermally altered and mineralised of the three granitic lithologies (Vonopartis et al., 2020a). This fractionated characteristic is geochemically demonstrated by the Al/Ti and Ge/Ti ratios in quartz (Figure 7.14), as well as whole-rock trace elemental ratios such as Rb/Sr and Zr/Hf (Vonopartis et al., 2020a). The majority of the quartz from the Lease granite is inferred to have formed after fluid saturation (Figure 7.14) suggesting that the Sn content should be higher than that derived from fractionation alone.

The Sn-in-quartz content from these granites ranges from the estimated Sn content of the primitive mantle of ± 0.14 ppm (Palme and O'Neill, 2003) in the Nebo granite, up to 21 ppm within the Lease quartz. The compositions of the quartzes generally cluster between 0.03 to 2 ppm (Figure 7.9m), which is comparable to quartz from other mineralised granitoids and pegmatites (Götze et al., 2004; Breiter et al., 2014; Hong et al., 2019). The increase in average whole-rock Sn content is mirrored by the increasing Sn-in-quartz content from the Nebo through the Bobbejaankop to the Lease quartz (Figure 7.11). The Sn-in-quartz content of the

hydrothermal pipes is typically below detection, and does not provide enough data to conclusively state the average Sn content of the pipe quartz. The Sn-in-quartz is considered an indication of the Sn content of the hydrothermal fluid. However, where Sn is measurable in the Pipe quartz, it is similar to that of the Lease quartz and does not reflect the highly mineralised nature of these pipes. Therefore, a late-stage depletion of Sn-in-quartz that is not reflected in the whole-rock geochemistry, may indicate the precipitation of Sn from the fluid. This decoupling of the whole-rock and quartz Sn content shows promise as a vector towards endogranitic Sn mineralisation.

7.5. Conclusions

The CL imagery and trace element in quartz investigation provided insight into the petrogenetic history of the Zaaipiaats tin field. The Nebo to Lease evolution is typical of an evolving A-Type granite system that transitions from magmatic to a magmatic-hydrothermal regime through to a very late-stage hydrothermal phase. The CL textures and the Al/Ti and Ge/Ti ratios of the Nebo quartz and early generations of the Bobbejaankop quartz indicate a magmatic origin. The later generations of the Bobbejaankop quartz exhibit a decrease in Ti and increase in Al and Ge, which indicates a more magmatic-hydrothermal environment. These increasingly magmatic-hydrothermal characteristics continued into the Lease quartz, and indicate the development of a fluid-saturated environment.

Therefore, the petrographic and geochemical evolution of the quartz is suggestive of a fractionating granitic system that became increasingly fluid saturated towards the apical portions of the intrusion. The late-stage Pipe quartz exhibits distinctly hydrothermal CL features, is Ti depleted and exhibits a marked Al and Ge enrichment. These are characteristics of a low-temperature late-stage acidic hydrothermal fluid that likely exsolved from the Bobbejaankop and Lease granites.

Despite the Sn content of the quartz being inconsistent, a proportional relationship was observed between the Sn-in-quartz and whole-rock Sn compositions of the granites. The Sn content of the quartz from the highly-mineralised hydrothermal pipes was primarily below detection. A late-stage depletion of Sn-in-quartz that is not reflected in the whole-rock geochemistry, is therefore proposed as a potential vector for endogranitic Sn mineralisation.

Chapter 8

Synthesis and Conclusion

8.1. Introduction

This chapter provides a synthesis of the geological, geochemical and spectral data that has been discussed in the previous chapters. This study has culminated in the proposal of a simple geological model, for the formation and mineralisation of the Zaaipplaats tin field. The proposed geological interpretation is a modification of existing petrogenetic models (Strauss and Truter, 1944; Strauss, 1954; Coetzee, 1986; Pollard et al., 1991b; Crocker et al., 2001) by integrating the insight gained from this research.

In addition, this synthesis chapter discusses the metallogenesis of A-Type granite suites, and the factors that influence their late-stage endogranitic tin mineralisation. The petrogenesis of the Zaaipplaats tin field, and its mineralised hydrothermal features, have been a subject of conjecture since they were first described by Kynaston et al. (1909).

8.2. Petrogenesis of the Zaaipplaats Tin Field

The Palaeoproterozoic Bushveld Igneous Complex and its felsic component, the Lebowa Granite Suite (2,054 Ma) (Scoates et al., 2021), are associated with a large enriched mantle plume, pinned below the Archean Kaapvaal craton (Zirakparvar et al., 2014; Zeh et al., 2015; Zeh et al., 2019). The Bushveld granites are considered to be the partial melting product of the Archaean basement, which crystallised at a depth of 4 to 5 km (Figure 2.14) (Skursch et al., 2020; Vonopartis et al., 2020a). These granitoids were emplaced above the almost crystallised Rustenburg Layered Suite and beneath the Rooiberg Group Volcanics (Skursch et al., 2020). The Nebo granite is the most volumetrically significant granitoid of the seven granitic facies that comprise the Lebowa Granite Suite (SACS, 1980; Robb et al., 2000; Kinnaird et al., 2004). The current consensus on the petrogenesis of the Nebo granite, favours a formation by the episodic emplacement of multiple, relatively shallow, sill-like intrusions (Wilson et al., 2000).

8.2.1. The Nebo Granite

The Nebo granite exhibits an internal geochemical homogeneity, from east to west (Hunt, 2005). However, it evolved from a hornblende leucogranite at its base, to a pinkish-red biotite granite towards the roof (Hill et al., 1996; Wilson et al., 2000; Kinnaird et al., 2004). The apical

regions of the Nebo granite in the Zaaipplaats tin field, is shown to be a coarse-grained equigranular leucogranite, composed of quartz, alkali-feldspar and re-equilibrated interstitial annite, after hornblende (Figures 6.18 and 6.19) (Vonopartis et al., 2020a). The magmatic nature of the Nebo granite is highlighted by the high-Ti, low-Al, low-Ge and the magmatic Al:Li ratio of its quartz (Figures 7.10 and 7.17). Vonopartis et al. (2020a) used fractionation proxies such as Zr/Hf, Rb/Ba and Rayleigh Fractionation to show that the Nebo granite at Zaaipplaats, is an evolved expression of the greater Nebo intrusion (Figures 2.15 and 2.16). However, the annitic mica is considered to be predominantly non-magmatic and is increasingly chloritised towards the roof facies. Therefore, it is evident that there was an increasing concentration of magmatic-hydrothermal fluid, during the upwards evolution of the Nebo granite.

8.2.2. The Bobbejaankop Granite

The Bobbejaankop granite is characterised as a coarse-grained, chloritised, muscovitised and brick-red granite in the cupola of the Nebo granite. The several metre wide transition from the Nebo to the Bobbejaankop granite, exhibits an increase in mica chloritisation, reddening of feldspar and aggregation of quartz (Vonopartis et al., 2020a). Trace elemental ratios in quartz (Al/Ti and Ge/Ti) (Figure 7.17), whole-rock fractionation proxies (Zr/Hf, TEDI and Rb/Sr) (Figure 2.15) and a slight REE enrichment (Figure 2.17) show the Bobbejaankop granite to be a fractionated product of the Nebo granite (Figure 2.15). Rayleigh fractionation suggests approximately 60% fractionation of the Nebo magma is required for the development of the Bobbejaankop magma (Vonopartis et al., 2020a). The magmatic kinship of the Nebo and Bobbejaankop granites is further highlighted by the shared trace elemental compositions of the Nebo quartz and cores of the Bobbejaankop quartz (Figure 7.14).

However, the rims of the Bobbejaankop quartz exhibit a notably more magmatic-hydrothermal signature (Figure 7.14). The growth of this latter generation of quartz linked neighbouring quartz crystals, and formed the characteristic synneusis textures of the Bobbejaankop granite (Figure 7.4d, f and 7.12b). The upwards accumulation of magmatic-hydrothermal fluid increasingly chloritised the original annitic mica, to a dark green Fe-chlorite (Figure 6.15). These fluids also caused the reddening of the feldspars and the precipitation of fluorite within miarolitic cavities (Figure 8.1b). The structural reordering of feldspar increased permeability and facilitated the pervasive upwards movement of fluids in the Bobbejaankop granite (Putnis et al., 2007; Vonopartis et al., 2020a).

The Bobbejaankop granite exhibits more prominent magmatic-hydrothermal characteristics than the Nebo granite. These features include: the abundance of fluorite and miarolitic cavities; haematised feldspars; the complete chloritisation of the trioctahedral mica to Fe-chlorite; the subsequent Fe-muscovitisation of the chlorite (Figure 6.21); an enrichment in LIL and HFS elements, shown via pXRF mapping (Figure 3.9) and whole-rock geochemistry (Vonopartis et al., 2020a); the increased multispectral signatures of chloritisation, muscovitisation and iron-oxide (Figure 3.4a-c); hydrothermal trace elemental compositions (high Al, high Ge and low Ti) of the Bobbejaankop quartz rims (Figures 7.9 and 7.17); and by whole-rock fluid-sensitive ratios (Nb/Ta and Y/Ho) (Vonopartis et al., 2020a). These many characteristics reflect a transition from a magmatic towards a more hydrothermally-dominated environment, from the Nebo to the Bobbejaankop granite.

Further crystallisation of the Bobbejaankop granite caused the fluid-saturation of the upper facies of the intrusion (Figure 8.1b) (Vonopartis et al., 2020a). The alignment and occurrence of schorl–foitite tourmaline orbicules, along the Bobbejaankop–Lease contact, indicates the separation of a Fe- and B-rich fluid phase (Figures 5.3 and 8.1b). The formation of these orbicules is thought to reflect the transition from a magmatic to magmatic-hydrothermal semi-crystalline regime (Candela, 1991; Thomas et al., 2003; Drivenes et al., 2015; Hong et al., 2017; Vonopartis et al., 2021b). This magmatic-hydrothermal transition and point of fluid saturation is corroborated by trace elements (Al, Ti and Ge) and their ratios (Al/Ti and Ge/Ti) in the later quartz generations of the Bobbejaankop granite (Figures 7.14, 7.17).

The initial magmatic, fractionally-controlled, evolution and concentration of incompatible elements is apparent in the Nebo quartz, some Bobbejaankop quartz and to a lesser degree in the Lease quartz (low Al/Ti and Ge/Ti) (Figures 7.14, 7.17a). It is noted that some of the late Bobbejaankop quartz and the early Lease quartz are compositionally similar and represent a more magmatic hydrothermal quartz stage. They exhibit higher Al/Ti and Ge/Ti ratios, display an increased scatter, and become increasingly Ti-poor, Ge-rich and Al-rich compared to the earlier magmatic quartz stage (Figure 7.14). This compositional shift indicates the formation of the later Bobbejaankop quartz and early Lease quartz in a dominantly magmatic-hydrothermal fluid environment (Figure 7.17) (Figure 8.1b).

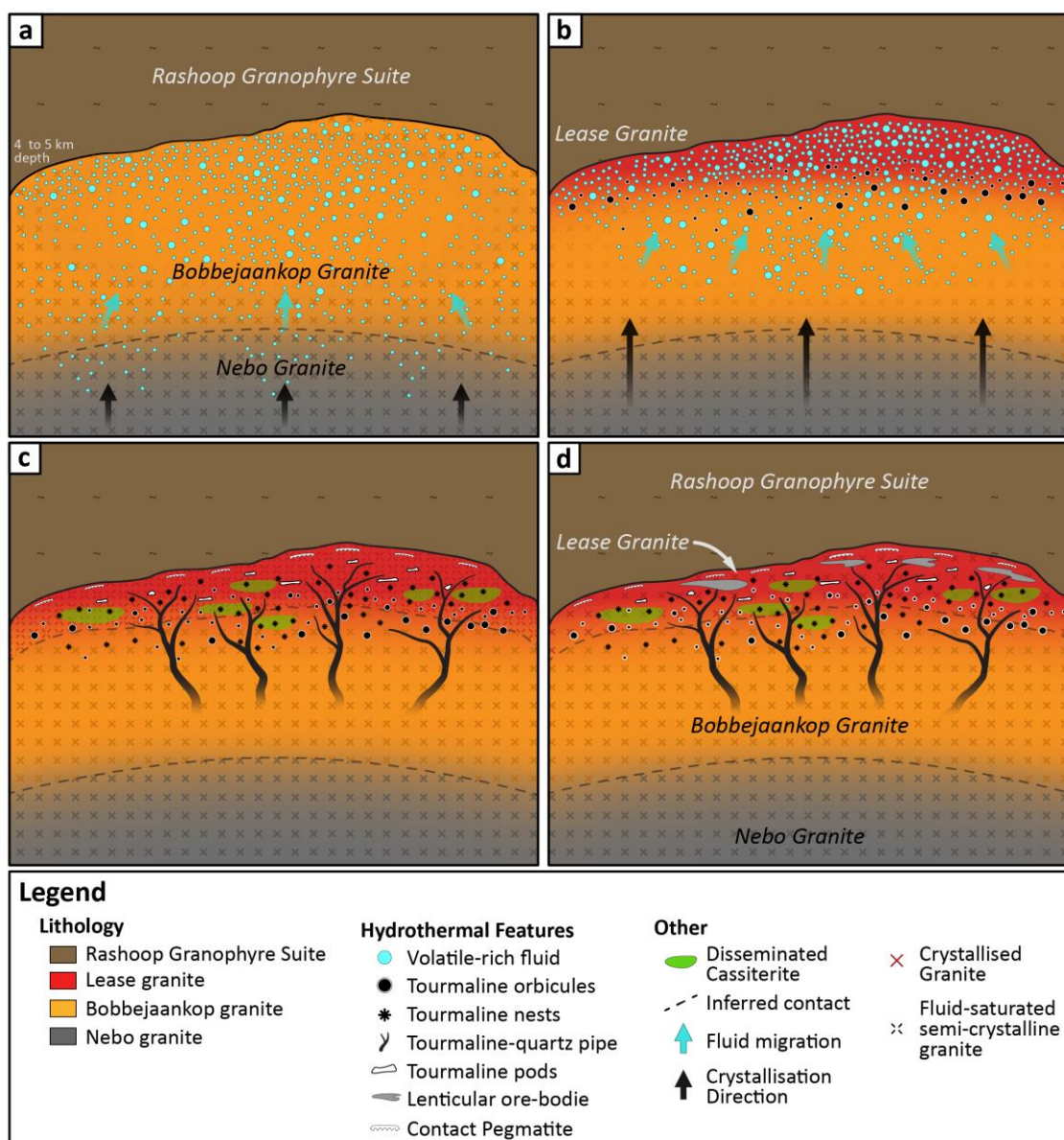


Figure 8.1. Geological model for the formation of the Zaaipiaats tin field and hydrothermal features. (a) Fractional crystallisation of the Nebo and the initial crystallisation of the fluid-rich Bobbejaankop granite. (b) Further crystallisation of the Bobbejaankop granite, causing the separation of an Fe- and B-rich fluid phase and the formation of tourmaline orbicules, fluid saturation and alteration of the semi-crystalline Lease microgranite. (c) Formation of an acidic, Fe³⁺, B- and metal-rich hydrothermal fluid that caused the sub-solidus tourmalinisation of the Lease granite, formation of the tourmaline-quartz hydrothermal pipes and disseminated cassiterite mineralisation. (d) The accumulation and ponding of greisenising hydrothermal fluids and the formation of the lenticular ore-bodies.

This increasingly magmatic-hydrothermal environment aligns with the petrological, pXRF and multispectral evidence, which displays increasing hydrothermal signatures, as the Bobbejaankop granite transitions into the Lease facies (Figures 2.7, 3.4, 3.9 and 7.16). This is further corroborated by whole-rock fluid-sensitive geochemical elements and ratios (Nb/Ta and Y/Ho) that indicate an increased interaction of F-rich magmatic-hydrothermal fluids in

the Lease granite (Figure 2.16). Therefore, the Lease microgranite represents the subsolidus alteration of the Bobbejaankop granite cupola, by the accumulation and ultimate saturation of magmatic-hydrothermal fluids (Figures 2.7, 8.1b) (Vonopartis et al., 2020a).

8.2.3. The Lease Granite

The Lease granite is petrographically characterised as a texturally heterogeneous, extensively chloritised, muscovitised and tourmalinised red microgranite. It is composed of red alkali-feldspar, quartz, Fe-chlorite, Fe-muscovite–muscovite and fluorite with Fe-schorl tourmaline and cassiterite-filled miarolitic cavities. Geochemically, the Lease granite is similar to the Bobbejaankop granite although, whole-rock fractionation proxies (Figure 2.15) and trace elements-in-quartz (Figure 7.14) show the Lease granite to be more fractionated. In addition, whole-rock geochemistry and pXRF mapping of these granites reveal a LIL and HFS element enrichment from the Bobbejaankop towards the Lease granite (Figures 2.12, 2.16, 2.17, 3.8 and 3.9) (Vonopartis et al., 2020a; Vonopartis et al., 2020b). This supports the upwards accumulation of incompatible-bearing magmatic-hydrothermal fluids within the peripheral Lease granite.

Fluid inclusions in the Bobbejaankop and Lease granite show these fluids to be hypersaline (Pollard et al., 1991a). Various other components, such as Sn, B and F in the fluids are apparent from the array of trace elements-in-quartz (Figure 7.9) and the abundance of hydrothermal phases, including cassiterite, tourmaline and fluorite (Vonopartis et al., 2020a). The concentration of Sn, Cl, F and B in the fluid is accounted for by their incompatible and fluid mobile nature (Manning, 1981; Pollard et al., 1987; Finch and Tomkins, 2017). However, the influx of Fe^{3+} in the late-stage fluid, implied by Fe-rich cassiterite and the Fe-schorl tourmaline, remains unclear (Figures 5.13b and 5.16b) (Vonopartis et al., 2021b).

The ferrous nature of A-Type granites is well-established (Eby, 1992; Bonin, 2007; Frost and Frost, 2011) and at the Zaaipplaats tin field is expressed as: the pervasive haematitic coating of feldspars (Putnis et al., 2007; Vonopartis et al., 2021b); the presence of FeCl in fluid inclusions (Pollard et al., 1991a); the Fe-rich nature of the early trioctahedral annites and later stage dioctahedral Fe-muscovites (Figure 6.9); the Fe-rich compositions of the chlorite (Figure 6.12) and cassiterite (Figure 5.13) from these granites; the Fe-schorl composition of the late-stage Lease granite and hydrothermal pipe tourmalinisation (Figure 5.16) (Vonopartis et al., 2021b); and the Fe-oxide spectral signatures shown by the Sentinel-2 mapping (Figure 3.4a)

(Vonopartis et al., 2020b). However, Fe-rich A-Type granites are commonly reduced (Loiselle and Wones, 1979; Bonin, 2007; Frost and Frost, 2011), and therefore the late-stage influx of Fe^{3+} is enigmatic.

Three potential sources for the Fe^{3+} in the late-stage magmatic-hydrothermal fluids were proposed by Vonopartis et al. (2021b): 1) The oxidation of Fe^{2+} to Fe^{3+} within the magmatic-hydrothermal fluids via a boiling event; 2) the liberation of tetrahedrally incorporated Fe^{3+} via the alteration of haematised alkali-feldspar; or 3) the interaction of the magmatic-hydrothermal fluids within the granitic cupola with external Fe^{3+} -bearing fluids. There is little supporting petrological or geochemical evidence in the Zaaipplaats tin field to suggest a boiling event, and is therefore an unlikely explanation (Vonopartis et al., 2021b). Thus, the source of the Fe^{3+} is suggested to be a combination of alkali-feldspar dissolution and the potential interaction with formational fluids.

The documented textural heterogeneity (Vonopartis et al., 2020a) and apparent geochemical fluctuations in the Ba/Rb and Sn mapping of the Lease granite (Figures 3.8 and 3.9) indicates an unequal distribution of the hydrothermal fluid. Internal differences in permeability and microstructure variations within the Lease granite are suggested to have caused the unequal distribution of magmatic-hydrothermal fluid (Vonopartis et al., 2020a). This resulted in a mosaic of dominant styles of alteration, and discrete zones of mineralisation within a single granitic facies (*i.e.* the Lease granite) (Figure 8.1c).

The evolution and saturation of late-stage hydrothermal fluid in the Lease granite is recorded by its quartz, tourmaline, cassiterite and mica mineral chemistry. The trace element compositions of the Lease quartz lack an early magmatic signature, which suggests an initial formation within a dominantly magmatic-hydrothermal environment. The rim of the Lease quartz displays an increasingly Ti-poor, Al-rich, Ge-rich composition and exhibits a larger degree of scatter in their Al/Ti and Ge/Ti ratios (Figures 7.13, 7.14 and 7.17). This is interpreted to indicate an increase in fluid acidity and the saturation of a late-stage magmatic-hydrothermal fluid in the Lease granite. The increased permeability, due to feldspar reordering, allowed the incipient and ubiquitous subsolidus tourmalinisation in the Lease granite. Vonopartis et al. (2021b) described the fluid that formed the Fe-schorl–schorl–foitite tourmalines in the Lease granite to be markedly different to that which formed the earlier schorl–foitite tourmaline in the Bobbejaankop granite. In addition, the cassiterite

mineralisation in the Lease granite is distinctly hydrothermal, and is associated with late-stage greisenisation and Fe-schorl tourmalinisation (Vonopartis et al., 2021b).

The saturation of these late-stage acidic F-, B- and metal-bearing fluids caused the extensive late-stage greisenisation in the Lease granite. The original trioctahedral micas in the Lease granite are shown to be completely altered to a dark green Fe-chlorite, as in the Bobbejaankop granite (Figures 6.15 and 6.21). However, unlike the Bobbejaankop granite, the Fe-chlorite in the Lease granite is further greisenised, to a pale-green/white Fe-muscovite–muscovite (Figures 6.9 and 6.21). This indicates a greater degree of fluid-rock interaction in the Lease granite, with an acidic, greisenising magmatic-hydrothermal fluid. The hydrolysis of feldspar and the ubiquitous formation of Fe-muscovite–muscovite via greisenisation, would have induced the co-precipitation of cassiterite. Therefore, the fluid-saturation of the granitic cupola, resulted in the sub-solidus tourmalinisation, muscovitisation, mineralisation and formation of the texturally heterogeneous Lease granite.

8.2.4. The Hydrothermal Pipes

The coalescence and channelisation of these fluids, as they percolated towards the subsolidus roof, resulted in the formation of large swarms of greisenising hydrothermal pipes (Figure 8.1c) (Candela, 1991; Vonopartis et al., 2021b). These hydrothermal pipes are comprised of a high-grade greisen core, then a melanocratic layer of Fe-schorl–schorl–foitite tourmaline, quartz and minor feldspar with a thin white quartz rim (Vonopartis et al., 2020a; Vonopartis et al., 2021b). These hydrothermal pipes radiated upwards from the Bobbejaankop into the Lease granite, and terminated below the roof contact (Figure 8.1c) (Vonopartis et al., 2020a; Vonopartis et al., 2021b). Smaller trapped accumulations of these fluids within the Lease granite formed pegmatitic pods of Fe-schorl–schorl–foitite tourmaline, quartz, feldspar and fluorite (Figure 5.4g). These pods were recorded to occasionally host economic quantities of cassiterite (Strauss, 1954; Coetzee, 1984; Crocker et al., 2001; Vonopartis et al., 2020a; Vonopartis et al., 2021b).

The trace elemental signatures and petrographic characteristics of the pipe quartz is dissimilar from the granitic quartzes. The quartz from the hydrothermal pipes are predominantly large euhedral trigonal crystals with double terminations (Figures 5.6e and 7.8), which indicate a low-temperature hydrothermal environment (Howie et al., 1992; Götze, 2009; Heaney et al., 2018). The Pipe quartz is very Ti-poor, Al- and Ge-rich and has the highest

Al/Ti and Ge/Ti ratios (Figure 7.17). Therefore, the pipes represent the most fractionated, low-temperature and hydrothermal lithology in the Zaaipiaats tin field. In conjunction with the Fe³⁺-rich schorl pipe tourmaline (Figure 5.16) and extensive greisenisation, these pipes are suggested to have formed from a very late-stage, acidic, B- and metal-bearing hydrothermal fluid.

The extensive greisenisation allowed the precipitation of significant amounts of transported Sn within the cores of the pipes (Strauss and Truter, 1944; Pollard et al., 1989; Vonopartis et al., 2020a; Vonopartis et al., 2021b). The extensive digestion of haematised feldspar would have provided the influx of Fe³⁺, required for the formation of the Fe-schorl tourmaline that surrounds the greisen cores (Vonopartis et al., 2021b).

The composition of the quartz from the Nebo, Bobbejaankop and Lease granites is distinctly magmatic to magmatic-hydrothermal (Figures 7.13 and 7.14). These magmatic-hydrothermal fluids are considered to be internally derived (Vonopartis et al., 2020a). However, Vonopartis et al (2021b) suggests that the interaction with formational fluids in the late-stages of the Zaaipiaats tin field cannot be disregarded, as various issues remain unresolved: the long-lived hydrothermal system of the Bushveld Granites (McNaughton et al., 1993; Robb et al., 2000); the enigmatic 1,950 Ma resetting event of the Bushveld Complex (Robb et al., 2000; Kinnaird et al., 2004); the Fe³⁺-bearing late-stage tourmaline of the Lease granite and hydrothermal pipes (Vonopartis et al., 2021b); and the inferred low temperature formation of the quartz in the pipes. Therefore, it is plausible that the late-stage hydrothermal fluids interacted with external low-temperature hydrothermal fluids.

8.2.5. Lenticular Ore-Bodies

Many of the hydrothermal pipes terminate into high-grade lenticular ore-bodies of an almost pure greisen (tourmaline-poor), below the overlying granophyres (Figure 8.1d) (Strauss and Truter, 1944; Crocker et al., 2001; Vonopartis et al., 2020a). However, access to these lenticular bodies is no longer possible due to back-filling (Vonopartis et al., 2020a). Thus, a reasonable formation mechanism is proposed by incorporating descriptions and interpretations from previous studies (Strauss and Truter, 1944; Strauss, 1954) with findings from this research.

It is plausible that the same metal-rich, buoyant and acidic fluids that formed the hydrothermal pipes, ponded beneath the carapace of the Lease granite. The extensive tourmalinisation in the pipes depleted the B content in the fluid, thus there was insufficient B for tourmaline formation in the lenticular ore-bodies. These final vestiges of the acidic brine ponded beneath the solidified carapace, extended laterally and formed the lenticular high-grade greisenised ore-bodies of the Zaaiplaats tin field (Figure 8.1d).

8.3. Insights on A-type Granite Fertility

Critical materials are those which are vital to current and future technologies, and for various reasons may potentially encounter supply issues (Watari et al., 2020). Therefore, the strategic management and guaranteed supply of these materials is paramount to continued technological advancements (Watari et al., 2020). As of 2020, the EU Critical Raw Materials List, identifies 30 materials that meet these criteria. Many of the elements on this list, including but not limited to HFS and LIL elements, can be sourced from A-Type granitoid associated mineralisation. Therefore, research into the metallogenic potential of A-Type granites is paramount for current and future mineral exploration. Tin is one of these critical elements and is used in various technologies, such as: touchscreens on smartphones; within solar power materials; wind turbines technology; nuclear power generation; geothermal energy solutions; biomass technologies; and in carbon capture and storage (Kinnaird et al., 2016; Watari et al., 2020).

The geochemical comparison of various stanniferous and barren A-Type granites from the African continent, revealed specific differences and trends. These differences either promote or inhibit the development of late-stage HFS element mineralisation. There are distinct mica compositional and evolutionary characteristics, exhibited by mineralised A-Type granitoids, which contrast with barren granite examples. The ferrous characteristic of A-Type granites (Eby, 1992; Bonin, 2007; Frost and Frost, 2011), is particularly apparent in the micas from granites that host endogranitic and pegmatitic mineralisation (Figure 6.20).

The trioctahedral micas from mineralised A-Type granite suites evolve along a Fe-Li mica trend, from annite through siderophyllite to Li-siderophyllite and potentially zinnwaldite (Figure 6.20). This is evident in the trioctahedral mica compositions from the Nebo granite, Nigerian Younger granites, El Portezuelo and Pikes Peak among others, which all exhibit a Fe-

Li evolution to a degree (Figure 6.20). In comparison, despite the micas from barren A-Type granites beginning with a trioctahedral annite composition, they evolve along a Mg-enrichment trend, from annite to Fe-biotite then Mg-biotite (Figure 6.20). This Mg evolution is exhibited by the micas from the Appalachians, the unmineralised Nigerian granites and the Gaborone Granite Suite (Figure 6.20) (Imeokparia, 1982; Foord et al., 1995; Lowell and Ahl, 2000; Shabani et al., 2003; Colombo et al., 2010; Johannes and Holtz, 2012). Moreover, most mineralised granitic lithologies host Fe-muscovitic dioctahedral micas, which are commonly attributed to late-stage greisenisation (Figure 6.20). This correlation reiterates the well-established importance of late-stage acidic fluids and greisenisation, in the mineralisation of granites (Heinrich, 1990; Taylor and Wall, 1993; Duchoslav et al., 2017; Wolf et al., 2018; Lehmann, 2020; Vonopartis et al., 2020a; Vonopartis et al., 2021b).

The divergent evolution between ferrous and magnesian micas, influences the incorporation of F and Sn into the trioctahedral mica structure, in the early stages of a felsic magma (Tischendorf et al., 2001). The development of more ferrous trioctahedral micas during granitic evolution, results in a greater incorporation of Sn and decreased uptake of F into the early micas (Christiansen and Lee, 1986; Tischendorf et al., 2001). This is apparent as the ferrous Nebo micas have significantly less F, in contrast to the magnesian micas in the Kgale granites (Figures 6.8j and 6.10j).

The decreased sequestration of F into the early-formed micas allowed a greater proportion of F to partition into the evolving magmatic-hydrothermal fluid of the Nebo granite. This consequently increased the acidity of the fluid and lowered the magmatic solidus. In addition, the sequestration of Sn into the Fe-mica provides a suitable Sn-hosting phase, which is readily altered at later stages (Taylor and Wall, 1993; Zhao et al., 2005; Heinrich, 2007; Duchoslav et al., 2017). This ferrous evolution of micas and late-stage F-enrichment is apparent in the mineralised Zaaiplaats tin granites, the Younger Granites of Central Nigeria and the Erongo Complex in Namibia (Figure 6.20a) (Imeokparia, 1981; Imeokparia, 1982; Kinnaird et al., 1985; Falster et al., 2018).

The increased presence of F (and B in some cases) is proposed as a key factor in mineralised A-Type granites, as it enhances the extent of granitic fractionation (Chorlton and Martin, 1978; Manning, 1981; Pollard et al., 1987; Finch and Tomkins, 2017; Vonopartis et al., 2021a). As expected, mineralised African A-type suites are more fractionated, with a Zr/Hf ratio close

to 15, whereas barren suites have a Zr/Hf ratio of 30 and above (Figure 4.13). The prolonging of granitic fractionation promoted the concentration of incompatible elements, thus improving the potential for metal- and fluid-saturation (Wolf et al., 2018; Lehmann, 2020; Vasyukova and Williams-Jones, 2020; Vonopartis et al., 2020a; Vonopartis et al., 2021a).

However, Vonopartis et al. (2021a) proposed that the opportunistic assimilation of crustal material had the ability to upgrade the economic potential of less fractionated and unfavourably sourced A-Type magmas. The Erongo and Spitzkoppe granites in Namibia are used as examples of this phenomenon (Vonopartis et al., 2021a). In addition to HFS elements, B in the Erongo granite is shown to be sourced from the Damaran metasediments (Trumbull et al., 2008; Falster et al., 2018). This assimilation accounts for the formation of tourmaline orbicules and promoted late-stage Sn mineralisation in the Erongo cupola. In contrast, the proximal and cogenetic Spitzkoppe stocks are barren, similarly fractionated, relatively tourmaline-poor and exhibit less crustal contamination (Haapala et al., 2007; Vonopartis et al., 2021a). Therefore, these examples highlight the substantial influence that assimilation imposes on the metallogenic potential of an A-Type magma.

In addition to fractionation and assimilation, Vonopartis et al. (2021a) discusses the implications of mantle plumes in promoting F and Cl content in a felsic magma. The crustal positioning of the plume would ideally be located beneath an Archean craton. This would allow crustal melting at granulitic facies, which facilitated the liberation of F, Cl and possibly Sn from hosting minerals (Finch and Tomkins, 2017). The early sourcing of these elements would significantly enhance the metallogenic potential of the resulting A-Type partial melts.

The presence of Cl is critical for metal complexation and transportation in hydrothermal fluids (Heinrich, 1990; Sherman, 2010; Duchoslav et al., 2017). The annites of the Nebo granite display a notable Cl content (Figure 6.6k) and fluid inclusions of the Bobbejaankop and Lease granites are shown to be hypersaline (Pollard et al., 1991a). Therefore, it is evident that there is an early abundance of Cl in the Zaaiplaats granitic system. The Cl content of the Nebo annites (Figure 6.6k) is not reflected in any of the micas from the Gaborone Granite Suite (Figure 6.8k). Although, there is no fluid inclusion data from the granites in Botswana, it is reasonable to conclude that the Cl-poor micas indicate a comparative Cl deficiency. Vonopartis et al. (2021a) suggested that lack of plume-related melting at high-temperature granulitic facies, in the formation of the Gaborone Granite Suite, reduced the potential F and

Cl content of the initial magma. This would have limited the extent of fractionation, metal transportation and ultimately would have hindered late-stage mineralisation in the Kgale granites.

An important event in the evolution of a mineralised granite suite is the formation and saturation of a compositionally suitable magmatic-hydrothermal fluid (Vonopartis et al., 2021a). The initial fractionally-controlled enrichment of the Nebo and initial Bobbejaankop granites is shown by their magmatic Al/Ti and Ge/Ti quartz ratios. In contrast, the later Bobbejaankop and most of the Lease granite exhibit dominantly magmatic-hydrothermal signatures, and are interpreted to have formed after fluid saturation (Figure 7.17). This subsequent fluid saturation significantly enhanced LIL and HFS element concentration in the Lease granite. This is evident by the exponential increase in average Sn content, from the Nebo through Bobbejaankop to the Lease granite (Figure 7.11) and concentration of Sn in the Lease granite as shown by pXRF mapping (Figures 3.8 and 3.10).

An acidic, F- and Cl-rich magmatic-hydrothermal fluid allowed the liberation of metals from metal-bearing phases, complexation in the fluid and their ultimate concentration into cupolas (Wolf et al., 2018; Lehmann, 2020; Vasyukova and Williams-Jones, 2020). The subsequent disruption in the physiochemical conditions of the fluid, caused by the interaction with formational waters, carapace fracture, boiling or greisenisation-induced neutralisation, could have initiated the precipitation of metals. Greisenisation, and the formation of ferrous dioctahedral micas, appears to be a common indication for late-stage HFS element mineralisation in most A-Type granite suites (Figure 6.16) (Lehmann, 2020; Vasyukova and Williams-Jones, 2020; Vonopartis et al., 2020a; Vonopartis et al., 2021a; Vonopartis et al., 2021b). Despite the evident interaction of the Kgale granite with hydrothermal fluids, the evolution and composition of the fluid was not conducive for late-stage mineralisation (Vonopartis et al., 2021a).

Therefore, the metallogenic evolution of A-Type granites proposed by Vonopartis et al. (2021a) is modified to include insights gained from the compositional investigation of mica and quartz: (i) magma generation from an enriched mantle source; (ii) high temperature melting beneath Archean cratons; (iii) extensive granitic fractionation; (iv) Fe-Li evolution of the trioctahedral micas; (v) the formation, accumulation and saturation of an acidic F- and Cl-rich magmatic-hydrothermal fluid; and (vi) a late-stage greisenisation event characterised by

Fe-muscovitisation, which induces metal precipitation. These six sequential stages are fundamental for a favourable metallogenic evolution of an A-Type granite suite. However, it is shown that this process may be augmented by the external enrichment of F, B, Cl or HFS elements during the evolution of the system.

8.4. Implications for Endogranitic Exploration

The use of geological proxies to vector endogranitic mineralisation is beneficial, as variations between mineralised and unmineralised facies in a granite are typically subtle. Vonopartis et al. (2020b) addressed this issue by demonstrating the effective use of remote sensing and pXRF field-mapping, in identifying hydrothermal fluid accumulation in granites. The spectral characteristics of chlorite and muscovite were used to develop band ratios $B6^3/(B7 \times B8 \times B9)$ and $(B5+B7)/B6$. These band ratios proved effective in identifying regions of increased chloritisation and muscovitisation respectively (Figure 3.4b, c).

The complementary pXRF mapping of incompatible elements, particularly the Rb/Ba isopleth (Figure 3.9), displays a concentration of hydrothermal fluids from the Bobbejaankop towards the Lease granite. The locations of fluid accumulation shown by pXRF mapping, correspond with regions of concentrated alteration inferred by remote sensing (Figure 3.10). These predicted locations of hydrothermal fluid concentrations are shown to frequently host disseminated cassiterite (Vonopartis et al., 2020b). Therefore, the combined use of these techniques provide an inexpensive tool to aid in the exploration for hydrothermal mineralisation.

The mineral chemistry of mica, tourmaline and quartz prove useful as proxies for endogranitic mineralisation in the Zaaipplaats tin field. Determination of the ferrous or magnesian nature and evolution of mica, indicates the likelihood of an A-Type granitoid to host late-stage mineralisation (Figure 6.20). The presence and evolution of Fe-Li trioctahedral micas in an A-Type granite is a positive metallogenic indicator (Figure 6.20b). In addition, the formation of late-stage Fe-rich dioctahedral micas via greisenisation, strongly suggests the precipitation of economically significant minerals (Figure 6.20).

Compositional differences between mineralised and barren tourmaline populations, from the Groenfontein tin mine, show a potential to be used as a proxy for tin mineralisation. The compositions of tourmaline reveal an affinity for cassiterite precipitation alongside Fe-schorl

tourmalines. These Fe-schorl tourmalines are restricted to the mineralised Lease microgranite and hydrothermal pipes (Vonopartis et al., 2021b). Therefore, tin mineralisation is confined above the Bobbejaankop–Lease contact, and to the late-stage expressions of the magmatic-hydrothermal fluid (Vonopartis et al., 2021b).

Trace-elements-in-quartz indicate the degree of granitic fractionation and can discriminate between magmatic, early- and late-magmatic-hydrothermal quartz (Figure 7.17). Moreover, the concentration of Sn-in-quartz is directly proportional to the whole-rock Sn content of the hosting granite (Figure 7.11). A decoupled depletion of Sn-in-quartz, relative to the whole-rock Sn content in the same granite, may indicate the precipitation of Sn from the fluid. Thus, trace elements-in-quartz demonstrate the ability to define the petrogenetic and hydrothermal evolution of a granitic system, determine the most fractionated lithologies and the point of fluid-saturation (Figure 7.17). Therefore, trace elements-in-quartz can vector towards granitoids with the potential for late-stage endogranitic mineralisation.

8.5. Future Research

This thesis has contributed to the understanding of the petrogenesis and mineralisation of the Zaaiplaats tin field and African A-Type granites. However, many questions remain unsolved and more have been identified as topics for future research.

The establishment of a trace elements-in-quartz method, in the LA-ICP-MS facilities at the University of the Witwatersrand, opens a new avenue of research into the evolution and mineralisation of the Bushveld Granites. The comparison of the Zaaiplaats data, with quartz from other mineralised systems in the Lebowa Granite Suite, will yield insight into the mechanisms of A-Type mineralisation. Moreover, the trace element analyses and mapping of minerals, including but not limited to mica, tourmaline, cassiterite and zircon may provide further insight into the petrogenesis of these granites (*cf.* Azadbakht and Lentz (2020) and Hong et al. (2017)).

The source of the B for the sporadic tourmalinisation in the Lebowa Granite Suite has not been addressed. Therefore, a B-isotopic study from the tourmalinised Bushveld Granites and B occurrences in the country rocks, can elucidate the controversy described by Vonopartis et al. (2021a). A similar approach to B isotopes in tourmaline is used by Trumbull et al. (2008), to unravel the evolution of tourmaline and source of B in the Erongo Ring Complex of Namibia.

This approach may be applied to the enigmatic source of Li in African A-Type granites. Understanding the origin of Li can explain the noted lack of Li in the Lebowa Granite Suite and Li-mineralisation in African A-Type granites (Vonopartis et al., 2021a).

A recent U-Pb dating of cassiterite and zircon from the tin mineralised Yazov granite, revealed the first documented evidence for inherited cassiterite in a granite (Neymark et al., 2020). A similar geochronological study may compare cassiterite from the Bobbejaankop and Lease granites with ages from the hydrothermal pipes and other occurrences of cassiterite. This would provide an age for the mineralisation of the South African tin province and describe any association with the 1,950 Ma age of the Bushveld Complex.

Trace elemental analyses of fluid inclusions in quartz, as demonstrated by Berni et al. (2020), could expand on the work by Pollard et al. (1991a). This will provide modern trace element and isotopic compositions of the magmatic-hydrothermal fluids. This research can be augmented by O, S and Fe isotopes, to determine the source of the late stage Fe^{3+} recorded by Fe-schorl tourmaline. A mass balance calculation using Fe^{3+} compositions of alkali-feldspars (Vilalva and Vlach, 2014) and Fe^{3+} -rich schorl (Novák et al., 2004) indicates the proposed alkali-feldspar source of Fe^{3+} for the Fe^{3+} -rich schorl is possible (Vonopartis et al., 2021b). Although, this Fe^{3+} -enrichment is difficult to further constrain and may be a topic for future research.

There is a poorly investigated mineralised part of the Lebowa Granite Suite 4 to 5 km North of Zaaiplaats, which is readily compared to the Bobbejaankop and Lease granites. These granites are on the farms of Appingendam Dam and Groenvley and are host to Sn-Mo-REE mineralisation (Crocker et al., 2001). A modern comparative study of the mineral compositions and geochemistry of these granites may explain the occurrence of REE mineralisation at Appingendam Dam and not at Zaaiplaats.

Despite being beyond the scope of this research, the overlying Rashoop Granophyre Suite was described during field mapping, however its formation and relationship to the granites remains debated (Skursch et al., 2020; Scoates et al., 2021). There is little geological data on the granophyres in the Zaaiplaats region and presents a potential geochemical and petrological research project. An investigation into the overlying granophyres will provide a more complete understanding of the Bushveld Complex and an indication to the possibility of undiscovered exogranitic mineralisation.

References

- Abdel-Rahman, A.-F.M. 1994. Nature of biotites from alkaline, calc-alkaline, and peraluminous magmas. *Journal of petrology*, 35, 525-541.
- Abdel-Rahman, A.-F.M. 1995. Chlorites in a spectrum of igneous rocks: mineral chemistry and paragenesis. *Mineralogical magazine*, 59, 129-141.
- Afshooni, S., Mirnejad, H., Esmaily, D. and Haroni, H.A. 2013. Mineral chemistry of hydrothermal biotite from the Kahang porphyry copper deposit (NE Isfahan), Central Province of Iran. *Ore Geology Reviews*, 54, 214-232.
- Aldiss, D., Tombale, A., Mapeo, R. and Chiepe, M. 1989. *The geology of the Kanye area*, Geological Survey Department. p. 170
- Allegre, C. and Minster, J. 1978. Quantitative models of trace element behavior in magmatic processes. *Earth and Planetary Science Letters*, 38, 1-25.
- Anderson, J.L. 1983. Proterozoic anorogenic granite plutonism of North America. *Geological Society of America Memoir*, 161, 133-154.
- Andreani, L., Stanek, K.P., Gloaguen, R., Krentz, O. and Domínguez-González, L. 2014. DEM-based analysis of interactions between tectonics and landscapes in the Ore Mountains and Eger Rift (East Germany and NW Czech Republic). *Remote Sensing*, 6, 7971-8001.
- Arth, J. 1976. Behaviour of trace elements during magmatic process summary of theoretical models and their applications. *Journal of Research of the U.S. Geological Survey*, 4, 41-47.
- Aseri, A.A., Linnen, R.L., Che, X.D., Thibault, Y. and Holtz, F. 2015. Effects of fluorine on the solubilities of Nb, Ta, Zr and Hf minerals in highly fluxed water-saturated haplogranitic melts. *Ore Geology Reviews*, 64, 736-746.
- Asran, A.M., Emam, A. and El-Fakharani, A. 2017. Geology, structure, geochemistry and ASTER-based mapping of Neoproterozoic Gebel El-Delhimmi granites, Central Eastern Desert of Egypt. *Lithos*, 358-372.
- Audétat, A., Garbe-Schönberg, D., Kronz, A., Pettke, T., Rusk, B., Donovan, J.J. and Lowers, H.A. 2015. Characterisation of a natural quartz crystal as a reference material for microanalytical determination of Ti, Al, Li, Fe, Mn, Ga and Ge. *Geostandards and Geoanalytical Research*, 39, 171-184.
- Azadbakht, Z. and Lentz, D.R. 2020. High-resolution LA-ICP-MS trace-element mapping of magmatic biotite: A new approach for studying syn-to post-magmatic evolution. *The Canadian Mineralogist*, 58, 293-311.
- Bacon, C.R. and Druitt, T.H. 1988. Compositional evolution of the zoned calcalkaline magma chamber of Mount Mazama, Crater Lake, Oregon. *Contributions to Mineralogy and Petrology*, 98, 224-256.
- Bailey, J.C. 1977. Fluorine in granitic rocks and melts: a review. *Chemical Geology*, 19, 1-42.
- Bailey, S. 1980. Summary of recommendations of AIPEA nomenclature committee. *Clay Minerals*, 15, 85-93.
- Bailey, S. and Lister, J.S. 1989. Structures, compositions, and X-ray diffraction identification of dioctahedral chlorites. *Clays and Clay Minerals*, 37, 193-202.
- Bailey, S.W. (Ed.) 1984. *Mica (Reviews in Mineralogy)*, 13, Mineralogical Society of America, p. 584.
- Bailie, R.H. and Robb, L.J. 2004. Polymetallic mineralization in the granites of the Bushveld Complex - examples from the central southeastern lobe. *South African Journal of Geology*, 107, 633-652.
- Bain, A.D.N. 1934. The Younger Intrusive Rocks of the Kudaru Hills, Nigeria. *Quarterly Journal of the Geological Society*, 90, 201-239.
- Balen, D. and Broska, I. 2011. Tourmaline nodules: products of devolatilization within the final evolutionary stage of granitic melt? *Geological Society, London, Special Publications*, 350, 53-68.

- Balen, D. and Petrinec, Z. 2011. Contrasting tourmaline types from peraluminous granites: a case study from Moslavačka Gora (Croatia). *Mineralogy and petrology*, 102, 117-134.
- Ballouard, C., Elburg, M.A., Tappe, S., Reinke, C., Ueckermann, H. and Doggart, S. 2020. Magmatic-hydrothermal evolution of rare metal pegmatites from the Mesoproterozoic Orange River pegmatite belt (Namaqualand, South Africa). *Ore Geology Reviews*, 116, 103252.
- Ballouard, C., Poujol, M., Boulvais, P., Branquet, Y., Tartese, R. and Vigneresse, J.-L. 2016. Nb-Ta fractionation in peraluminous granites: A marker of the magmatic-hydrothermal transition. *Geology*, 44, 231-234.
- Barbarin, B. 1999. A review of the relationships between granitoid types, their origins and their geodynamic environments. *Lithos*, 46, 605-626.
- Bartoli, O., Acosta-Vigil, A., Ferrero, S. and Cesare, B. 2016. Granitoid magmas preserved as melt inclusions in high-grade metamorphic rock. *American Mineralogist*, 101, 1543-1559.
- Batchelor, R. and Bowden, P. 1986. Major and trace element analyses of volcanic and sub-volcanic igneous rocks from the Nigeria–Niger anorogenic province. *Overseas Development Administration. Research Scheme*, 2679.
- Batchelor, R.A. and Bowden, P. 1985. Petrogenetic interpretation of granitoid rock series using multicationic parameters. *Chemical geology*, 48, 43-55.
- Bau, M. 1996. Controls on the fractionation of isovalent trace elements in magmatic and aqueous systems: evidence from Y/Ho, Zr/Hf, and lanthanide tetrad effect. *Contributions to Mineralogy and Petrology*, 123, 323-333.
- Bau, M. and Dulski, P. 1995. Comparative study of yttrium and rare-earth element behaviours in fluorine-rich hydrothermal fluids. *Contributions to Mineralogy and Petrology*, 119, 213-223.
- Bayliss, P. 1975. Nomenclature of the trioctahedral chlorites. *The Canadian Mineralogist*, 13, 178-180.
- Bayliss, P. 1983. Polytypes of pennantite. *The Canadian Mineralogist*, 21, 545-547.
- Bea, F., Pereira, M. and Stroh, A. 1994. Mineral/leucosome trace-element partitioning in a peraluminous migmatite (a laser ablation-ICP-MS study). *Chemical Geology*, 117, 291-312.
- Beaufort, D., Rigault, C., Billon, S., Billault, V., Inoue, A., Inoué, S., Patrier, P. and Ferrage, E. 2015. Chlorite and chloritization processes through mixed-layer mineral series in low-temperature geological systems—a review. *Clay Minerals*, 50, 497-523.
- Benincasa, E., Brigatti, M.F., Poppi, L. and Barredo, F.B. 2003. Crystal chemistry of dioctahedral micas from peraluminous granites: the Pedrobernardo pluton (Central Spain). *European Journal of Mineralogy*, 15, 543-550.
- Benn, C. 2012. Lithological discrimination in deeply weathered terrains using multielemental geochemistry—an example from the Yanfolila gold project, Mali. *Explore*, 156, 1-8.
- Bennett, J.M., Kemp, A.I. and Roberts, M.P. 2020. Microstructural controls on the chemical heterogeneity of cassiterite revealed by cathodoluminescence and elemental X-ray mapping. *American Mineralogist: Journal of Earth and Planetary Materials*, 105, 58-76.
- Berni, G.V., Wagner, T. and Fusswinkel, T. 2020. From a F-rich granite to a NYF pegmatite: Magmatic-hydrothermal fluid evolution of the Kymi topaz granite stock, SE Finland. *Lithos*, 105538.
- Berni, G.V., Wagner, T., Fusswinkel, T. and Wenzel, T. 2017. Magmatic-hydrothermal evolution of the Kymi topaz granite stock, SE Finland: mineral chemistry evidence for episodic fluid exsolution. *Lithos*, 292, 401-423.
- Beyth, M., Stern, R.J., Altherr, R. and Kröner, A. 1994. The late Precambrian Timna igneous complex, southern Israel: evidence for comagmatic-type sanukitoid monzodiorite and alkali granite magma. *Lithos*, 31, 103-124.
- Bierwirth, P. 2002. Evaluation of ASTER satellite data for geological applications. *Consultancy Report to Geoscience Australia: Symonston*.

- Blevin, P.L. and Chappell, B.W. 1992. The role of magma sources, oxidation states and fractionation in determining the granite metallogeny of eastern Australia. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 83, 305-316.
- Boardman, J. and Kruse, F. 1994. Automated spectral analysis: a geological example using AVIRIS data, north Grapevine Mountains, Nevada: in Proceedings, ERIM Tenth Thematic Conference on Geologic Remote Sensing. *Environmental Research Institute of Michigan, Ann Arbor, MI*, pp. 1-407-1-418.
- Bonin, B. 1990. From orogenic to anorogenic settings: evolution of granitoid suites after a major orogenesis. *Geological Journal*, 25, 261-270.
- Bonin, B. 2007. A-type granites and related rocks: Evolution of a concept, problems and prospects. *Lithos*, 97, 1-29.
- Bonin, B., Bébien, J. and Masson, P. 2002. Granite: A planetary point of view. *Gondwana Research*, 5, 261-273.
- Boudreaux, A.P. 2014. *Mineralogy and geochemistry of the Erongo Granite and interior quartz-tourmaline orbicules and NYF-type miarolitic pegmatites, Namibia*. Master of Science, University of New Orleans Thesis. p. 1-246.
- Bowden, P., Kinnaird, J.A., Diehl, M. and Pirajno, F. 1990. Anorogenic granite evolution in Namibia—a fluid contribution. *Geological Journal*, 25, 381-390.
- Bowden, P., Van Breemen, O., Hutchinson, J. and Turner, D.C. 1976. Paleozoic and Mesozoic age trends for some ring complexes in Niger and Nigeria. *Nature*, 259, 297–299.
- Breiter, K., Ackerman, L., Ďurišová, J., Svojtka, M. and Novák, M. 2014. Trace element composition of quartz from different types of pegmatites: A case study from the Moldanubian Zone of the Bohemian Massif (Czech Republic). *Mineralogical Magazine*, 78, 703-722.
- Breiter, K. and Müller, A. 2009. Evolution of rare metal-specialised granite melt documented by quartz chemistry. *European Journal of Mineralogy*, 21, 335-346.
- Brigatti, M.F. and Guggenheim, S. 2002. Mica crystal chemistry and the influence of pressure, temperature, and solid solution on atomistic models. *Reviews in Mineralogy and Geochemistry*, 46, 1-97.
- Brigatti, M.F., Lugli, C., Poppi, L., Foord, E.E. and Kile, D.E. 2000. Crystal chemical variations in Li- and Fe-rich micas from Pikes Peak batholith (central Colorado). *American Mineralogist*, 85, 1275-1286.
- Buriánek, D. and Novák, M. 2007. Compositional evolution and substitutions in disseminated and nodular tourmaline from leucocratic granites: examples from the Bohemian Massif, Czech Republic. *Lithos*, 95, 148-164.
- Burt, D.M. 1981. Acidity-salinity diagrams; application to greisen and porphyry deposits. *Economic geology*, 76, 832-843.
- Burt, D.M. and Perchuk, L. 1991. Vector representation of lithium and other mica compositions. In: *Progress in metamorphic and magmatic petrology*, 113-129.
- Butler, J., Bowden, P. and Smith, A. 1962. K/Rb ratios in the evolution of the Younger Granites of Northern Nigeria. *Geochimica et Cosmochimica Acta*, 26, 89-100.
- Candela, P.A. 1991. Physics of aqueous phase evolution in plutonic environments. *American Mineralogist*, 76, 1081-1091.
- Cawthorn, R.G. and Walraven, F. 1998. Emplacement and crystallization time for the Bushveld Complex. *Journal of Petrology*, 39, 1669-1687.
- Cerny, P. and Burt, D. 1984. Paragenesis, crystallochemical characteristics, and geochemical evolution in micas in granite pegmatites. *Micas*. *Reviews in Mineralogy*, Vol. 13, Mineralogical Society of America, 257-297.
- Cerny, P., Roberts, W., Ercit, T. and Chapman, R. 1985. Wodginite and associated oxide minerals from the Peerless pegmatite, Pennington County, South Dakota. *American Mineralogist*, 70, 1044-1049.

- Chaoka, T.R. 1988. *The Geology, Petrology and Geochemistry of the Kanye Volcanics and Nnywane Formation: Ramotswa Area, Southeast Botswana*. Unpub. M.Sc, Memorial Univ. Newfoundland. p. 172.
- Chappel, B. and White, A. 1974. Two contrasting granite types. *Pacific geology*, 8, 173-174.
- Chappell, B.W. and White, A.J.R. 2001. Two contrasting granite types: 25 years later. *Australian Journal of Earth Sciences*, 48, 489-499.
- Charles, J.-H., Whitehouse, M., Andersen, J.Ø., Shail, R. and Searle, M. 2018. Age and petrogenesis of the Lundy granite: Paleocene intraplate peraluminous magmatism in the Bristol Channel, UK. *Journal of the Geological Society*, 175, 44-59.
- Chaussidon, M. and Libourel, G. 1993. Boron partitioning in the upper mantle: an experimental and ion probe study. *Geochimica et Cosmochimica Acta*, 57, 5053-5062.
- Chaussidon, M. and Marty, B. 1995. Primitive boron isotope composition of the mantle. *Science*, 269, 383-386.
- Chen, G.-N. and Grapes, R. 2007. *Granite genesis: in-situ melting and crustal evolution*, Dordrecht , Netherlands, Springer. p. 278
- Chicharro, E., Martín-Crespo, T., Gómez-Ortiz, D., López-García, J.Á., Oyarzun, R. and Villaseca, C. 2015. Geology and gravity modeling of the Logrosán Sn-(W) ore deposits (Central Iberian Zone, Spain). *Ore Geology Reviews*, 65, 294-307.
- Chorlton, L.B. and Martin, R.F. 1978. The effect of boron on the granite solidus. *The Canadian Mineralogist*, 16, 239-244.
- Christiansen, E.H. and Lee, D.E. 1986. Fluorine and chlorine in granitoids from the Basin and Range province, western United States. *Economic Geology*, 81, 1484-1494.
- Ciesielczuk, J.M. 2012. Chlorite of hydrothermal origin formed in the Strzelin and Borów granites (Fore-Sudetic Block, Poland). *Geological Quarterly*, 56, 333-344, doi: [http://dx. doi. org/10.7306/gq.1025](http://dx.doi.org/10.7306/gq.1025).
- Clark, C.M. 2007. Tourmaline: Structural formula calculations. *The Canadian Mineralogist*, 45, 229-237.
- Clarke, D.B. 1992. *Granitoid Rocks. Topics in the Earth Sciences*, London., Chapman and Hall. p. 284
- Clemens, J. and Stevens, G. 2012. What controls chemical variation in granitic magmas? *Lithos*, 134, 317-329.
- Cocker, M.D. 1999. Geochemical mapping in Georgia, USA: a tool for environmental studies, geologic mapping and mineral exploration. *Journal of Geochemical Exploration*, 67, 345-360.
- Coetzee, J. 1984. *A Geochemical and Petrographical Investigation of the Low-Grade Tin Deposits in the Bobbejaankop Granite at the Zaaipplaats Tin Mine*. Unpub. M.Sc, University of Pretoria, p. 126.
- Coetzee, J. 1986. The Lease Granite - A Granophyric, Mirolitic Mineralised Granite at the Apical Region of a Tin-Tungsten System. *Transcripts of the Geological Society of South Africa*, 89, 335-345.
- Coetzee, J. and Twist, D. 1989. Disseminated Tin Mineralisation in the Roof of the Bushveld Granite Pluton at the Zaaipplaats Mine, with Implications for the Genesis of Magmatic Hydrothermal Tin Systems. *Economic Geology*, 84, 1817-1834.
- Collins, W.J., Beams, S.D., White, A.J.R. and Chappell, B.W. 1982. Nature and Origin of A-Type Granites with Particular Reference to Southeastern Australia. *Contributions to Mineralogy and Petrology*, 80, 189-200.
- Collins, W.J., Huang, H.-Q., Bowden, P. and Kemp, A. 2020. Repeated S-I-A-type granite trilogy in the Lachlan Orogen and geochemical contrasts with A-type granites in Nigeria: implications for petrogenesis and tectonic discrimination. *Geological society, London, special publications*, 491, 53-76.

- Colombo, F., Lira, R. and Dorais, M.J. 2010. Mineralogy and crystal chemistry of micas from the A-type El Portezuelo Granite and related pegmatites, Catamarca (NW Argentina). *Journal of Geosciences*, 55, 43-56.
- Corrie, P.K., Ninomiya, Y. and Aitchson, J.C. 2010. Applying Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Spectral Indices for Geological Mapping and Mineral Identification on the Tibetan Plateau. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science*, 48, 464-469.
- Cortes, C. and Vapnik, V. 1995. Support vector machine. *Machine learning*, 20, 273-297.
- Costi, H.T., Horbe, A.M.C., Borges, R.M.K., Dall'agnol, R., Rossi, A. and Sighnolfi, G. 2000. Mineral chemistry of cassiterites from Pitinga Province, Amazonian craton, Brazil. *Revista Brasileira de Geociências*, 30, 775-782.
- Creaser, R.A., Price, R.C. and Wormald, R.J. 1991. A-type granites revisited: Assessment of a residual-source model. *Geology*, 19(2), 163-166.
- Crocker, I. 1979. Metallogenic aspects of the Bushveld granites: fluorite, tin and associated rare-metal carbonate mineralisation. *Special Publication of the Geological Society of South Africa*, 5, 275-295.
- Crocker, I.T., Eales, H.V. and Ehlers, D.L. 2001. *The Fluorite, Cassiterite and Sulphide Deposits Associated with the Acid Rocks of the Bushveld Complex*, Pretoria Council for Geoscience. p. 151
- Crockett, R. 1972. *Geological Map of the Kanye Area (QDS 2425C) at 1: 125,000*, 1:125 000.
- Crosta, A.P., Azevedo, F. and Brodie, C. 2003. Targeting key alteration minerals in epithermal deposits in Patagonia, Argentina, using ASTER imagery and principal component analysis. *International Journal of Remote Sensing*, 24, 4233-4240.
- Cui, X., Wang, Q., Deng, J., Wu, H. and Shu, Q. 2019. Genesis of the Xiaolonghe quartz vein type Sn deposit, SW China: Insights from cathodoluminescence textures and trace elements of quartz, fluid inclusions, and oxygen isotopes. *Ore Geology Reviews*, 111, 102929.
- Cuney, M. and Barbey, P. 2014. Uranium, rare metals, and granulite-facies metamorphism. *Geoscience Frontiers*, 5, 729-745.
- De Caritat, P., Hutcheon, I. and Walshe, J.L. 1993. Chlorite geothermometry: a review. *Clays and clay minerals*, 41, 219-239.
- de La Roche, d.H., Letierrier, J.t., Grandclaude, P. and Marchal, M. 1980. A classification of volcanic and plutonic rocks using R1R2-diagram and major-element analyses—its relationships with current nomenclature. *Chemical geology*, 29, 183-210.
- De Waal, S. 1970. Nickel minerals from Barberton, South Africa: II. Nimite, a nickel-rich chlorite. *American Mineralogist: Journal of Earth and Planetary Materials*, 55, 18-30.
- De Waal, S.A. 1972. The Bushveld Granites in the Zaaipplaats Area. *Transactions of the Geological Society of South Africa*, 75, 135-143.
- de Wit, M. and Thiar, C. 2005. Metallogenic fingerprints of Archaean cratons. *Geological Society, London, Special Publications*, 248, 59-70.
- Debowski, B.P., Alves, M.I., Santos, A.C., Tavares Jr, A.D. and Gerald, M.C. 2019. Contribution to the understanding of the Rondonia Tin Province granites (SW Amazonian Craton) origin using U-Pb and Lu-Hf in zircon by LA-ICP-MS: implications to A-type granite genesis. *Journal of the Geological Survey of Brazil*, 2, 151-164.
- Deering, D. and Haas, R. 1980. Using Landsat digital data for estimating green biomass. *NASA Technical Memorandum*, 80727, 1.
- Dill, H.G. 2010. The “chessboard” classification scheme of mineral deposits: Mineralogy and geology from aluminum to zirconium. *Earth-Science Reviews*, 100, 1-420.
- Dostal, J. and Chatterjee, A.K. 2000. Contrasting behaviour of Nb/Ta and Zr/Hf ratios in a peraluminous granitic pluton (Nova Scotia, Canada). *Chemical Geology*, 163, 207-218.

- Drivenes, K., Larsen, R.B., Müller, A., Sørensen, B.E., Wiedenbeck, M. and Raanes, M.P. 2015. Late-magmatic immiscibility during batholith formation: assessment of B isotopes and trace elements in tourmaline from the Land's End granite, SW England. *Contributions to Mineralogy and Petrology*, 169, 1-27.
- Ducart, D.F., Silva, A.M., Toledo, C.L.B. and Assis, L.M.d. 2016. Mapping iron oxides with Landsat-8/OLI and EO-1/Hyperion imagery from the Serra Norte iron deposits in the Carajás Mineral Province, Brazil. *Brazilian Journal of Geology*, 46, 331-349.
- Duchoslav, M., Marks, M., Drost, K., McCammon, C., Marschall, H., Wenzel, T. and Markl, G. 2017. Changes in tourmaline composition during magmatic and hydrothermal processes leading to tin-ore deposition: the Cornubian Batholith, SW England. *Ore Geology Reviews*, 83, 215-234.
- Durance, P., Jowitt, S. and Bush, K. 2014. An assessment of portable X-ray fluorescence spectroscopy in mineral exploration, Kurnalpi Terrane, Eastern Goldfields Superterrane, Western Australia. *Applied Earth Science*, 123, 150-163.
- Dutrow, B.L. and Henry, D.J. 2011. Tourmaline: a geologic DVD. *Elements*, 7, 301-306.
- Dutrow, B.L. and Henry, D.J. 2018. Tourmaline compositions and textures: reflections of the fluid phase. *Journal of Geosciences*, 63, 99-110.
- Dyar, M.D., Taylor, M.E., Lutz, T.M., Francis, C.A., Guidotti, C.V. and Wise, M. 1998. Inclusive chemical characterization of tourmaline; Mossbauer study of Fe valence and site occupancy. *American mineralogist*, 83, 848-864.
- Eby, G.N. 1990. The A-type granitoids: A review of their occurrence and chemical characteristics and speculations on their petrogenesis. *Lithos*, 26, 115-134.
- Eby, G.N. 1992. Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. *Geology*, 20, 641-644.
- Eggerton, R.A. and Banfield, J.F. 1985. The alteration of granitic biotite to chlorite. *American Mineralogist*, 70, 902-910.
- Ekwere, S. 1985. Li, F and Rb contents and Ba/Rb and Rb/Sr ratios as indicators of postmagmatic alteration and mineralization in the granitic rocks of the Banke and Ririwai Younger Granite complexes, Northern Nigeria. *Mineralium Deposita*, 20, 89-93.
- El Bouseily, A. and El Sokkary, A. 1975. The relation between Rb, Ba and Sr in granitic rocks. *Chemical Geology*, 16, 207-219.
- EPS 2007. Method 6200: Field Portable X-ray Fluorescence Spectrometry for the Determination of Elemental Concentrations in Soil and Sediment. In: US Environmental Protection Agency, O.O.S.W.
- Eriksson, P.G., Reczko, B.F. and Piper, D.P. 1996. An interpretation of boron contents within a Palaeoproterozoic volcano-sedimentary succession: Pretoria Group, Transvaal Supergroup, South Africa. *Precambrian Research*, 78, 273-287.
- Falcon, L.M. 1985. Tin in South Africa. *Journal of the South African Institute of Mining and Metallurgy*, 85, 333-345.
- Falster, A.U., Simmons, W.B., Webber, K.L. and Boudreaux, A.P. 2018. Mineralogy and Geochemistry of the Erongo Sub-Volcanic Granite-Miarolitic-Pegmatite Complex, Erongo, Namibia Miarolitic Pegmatites, Erongo. *The Canadian Mineralogist*, 56, 425-449.
- Finch, E. and Tomkins, A. 2017. Fluorine and chlorine behaviour during progressive dehydration melting: Consequences for granite geochemistry and metallogeny. *Journal of Metamorphic Geology*, 35, 739-757.
- Finn, C.A., Bedrosian, P.A., Cole, J.C., Khoza, T.D. and Webb, S.J. 2015. Mapping the 3D extent of the Northern Lobe of the Bushveld layered mafic intrusion from geophysical data. *Precambrian Research*, 268, 279-294.

- Foord, E., Černý, P., Jackson, L., Sherman, D.M. and Eby, R. 1995. Mineralogical and geochemical evolution of micas from miarolitic pegmatites of the anorogenic Pikes Peak batholith, Colorado. *Mineralogy and Petrology*, 55, 1-26.
- Förster, H.-J., Tischendorf, G., Rhede, D., Naumann, R., Gottesmann, B. and Lange, W. 2005. Cs-rich lithium micas and Mn-rich lithian siderophyllite in miarolitic NYF pegmatites of the Königshain granite, Lausitz, Germany. *Neues Jahrbuch für Mineralogie-Abhandlungen: Journal of Mineralogy and Geochemistry*, 182, 81-93.
- Förster, H.-J., Tischendorf, G., Trumbull, R. and Gottesmann, B. 1999. Late-collisional granites in the Variscan Erzgebirge, Germany. *Journal of Petrology*, 40, 1613-1645.
- Foster, M.D. 1960a. Interpretation of the composition of lithium micas. *U.S. Geological Survey, Professional Paper*, 354-E, 115-147.
- Foster, M.D. 1960b. Interpretation of the composition of trioctahedral micas. *U.S. Geological Survey, Professional Paper*, 354-B, 11-46.
- Foster, M.D. 1962. Interpretation and a classification of the chlorite. *U.S. Geological Survey, Professional Paper*, 414, 1-33.
- Fourie, D.S. and Harris, C. 2011. O-isotope Study of the Bushveld Complex Granites and Granophyres: Constraints on Source Composition and Assimilation. *Journal of Petrology*, 52, 2221-2242.
- Fournier, H., Lee, J., Camacho, A. and Creaser, R. 2014. Retrogression of eclogite-facies shear zones by short-lived fluid infiltration during the Caledonian orogeny, Lofoten islands, Norway. *Geological Society, London, Special Publications*, 390, 443-466.
- Frindt, S., Haapala, I. and Pakkanen, L. 2004a. Anorogenic Gross Spitzkoppe granite stock in central western Namibia: Part I. Petrology and geochemistry. *American Mineralogist*, 89, 841-856.
- Frindt, S., Trumbull, R.B. and Romer, R.L. 2004b. Petrogenesis of the Gross Spitzkoppe topaz granite, central western Namibia: a geochemical and Nd–Sr–Pb isotope study. *Chemical Geology*, 206, 43-71.
- Fron del, C. 1955. Two chlorites: gonyerite and melanolite. *American Mineralogist: Journal of Earth and Planetary Materials*, 40, 1090-1094.
- Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J. and Frost, C.D. 2001. A geochemical classification for granitic rocks. *Journal of Petrology*, 42, 2033-2048.
- Frost, C.D. and Frost, B.R. 2011. On Ferroan (A-type) Granitoids: their Compositional Variability and Modes of Origin. *Journal of Petrology*, 52, 39-53.
- Fuchsloch, W.C. 2018. *Pegmatites of the Cape cross-U is pegmatite belt, Namibia: structural, mineralogical, geochemical and mineral chemical characterization with implications for petrogenesis and mineralisation*. PhD Thesis, University of the Witwatersrand. p. 210.
- Gad, S. and Raef, A. 2012. Factor analysis approach for composited ASTER band ratios and wavelet transform pixel-level image fusion: lithological mapping of the Neoproterozoic Wadi Kid area, Sinai, Egypt. *International journal of remote sensing*, 33, 1488-1506.
- Gao, P., Zheng, Y.F. and Zhao, Z.F. 2016. Experimental melts from crustal rocks: A lithochemical constraint on granite petrogenesis. *Lithos*, 226, 133-157.
- Gao, S., Liu, X., Yuan, H., Hattendorf, B., Günther, D., Chen, L. and Hu, S. 2002. Determination of forty two major and trace elements in USGS and NIST SRM glasses by laser ablation-inductively coupled plasma-mass spectrometry. *Geostandards Newsletter*, 26, 181-196.
- Girei, M.B., Li, H., Algeo, T.J., Bonin, B., Ogunleye, P.O., Bute, S.I. and Ahmed, H.A. 2019. Petrogenesis of A-type granites associated with Sn–Nb–Zn mineralization in Ririwai complex, north-Central Nigeria: Constraints from whole-rock SmNd and zircon LuHf isotope systematics. *Lithos*, 340, 49-70.
- GMRD-Sudan. 1981. *Geological map of the Sudan*. Khartoum: Ministry of Energy & Mines, Geological & Mineral Resources Department (GMRD).

- Götte, T. 2018. Trace element composition of authigenic quartz in sandstones and its correlation with fluid–rock interaction during diagenesis. *Geological Society, London, Special Publications*, 435, 373-387.
- Götze, J. 2009. Chemistry, textures and physical properties of quartz—geological interpretation and technical application. *Mineralogical Magazine*, 73, 645-671.
- Götze, J., Plötze, M., Graupner, T., Hallbauer, D.K. and Bray, C.J. 2004. Trace element incorporation into quartz: a combined study by ICP-MS, electron spin resonance, cathodoluminescence, capillary ion analysis, and gas chromatography. *Geochimica et Cosmochimica Acta*, 68, 3741-3759.
- Götze, J., Plötze, M. and Habermann, D. 2001. Origin, spectral characteristics and practical applications of the Cathodoluminescence (CL) of quartz – a review. *Mineralogy and Petrology*, 71, 225–250.
- Grapes, R.H. and Müller-Sigmund, H. 2010. Lightning-strike fusion of gabbro and formation of magnetite-bearing fulgurite, Cornone di Blumone, Adamello, Western Alps, Italy. *Mineralogy and Petrology*, 99, 67-74.
- Grebennikov, A. 2014. A-type granites and related rocks: petrogenesis and classification. *Russian Geology and Geophysics*, 55, 1353-1366.
- Green, A.A., Berman, M., Switzer, P. and Craig, M.D. 1988. A transformation for ordering multispectral data in terms of image quality with implications for noise removal. *IEEE Transactions on geoscience and remote sensing*, 26, 65-74.
- Green, T. and Pearson, N. 1987. An experimental study of Nb and Ta partitioning between Ti-rich minerals and silicate liquids at high pressure and temperature. *Geochimica et Cosmochimica Acta*, 51, 55-62.
- Green, T.H. 1995. Significance of Nb/Ta as an indicator of geochemical processes in the crust-mantle system. *Chemical Geology*, 120, 347-359.
- Grobler, D.F. 1996. *The Geology, Geochemistry and Geochronology of the Gaborone Granite Suite and Kanye Formation North of Mafikeng, South Africa*. Unpub. PhD dissertation, University of the Witwatersrand. p. 457.
- Grobler, D.F. and Walraven, F. 1993. Geochronology of Gaborone Granite Complex extensions in the area north of Mafikeng, South Africa. *Chemical Geology (Isotope Geoscience Section)*, 105, 319-337.
- Guarino, V. and Brigatti, M.F. 2018. Crystallization conditions of micas in oxidized igneous systems. *American Mineralogist*, 103, 1999-2010.
- Haapala, I. 1997. Magmatic and postmagmatic processes in tin-mineralized granites: topaz-bearing leucogranite in the Eurajoki rapakivi granite stock, Finland. *Journal of Petrology*, 38, 1645-1659.
- Haapala, I., Frindt, S. and Kandara, J. 2007. Cretaceous Gross Spitzkoppe and Klein Spitzkoppe stocks in Namibia: Topaz-bearing A-type granites related to continental rifting and mantle plume. *Lithos*, 97, 174-192.
- Hall, A. 1971. Greisenisation in the granite of Cligga Head, Cornwall. *Proceedings of the Geologists' Association*, 82, 209-IN1.
- Hallbauer, D. 1992. The use of selected trace elements in vein quartz and quartz pebbles in identifying processes of formation and source rocks. *Geological Society of South Africa*, 24, 157-159.
- Halter, W.E., Williams-Jones, A.E. and Kontak, D.J. 1998. Origin and evolution of the greisenizing fluid at the East Kemptville tin deposit, Nova Scotia, Canada. *Economic Geology*, 93, 1026-1051.
- Hanson, G.N. 1978. The application of trace elements to the petrogenesis of igneous rocks of granitic composition. *Earth and planetary science letters*, 38, 26-43.
- Hawthorne, F.C. and Dirlam, D.M. 2011. Tourmaline the indicator mineral: From atomic arrangement to Viking navigation. *Elements*, 7, 307-312.
- Hawthorne, F.C. and Henry, D.J. 1999. Classification of the minerals of the tourmaline group. *European journal of mineralogy*, 11, 201-215.

- Heaney, P.J. and Post, J.E. 1992. The widespread distribution of a novel silica polymorph in microcrystalline quartz varieties. *Science*, 255, 441-443.
- Heaney, P.J., Prewitt, C.T. and Gibbs, G.V. 2018. *Silica: Physical Behavior, Geochemistry, and Materials Applications*, 19 Walter de Gruyter GmbH & Co KG. p. 624.
- Heinrich, C.A. 1990. The chemistry of hydrothermal tin (-tungsten) ore deposition. *Economic Geology*, 85, 457-481.
- Heinrich, C.A. 2007. Fluid-fluid interactions in magmatic-hydrothermal ore formation. *Reviews in Mineralogy and Geochemistry*, 65, 363-387.
- Heinrich, C.A., Gunther, D., Audétat, A., Ulrich, T. and Frischknecht, R. 1999. Metal fractionation between magmatic brine and vapor, determined by microanalysis of fluid inclusions. *Geology*, 27, 755-758.
- Henderson, C., Martin, J.S. and Mason, R. 1989. Compositional relations in Li-micas from SW England and France: an ion-and electron-microprobe study. *Mineralogical Magazine*, 53, 427-449.
- Henry, D. and Dutrow, B. 2012. Tourmaline at diagenetic to low-grade metamorphic conditions: Its petrologic applicability. *Lithos*, 154, 16-32.
- Henry, D.J. and de Brodtkorb, M.K. 2009. Mineral chemistry and chemical zoning in tourmalines, Pampa del Tamboreo, San Luis, Argentina. *Journal of South American Earth Sciences*, 28, 132-141.
- Henry, D.J. and Guidotti, C.V. 1985. Tourmaline as a petrogenetic indicator mineral: an example from the staurolite-grade metapelites of NW Maine. *American mineralogist*, 70, 1-15.
- Henry, D.J., Novák, M., Hawthorne, F.C., Ertl, A., Dutrow, B.L., Uher, P. and Pezzotta, F. 2011. Nomenclature of the tourmaline-supergroup minerals. *American Mineralogist*, 96, 895-913.
- Henry, D.J., Sun, H., Slack, J.F. and Dutrow, B.L. 2008. Tourmaline in meta-evaporites and highly magnesian rocks: perspectives from Namibian tourmalinites. *European Journal of Mineralogy*, 20, 889-904.
- Hey, M.H. 1954. A new review of the chlorites. *Mineralogical Magazine and Journal of the Mineralogical Society*, 30, 277-292.
- Heynke, U., Leeder, O. and Schulz, H. 1992. On distinguishing quartz of hydrothermal or metamorphogenic origin in different monomineralic veins in the eastern part of Germany. *Mineralogy and Petrology*, 46, 315-329.
- Higashi, S. 1980. Mineralogical studies of hydrothermal dioctahedral mica minerals, Memoir Faculty Sei Kochi University, Ser.E, 1, 1-39.
- Hill, M., Barker, F., Hunter, D. and Knight, R. 1996. Geochemical Characteristics and Origin of the Lebowa Granite Suite, Bushveld Complex. *International Geology Review*, 38, 195-227.
- Hong, W. 2017. *Magmatic-hydrothermal volatile exsolution and mineralisation in Tasmanian Sn granites*. PhD, University of Tasmania. p. 304.
- Hong, W., Cooke, D.R., Zhang, L., Fox, N. and Thompson, J. 2017. Tourmaline-rich features in the Heemskirk and Pieman Heads granites from western Tasmania, Australia: Characteristics, origins, and implications for tin mineralization. *American Mineralogist*, 102, 876-899.
- Hong, W., Cooke, D.R., Zhang, L., Fox, N. and Thompson, J. 2019. Cathodoluminescence features, trace elements, and oxygen isotopes of quartz in unidirectional solidification textures from the Sn-mineralized Heemskirk Granite, western Tasmania. *American Mineralogist*, 104, 100-117.
- Howie, R., Zussman, J. and Deer, W. 1992. *An introduction to the rock-forming minerals*, Longman. p. 790.
- Huang, R. and Audétat, A. 2012. The titanium-in-quartz (TitaniQ) thermobarometer: A critical examination and re-calibration. *Geochimica et Cosmochimica Acta*, 84, 75-89.
- Huang, W.-L. and Wyllie, P. 1981. Phase relationships of S-type granite with H₂O to 35 kbar: Muscovite granite from Harney Peak, South Dakota. *Journal of Geophysical Research: Solid Earth*, 86, 10515-10529.

- Hunt, J.P. 2005. *Geological characteristics of iron-oxide-copper-gold (IOCG) type mineralisation in the western Bushveld Complex*, Unpub. MSc, University of the Witwatersrand. p. 267.
- Hunter, D.R. 1975. The regional geological setting of the Bushveld Complex (An adjunct to the provisional tectonic map of the Bushveld Complex). *University of the Witwatersrand, Economic Geology Research Unit*, 18.
- Icenhower, J. and London, D. 1996. Experimental partitioning of Rb, Cs, Sr, and Ba between alkali feldspar and peraluminous melt. *American Mineralogist*, 81, 719-734.
- IMA 2020. The New IMA List of Minerals. International Mineralogical Association (IMA).
- Imeokparia, E. 1982. Tin content of biotites from the Afu younger granite complex, Central Nigeria. *Economic Geology*, 77, 1710-1724.
- Imeokparia, E.G. 1981. Fluorine in biotites from the AFU younger granite complex (central Nigeria). *Chemical Geology*, 32, 247-254.
- Ismail, I., Baioumy, H., Ouyang, H., Mossa, H. and Aly, H.F. 2015. Origin of fluorite mineralizations in the Nuba Mountains, Sudan and their rare earth element geochemistry. *Journal of African Earth Sciences*, 112, 276-286.
- Jacamon, F. and Larsen, R.B. 2009. Trace element evolution of quartz in the charnockitic Kleivan granite, SW-Norway: The Ge/Ti ratio of quartz as an index of igneous differentiation. *Lithos*, 107, 281-291.
- Jahn, B.-m.W., Fuyuan; Capdevila, R; Martineau, F; Zhao, Zhenhua; Wang, Yixian 2001. Highly evolved juvenile granites with tetrad REE patterns: the Woduhe and Baerzhe granites from the Great Xing'an Mountains in NE China. *Lithos*, 59, 171-198.
- Jenness, J. 2006. Topographic position index (TPI) v. 1.2. Jenness Enterprises. *Tech. rep.*
- Jiang, H., Li, W.Q., Jiang, S.Y., Wang, H. and Wei, X.P. 2016. Geochronological, geochemical and Sr-Nd-Hf isotopic constraints on the petrogenesis of Late Cretaceous A-type granites from the Sibumasu Block, Southern Myanmar, SE Asia. *Lithos*, 268, 32-47.
- Jiang, S.-Y., Yang, J.-H., Novák, M. and Selway, J. 2003. Chemical and boron isotopic compositions of tourmaline from the Lavicky leucogranite, Czech Republic. *Geochemical Journal*, 37, 545-556.
- Jiang, W.-T., Peacor, D.R. and Buseck, P.R. 1994. Chlorite geothermometry?—contamination and apparent octahedral vacancies. *Clays and clay minerals*, 42, 593-605.
- Jiang, X.-Y., Ling, M.-X., Wu, K., Zhang, Z.-K., Sun, W.-D., Sui, Q.-L. and Xia, X.-P. 2018. Insights into the origin of coexisting A1-and A2-type granites: Implications from zircon Hf-O isotopes of the Huayuangong intrusion in the Lower Yangtze River Belt, eastern China. *Lithos*, 318, 230-243.
- Jochum, K.P., Weis, U., Stoll, B., Kuzmin, D., Yang, Q., Raczek, I., Jacob, D.E., Stracke, A., Birbaum, K. and Frick, D.A. 2011. Determination of reference values for NIST SRM 610–617 glasses following ISO guidelines. *Geostandards and Geoanalytical Research*, 35, 397-429.
- Johannes, W. and Holtz, F. 2012. *Petrogenesis and experimental petrology of granitic rocks*, Springer Science & Business Media. p. 335
- Jolliff, B., Papike, J. and Shearer, C. 1987. Fractionation trends in mica and tourmaline as indicators of pegmatite internal evolution: Bob Ingersoll pegmatite, Black Hills, South Dakota. *Geochimica et Cosmochimica Acta*, 51, 519-534.
- Juniper, D.N. and Kleeman, J.D. 1979. Geochemical Characterisation of some Tin-Mineralising Granites of New South Wales. *Journal of Geochemical Exploration*, 11, 321-333.
- Kamaunji, V.D., Wang, L.-X., Ahmed, H.A., Zhu, Y.-X., Vincent, V.I. and Girei, M.B. 2020. Coexisting A 1 and A 2 granites of Kudaru Complex: implications for genetic and tectonic diversity of A-type granite in the Younger Granite province, north-central Nigeria. *International Journal of Earth Sciences*, 109, 511-535.
- Kandara, J. 1998. *Petrography and geochemistry of the Klein Spitzkoppe granite complex, central-western Namibia*. Unpublished M. Sc. thesis, Department of Geology, University of Helsinki.

- Key, R.M. 1983. *The geology of the area around Gaborone and Lobatse, Kweneng, Kgatleng, Southern and South East districts*, Geological Survey Department, Ministry of Mineral Resources & Water Affairs. p. 230
- Key, R.M. and Ayres, N. 2000. The 1998 edition of the national geological map of Botswana. *Journal of African Earth Sciences*, 30, 427-451.
- Key, R.M. and Wright, E.P. 1982. The genesis of the Gaborone rapakivi granite complex in Southern Africa. *Journal of the Geological Society*, 132, 109-126.
- Kinnaid, J. 1985. Hydrothermal alteration and mineralization of the alkaline anorogenic ring complexes of Nigeria. *Journal of African Earth Sciences* (1983), 3, 229-251.
- Kinnaid, J.A. 1987. *Hydrothermal alteration and mineralisation of the Nigerian anorogenic ring complexes: with special reference to the Saiya Shokobo complex*. PhD. Thesis, St. Andrews University. p. 533.
- Kinnaid, J.A., Ixer, R.A. and Odling, N.W.A. 1985. Mineralogy, geochemistry and mineralisation of the Ririwai complex, northern Nigeria. *Journal of African Earth Sciences*, 3, 185-222.
- Kinnaid, J.A., Kruger, F.J. and Cawthorn, R.G. 2004. Rb-Sr and Nd-Sm isotopes in fluorite related to the granites of the Bushveld Complex. *South African Journal of Geology*, 107, 413-430.
- Kinnaid, J.A., Nex, P.A. and Milani, L. 2016. Tin in Africa. *Episodes*, 39, 361-380.
- Kirkland, C., Daly, J., Eide, E. and Whitehouse, M. 2007. Tectonic evolution of the Arctic Norwegian Caledonides from a texturally-and structurally-constrained multi-isotopic (Ar-Ar, Rb-Sr, Sm-Nd, U-Pb) study. *American Journal of Science*, 307, 459-526.
- Kleemann, G.J. 1985. *The geochemistry and petrology of the roofrocks of the Bushveld Complex east of Groblersdal*. M.Sc Dissertation, University of Pretoria. p. 178.
- Kleemann, G.J. and Twist, D. 1989. The Compositionally-zoned Sheet-like Granite Pluton of the Bushveld Complex: Evidence Bearing on the Nature of A-type Magmatism. *Journal of Petrology*, 30, 1383-1414.
- Koike, K., Nagano, S. and Kawaba, K. 1998. Construction and analysis of interpreted fracture planes through combination of satellite-image derived lineaments and digital elevation model data. *Computers & Geosciences*, 24, 573-583.
- Konopelko, D., Biske, G., Seltnann, R., Eklund, O. and Belyatsky, B. 2007. Hercynian post-collisional A-type granites of the Kokshaal Range, southern Tien Shan, Kyrgyzstan. *Lithos*, 97, 140-160.
- Konopelko, D., Seltnann, R., Biske, G., Lepekhina, E. and Sergeev, S. 2009. Possible source dichotomy of contemporaneous post-collisional barren I-type versus tin-bearing A-type granites, lying on opposite sides of the South Tien Shan suture. *Ore Geology Reviews*, 35, 206-216.
- Krivovichev, S.V., Armbruster, T., Organova, N.I., Burns, P.C., Seredkin, M.V. and Chukanov, N.V. 2004. Incorporation of sodium into the chlorite structure: the crystal structure of glagolevite, Na (Mg, Al)₆ [Si₃AlO₁₀](OH, O)₈. *American Mineralogist*, 89, 1138-1141.
- Kynaston, H., Mellor, E.T. and Swinburne, U.P. 1909. *The geology of the Waterberg Tin-fields*, Geological Survey of Pretoria. p. 124.
- Labuschagne, L.S. 2004. Evolution of the ore-forming fluids in the Rooiberg tin field, South Africa. *Memoir - Council for Geoscience*, 126.
- Landenberger, B. and Collins, W. 1996. Derivation of A-type granites from a dehydrated charnockitic lower crust: evidence from the Chaelundi Complex, Eastern Australia. *Journal of Petrology*, 37, 145-170.
- Larsen, R., Jacamon, F. and Kronz, A. 2009. Trace element chemistry and textures of quartz during the magmatic hydrothermal transition of Oslo Rift granites. *Mineralogical Magazine*, 73, 691-707.
- Larsen, R.B., Henderson, I., Ihlen, P.M. and Jacamon, F. 2004. Distribution and petrogenetic behaviour of trace elements in granitic pegmatite quartz from South Norway. *Contributions to Mineralogy and Petrology*, 147, 615-628.

- Larsen, R.B., Polve, M. and Juve, G. 2000. Granite pegmatite quartz from Evje-Iveland: trace element chemistry and implications for the formation of high-purity quartz. *Norges Geologiske Undersøkelse*, 436, 57-66.
- Le Vaillant, M., Barnes, S.J., Fiorentini, M.L., Santaguida, F. and Törmänen, T. 2016. Effects of hydrous alteration on the distribution of base metals and platinum group elements within the Kevitsa magmatic nickel sulphide deposit. *Ore Geology Reviews*, 72, 128-148.
- Le Vaillant, M., Barnes, S.J., Fisher, L., Fiorentini, M.L. and Caruso, S. 2014. Use and calibration of portable X-Ray fluorescence analysers: application to lithogeochemical exploration for komatiite-hosted nickel sulphide deposits. *Geochemistry: Exploration, Environment, Analysis*, 14, 199-209.
- Legros, H., Marignac, C., Tabary, T., Mercadier, J., Richard, A., Cuney, M., Wang, R.-C., Charles, N. and Lespinasse, M.-Y. 2018. The ore-forming magmatic-hydrothermal system of the Piaotang W-Sn deposit (Jiangxi, China) as seen from Li-mica geochemistry. *American Mineralogist: Journal of Earth and Planetary Materials*, 103, 39-54.
- Lehmann, B. 2020. Formation of tin ore deposits: A reassessment. *Lithos*, 105756.
- Lemière, B. 2018. A review of pXRF (field portable X-ray fluorescence) applications for applied geochemistry. *Journal of Geochemical Exploration*, 188, 350-363.
- Lenthal, D.H. 1974. Tin Production from the Bushveld Granites. *Economic Geology Research Unit (EGRU), Univ. Witwatersrand*, 93.
- Lenthall, D.H. and Hunter, D.R. 1977. The Geochemistry of the Bushveld Granites in the Potgietersrus Tin-Field. *Precambrian Research*, 5, 359-400.
- Li, H., Watanabe, K. and Yonezu, K. 2014. Geochemistry of A-type granites in the Huangshaping polymetallic deposit (South Hunan, China): Implications for granite evolution and associated mineralization. *Journal of Asian Earth Sciences*, 88, 149-167.
- Lillesand, T., Kiefer, C.W. and Chipman, J. 2014. *Remote sensing and image interpretation*, John Wiley & Sons. p. 720.
- Lira, R. and Poklepovic, M.F. 2017. Tourmaline orbicules in peraluminous monzogranites of Argentina: A study case of fluid-rock interaction between leucogranite and country-rock metasediments. *Journal of South American Earth Sciences*, 80, 272-290.
- Loiselle, M. and Wones, D. Characteristics and origin of anorogenic granites. *Geological Society of America*, 11, 468. Abstracts with Programs, 1979.
- London, D. 1999. Stability of tourmaline in peraluminous granite systems: the boron cycle from anatexis to hydrothermal aureoles. *European Journal of Mineralogy*, 11, 253-262.
- London, D. and Manning, D.A. 1995. Chemical variation and significance of tourmaline from southwest England. *Economic geology*, 90, 495-519.
- London, D., Morgan, G.B. and Hervig, R.L. 1989. Vapor-undersaturated experiments with Macusani glass + H₂O at 200 MPa, and the internal differentiation of granitic pegmatites. *Contributions to Mineralogy and Petrology*, 102, 1-17.
- Lowe, K. 1995. *Geology and geochemistry of the Gaborone granite complex and Kanye volcanic formation, southeastern Botswana*. Unpub. M.Sc, University of the Witwatersrand. p. 167.
- Lowell, G. and Ahl, M. 2000. Chemistry of dark zinnwaldite from Bom Futuro tin mine, Rondônia, Brazil. *Mineralogical Magazine*, 64, 699-709.
- Luth, W.C. 1969. The systems NaAlSi₃O₈-SiO₂ and KAlSi₂O₈ to 20 kb and the relationship between H₂O content, P_{H₂O} in granitic magmas. *American Journal of Science*, 267-A, 325-341.
- Manning, D. 1981. The effect of fluorine on liquidus phase relationships in the system Qz-Ab-Or with excess water at 1 kb. *Contributions to Mineralogy and Petrology*, 76, 206-215.
- Manning, D., Hill, P. and Howe, J. 1996. Primary lithological variation in the kaolinized St Austell Granite, Cornwall, England. *Journal of the Geological Society*, 153, 827-838.

- Marks, M.A., Marschall, H.R., Schühle, P., Guth, A., Wenzel, T., Jacob, D.E., Barth, M. and Markl, G. 2013. Trace element systematics of tourmaline in pegmatitic and hydrothermal systems from the Variscan Schwarzwald (Germany): the importance of major element composition, sector zoning, and fluid or melt composition. *Chemical Geology*, 344, 73-90.
- Matthew, M.W., Alber-Golden, S.M., Berk, A., Felde, G., Anderson, G.P., Gorodetzky, D., Paswaters, S. and Shippert, M. 2002. Atmospheric correction of spectral imagery: evaluation of the FLAASH algorithm with AVIRIS data. *Applied Imagery Pattern Recognition Workshop*, 157-163.
- McCarthy, T.S. and Fripp, R.E.P. 1980. The Crystallization History of a Granitic Magma, as Revealed by Trace Element Abundances. *Journal of Geology*, 88, 211-224.
- McCarthy, T.S. and Hasty, R.A. 1976. Trace element distribution and their relationship to the crystallization of granitic melts. *Geochimica et Cosmochimica Acta*, 40, 1351-1358.
- McDonough, W.F. and Sun, S.S. 1995. The composition of the Earth. *Chemical Geology*, 120, 223-253.
- McNaughton, N.J., Pollard, P.J., Groves, D.I. and Taylor, R.G. 1993. A Long-Lived Hydrothermal System in Bushveld Granites at the Zaaipplaats Tin Mine: Lead Isotope Evidence. *Economic Geology*, 88, 27-43.
- Meibom, A. and Anderson, D.I. 2003. The statistical upper mantle assemblage. *Earth and Planetary Science Letters*, 217, 123-139.
- Merensky, H. 1908. The rocks belonging to the area of the Bushveld Granite Complex, in which tin may be expected, with descriptions of the deposits actually found. *South African Journal of Geology*, 11, 25-42.
- Mészárosová, N., Skála, R., Matoušková, Š., Mikysek, P., Plášil, J. and Císařová, I. 2018. Hydrothermal-to-metasomatic overprint of the neovolcanic rocks evidenced by composite apatite crystals: a case study from the Maglovec Hill, Slanské vrchy Mountains, Slovakia. *Geologica Carpathica*, 69, 439-452.
- Migdisov, A.A. and Williams-Jones, A. 2014. Hydrothermal transport and deposition of the rare earth elements by fluorine-bearing aqueous liquids. *Mineralium Deposita*, 49, 987-997.
- Milner, S., Le Roex, A. and O'Connor, J. 1995. Age of Mesozoic igneous rocks in northwestern Namibia, and their relationship to continental breakup. *Journal of the Geological Society*, 152, 97-104.
- Mlynarczyk, M.S. and Williams-Jones, A.E. 2006. Zoned tourmaline associated with cassiterite: implications for fluid evolution and tin mineralization in the San Rafael Sn–Cu deposit, southeastern Peru. *The Canadian Mineralogist*, 44, 347-365.
- Möller, P., Dulski, P., Szacki, W., Malow, G. and Riedel, E. 1988. Substitution of tin in cassiterite by tantalum, niobium, tungsten, iron and manganese. *Geochimica et Cosmochimica Acta*, 52, 1497-1503.
- Monecke, T., Kempe, U., Monecke, J., Sala, M. and Wolf, D. 2002. Tetrad effect in rare earth element distribution patterns: a method of quantification with application to rock and mineral samples from granite-related rare metal deposits. *Geochimica et Cosmochimica Acta*, 66, 1185-1196.
- Monecke, T., Kempe, U., Petersen, S., Götze, J., Herzig, P. and Wolf, D. 1999. Trace element characteristics of quartz from the TAG hydrothermal mound (Mid-Atlantic Ridge at 26° 08' N). *Mineral Deposits: Processes to Processing. Balkema, Rotterdam, The Netherlands*, 551, p. 554.
- Monier, G. and Robert, J.-L. 1986. Evolution of the miscibility gap between muscovite and biotite solid solutions with increasing lithium content: an experimental study in the system K₂O–Li₂O–MgO–FeO–Al₂O₃–SiO₂–H₂O–HF at 600 C, 2 kbar P H₂O: comparison with natural lithium micas. *Mineralogical Magazine*, 50, 641-651.
- Moore, M., Davis, D., Robb, L., Jackson, M. and Grobler, D. 1993. Archean rapakivi granite-anorthosite-rhyolite complex in the Witwatersrand basin hinterland, southern Africa. *Geology*, 21, 1031-1034.

- Morgan, G.B. 2016. A spreadsheet for calculating normative mole fractions of end-member species for Na-Ca-Li-Fe²⁺-Mg-Al tourmalines from electron microprobe data. *American Mineralogist*, 101, 111-119.
- Mottana, A., Sassi, F.P., Thompson, J.B. and Guggenheim, S. 2018. *Micas: Crystal chemistry & metamorphic petrology*, Walter de Gruyter GmbH & Co KG. p. 513.
- Mountrakis, G., Im, J. and Ogole, C. 2011. Support vector machines in remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66, 247-259.
- Müller, A., Herklotz, G. and Giegling, H. 2018. Chemistry of quartz related to the Zinnwald/Cínovec Sn-W-Li greisen-type deposit, Eastern Erzgebirge, Germany. *Journal of Geochemical Exploration*, 190, 357-373.
- Müller, A., Ihlen, P.M. and Kronz, A. 2008. Quartz chemistry in polygeneration Sveconorwegian pegmatites, Froland, Norway. *European Journal of Mineralogy*, 20, 447-463.
- Muller, A. and Koch-Muller, M. 2009. Hydrogen speciation and trace element contents of igneous, hydrothermal and metamorphic quartz from Norway. *Mineralogical Magazine*, 73, 569-583.
- Müller, A., René, M., Behr, H.-J. and Kronz, A. 2003. Trace elements and cathodoluminescence of igneous quartz in topaz granites from the Hub Stock (Slavkovský Les Mts., Czech Republic). *Mineralogy and Petrology*, 79, 167-191.
- Müller, A., Seltmann, R. and Behr, H.-J. 2000. Application of cathodoluminescence to magmatic quartz in a tin granite—case study from the Schellerhau Granite Complex, Eastern Erzgebirge, Germany. *Mineralium Deposita*, 35, 169-189.
- Müller, A., van den Kerkhof, A.M., Behr, H.-J., Kronz, A. and Koch-Müller, M. 2010. The evolution of late-Hercynian granites and rhyolites documented by quartz—a review. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 100, 185-204.
- Nachit, H., Ibhi, A. and Ohoud, M.B. 2005. Discrimination between primary magmatic biotites, reequilibrated biotites and neoformed biotites. *Comptes Rendus Geoscience*, 337, 1415-1420.
- Nagaseki, H. and Hayashi, K.-i. 2008. Experimental study of the behavior of copper and zinc in a boiling hydrothermal system. *Geology*, 36, 27-30.
- Nash, W. and Crecraft, H. 1985. Partition coefficients for trace elements in silicic magmas. *Geochimica et Cosmochimica Acta*, 49, 2309-2322.
- Neiva, A.M.R., Silva, P.B., Corfu, F. and Ramos, J.M.F. 2011. Sequential melting and fractional crystallization: Granites from Guarda-Sabugal area, central Portugal. *Geochemistry*, 71, 227-245.
- Nelson, S.A. 2015. *Phyllosilicates (Micas, Chlorite, Talc and Serpentine)* [Online]. Tulane University. Available: <https://www.tulane.edu/~sanelson/eens211/phyllosilicates.pdf> [Accessed 27 February 2021].
- Nesse, W.D. 2009. *Introduction to mineralogy*, London, Oxford University Press. p. 438
- Neymark, L., Holm-Denoma, C.S., Larin, A., Moscati, R.J. and Plotkina, Y.V. 2020. LA-ICPMS U-Pb dating reveals cassiterite inheritance in the Yazov granite, Eastern Siberia: Implications for tin mineralization. *Mineralium Deposita*, 1-18.
- Nie, X., Wang, Z., Chen, L., Wang, G. and Li, Z. 2020. Geochemical Contrasts between Late Triassic Rb-Rich and Barren Pegmatites from Ningshan Pegmatite District, South Qinling Orogen, China: Implications for Petrogenesis and Rare Metal Exploration. *Minerals*, 10, 582.
- Norberg, N., Harlov, D., Neusser, G., Wirth, R. and Rhede, D. 2014. Element mobilization during feldspar metasomatism: an experimental study. *European Journal of Mineralogy*, 26, 71-82.
- Norrish, K. and Hutton, J.T. 1969. An accurate X-ray spectrographic method for the analysis of geologic samples. *Geochimica et Cosmochimica Acta*, 33, 431-454.
- Novák, M., Povondra, P., Selway, J.B., 2004. Schorl-oxy-schorl to dravite-oxy-dravite tourmaline from granitic pegmatites; examples from the Moldanubicum, Czech Republic. *European Journal of Mineralogy*, 16, 323-333.

- Ogunleye, P., Garba, I. and Ike, E. 2006. Factors contributing to enrichment and crystallization of niobium in pyrochlore in the Kaffo albite arfvedsonite granite, Ririwai Complex, Younger Granites province of Nigeria. *Journal of African Earth Sciences*, 44, 372-382.
- Palme, H. and O'Neill, H.S.C. 2003. Cosmochemical estimates of mantle composition. *The Mantle and Core. Treatise on geochemistry* 2 ed. Amsterdam, Elsevier. p. 568.
- Pan, Y. 1997. Controls on the fractionation of isovalent trace elements in magmatic and aqueous systems: evidence from Y/Ho, Zr/Hf, and lanthanide tetrad effect—a discussion of the article by M. Bau (1996). *Contributions to Mineralogy and Petrology*, 128, 405-408.
- Parra, T., Vidal, O. and Theye, T. 2005. Experimental data on the Tschermak substitution in Fe-chlorite. *American Mineralogist*, 90, 359-370.
- Pathak, M. and Kumar, S. 2019. Petrology, geochemistry and zircon U–Pb–Lu–Hf isotopes of Paleoproterozoic granite gneiss from Bomdila in the western Arunachal Himalaya, NE India. *Geological Society, London, Special Publications*, 481, 341-377.
- Paton, C., Hellstrom, J., Paul, B., Woodhead, J. and Hergt, J. 2011. Lolite: Freeware for the visualisation and processing of mass spectrometric data. *Journal of Analytical Atomic Spectrometry*, 26, 2508-2518.
- Paton, C., Woodhead, J.D., Hellstrom, J.C., Hergt, J.M., Greig, A. and Maas, R. 2010. Improved laser ablation U-Pb zircon geochronology through robust downhole fractionation correction. *Geochemistry, Geophysics, Geosystems*, p. 11.
- Peacor, D.R., Rouse, R.C. and Bailey, S.W. 1988. Crystal structure of franklinfurnaceite; a tri-dioctahedral zincosilicate intermediate between chlorite and mica. *American Mineralogist*, 73, 876-887.
- Pearce, J.A., Harris, N.B. and Tindle, A.G. 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of petrology*, 25, 956-983.
- Perkins, T., Adler-Golden, S., Matthew, M., Berk, A., Anderson, G., Gardner, J. and Felde, G. 2005. Retrieval of atmospheric properties from hyper and multispectral imagery with the FLAASH atmospheric correction algorithm. *Remote Sensing, International Society for Optics and Photonics*, 5979, p. 59790E.
- Pirajno, F. 1990. Geology, geochemistry and mineralisation of the Erongo Volcanic Complex, Namibia. *South African Journal of Geology*, 93, 485-504.
- Pirajno, F. 1994. Mineral resources of anorogenic alkaline complexes in Namibia: a review. *Australian Journal of Earth Sciences*, 41, 157-168.
- Pirajno, F., Phillips, D. and Armstrong, R.A. 2000. Volcanology and eruptive histories of the Erongo volcanic complex and the Paresis igneous complex, Namibia: implications for mineral deposit styles. *Communications of the Geological Survey of Namibia*, 12, 301-312.
- Pirajno, F. and Smithies, R. 1992. The FeO/(FeO+ MgO) ratio of tourmaline: a useful indicator of spatial variations in granite-related hydrothermal mineral deposits. *Journal of Geochemical Exploration*, 42, 371-381.
- Pokrovskii, V.A. and Helgeson, H.C. 1997. Thermodynamic properties of aqueous species and the solubilities of minerals at high pressures and temperatures: the system Al_2O_3 - H_2O - KOH . *Chemical Geology*, 137, 221-242.
- Pollard, P., Pichavant, M. and Charoy, B. 1987. Contrasting evolution of fluorine- and boron-rich tin systems. *Mineralium Deposita*, 22, 315-321.
- Pollard, P.J., Andrew, A.S. and Taylor, R.G. 1991a. Fluid Inclusion and Stable Isotope Evidence for Interaction between Granites and Magmatic Hydrothermal Fluids during Formation of Disseminated and Pipe-Style Mineralization at the Zaaiplaats Tin Mine. *Economic Geology*, 86, 121-141.

- Pollard, P.J. and Taylor, R.G. 1986. Progressive Evolution of Alteration and Tin Mineralisation: Controls by Interstitial Permeability and Fracture-Related Tapping of Magmatic Fluid Reservoirs in Tin Granites. *Economic Geology*, 81, 1795-1800.
- Pollard, P.J., Taylor, R.G. and Tate, N.M. 1989. Textural evidence for quartz and feldspar dissolution as a mechanism of formation for Maggs Pipe, Zaaiplaats tin mine, South Africa. *Mineralium Deposita*, 24, 210-218.
- Pollard, P.J., Taylor, R.G., Taylor, R.P. and Groves, D.I. 1991b. Petrographic and Geochemical Evolution of Pervasively Altered Bushveld Granites at the Zaaiplaats Tin Mine. *Economic Geology*, 88, 1401-1453.
- Price, J.D., Hogan, J.P., Gilbert, M.C., London, D. and Morgan, G.B. 1999. Experimental study of titanite-fluorite equilibria in the A-type Mount Scott Granite: Implications for assessing F contents of felsic magma. *Geology*, 27, 951-954.
- Putnis, A. 2002. Mineral replacement reactions: from macroscopic observations to microscopic mechanisms. *Mineralogical Magazine*, 66, 689-708.
- Putnis, A., Hinrichs, R., Putnis, C.V., Golla-Schindler, U. and Collins, L.G. 2007. Hematite in porous red-clouded feldspars: evidence of large-scale crustal fluid-rock interaction. *Lithos*, 95, 10-18.
- Rahaman, M., Van Breemen, O., Bowden, P. and Bennett, J. 1984. Age migrations of anorogenic ring complexes in Northern Nigeria. *The Journal of Geology*, 92, 173-184.
- Read, H.H. 1957. The granite controversy. *Geologiska Föreningen i Stockholm Förhandlingar*, 79, 591-593.
- René, M. 2018. Petrology, geochemistry and mineralogy of greisens associated with tin-tungsten mineralisation: Hub stock deposit at Krásno-Horní Slavkov ore district, Czech Republic. *Contributions to Mineralisation; Al-Juboury, Al, Ed.; InTech: Rijeka, Croatia*, 1-22.
- Renne, P.R., Glen, J.M., Milner, S.C. and Duncan, A.R. 1996. Age of Etendeka flood volcanism and associated intrusions in southwestern Africa. *Geology*, 24, 659-662.
- Rieder, M., Cavazzini, G., D'yakonov, Y.S., Frank-Kamenetskii, V., Gottardi, G., Guggenheim, S., Müller, G., Neiva, A., Radoslovich, E., Robert, J.-L., Sassi, F., Takeda, H., Weiss, Z. and Wones, D. 1999. Nomenclature of the micas. *The Canadian Mineralogist*, 36, 905-912.
- Rieder, M., Huka, M., Kučerová, D., Minařík, L., Obermajer, J. and Povondra, P. 1970. Chemical composition and physical properties of lithium-iron micas from the Krušné hory Mts.(Erzgebirge). *Contributions to Mineralogy and Petrology*, 27, 131-158.
- Rieder, R., Economou, T., Wänke, H., Turkevich, A., Crisp, J., Brückner, J., Dreibus, G. and McSween, H. 1998. The chemical composition of Martian soil and rocks returned by the mobile alpha proton X-ray spectrometer: Preliminary results from the X-ray mode. *Science*, 278, 1771-1774.
- Robb, L. 2005. *Introduction to ore-forming processes*, Oxford, UK, Blackwell Publishing. p. 373.
- Robb, L.J., Freeman, L.A. and Armstrong, R.A. 2000. Nature and longevity of hydrothermal fluid flow and mineralisation in granites of the Bushveld Complex, South Africa. *Earth Sciences*, 91, 269-281.
- Rockwell, B.W. 2012. Description and validation of an automated methodology for mapping mineralogy, vegetation, and hydrothermal alteration type from ASTER satellite imagery with examples from the San Juan Mountains, Colorado, U.S. *Geological Survey Scientific Investigations Map 3190*; U.S. Geological Survey: Reston, VA, USA, 2012; p. 35.
- Rowan, L.C. and Mars, J.C. 2003. Lithologic mapping in the Mountain Pass, California area using advanced spaceborne thermal emission and reflection radiometer (ASTER) data. *Remote sensing of Environment*, 84, 350-366.
- Rudnick, R. and Gao, S. 2003. Composition of the continental crust. *The Crust. Treatise on geochemistry* 2 ed. New York, Elsevier. p. 568.

- Rusk, B. and Reed, M. 2002. Scanning electron microscope–cathodoluminescence analysis of quartz reveals complex growth histories in veins from the Butte porphyry copper deposit, Montana. *Geology*, 30, 727-730.
- Ryan, J.G., Leeman, W.P., Morris, J.D. and Langmuir, C.H. 1996. The boron systematics of intraplate lavas: Implications for crust and mantle evolution. *Geochimica et Cosmochimica Acta*, 60, 415-422.
- Sabins, F.F. 1999. Remote sensing for mineral exploration. *Ore Geology Reviews*, 14, 157 - 183.
- SACS 1980. Stratigraphy of South Africa. Part 1 (L.E. Kent, comp.), Lithostratigraphy of the Republic of South Africa. *Handbook of the Geological Survey of South Africa*, 8, 690.
- Sakoma, E., Martin, R. and Williams-Jones, A. 2000. The late stages of evolution of the Kwandonkaya A-type granite complex, Nigeria, as deduced from mafic minerals. *Journal of African Earth Sciences*, 30, 329-350.
- Salih, M.-A., Abdallsamed, M.-I., Ma, C.-Q., Mustafa, H.-A., Ahmed, H.-A. and Wang, L.-X. 2020. Genesis of alkaline-peralkaline A-type granite from El Dair complex, SW Arabian-Nubian Shield, Sudan: geochronology, geochemistry and isotopic constraints. *Arabian Journal of Geosciences*, 13, 42.
- Salvi, S., Pokrovski, G.S. and Schott, J. 1998. Experimental investigation of aluminum-silica aqueous complexing at 300°C. *Chemical Geology*, 151, 51-67.
- Samson, I.M. and Sinclair, W.D. 1992. Magmatic hydrothermal fluids and the origin of quartz-tourmaline orbicules in the Seagull batholith, Yukon Territory. *The Canadian Mineralogist*, 30, 937-954.
- Schowengerdt, R.A. 2007. *Remote Sensing: Models and Methods for Image Processing*, San Diego, Elsevier. p. 522.
- Schrön, W., Schmädicke, E., Thomas, R. and Schmidt, W. 1988. Geochemische Untersuchungen an Pegmatitquarzen. *Zeitschrift für geologische Wissenschaften*, 16, 229-244.
- Scoates, J.S., Wall, C.J., Friedman, R.M., Weis, D., Mathez, E.A. and VanTongeren, J.A. 2021. Dating the Bushveld Complex: Timing of Crystallization, Duration of Magmatism, and Cooling of the World's Largest Layered Intrusion and Related Rocks. *Journal of Petrology*, 62, 1-39.
- Shabani, A.A., Lalonde, A.E. and Whalen, J.B. 2003. Composition of biotite from granitic rocks of the Canadian Appalachian orogen: a potential tectonomagmatic indicator? *The Canadian Mineralogist*, 41, 1381-1396.
- Shabani, A.A.T. 2009. Mineral chemistry of chlorite replacing biotite from granitic rocks of the Canadian Appalachians. *Journal of Sciences, Islamic Republic of Iran*, p. 20.
- Shahzad, F. and Gloaguen, R. 2011. TecDEM: A MATLAB based toolbox for tectonic geomorphology, Part 1: Drainage network preprocessing and stream profile analysis. *Computers & Geosciences*, 37, 250-260.
- Sharp, T., El Goresy, A., Wopenka, B. and Chen, M. 1999. A post-stishovite SiO₂ polymorph in the meteorite Shergotty: Implications for impact events. *Science*, 284, 1511-1513.
- Shaw, D. 1968. A review of K-Rb fractionation trends by covariance analysis. *Geochimica et Cosmochimica Acta*, 32, 573-601.
- Sherman, D. 2010. Metal complexation and ion association in hydrothermal fluids: insights from quantum chemistry and molecular dynamics. *Geofluids*, 10, 41-57.
- Shihua, S. and Jie, Y. 2000. Actual Fe-Li mica series as a series with □_{VI} constant but not with Al_{IV} or Al_{VI}. *Mineralogical Magazine*, 64, 755-775.
- Sibiya, V.B.B. 1988. *The Gaborone granite complex Botswana, southern Africa: an atypical rapakivi granite-massif anorthosite association*. Free University Press. p. 449.
- Simons, B., Andersen, J.C., Shail, R.K. and Jenner, F.E. 2017. Fractionation of Li, Be, Ga, Nb, Ta, In, Sn, Sb, W and Bi in the peraluminous Early Permian Variscan granites of the Cornubian Batholith: precursor processes to magmatic-hydrothermal mineralisation. *Lithos*, 278, 491-512.

- Sinclair, W.D. and Richardson, J.M. 1992. Quartz-tourmaline orbicules in the Seagull batholith, Yukon Territory. *The Canadian Mineralogist*, 30, 923-935.
- Singh, L.G. and Vallinayagam, G. 2012. Petrological and Geochemical Constraints in the Origin and Associated Mineralization of A-Type Granite Suite of the Dhiran Area, Northwestern Peninsular India. *Geosciences*, 2, 66-80.
- Sisson, T. 1994. Hornblende-melt trace-element partitioning measured by ion microprobe. *Chemical Geology*, 117, 331-344.
- Skinner, B.J. and Appleman, D.E. 1963. Melanophlogite, a cubic polymorph of silica. *American Mineralogist: Journal of Earth and Planetary Materials*, 48, 854-867.
- Skursch, O., Tegner, C., Leshner, C.E. and Cawthorn, R.G. 2020. Two expressions of the transition from mafic cumulates to granitoids in the Bushveld Complex, South Africa: Examples from the western and eastern limbs. *Lithos*, 372, 105671.
- Slack, J.F. 1996. Tourmaline associations with hydrothermal ore deposits. *Reviews in Mineralogy and Geochemistry*, 33, 559-643.
- Slack, J.F. and Trumbull, R.B. 2011. Tourmaline as a recorder of ore-forming processes. *Elements*, 7, 321-326.
- Söhnge, P.G. 1944. The Structure, Ore Genesis and Mineral Sequence of the Cassiterite Deposit in the Zaaiplaats Tin Mine, Potgietersrust District, Transvaal. *Transactions of the Geological Society of South Africa*, 47, 157-181.
- Soltani Dehnavi, A., McFarlane, C.R., Lentz, D.R., McClenaghan, S.H. and Walker, J.A. 2019. Chlorite-white mica pairs' composition as a micro-chemical guide to fingerprint massive sulfide deposits of the bathurst mining camp, Canada. *Minerals*, 9, 125.
- Spera, F.J., Bohrsen, W.A., Till, C.B. and Ghiorso, M.S. 2007. Partitioning of trace elements among coexisting crystals, melt, and supercritical fluid during isobaric crystallization and melting. *American Mineralogist*, 92, 1881-1898.
- Štemprok, M. 1987. Greisenization (a review). *Geologische Rundschau*, 76, 169-175.
- Stepanov, A., Mavrogenes, J.A., Meffre, S. and Davidson, P. 2014. The key role of mica during igneous concentration of tantalum. *Contributions to Mineralogy and Petrology*, 167, 1009.
- Stone, M., Klomínský, J. and Rajpoot, G. 1997. Composition of trioctahedral micas in the Karlovy Vary pluton, Czech Republic and a comparison with those in the Cornubian batholith, SW England. *Mineralogical Magazine*, 61, 791-807.
- Strauss, C.A. 1954. The geology and mineral deposits of the Potgietersrus tinfields. *South African Geological Survey Memoirs*, 46, 241.
- Strauss, C.A. and Truter, F.C. 1944. The Bushveld Granites in the Zaaiplaats Tin Mining Area. *Transactions of the Geological Society of South Africa*, 47, 47-77.
- Stussi, J. and Cuney, M. 1996. Nature of biotites from alkaline, calc-alkaline and peraluminous magmas by Abdel-Fattah M. Abdel-Rahman: a comment. *Journal of Petrology*, 37, 1025-1029.
- Sun, S.-S. and McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *Geological Society, London, Special Publications*, 42, 313-345.
- Suttner, L.J. and Leininger, R.K. 1972. Comparison of the trace element content of plutonic, volcanic, and metamorphic quartz from southwestern Montana. *Geological Society of America Bulletin*, 83, 1855-1862.
- Taewoo, K. 2017. *Mineralogy and Geochemistry of granitic pegmatite, Lichenhills, Outback Nunatak, North Victoria land, Antarctica*. Seoul National University. p. 87.
- Taylor, J.R. and Wall, V.J. 1993. Cassiterite solubility, tin speciation, and transport in a magmatic aqueous phase. *Economic Geology*, 88, 437-460.

- Taylor, S.R. and McLennan, S.M. 1985. The continental crust: its composition and evolution. Blackwell Publishing, Oxford, p. 312.
- Teng, F.-Z., Rudnick, R.L., McDonough, W.F. and Wu, F.-Y. 2009. Lithium isotopic systematics of A-type granites and their mafic enclaves: Further constraints on the Li isotopic composition of the continental crust. *Chemical Geology*, 262, 370-379.
- Thiéblemont, D., Liégeois, J., Fernandez-Alonso, M., Ouabadi, A., Le Gall, B., Maury, R., Jalludin, M., Vidal, M., Ouattara Gbélé, C. and Tchaméni, R. 2016. *Geological Map of Africa at 1: 10M scale*.
- Thomas, R., Förster, H.-J. and Heinrich, W. 2003. The behaviour of boron in a peraluminous granite-pegmatite system and associated hydrothermal solutions: a melt and fluid-inclusion study. *Contributions to Mineralogy and Petrology*, 144, 457-472.
- Tillberg, M., Maskenskaya, O.M., Drake, H., Hogmalm, J.K., Broman, C., Fallick, A.E. and Åström, M.E. 2019. Fractionation of Rare Earth Elements in Greisen and Hydrothermal Veins Related to A-Type Magmatism. *Geofluids*, 2019, 4523214.
- Tindle, A.G., Breaks, F.W. and Selway, J.B. 2002. Tourmaline in petalite-subtype granitic pegmatites: evidence of fractionation and contamination from the Pakeagama Lake and Separation Lake areas of northwestern Ontario, Canada. *The Canadian Mineralogist*, 40, 753-788.
- Tischendorf, G., Förster, H.-J. and Gottesmann, B. 2001. Minor-and trace-element composition of trioctahedral micas: a review. *Mineralogical Magazine*, 65(2), 249-276.
- Tischendorf, G., Forster, H.-J., Gottesmann, B. and Rieder, M. 2007. True and brittle micas: composition and solid-solution series. *Mineralogical Magazine*, 71, 285-320.
- Tischendorf, G., Gottesmann, B., Foerster, H.-J. and Trumbull, R.B. 1997. On Li-bearing micas: estimating Li from electron microprobe analyses and an improved diagram for graphical representation. *Mineralogical Magazine*, 61(6), 809-834.
- Tischendorf, G., Rieder, M., Förster, H.-J., Gottesmann, B. and Guidotti, C.V. 2004. A new graphical presentation and subdivision of potassium micas. *Mineralogical Magazine*, 68, 649-667.
- Tomkeieff, S.I. 1942. On the origin of the name 'quartz'. *Mineralogical Magazine and Journal of the Mineralogical Society*, 26, 172-178.
- Trumbull, R., Krienitz, M.-S., Gottesmann, B. and Wiedenbeck, M. 2008. Chemical and boron-isotope variations in tourmalines from an S-type granite and its source rocks: the Erongo granite and tourmalinites in the Damara Belt, Namibia. *Contributions to Mineralogy and Petrology*, 155, 1-18.
- Trumbull, R.B., Förster, H.-J. and Rhede, D. 2010. REE-Y-Th-U-bearing accessory minerals and their contribution to the lanthanide and actinide trace-element budget in an anorogenic granite from the Erongo Complex, NW Namibia. *Z. Geol. Wiss*, 38, 145-165.
- Tuttle, O.F. and Bowen, N.L. 1958. *Origin of Granite in the Light of Experimental Studies in the System: NaAlSi₃O₈*, Geological Society of America. p. 153
- Uribe-Mogollon, C. and Maher, K. 2020. White Mica Geochemistry: Discriminating Between Barren and Mineralized Porphyry Systems. *Economic Geology*, 115, 325-354.
- Vail, J.R. 1985. Alkaline ring complexes in Sudan. *Journal of African Earth Sciences*, 3, 51-59.
- Vail, J.R. 1989. Ring complexes and related rocks in Africa. *Journal of African Earth Sciences*, 8, 19-40.
- Van Breemen, O., Hutchinson, J. and Bowden, P. 1975. Age and origin of the Nigerian Mesozoic granites: a Rb-Sr isotopic study. *Contributions to Mineralogy and Petrology*, 50, 157-172.
- van der Meer, F.D., van der Werff, H.M.A., van Ruitenbeek, F.J.A., Hecker, C.A., Baller, W.H., Noomen, M.F., van der Meijde, M., Carranza, J.M., de Smeth, B.J. and Woldai, T. 2012. Multi- and hyperspectral geologic remote sensing: A review. *International Journal of Applied Earth Observation and Geoinformation*, 14, 112-128.
- Van der Werff, H. and Van der Meer, F. 2015. Sentinel-2 for mapping iron absorption feature parameters. *Remote sensing*, 7, 12635-12653.

- van Hinsberg, V.J., Henry, D.J. and Dutrow, B.L. 2011a. Tourmaline as a petrologic forensic mineral: A unique recorder of its geologic past. *Elements*, 7, 327-332.
- van Hinsberg, V.J., Henry, D.J. and Marschall, H.R. 2011b. Tourmaline: an ideal indicator of its host environment. *The Canadian Mineralogist*, 49, 1-16.
- Van Hinsbergen, D.J., Buiter, S.J., Torsvik, T.H., Gaina, C. and Webb, S.J. 2011. The formation and evolution of Africa from the Archaean to Present: introduction. *Geological Society, London, Special Publications*, 357, 1-8.
- Vapnik, V. SVM method of estimating density, conditional probability, and conditional density. 2000. IEEE International Symposium on Circuits and Systems. Emerging Technologies for the 21st Century. Proceedings (IEEE Cat No. 00CH36353), 2000. IEEE, 749-752.
- Vasyukova, O. and Williams-Jones, A. 2020. Partial melting, fractional crystallisation, liquid immiscibility and hydrothermal mobilisation—A ‘recipe’ for the formation of economic A-type granite-hosted HFSE deposits. *Lithos*, 356, 105300.
- Veksler, I.V. 2004. Liquid immiscibility and its role at the magmatic–hydrothermal transition: a summary of experimental studies. *Chemical Geology*, 210, 7-31.
- Veksler, I.V., Thomas, R. and Schmidt, C. 2002. Experimental evidence of three coexisting immiscible fluids in synthetic granitic pegmatite. *American Mineralogist*, 87, 775-779.
- Vidal, O. and Goffé, B. 1991. Cookeite $\text{LiAl}_4(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_8$: Experimental study and thermodynamical analysis of its compatibility relations in the $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2-\text{H}_2\text{O}$ system. *Contributions to Mineralogy and Petrology*, 108, 72-81.
- Villanova-de-Benavent, C., Tredoux, M., Aiglsperger, T. and Proenza, J. 2014. Ni–Mg-phylosilicates from Bon Accord, Barberton, South Africa: new data on willemseite and nimite. 21st General meeting of the IMA (IMA2014), Gauteng, South Africa, September, 2014. 1-5.
- Viswanathan, S. 1972. Geochemical Behaviour of Rb, Ba, Pb, Ti, Mn and Zn During Progressive Chloritization of Granitic Biotites. *Current Science Association*, 41, 655-658.
- Vilalva, F.C.J., Vlach, S.R.F., 2014. Geology, petrography and geochemistry of the A-type granites from the Morro Redondo Complex (PR-SC), southern Brazil, Graciosa Province. *Anais da Academia Brasileira de Ciencias*, 86, 85-116.
- Von Gruenewaldt, G.V. and Strydom, J.H. 1985. Geochemical Distribution Patterns Surrounding Tin-Bearing Pipes and the Origin of the Mineralizing Fluids at the Zaaipplaats Tin Mine, Potgietersrus District. *Economic Geology*, 80, 1201-1211.
- Vonopartis, L.C., Booysen, R., Nex, P.A.M., Kinnaird, J.A. and Robb, L.J. 2020b. Combined satellite and portable XRF exploration mapping of the Zaaipplaats tin field, South Africa. *South African Journal of Geology (in review)*.
- Vonopartis, L.C., Kinnaird, J.A., Nex, P.A.M., Robb, L.J., 2021a. African A-Type granites: A geochemical review on metallogenic potential. *Lithos*, 396-397
- Vonopartis, L.C., Nex, P.A.M., Kinnaird, J.A. and Robb, L.J. 2020a. Evaluating the Changes from Endogranitic Magmatic to Magmatic-Hydrothermal Mineralization: The Zaaipplaats Tin Granites, Bushveld Igneous Complex, South Africa. *Minerals*, 10, 379.
- Vonopartis, L.C., Van Niekerk, D., Nex, P.A.M., Kinnaird, J.A. and Robb, L.J. 2021b. Tourmaline and cassiterite compositions from A-Type Lebowa Granite Suite, South Africa Suite: A case study from the Zaaipplaats Tin Field. *The Canadian Mineralogist (in review)*.
- Walker, F.D.L., Lee, M.R. and Parsons, I. 1995. Micropores and micropore texture in alkali feldspars: geochemical and geophysical implications. *Mineralogical Magazine*, 59, 505-534.
- Walraven, F. 1986. Stratigraphy and structure of the Nebo Granite, Bushveld Complex, South Africa. *Abstracts Geocongress' 86*, 637-642.
- Walraven, F. and Hattingh, E. 1993. Geochronology of the Nebo Granite, Bushveld Complex. *South African Journal of Geology*, 96, 31-41.

- Walraven, F., Strydom, J.H. and Strydom, N. 1990. Rb-Sr open-system behaviour and its application as a pathfinder for Sn mineralisation in granites of the Bushveld Complex, South Africa. *Journal of Geochemical Exploration*, 37, 333-350.
- Walshe, J.L. 1986. A six-component chlorite solid solution model and the conditions of chlorite formation in hydrothermal and geothermal systems. *Economic Geology*, 81, 681-703.
- Wark, D.A. and Watson, E.B. 2006. TitaniQ: a titanium-in-quartz geothermometer. *Contributions to Mineralogy and Petrology*, 152, 743-754.
- Watari, T., Nansai, K. and Nakajima, K. 2020. Review of critical metal dynamics to 2050 for 48 elements. *Resources, Conservation and Recycling*, 155, 104669.
- Weiss, Z. 1991. Interpretation of chemical composition and X-ray diffraction patterns of chlorites. *Geologica Carpathica*, 42, 93-104.
- Whalen, J.B., Currie, K.L. and Chappell, B.W. 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and Petrology*, 95, 407-419.
- White, A.J.R. 1979. Sources of Granitic Magma. *Abstracts of Papers to be Presented at the Annual Meetings of the Geological Society of America and Associated Societies*. San Diego, California.
- Whitney, D.L. and Evans, B.W. 2010. Abbreviations for names of rock-forming minerals. *American mineralogist*, 95, 185-187.
- Wiewióra, A. and Weiss, Z. 1990. Crystallochemical classifications of phyllosilicates based on the unified system of projection of chemical composition: II. The chlorite group. *Clay Minerals*, 25, 83-92.
- Wigand, M., Schmitt, A.K., Trumbull, R.B., Villa, I.M. and Emmermann, R. 2004. Short-lived magmatic activity in an anorogenic subvolcanic complex: $^{40}\text{Ar}/^{39}\text{Ar}$ and ion microprobe U–Pb zircon dating of the Erongo, Damaraland, Namibia. *Journal of volcanology and geothermal research*, 130, 285-305.
- Wigand, M.O. 2005. *Geochemie und Geochronologie des Erongo-Komplexes, Namibia*. GeoForschungsZentrum Potsdam. p. 99.
- Williamson, B., Müller, A. and Shail, R. 2010. Source and partitioning of B and Sn in the Cornubian batholith of southwest England. *Ore Geology Reviews*, 38, 1-8.
- Williamson, B., Spratt, J., Adams, J., Tindle, A. and Stanley, C. 2000. Geochemical constraints from zoned hydrothermal tourmalines on fluid evolution and Sn mineralization: an example from fault breccias at Roche, SW England. *Journal of Petrology*, 41, 1439-1453.
- Wilson, A.H. 2012. A chill sequence to the Bushveld Complex: insight into the first stage of emplacement and implications for the parental magmas. *Journal of Petrology*, 53, 1123-1168.
- Wilson, J., Ferre, E.C. and Lespinasse, P. 2000. Repeated tabular injection of high-level alkaline granites in the eastern Bushveld, South Africa. *Journal of the Geological Society*, 157, 1077-1088.
- Wilson, M.G.C. and Anhaeusser, C.R. 1998. *The Mineral Resources of South Africa*, Silverton, Council for Geosciences. p. 740.
- Winter, J.D.N. 2010. *Principles of Igneous and Metamorphic Petrology*, Prentice Hall. p. 702
- Witt, W. 1988. Evolution of high-temperature hydrothermal fluids associated with greisenization and feldspathic alteration of a tin-mineralized granite, northeast Queensland. *Economic Geology*, 83, 310-334.
- Wolf, M., Romer, R.L., Franz, L. and López-Moro, F.J. 2018. Tin in granitic melts: The role of melting temperature and protolith composition. *Lithos*, 310, 20-30.
- Wolf, M.B. and London, D. 1997. Boron in granitic magmas: stability of tourmaline in equilibrium with biotite and cordierite. *Contributions to Mineralogy and Petrology*, 130, 12-30.
- Wu, D., Pan, J., Xia, F., Huang, G. and Lai, J. 2019. The Mineral Chemistry of Chlorites and Its Relationship with Uranium Mineralization from Huangsha Uranium Mining Area in the Middle Nanling Range, SE China. *Minerals*, 9, 199.
- Wyllie, P.J. 1977. Crustal anatexis: an experimental review. *Tectonophysics*, 43, 41-71.

- Xie, X., Byerly, G.R. and Ferrell Jr, R.E. 1997. Ilb trioctahedral chlorite from the Barberton greenstone belt: crystal structure and rock composition constraints with implications to geothermometry. *Contributions to Mineralogy and Petrology*, 126, 275-291.
- Yamaguchi, Y. and Naito, C. 2003. Spectral indices for lithologic discrimination and mapping by using the ASTER SWIR bands. *International Journal of Remote Sensing*, 24, 4311-4323.
- Yang, S.-Y., Jiang, S.-Y., Zhao, K.-D., Dai, B.-Z. and Yang, T. 2015. Tourmaline as a recorder of magmatic–hydrothermal evolution: an in situ major and trace element analysis of tourmaline from the Qitianling batholith, South China. *Contributions to Mineralogy and Petrology*, 170, 42.
- Yavuz, F., Kumral, M., Karakaya, N., Karakaya, M.Ç. and Yıldırım, D.K. 2015. A Windows program for chlorite calculation and classification. *Computers & geosciences*, 81, 101-113.
- Yin, R., Han, L., Huang, X.-L., Li, J., Li, W.-X. and Chen, L.-L. 2019. Textural and chemical variations of micas as indicators for tungsten mineralization: Evidence from highly evolved granites in the Dahutang tungsten deposit, South China. *American Mineralogist*, 104, 949-965.
- Young, N.E., Anderson, R.S., Chignell, S.M., Vorster, A.G., Lawrence, R. and Evangelista, P.H. 2017. A survival guide to Landsat preprocessing. *Ecology*, 98, 920-932.
- Zagorsky, V.Y., Peretyazhko, I.S., Sapozhnikov, A.N., Zhukhlistov, A.P. and Zvyagin, B.B. 2003. Borocookeite, a new member of the chlorite group from the Malkhan gem tourmaline deposit, Central Transbaikalia, Russia. *American Mineralogist*, 88, 830-836.
- Zane, A. and Rizzo, G. 1999. The compositional space of muscovite in granitic rocks. *The Canadian Mineralogist*, 37, 1229-1238.
- Zane, A. and Weiss, Z. 1998. A procedure for classifying rock-forming chlorites based on microprobe data. *Rendiconti Lincei*, 9, 51-56.
- Zaraisky, G.P., Aksyuk, A.M., Devyatova, V.N., Udoratina, O.V. and Chevychelov, V.Y. 2009. The Zr/Hf Ratio as a Fractionation Indicator of Rare-Metal Granites. *Petrology*, 17, 25-45.
- Zeh, A., Allan, H.W., Gudelius, D. and Gerdes, A. 2019. Hafnium Isotopic Composition of the Bushveld Complex requires Mantle Melt-Upper Crust Mixing: New Evidence from Zirconology of Mafic, Felsic and Metasedimentary Rocks. *Journal of Petrology*, 60(11), 2169-2200.
- Zeh, A., Gerdes, A. and Barton Jr, J.M. 2009. Archean accretion and crustal evolution of the Kalahari Craton—the zircon age and Hf isotope record of granitic rocks from Barberton/Swaziland to the Francistown Arc. *Journal of Petrology*, 50, 933-966.
- Zeh, A., Ovtcharova, M., Wilson, A.H. and Schaltegger, U. 2015. The Bushveld Complex was emplaced and cooled in less than one million years – results of zirconology, and geotectonic implications. *Earth and Planetary Science Letters*, 418, 103-114.
- Zhao, K.-D., Jiang, S.-Y., Jiang, Y.-H. and Wang, R.-C. 2005. Mineral chemistry of the Qitianling granitoid and the Furong tin ore deposit in Hunan Province, South China: implication for the genesis of granite and related tin mineralization. *European Journal of Mineralogy*, 17, 635-648.
- Zhou, G., Wu, Y., Wang, H., Qin, Z., Zhang, W., Zheng, J. and Yang, S. 2017. Petrogenesis of the Huashanguan A-type granite complex and its implications for the early evolution of the Yangtze Block. *Precambrian Research*, 292, 57-74.
- Zirakparvar, N.A., Mathez, E.A., Scoates, J.S. and Wall, C.J. 2014. Zircon Hf isotope evidence for an enriched mantle source for the Bushveld Igneous Complex. *Contributions to Mineralogy and Petrology*, 168, 1050.

Appendices

Appendix A: Glossary of important terms

Term	Definition
Alkaline	Rocks which have a sufficiently high alkali (K and Na) content to crystallise alkaline minerals.
Anorogenic Magmatism	The formation or intrusion of magmas that is not directly related to an orogenic event.
Borosilicate Phase	Through extensive fractional crystallisation, the concentration of volatiles such as B and H ₂ O allows the separation of an immiscible hydrous boron-rich siliceous phase.
Chloritisation	The process of alteration in which existing minerals are altered to chlorite through the interaction with magmatic-hydrothermal or hydrothermal fluids.
Craton	A large, stable piece of the Earth's continental lithosphere, which is composed of the amalgamation of ancient crystalline basement rocks.
Disseminated Mineralisation	A style of mineralisation in which ore minerals are scattered among the primary mineralogy of the host rock.
Economic	An occurrence of a specific commodity, in a sufficient quantity to financially justify the cost of mining during the present economy.
Endogranitic	Occurring within a granitic rock.
Exogranitic	Occurring outside, yet originating from a granitic rock
Exsolution	A petrographic texture which refers to the separation of two distinct mineral phases from a previously homogeneous solid solution.
Grade	The quantity of ore-mineral in an orebody.
Granite	A coarse-grained intrusive igneous rock which consists of feldspar, quartz, mica and/or amphibole minerals.
Greisenisation	The process of alteration in which feldspars and micas are altered to quartz, dioctahedral mica $\pm$ topaz $\pm$ tourmaline from the interaction with a fluorine-bearing hydrothermal fluid.
Growth Impingements	A petrographic texture of quartz, seen in cathodoluminescence, which refers to the hindering of a crystallographic growth on the side of a quartz crystal by the adhesion of bubbles, liquid, melt or an adjacent mineral.
Hydrothermal	A hot fluid phase.

Interstitial	A petrographic texture which refers to a mineral which occurs within the spaces between other mineral grains.
Isoleth Map	Map that uses lines to show areas of the same value with the areas between the lines being interpolated.
Magmatic	Molten or semi-crystalline melt from which minerals and rocks form.
Magmatic-Hydrothermal	Hot fluids which are specifically derived from within its hosting magmatic body.
Mantle Plume	The localised upwelling of mantle material that is more buoyant than the surrounding mantle material.
Metallogenic	A genetic term which relates to the formation of mineral deposits
Metaluminous	Rocks with an alumina saturation index of $Al_2O_3 < (CaO + Na_2O + K_2O)$ and $Al_2O_3 > (Na_2O + K_2O)$.
Miarolitic Cavity	Small irregularly shaped cavities, commonly found in felsic igneous rocks and pegmatites. These cavities are associated with hydrothermal fluids. They are lined by inwards projecting crystals and commonly infilled by quartz or another hydrothermal phase.
Microclinisation	The process of potassic alteration in involving an exchange of K for Na within mineral reactions, typically associated with the replacement of albitic plagioclase by potassic microcline.
Mineralised	A rock or lithology hosting economically important minerals or metals.
Multispectral	A set of data that has captured two or more wavelength ranges (bands) from the electromagnetic spectrum.
Oscillatory Growth	A petrographic texture of quartz, seen in cathodoluminescence, which refers to the repetitive sequence of distinct fine-grained cathodoluminescence bands during crystallographic growth.
Peralkaline	Rocks with alkaline geochemical characteristics and have an alumina saturation index of $Al_2O_3 < (Na_2O + K_2O)$
Peraluminous	Rocks with aluminous geochemical characteristics and have an alumina saturation index of $Al_2O_3 > (CaO + Na_2O + K_2O)$.
Petrogenesis	The processes and mechanisms that form igneous rocks.
Phenocryst	A petrographic texture which refers to a rock which hosts large mineral grains set within a finer-grained groundmass.

Platform	The physical structure on which the instruments are mounted.
Sector Zonation	A petrographic texture which refers to compositional differences within adjacent or coeval sectors within a single mineral
Space-Borne	A satellite or space vehicle that is orbiting the Earth.
Spatial Resolution	The number and size of the wavelength intervals which a sensor is capable to detect within the electromagnetic spectrum.
Spectral Resolution	The smallest size of an object that can be detected by a sensor.
Stanniferous	A rock or object that contains tin.
Terrane	A region with distinct geological features and characteristics.
Tin Province	A large area characterised by multiple episodes and styles of tin mineral mineralisation.
Tourmalinisation	The process of alteration in which feldspar and mica are converted to tourmaline from the interaction with a boron-bearing hydrothermal fluid.

Appendix B: List of samples from the Zaaiplaats tin field and Gaborone Granite Suite.

Sample		Type	TS	W.R	Qz	Mica	Tur	Cst	Alteration	BHC Depth (m)		Location			
										From	To	x	y	Mine	Country
FT3990	BG	Ocp	No	No	Y	Y	N	N	Mcl, Chl	-	-	28.775687	-24.054013	Groenfontein	ZAF
FT3983	BG	Ocp	No	No	Y	Y	Y	Y	Mcl, Gr, Tur	-	-	28.776096	-24.058519	Groenfontein	ZAF
FT3981	BG	Flt	No	No	Y	Y	Y	Y	Mcl, Gr, Tur	-	-	28.776096	-24.058519	Groenfontein	ZAF
FT3977	BG	Ocp	No	No	Y	Y	N	N	Mcl, Chl	-	-	28.774972	-24.057086	Groenfontein	ZAF
FT3972	BG	Ocp	No	No	Y	Y	N	N	Mcl, Gr, Chl, Tur	-	-	28.774959	-24.057171	Groenfontein	ZAF
FT3997	BG	Ocp	Yes	No	Y	Y	Y	N	Mcl, Gr, Chl, Tur	-	-	28.774915	-24.06515	Groenfontein	ZAF
FT3996	BG	Ocp	Yes	No	Y	Y	Y	N	Mcl, Gr, Chl, Tur	-	-	28.777421	-24.056847	Groenfontein	ZAF
FT3982	BG	Flt	Yes	No	Y	Y	Y	N	Mcl, Gr, Chl, Tur	-	-	28.776096	-24.058519	Groenfontein	ZAF
FT3979	BG	Flt	Yes	No	Y	Y	Y	Y	Mcl, Gr, Chl, Tur	-	-	28.774959	-24.057171	Groenfontein	ZAF
FT3978	BG	Ocp	Yes	No	Y	Y	N	N	Mcl, Chl	-	-	28.773073	-24.059811	Groenfontein	ZAF
FT3961	BG	Ocp	No	Yes	Y	Y	N	N	Mcl, Chl	-	-	28.781356	-24.068601	Groenfontein	ZAF
FT3960	BG	Ocp	No	Yes	Y	Y	N	N	Mcl, Chl	-	-	28.777423	-24.067375	Groenfontein	ZAF
FT3959	BG	Ocp	No	Yes	Y	Y	N	N	Mcl, Chl	-	-	28.778561	-24.06195	Groenfontein	ZAF
FT3946	BG	Ocp	No	Yes	Y	Y	N	N	Mcl, Chl	-	-	28.774385	-24.065046	Groenfontein	ZAF
FT3945	BG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.774369	-24.059516	Groenfontein	ZAF
FT3943	BG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.777834	-24.056758	Groenfontein	ZAF
FT3942	BG	Flt	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.776304	-24.057858	Groenfontein	ZAF
FT3941	BG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.774037	-24.060835	Groenfontein	ZAF
FT3940	BG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.774037	-24.060835	Groenfontein	ZAF
FT3939	BG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.774037	-24.060835	Groenfontein	ZAF
FT3118	BG	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	28.780731	-24.07145	Groenfontein	ZAF
FT3105	BG	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	28.773935	-24.0599	Groenfontein	ZAF
FT3962	BG-LG	Ocp	No	No	Y	Y	N	N	Mcl, Chl	-	-	28.771938	-24.062939	Groenfontein	ZAF
FT3963	BG-LG	Ocp	Yes	No	Y	Y	N	N	Mcl, Chl	-	-	28.771925	-24.062938	Groenfontein	ZAF
FT3994	LG	Ocp	No	No	Y	Y	Y	Y	Mcl, Gr, Chl, Tur	-	-	28.773659	-24.068778	Groenfontein	ZAF
FT3994	LG	Ocp	No	No	Y	Y	Y	Y	Mcl, Gr, Chl, Tur	-	-	28.773659	-24.068778	Groenfontein	ZAF
FT3993	LG	Ocp	No	No	Y	Y	Y	Y	Mcl, Gr, Chl, Tur	-	-	28.773185	-24.068581	Groenfontein	ZAF

Appendix B: Samples continued.

FT3957	LG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.772122	-24.067839	Groenfontein	ZAF
FT3956	LG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.770015	-24.067958	Groenfontein	ZAF
FT3955	LG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.778967	-24.071975	Groenfontein	ZAF
FT3954	LG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.777857	-24.071657	Groenfontein	ZAF
FT3953	LG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.776431	-24.072066	Groenfontein	ZAF
FT3952	LG	Ocp	No	Yes	Y	Y	Y	N	Mcl, Gr, Chl, Tur	-	-	28.776126	-24.073217	Groenfontein	ZAF
FT3951	LG	Ocp	No	Yes	Y	Y	Y	N	Mcl, Gr, Chl, Tur	-	-	28.773478	-24.070677	Groenfontein	ZAF
FT3950	LG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.775349	-24.068159	Groenfontein	ZAF
FT3949	LG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.774229	-24.068956	Groenfontein	ZAF
FT3948	LG	Ocp	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.773752	-24.06946	Groenfontein	ZAF
FT3117	LG	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.780487	-24.072221	Groenfontein	ZAF
FT3116	LG	Ocp	Yes	Yes	Y	Y	Y	N	Mcl, Gr, Chl, Tur	-	-	28.780226	-24.073232	Groenfontein	ZAF
FT3115	LG	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.779651	-24.074094	Groenfontein	ZAF
FT3107	LG	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	-	-	28.768876	-24.065046	Groenfontein	ZAF
FT3106	LG	Ocp	Yes	Yes	Y	Y	Y	N	Mcl, Gr, Chl, Tur	-	-	28.769866	-24.063699	Groenfontein	ZAF
FT3944	NG	Ocp	No	Yes	Y	Y	N	N	Chl	-	-	28.77895	-24.0554	Groenfontein	ZAF
FT3938	NG	Ocp	No	Yes	Y	Y	N	N	Chl	-	-	28.788993	-24.064183	Groenfontein	ZAF
FT3937	NG	Ocp	No	Yes	Y	Y	N	N	Chl	-	-	28.789274	-24.06373	Groenfontein	ZAF
FT3119	NG	Ocp	Yes	Yes	Y	Y	N	N	Chl	-	-	28.79204	-24.060416	Groenfontein	ZAF
FT3103	NG	Ocp	Yes	Yes	Y	Y	N	N	Chl	-	-	28.779389	-24.05391	Groenfontein	ZAF
FT3102	NG	Ocp	Yes	Yes	Y	Y	N	N	Chl	-	-	28.780233	-24.053387	Groenfontein	ZAF
ZP15-1	LG	BHC	Yes	No	Y	Y	Y	N	Mcl, Gr, Chl, Tur	0.17	0.5	28.754156	-24.047741	Zaaiplaats	ZAF
ZP15-2	LG	BHC	Yes	Yes	Y	Y	Y	Y	Mcl, Gr, Chl, Tur	7.19	7.52	"	"	Zaaiplaats	ZAF
ZP15-3	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	13.09	13.47	"	"	Zaaiplaats	ZAF
ZP15-4	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	20.1	20.39	"	"	Zaaiplaats	ZAF
ZP15-V	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	37.53	37.91	"	"	Zaaiplaats	ZAF
ZP46-1	LG	BHC	No	No	Y	Y	N	N	Mcl, Gr, Chl	0.83	1.07	28.750316	-24.045834	Zaaiplaats	ZAF
ZP46-2	LG	BHC	No	No	Y	Y	N	N	Mcl, Gr, Chl	4.29	4.65	"	"	Zaaiplaats	ZAF
ZP46-3	LG	BHC	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	7.15	7.52	"	"	Zaaiplaats	ZAF

Appendix B: Samples continued.

ZP46-4	LG	BHC	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	7.92	8.25	"	"	Zaaiplaats	ZAF
ZP46-5	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	10.58	10.81	"	"	Zaaiplaats	ZAF
ZP46-6	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	12.31	12.62	"	"	Zaaiplaats	ZAF
ZP46-7	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	18.36	18.75	"	"	Zaaiplaats	ZAF
ZP46-8	BG	BHC	No	Yes	Y	Y	N	N	Mcl, Gr, Chl	21.09	21.49	"	"	Zaaiplaats	ZAF
ZP46-V	BG	BHC	Yes	No	Y	Y	N	N	Mcl, Gr, Chl	15.93	16.91	"	"	Zaaiplaats	ZAF
ZP47-1	LG	BHC	Yes	No	Y	Y	Y	N	Mcl, Gr, Chl, Tur	0.34	0.72	28.750065	-24.045458	Zaaiplaats	ZAF
ZP47-2	LG	BHC	Yes	Yes	Y	Y	Y	Y	Mcl, Gr, Chl, Tur	1.23	1.56	"	"	Zaaiplaats	ZAF
ZP47-3	LG	BHC	No	No	Y	Y	N	N	Mcl, Gr, Chl	4.15	4.36	"	"	Zaaiplaats	ZAF
ZP47-4	LG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	4.36	4.63	"	"	Zaaiplaats	ZAF
ZP47-5	LG	BHC	Yes	No	Y	Y	N	N	Mcl, Gr, Chl	7.76	8	"	"	Zaaiplaats	ZAF
ZP47-6	LG	BHC	Yes	No	Y	Y	N	N	Mcl, Gr, Chl	8.82	9	"	"	Zaaiplaats	ZAF
ZP47-7	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	16	16.23	"	"	Zaaiplaats	ZAF
ZP47-8	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	18.2	18.53	"	"	Zaaiplaats	ZAF
ZP47-9	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	90.62	90.19	"	"	Zaaiplaats	ZAF
ZP47-10	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	111.69	112.06	"	"	Zaaiplaats	ZAF
ZP47-11	BG	BHC	Yes	Yes	Y	Y	N	N	Mcl, Gr, Chl	140.71	141.02	"	"	Zaaiplaats	ZAF
GG14	TG	Ocp	Yes	Yes	Y	Y	N	N	Alb, Mcl, Chl	-	-	25.565254	-25.194752	-	BWA
GG16	TG	Ocp	Yes	Yes	Y	Y	N	N	Alb, Mcl, Chl	-	-	25.587537	-25.125636	-	BWA
GG18	TG	Ocp	Yes	Yes	Y	Y	N	N	Alb, Mcl, Chl	-	-	25.614441	-25.095622	-	BWA
GG19	TG	Ocp	Yes	Yes	Y	Y	N	N	Alb, Mcl, Chl	-	-	25.514987	-25.192172	-	BWA
GG24	TG	Ocp	Yes	Yes	Y	Y	N	N	Alb, Mcl, Chl	-	-	25.469504	-25.208726	-	BWA
GG25	TG	Ocp	Yes	Yes	Y	Y	N	N	Alb, Mcl, Chl	-	-	25.52501	-25.154585	-	BWA
GG01	KG Mn	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.650846	-25.589002	-	BWA
GG04	KG Mn	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.675007	-25.589019	-	BWA
GG06	KG Mn	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.678854	-25.589321	-	BWA
GG10	KG Mn	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.617889	-25.491745	-	BWA
GG12	KG Mn	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.612271	-25.286923	-	BWA
GG17	KG Mn	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.59213	-25.120667	-	BWA
GG20	KG Mn	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.48776	-25.20244	-	BWA

Appendix B: Samples continued.

GG02	KG Mg	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.681169	-25.566786	-	BWA
GG05	KG Mg	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.675043	-25.592072	-	BWA
GG08	KG Mg	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.666934	-25.553774	-	BWA
GG09	KG Mg	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.569742	-25.579362	-	BWA
GG11	KG Mg	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.608671	-25.420619	-	BWA
GG22	KG Mg	Ocp	Yes	Yes	Y	Y	N	N	Mcl, Chl	-	-	25.479818	-25.203674	-	BWA

Abbreviations: Bobbejaankop Granite (BG); Lease Granite (LG); Nebo Granite (NG); Outcrop (Ocp); Float (Flt); Bore-Hole Core (BHC); Thin-Section (TS); Whole-rock analyses (W.R); Quartz (Qz); Tourmaline (Tur); Cassiterite (Cst); Microclinisation (Mcl); Albitisation (Alb); Chloritisation (Chl); Tourmalinisation (Tml); Greisenisation (Gr); South Africa (ZAF); Botswana (BWA).

Appendix C: Whole-Rock XRF and ICP-MS.

Appendix C1: Whole-Rock XRF majors and ICP-MS traces standards and data.

Representative rock samples from each locality were collected in-situ outcrop, using sledgehammers, pick hammers and angle grinders to ensure the samples were fresh and unweathered. Samples ranged in size and of appropriate mass to ensure sufficient material for all sectioning and XRF & ICP-MS analyses (>200g of powdered material). The samples were crushed using the carbon-steel jaw crusher and milled in a carbon-steel swing mill at the School of Geosciences, University of the Witwatersrand. The crusher and mill were cleaned with acetone between samples to avoid cross contamination.

The whole-rock XRF analyses were run on an Panalytical PW2404 X-ray fluorescence (XRF) spectrometer at the Earth Lab of the University of the Witwatersrand, Johannesburg. Replicate analyses were done on samples and were found to be within an acceptable degree of variability, showing the data to be precise. Various certified reference materials (Appendix C1 Table 1) were analysed with the unknown samples and were found to be within error. Blanks were run simultaneously with other samples to insure no contamination during analyses. Samples were handled and prepared in a clean laboratory environment.

Appendix C1 Table 1: Certified Reference Materials used in XRF Majors analyses

- NIM-P	- NIM-G
- NIM-D	- PCC1
- W2	- BHVO2
- NIM-S	- AGV2
- GSP2	- G2
- BCR2	- DTS1
- NIM-N	

Trace elements were determined using the Perkin Elmer DRC-e inductively coupled plasma mass spectrometer (ICP-MS) at the Earth Lab of the University of the Witwatersrand, Johannesburg. The unknown samples were analysed against certified primary solution standards (BCR2, BHVO2 and NIM-G) and internal reference materials (AGV-2, BCR-1 and BR-1) with every run to ensure the reliability of the data. Blanks were run simultaneously with other samples to insure no contamination during analyses. Samples were handled and prepared in a clean laboratory environment.

Appendix C2: Whole-Rock XRF majors and ICP-MS traces from the Zaaiplaats tin field.

Lithology	NG	NG	NG	NG	NG	BG	BG	BG	BG	BG	BG
Sample No.	GR3102	GR3938	GR3944	GR3103	GR3937	GR3952	GR3946	GR3942	GR3945	GR3959	GR3105
SiO ₂ (wt%)	76.40	75.71	76.02	76.29	76.21	76.31	76.42	75.75	75.83	76.61	75.13
TiO ₂	0.10	0.14	0.14	0.12	0.13	0.12	0.08	0.09	0.08	0.09	0.10
Al ₂ O ₃	11.89	11.82	11.74	11.72	11.67	11.93	11.68	11.62	11.60	11.56	11.53
FeO	2.19	2.59	2.69	2.41	2.80	1.45	2.19	2.43	2.47	2.28	2.59
MnO	0.04	0.07	0.04	0.02	0.02	0.00	0.03	0.02	0.02	0.01	0.03
MgO	0.06	0.07	0.06	0.10	0.10	0.12	0.11	0.10	0.06	0.11	0.09
CaO	0.35	0.64	0.37	0.26	0.23	0.15	0.90	1.04	1.04	0.55	1.43
Na ₂ O	3.30	2.78	3.18	2.94	3.08	2.70	2.71	3.03	2.91	2.87	2.70
K ₂ O	5.03	5.14	5.06	5.06	4.91	5.51	4.99	4.72	5.30	4.90	5.28
P ₂ O ₅	0.04	0.02	0.02	0.03	0.03	0.02	0.04	0.02	0.01	0.02	0.02
Cr ₂ O ₃	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
NiO	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00
LOI	0.89	1.26	0.74	1.04	0.97	0.82	1.08	1.19	0.91	1.06	0.95
Total	100.30	100.24	100.06	99.99	100.19	99.13	100.24	100.02	100.23	100.07	99.86
Li (ppm)	20.94	18.53	13.15	9.82	11.73	5.23	13.50	11.58	14.23	8.33	9.87
P	170.48	67.73	56.75	113.32	98.29	21.15	121.47	44.73	11.79	51.96	41.75
Sc	1.09	0.97	0.69	0.94	1.05	0.53	0.81	0.86	0.67	0.97	0.65
Ti	479.37	668.03	1092.34	622.15	962.93	701.37	468.22	411.04	450.38	511.85	568.66
V	1.58	1.49	0.33	1.27	1.65	0.45	0.51	1.05	0.22	1.06	1.52
Cr	2.33	2.47	3.10	1.70	5.72	3.30	4.02	1.47	1.97	2.81	5.74
Co	0.83	0.72	0.61	0.59	0.65	0.58	0.74	0.68	1.16	0.59	0.72
Ni	2.40	3.35	3.87	2.24	6.90	6.67	6.22	1.79	3.17	3.42	4.25
Cu	16.42	13.91	8.57	44.16	14.49	4.57	42.24	3.11	29.69	2.65	32.44
Zn	79.85	81.04	46.12	31.47	78.16	-0.64	2.82	14.62	19.45	-9.26	30.69
Ga	27.97	26.20	26.08	27.89	21.10	23.93	34.58	26.66	33.93	33.51	19.38
Rb	316.71	279.05	221.95	284.64	198.82	319.75	430.71	366.81	408.02	364.67	241.45
Sr	19.09	8.71	5.82	10.01	6.95	5.28	5.57	5.47	4.15	5.58	2.45
Y	121.37	168.59	122.17	214.04	105.86	64.44	169.31	153.62	551.24	81.36	207.21
Zr	366.55	404.57	357.85	418.65	365.39	208.38	243.71	427.97	245.82	237.86	276.92
Nb	50.10	30.87	40.28	40.13	41.43	23.90	61.60	50.14	30.71	49.68	36.70
Ba	306.16	180.05	92.00	279.54	193.56	145.86	105.61	89.55	79.50	94.23	42.86
Sn	6.80	7.29	10.19	8.47	7.62	9.15	13.34	10.83	15.45	8.45	7.93
Cs	3.04	3.15	0.90	1.98	1.00	1.61	1.54	1.98	0.97	2.99	0.96
Hf	14.06	13.18	11.93	14.59	13.32	9.56	11.86	18.46	11.50	11.26	10.47
Ta	3.91	2.45	2.79	3.04	3.16	2.20	4.72	4.04	2.10	3.98	2.12
W	1.76	2.49	3.24	2.62	3.71	3.53	5.81	1.75	19.17	2.08	10.03
Pb	47.55	30.10	83.66	25.46	12.84	3.45	6.97	9.33	13.16	7.04	6.19
Th	38.60	42.75	40.41	41.08	29.95	39.64	60.09	51.43	62.12	45.34	44.08
U	11.58	10.48	7.60	10.12	4.00	7.47	15.44	15.79	27.85	9.15	9.73
La (ppm)	107.44	111.62	77.02	94.83	53.58	45.62	110.52	108.45	99.97	51.98	109.50
Ce	171.35	213.15	147.45	132.74	110.86	82.68	194.35	204.45	278.15	78.65	180.77
Pr	17.82	22.76	17.15	21.96	12.23	6.07	20.49	20.50	43.15	8.49	21.20
Nd	63.15	87.96	66.90	91.89	49.53	20.74	73.22	77.40	203.31	29.37	79.41
Sm	11.38	18.34	14.33	21.65	10.74	4.06	15.28	15.94	64.78	6.13	16.86
Eu	0.98	0.78	0.56	1.17	0.86	0.22	0.47	0.42	1.18	0.23	0.35
Gd	12.76	21.02	16.36	26.14	12.15	5.55	18.01	17.56	65.93	7.32	18.21
Tb	1.95	3.28	2.62	4.40	2.04	1.08	3.08	2.70	12.78	1.40	3.02
Dy	13.29	22.20	17.38	28.63	13.93	8.69	22.20	18.14	88.72	10.55	20.72
Ho	2.98	4.72	3.76	6.12	3.06	2.10	4.98	3.99	19.08	2.54	4.64
Er	9.43	14.08	10.92	16.86	9.14	6.67	15.25	12.53	56.56	8.19	14.18
Tm	1.57	2.03	1.59	2.44	1.37	1.11	2.51	1.99	8.95	1.46	2.31
Yb	10.80	13.30	10.49	15.37	8.97	7.87	17.35	13.93	58.99	11.37	15.60
Lu	1.57	1.89	1.55	2.10	1.33	1.16	2.63	2.11	8.24	1.80	2.19

Appendix C1: Continued.

BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	LG	LG	LG
GR3941	GR3943	GR3961	ZP15-3	ZP15-4	ZP46-7	ZP46-8	ZP47-8	ZP47-10	ZP47-11	GR3116	GR3939	GR3957
75.96	76.18	77.13	77.35	76.12	76.75	76.00	75.28	75.04	74.59	75.01	75.20	74.22
0.09	0.14	0.09	0.08	0.07	0.10	0.10	0.08	0.08	0.09	0.07	0.07	0.06
11.52	11.44	11.39	11.46	11.69	12.26	11.78	10.99	11.30	11.34	12.25	12.20	12.16
2.96	2.86	2.08	1.62	1.95	1.35	1.78	3.70	3.95	3.41	1.56	2.52	2.44
0.02	0.02	0.02	0.02	0.04	0.01	0.01	0.01	0.01	0.01	0.02	0.06	0.04
0.08	0.05	0.11	0.10	0.10	0.23	0.10	0.08	0.08	0.10	0.08	0.20	0.21
0.97	0.42	0.38	0.36	1.04	0.09	0.69	0.92	0.71	0.79	1.47	1.01	1.33
2.81	3.09	2.90	2.70	2.84	1.79	2.68	2.29	2.79	2.38	2.94	2.06	2.83
5.14	4.91	4.57	5.25	5.15	5.65	5.42	5.24	5.24	5.53	5.16	5.07	4.82
0.02	0.02	0.03	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.01	0.01	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01
0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
1.00	0.86	1.10	0.67	1.05	1.04	0.82	0.90	0.74	0.90	1.30	1.88	1.45
100.59	100.00	99.84	99.62	100.08	99.29	99.39	99.50	99.96	99.16	99.88	100.28	99.59
17.49	24.32	10.96	14.61	17.11	21.28	14.61	8.22	6.75	8.47	11.65	19.63	22.45
36.63	49.39	100.58	14.44	10.66	11.23	14.44	10.63	8.41	8.07	22.79	40.15	7.44
0.99	1.10	0.83	1.44	1.53	1.80	1.44	1.61	1.44	1.26	1.14	1.21	0.98
388.23	682.97	525.04	962.94	1067.70	1051.47	962.94	1176.07	1128.64	426.51	463.77	291.62	376.59
1.28	1.32	0.57	2.13	1.39	0.60	2.13	0.63	0.83	0.60	1.32	1.84	0.20
1.96	1.97	2.42	2.40	1.46	1.57	2.40	3.28	1.43	1.23	1.68	3.83	2.41
0.99	0.48	0.97	60.62	0.66	0.84	60.62	0.34	0.39	0.23	0.43	1.18	1.10
2.73	2.29	3.74	18.26	1.56	1.50	18.26	1.20	1.46	1.13	2.26	5.36	3.72
46.92	20.95	14.60	22.24	16.03	6.28	22.24	5.18	18.88	2.13	15.00	26.01	222.46
41.06	87.08	20.00	47.15	51.46	60.32	47.15	24.52	34.77	39.46	39.86	22.31	57.87
26.99	24.27	32.24	33.28	32.49	38.65	33.28	28.36	32.47	35.93	34.36	32.28	40.78
386.94	335.37	306.74	407.97	422.23	446.17	407.97	412.64	344.88	382.06	470.88	640.53	459.39
3.56	7.54	6.17	7.65	5.67	8.04	7.65	6.09	4.96	5.70	3.19	6.09	10.22
179.50	144.34	101.09	119.20	154.43	184.64	119.20	127.49	93.97	178.42	157.89	258.31	211.24
237.52	329.35	256.18	209.47	247.26	309.50	209.47	297.03	254.78	244.35	389.41	401.46	352.02
50.03	31.99	48.43	51.24	50.32	77.44	51.24	33.72	41.08	42.21	110.48	103.13	110.39
74.74	216.20	131.60	149.96	129.97	124.94	149.96	164.06	151.68	186.91	93.33	215.11	130.53
13.05	11.81	8.42	17.77	17.88	22.45	17.77	15.16	54.41	19.36	17.62	43.16	80.02
1.19	2.22	1.27	3.18	2.18	2.55	3.18	3.92	2.57	3.43	3.60	4.97	1.53
9.68	10.77	12.12	9.80	12.67	16.50	9.80	13.93	11.42	11.21	20.36	21.10	20.93
3.29	2.37	3.40	3.70	4.47	5.61	3.70	4.65	4.85	3.60	7.48	8.39	7.72
8.60	3.82	1.31	7.64	5.30	8.99	7.64	11.06	11.62	6.61	8.90	12.97	99.89
10.73	23.66	10.25	32.81	11.40	8.73	32.81	6.79	6.85	4.72	13.57	11.79	16.56
34.15	42.74	53.81	41.00	43.52	54.43	41.00	38.78	38.49	45.66	48.71	69.75	77.14
11.64	12.17	12.78	12.67	17.44	18.60	12.67	15.66	5.73	11.63	17.21	28.76	31.34
124.50	172.42	53.14	84.57	63.62	74.96	84.57	62.81	90.33	83.23	61.12	113.06	91.59
244.21	289.42	102.89	150.77	113.62	151.30	150.77	123.63	160.90	171.13	121.26	211.54	138.60
29.51	31.42	10.52	13.27	10.26	13.85	13.27	9.73	10.90	13.97	10.62	17.30	12.57
122.39	118.61	41.64	48.84	39.02	49.20	48.84	39.46	38.43	58.64	39.67	59.05	39.53
27.16	21.29	9.78	13.87	11.79	13.73	13.87	13.08	10.52	20.97	8.78	11.82	8.02
0.52	1.13	0.31	0.54	0.33	0.34	0.54	0.35	0.33	0.67	0.36	0.56	0.53
27.54	23.90	11.48	14.64	13.03	14.61	14.64	14.67	10.84	24.17	10.40	15.00	10.71
4.14	3.38	2.10	2.49	2.56	2.80	2.49	2.68	1.92	4.77	1.94	2.67	2.13
25.60	20.94	15.54	17.86	21.47	24.01	17.86	22.78	14.52	23.16	15.75	21.03	18.65
5.03	4.23	3.54	3.70	4.61	5.46	3.70	4.86	3.19	5.05	3.90	5.20	4.98
14.85	12.50	10.95	10.96	15.13	15.68	10.96	16.41	10.42	15.26	14.00	18.53	18.05
2.18	1.80	1.84	1.67	2.12	2.73	1.67	2.26	1.64	3.23	2.51	3.40	3.48
14.41	11.94	13.53	11.01	15.18	21.07	11.01	16.69	11.56	22.85	18.66	25.37	26.78
2.02	1.73	1.99	1.53	2.10	2.77	1.53	2.31	1.69	2.78	2.84	3.90	4.31

Appendix C1: Continued.

LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG
GR3953	GR3954	GR3106	GR3948	GR3950	GR3958	GR3107	GR3115	GR3955	GR3940	LT1	LT2	LT3
75.34	76.63	76.81	76.08	75.79	75.38	74.88	76.18	75.70	75.43	75.10	75.29	76.05
0.06	0.07	0.06	0.06	0.06	0.06	0.06	0.09	0.06	0.05	0.07	0.07	0.07
12.12	12.12	12.11	12.11	12.09	12.06	12.03	11.87	11.85	11.64	12.10	12.05	12.34
2.42	1.59	0.96	1.46	1.99	2.79	2.48	2.59	1.66	2.00	2.30	2.75	1.67
0.07	0.08	0.07	0.02	0.04	0.02	0.05	0.02	0.05	0.01	0.04	0.04	0.03
0.15	0.13	0.17	0.09	0.10	0.15	0.16	0.14	0.11	0.16	0.19	0.13	0.13
0.84	0.62	1.16	0.98	0.79	0.63	0.49	0.72	1.18	1.53	1.32	0.64	0.88
2.29	2.01	2.63	2.98	2.65	2.39	2.28	0.90	2.19	2.26	2.42	2.41	2.55
5.11	5.16	4.98	5.02	5.12	5.19	5.10	6.32	5.04	5.36	5.07	5.21	5.21
0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.03
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.48	1.40	1.36	1.03	1.43	1.42	1.18	1.46	1.74	1.43	1.52	1.13	1.29
99.90	99.83	100.35	99.85	100.08	100.12	98.73	100.31	99.59	99.90	100.15	99.74	100.25
13.51	19.82	15.45	11.26	12.47	15.86	30.86	17.18	14.23	16.74	16.30	13.00	13.00
56.72	13.85	66.85	9.45	36.74	63.26	31.63	30.57	3.42	25.90	3.50	20.10	49.60
0.93	0.84	0.89	0.66	0.89	1.12	0.81	1.01	0.92	1.08	0.70	1.20	1.20
335.66	383.66	301.38	382.62	349.73	356.49	295.52	386.83	344.98	216.56	352.60	361.60	360.90
0.38	0.21	0.86	0.35	0.23	0.84	0.58	1.66	0.36	1.39	0.30	0.50	0.40
1.94	3.02	5.31	4.25	1.87	2.86	1.35	2.19	2.44	2.27	2.30	2.20	1.90
2.71	0.77	0.84	0.70	0.67	0.81	0.51	0.97	0.48	0.98	0.50	2.00	0.70
3.54	6.68	3.72	5.20	2.61	3.23	1.84	2.46	2.99	2.81	2.70	3.20	2.50
8.24	17.22	3.70	99.23	77.05	174.19	400.06	42.03	0.24	53.30	16.20	13.60	20.00
5.43	11.95	16.03	50.36	13.65	3.69	38.10	72.69	4.70	56.30	29.00	29.60	21.60
37.70	38.42	33.28	35.33	35.35	40.83	36.60	39.02	34.54	33.12	30.40	31.80	31.50
477.52	594.48	506.22	451.55	519.13	552.52	535.09	631.01	504.01	529.69	470.90	560.20	560.10
5.18	7.67	6.28	4.84	4.73	7.76	7.01	3.59	4.76	4.89	4.60	5.20	5.70
170.91	241.18	206.22	172.19	164.40	156.53	115.84	185.73	124.72	175.79	64.20	169.00	124.20
365.89	349.50	358.14	332.11	301.78	321.85	360.91	319.53	329.48	160.77	340.10	386.40	419.20
98.09	122.58	100.27	68.98	118.00	112.18	95.00	82.32	114.64	89.22	115.30	111.50	133.20
248.47	161.37	162.50	193.00	126.21	135.25	124.84	130.38	98.59	107.12	76.00	128.80	100.50
45.63	10.42	9.47	13.40	22.61	39.45	165.52	25.52	8.70	18.21	6.40	7.00	6.70
2.47	2.95	2.88	8.94	2.04	2.54	2.16	4.41	3.79	2.41	2.30	3.00	2.80
21.64	20.34	18.10	16.02	17.38	19.14	18.69	15.00	19.44	10.19	17.20	19.90	21.40
7.40	9.00	7.83	4.48	8.63	7.69	7.70	5.79	8.62	8.91	9.60	9.70	10.20
7.35	15.57	5.37	5.94	15.33	22.43	12.26	5.73	7.26	9.99	9.70	16.90	12.80
9.88	17.34	10.68	13.88	37.04	9.64	15.26	16.87	10.08	33.58	12.10	10.90	14.10
84.21	95.85	57.78	55.33	82.82	82.61	65.78	68.04	80.88	41.55	48.30	72.60	66.60
15.96	34.54	22.40	11.77	20.69	16.09	24.09	26.67	15.02	44.07	12.60	13.10	14.30
141.72	22.25	95.07	99.96	116.28	95.03	193.42	484.66	71.60	166.20	58.80	89.70	67.30
204.63	20.34	134.70	138.06	170.70	155.98	301.92	451.43	115.79	271.86	108.40	128.40	113.90
15.78	3.12	11.80	14.15	17.15	14.21	25.66	42.17	12.47	24.53	8.20	12.70	9.20
47.44	17.24	38.28	47.29	58.89	44.11	79.91	108.67	44.35	72.13	25.50	43.40	29.30
7.99	7.73	8.58	8.64	9.91	9.40	8.70	16.08	9.63	12.88	5.40	10.40	7.70
0.47	0.46	0.51	0.43	0.45	0.49	0.52	0.83	0.44	0.55	0.30	0.60	0.40
11.36	10.30	10.71	11.79	11.65	10.98	10.55	20.17	10.68	14.46	4.90	9.50	7.20
1.94	2.50	1.96	2.14	2.04	2.15	1.40	2.63	1.77	2.44	1.00	2.40	1.90
15.96	22.18	15.24	17.18	16.24	17.34	10.11	17.20	13.04	18.59	6.50	15.50	12.30
4.14	5.87	3.83	4.29	4.09	4.29	2.49	3.66	3.21	4.31	1.70	4.20	3.30
14.83	20.64	13.05	14.36	14.39	14.91	9.23	12.28	11.70	14.62	6.10	14.60	11.60
2.85	3.85	2.40	2.63	2.66	2.97	1.74	1.98	2.25	2.45	1.20	2.90	2.30
21.77	28.23	17.40	19.48	20.54	24.00	13.41	13.61	18.00	17.31	9.80	23.50	18.70
3.53	4.41	2.60	3.14	3.32	3.74	2.00	1.95	2.88	2.49	1.70	4.00	3.20

Appendix C1: Continued.

LG	LG	LG	LG	TZ	TZ	TZ	TZ
ZP15-2	ZP47-2	ZP47-4	ZP47-7	ZP46-3	ZP46-4	ZP46-5	ZP46-6
75.68	75.52	76.03	75.79	75.77	74.96	76.53	77.68
0.08	0.07	0.09	0.09	0.08	0.08	0.08	0.08
12.13	12.43	12.85	11.13	11.94	11.67	11.37	11.48
v2.28	1.56	1.53	1.79	2.07	3.40	2.93	1.28
0.03	0.01	0.02	0.02	0.01	0.01	0.01	0.01
0.12	0.13	0.28	0.11	0.08	0.10	0.08	0.13
1.02	0.91	0.37	1.07	0.73	0.93	0.73	0.22
2.84	2.51	1.07	2.39	2.83	2.32	2.59	2.31
5.00	5.59	5.79	5.29	5.48	5.54	5.15	5.30
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.06	1.08	1.58	1.21	0.80	0.92	0.72	0.79
100.25	99.83	99.63	98.90	99.79	99.93	100.21	99.29
21.28	17.11	6.81	9.81	6.81	15.65	5.73	7.39
11.23	10.66	6.31	15.59	6.31	14.81	21.79	5.32
1.80	1.53	1.70	1.60	1.70	1.97	1.29	1.76
1051.47	1067.70	1005.28	931.57	1005.28	620.26	371.66	292.32
0.60	1.39	1.59	1.34	1.59	0.25	0.24	0.22
1.57	1.46	1.33	1.32	1.33	1.61	1.90	1.81
0.84	0.66	0.46	0.28	0.46	0.79	0.50	0.56
1.50	1.56	1.30	1.33	1.30	1.97	2.19	2.36
6.28	16.03	7.55	4.40	7.55	135.77	28.97	214.14
60.32	51.46	26.21	25.61	26.21	119.19	22.41	28.39
38.65	32.49	29.21	28.14	29.21	35.42	30.03	30.79
446.17	422.23	376.77	357.55	376.77	306.04	383.17	323.13
8.04	5.67	4.59	6.42	4.59	8.28	5.01	5.65
184.64	154.43	119.07	119.14	119.07	40.43	25.80	25.85
309.50	247.26	322.91	284.97	322.91	352.78	248.64	345.76
77.44	50.32	40.46	46.58	40.46	57.07	38.81	34.60
124.94	129.97	170.77	148.32	170.77	139.94	123.75	166.45
22.45	17.88	30.89	19.17	30.89	13.57	33.56	26.70
2.55	2.18	3.89	3.40	3.89	1.22	1.59	1.28
16.50	12.67	16.21	12.65	16.21	18.60	11.98	17.38
5.61	4.47	4.59	5.74	4.59	4.76	3.25	2.01
8.99	5.30	5.17	7.19	5.17	6.84	2.61	1.55
8.73	11.40	5.96	4.24	5.96	21.03	4.83	5.56
54.43	43.52	44.09	53.05	44.09	5.91	9.74	5.05
18.60	17.44	6.95	6.17	6.95	3.41	3.25	4.50
74.96	63.62	61.11	69.76	61.11	55.17	35.98	53.36
151.30	113.62	99.36	132.57	99.36	71.88	58.09	67.15
13.85	10.26	8.92	9.95	8.92	6.12	5.49	5.28
49.20	39.02	35.77	38.82	35.77	16.09	15.54	12.18
13.73	11.79	12.88	12.81	12.88	2.54	2.82	1.38
0.34	0.33	0.35	0.33	0.35	0.15	0.15	0.10
14.61	13.03	13.92	14.46	13.92	2.56	2.57	1.29
2.80	2.56	2.60	2.70	2.60	0.45	0.45	0.20
24.01	21.47	22.57	21.49	22.57	3.18	3.05	1.50
5.46	4.61	4.88	4.42	4.88	0.73	0.64	0.39
15.68	15.13	17.33	13.82	17.33	2.46	2.00	1.56
2.73	2.12	2.44	1.97	2.44	0.46	0.34	0.32
21.07	15.18	20.25	13.83	20.25	3.59	2.42	2.73
2.77	2.10	2.60	1.96	2.60	0.59	0.35	0.49

Abbreviations: BG = Bobbejaankop Granite; LG = Lease Granite; NG = Nebo Granite; and TZ = Transitional Zone.

Appendix C3: Whole-Rock XRF majors and ICP-MS traces from the Gaborone Granite Suite.

Sample No.	GG01	GG04	GG06	GG10	GG12	GG17
Lithology	Kgale Granite	Kgale Granite	Kgale Granite	Kgale Granite	Kgale Granite	Kgale Granite
Facies	Main Phase	Main Phase	Main Phase	Main Phase	Main Phase	Main Phase
SiO ₂ (wt%)	75.72	75.68	76.47	77.25	76.16	78.21
TiO ₂	0.28	0.31	0.29	0.23	0.26	0.21
Al ₂ O ₃	11.90	11.46	11.34	11.41	11.90	11.01
FeO ^{tot}	2.18	2.89	2.78	2.29	2.42	1.94
MnO	0.03	0.03	0.02	0.03	0.04	0.02
MgO	0.19	0.65	0.12	0.04	0.12	0.24
CaO	0.09	0.30	0.14	0.12	0.70	0.17
Na ₂ O	3.35	2.79	3.22	3.16	2.98	2.11
K ₂ O	5.29	5.35	4.88	5.45	5.36	5.37
P ₂ O ₅	0.03	0.03	0.04	0.02	0.04	0.02
Cr ₂ O ₃	0.01	0.00	0.01	0.00	0.01	0.01
NiO	0.00	0.00	0.00	0.00	0.00	0.00
LOI	0.75	0.66	0.66	0.27	0.46	0.74
Total	99.82	100.15	99.97	100.27	100.45	100.05
Li (ppm)	9.25	33.36	3.97	0.26	9.99	12.22
P	97.70	93.23	119.35	51.88	164.42	51.06
Sc	3.51	3.98	3.67	3.02	3.11	2.08
Ti	1487.22	1398.92	1590.57	1264.09	1534.26	1073.44
V	1.97	1.02	2.91	0.59	2.37	2.23
Cr	1.93	1.29	3.03	1.74	2.81	1.56
Co	1.35	1.09	1.27	1.81	1.92	1.37
Ni	3.88	1.56	3.86	3.05	1.87	2.39
Cu	10.18	4.85	5.10	2.66	5.27	3.55
Zn	20.79	27.63	80.74	63.21	56.83	32.67
Ga	33.78	33.77	29.02	35.31	30.30	26.89
Rb	330.44	333.46	287.29	362.51	354.32	417.20
Sr	8.63	9.45	14.30	5.28	45.03	16.93
Y	88.18	89.28	62.60	90.81	90.86	48.34
Zr	409.68	487.44	437.19	390.88	243.45	207.93
Nb	42.63	41.93	46.51	42.86	45.52	42.70
Ba	201.57	150.56	234.02	67.55	322.21	214.62
Sn	6.83	8.44	8.28	8.53	9.80	8.92
Cs	2.90	7.62	2.14	3.10	3.16	3.75
Hf	12.29	14.91	13.50	12.62	7.77	6.77
Ta	2.13	2.44	2.51	2.61	2.44	2.51
W	0.56	0.45	0.35	0.38	0.85	0.90
Pb	22.37	22.06	16.59	42.84	39.56	18.99
Th	21.20	21.75	21.47	20.38	23.04	22.99
U	5.46	6.55	6.06	5.30	4.89	6.37
Tl	2.09	2.18	1.71	2.39	2.50	2.64
Sb	0.26	0.14	0.21	0.15	0.21	0.19
La (ppm)	106.78	115.99	61.97	131.40	124.20	95.92
Ce	200.95	230.41	170.83	234.46	241.09	220.64
Pr	25.19	25.53	15.36	31.95	26.87	21.13
Nd	88.56	90.07	54.28	108.98	92.85	69.21
Sm	16.11	15.99	10.68	19.81	15.69	11.46
Eu	0.78	0.74	0.55	0.89	0.87	0.45
Gd	15.28	15.08	10.27	17.76	14.68	9.30
Tb	2.41	2.34	1.70	2.92	2.30	1.43
Dy	15.48	15.23	11.38	19.26	14.97	9.42
Ho	3.27	3.23	2.44	3.94	3.20	1.94
Er	9.69	9.80	7.62	11.53	9.47	5.93
Tm	1.54	1.57	1.26	1.85	1.46	1.00
Yb	10.83	10.75	8.89	12.56	9.37	6.70
Lu	1.47	1.58	1.33	1.75	1.35	0.94

Appendix C2: Continued.

GG20 Kgale Granite Main Phase	GG02 Kgale Granite Marginal Phase	GG05 Kgale Granite Marginal Phase	GG08 Kgale Granite Marginal Phase	GG09 Kgale Granite Marginal Phase	GG11 Kgale Granite Marginal Phase
76.54	71.13	75.43	72.67	72.20	74.53
0.22	0.52	0.35	0.46	0.51	0.26
11.34	12.40	11.48	12.07	12.27	12.39
2.35	5.04	3.60	4.71	5.06	2.70
0.02	0.06	0.07	0.07	0.04	0.03
0.06	0.28	0.15	0.19	0.29	0.20
0.28	0.90	0.24	0.43	0.64	0.32
2.99	3.79	3.24	3.88	4.01	2.89
5.39	5.10	5.29	5.13	4.80	5.68
0.03	0.12	0.05	0.08	0.11	0.03
0.00	0.01	0.01	0.00	0.01	0.01
0.00	0.00	0.00	0.00	0.00	0.00
0.61	0.90	0.51	0.41	0.48	1.09
99.83	100.25	100.42	100.10	100.42	100.13
1.71	3.24	2.06	4.72	2.81	4.97
78.80	506.52	158.15	311.25	438.50	103.78
3.29	7.02	3.88	5.23	7.28	3.02
1199.49	2746.41	1952.89	2436.41	2767.16	1319.41
0.63	7.74	3.82	8.12	8.01	3.47
1.70	1.88	2.02	3.93	5.53	5.99
0.74	2.56	2.02	2.60	2.76	2.29
2.08	2.39	2.81	5.67	3.35	3.16
6.46	7.44	6.39	7.38	9.53	4.99
59.27	147.07	110.92	142.69	91.34	53.99
29.58	31.84	32.16	40.19	32.54	31.34
394.09	227.38	289.82	265.72	245.29	356.09
8.77	34.75	13.47	28.00	31.22	33.10
75.47	78.50	67.81	204.63	105.28	74.65
425.09	623.33	354.11	389.10	503.90	258.53
49.63	31.36	36.46	34.97	33.94	39.33
117.56	627.12	311.39	518.21	686.20	364.83
10.37	5.18	6.63	6.20	5.65	11.07
6.30	2.07	4.47	5.80	2.43	2.79
15.09	16.14	10.22	11.65	13.50	8.55
3.25	1.78	2.01	1.92	1.90	2.53
1.26	0.40	0.41	0.52	0.48	0.63
47.98	32.25	37.80	33.76	60.39	22.23
25.33	14.35	16.86	16.22	15.43	23.86
8.51	4.11	4.08	4.36	4.07	6.22
2.70	1.68	2.30	1.79	2.08	2.40
0.25	0.21	0.19	0.13	0.51	0.22
83.53	84.30	91.11	223.45	113.81	120.84
208.10	170.29	204.67	247.30	185.56	241.19
18.69	20.18	23.61	44.39	24.77	25.61
64.01	75.78	83.07	184.27	95.29	87.40
11.68	14.45	15.38	33.68	17.88	14.57
0.31	2.14	1.41	4.10	2.61	0.91
10.39	14.16	13.47	35.91	17.96	13.10
1.76	2.20	2.13	5.30	2.74	1.98
12.10	14.44	13.69	33.38	17.77	12.75
2.64	3.05	2.77	7.08	3.77	2.68
8.38	9.04	8.12	20.33	10.87	8.06
1.43	1.41	1.29	2.96	1.66	1.31
10.01	9.52	8.78	18.95	10.94	8.73
1.47	1.40	1.25	2.82	1.59	1.26

Appendix C2: Continued.

GG22 Kgale Granite Marginal Phase	GG14 Thamaga Granite	GG16 Thamaga Granite	GG18 Thamaga Granite	GG19 Thamaga Granite	GG24 Thamaga Granite	GG25 Thamaga Granite
75.09	75.45	73.37	69.91	74.50	64.22	76.37
0.35	0.27	0.27	0.44	0.27	0.61	0.23
11.49	12.35	13.38	13.96	12.22	15.02	11.90
3.37	2.19	2.27	3.95	2.53	4.65	2.15
0.03	0.03	0.05	0.05	0.03	0.06	0.03
0.11	0.16	0.21	0.30	0.13	0.87	0.11
0.24	0.32	1.03	2.43	0.86	2.82	0.68
2.93	2.77	3.24	3.49	3.06	4.08	2.92
5.53	5.75	5.60	4.58	5.38	5.43	5.52
0.04	0.04	0.06	0.11	0.04	0.17	0.03
0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.45	0.79	0.53	0.50	0.59	2.24	0.45
99.64	100.13	100.02	99.73	99.62	100.18	100.40
11.00	18.39	25.49	19.85	5.60	5.39	31.50
72.88	128.04	224.33	396.55	119.16	112.09	660.61
2.83	3.21	3.09	4.81	3.62	3.90	6.76
1137.71	1441.33	1694.76	2337.98	1417.89	1742.29	3225.43
1.57	6.08	8.29	10.80	2.12	2.00	29.35
1.08	1.76	2.23	2.50	1.11	1.75	7.14
1.22	3.08	4.61	4.06	2.08	1.97	8.96
1.44	6.17	3.25	3.65	3.99	3.97	7.95
4.88	6.58	5.51	4.34	5.63	5.47	24.21
52.84	35.52	45.44	61.82	69.59	72.89	82.69
29.32	37.28	33.61	33.49	31.25	29.10	29.08
394.62	489.72	461.84	188.79	329.18	283.80	342.81
35.11	22.60	41.46	118.79	45.91	12.33	80.32
76.70	130.02	87.60	69.47	96.24	66.75	66.22
257.92	272.07	213.47	238.76	348.87	393.02	190.98
40.57	30.08	31.63	35.90	41.57	39.52	33.58
292.29	214.18	336.25	571.52	369.41	257.86	590.66
8.35	12.29	11.83	8.15	8.10	7.12	7.89
11.35	8.72	22.55	4.23	6.31	2.61	5.19
8.61	9.50	7.07	7.45	11.29	11.82	5.70
2.51	2.55	2.47	2.09	2.40	2.21	1.89
1.31	0.75	2.83	0.50	1.32	0.34	0.45
44.39	48.85	48.66	40.28	49.22	48.19	25.78
24.97	36.93	28.44	21.93	24.40	19.50	21.82
7.17	6.99	7.64	3.91	4.42	4.79	3.55
2.82	3.14	3.29	1.27	2.33	2.49	2.65
0.27	0.23	0.29	0.20	0.24	0.17	0.17
106.77	386.65	158.65	108.93	135.52	81.62	97.78
208.91	229.36	280.28	199.71	226.74	175.99	191.87
22.91	75.33	29.66	23.34	27.47	18.58	21.44
78.56	247.81	97.84	82.52	96.44	66.64	75.57
13.37	38.52	15.71	13.94	16.20	12.24	13.08
0.68	3.04	1.09	1.58	1.01	0.84	1.62
12.44	28.91	14.41	12.77	15.54	11.25	11.83
1.96	4.16	2.22	1.94	2.39	1.82	1.81
12.88	24.10	14.46	12.21	15.35	12.10	11.70
2.75	4.51	3.02	2.58	3.32	2.57	2.47
8.34	12.77	9.00	7.66	9.88	7.87	7.27
1.34	2.02	1.52	1.21	1.57	1.28	1.14
8.80	13.67	10.42	8.05	10.32	8.74	7.60
1.28	1.85	1.47	1.17	1.51	1.29	1.11

Appendix D: Partition Coefficients for Rayleigh Fractionation Modelling.

Mineral	Elemental K_D			Modal Proportions
	Rb	Sr	Ba	
K-feldspar	0.7	5.2	4.5	50%
Plagioclase	0.06	2.8	3.77	10%
Biotite	2.85	0.31	0.6	-
Hornblende	0.4	0.4	0.3	10%
Quartz	0	0	0	30%
BULK K_D	0.4	2.92	2.66	100 %

Acceptable partition coefficients are taken from various publications (Wyllie, 1977; Bacon and Druitt, 1988; Bea et al., 1994; Sisson, 1994).

Appendix E: Portable XRF outcrop data and GPS locations.

Appendix E-1: Averages of the three analyses (ppm), from each of the Portable XRF outcrop locations.

Outcrop #	t1-1	t1-2	t1-3	t1-4	t1-5	t1-6	t1-7	t1-8	t1-9	t1-10	t1-11	t1-12	t1-13	t1-14	t1-15	t1-16
Ca	1656.59	1561.98	2991.13	1145.20	3251.69	1401.05	1656.81	1554.86	1377.89	1605.07	919.98	1394.72	1215.69	1369.78	1214.57	1259.90
S	717.22	695.77	1161.17	584.35	837.83	490.71	1077.80	894.92	589.05	1293.11	434.34	512.69	647.17	509.99	611.24	598.12
K	34847.56	37984.22	46300.58	29017.65	38398.33	33946.21	34068.29	40731.02	39496.38	41182.05	36593.29	44588.63	36830.79	42212.40	34707.49	33009.50
Sc	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ti	1033.92	860.63	2514.90	774.32	795.44	1413.41	1760.23	1033.21	614.07	1050.69	589.56	971.24	479.91	805.97	700.64	717.99
V	43.57	47.76	237.57	45.50	35.01	32.41	38.38	39.09	39.89	-	-	39.30	39.66	37.78	31.87	23.74
Cr	172.20	45.61	453.40	73.71	21.45	42.27	53.81	82.06	60.21	40.61	25.16	48.44	64.57	83.60	-	-
Mn	257.63	246.60	716.31	257.18	355.31	254.11	452.29	333.42	266.75	245.47	306.49	194.68	190.88	337.13	231.21	192.82
Fe	10842.28	7567.78	16343.07	8688.47	13606.25	10699.40	11673.53	12880.94	8431.82	9086.52	9878.43	11082.20	7358.38	10856.74	8326.77	9845.28
Co	81.37	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ni	54.11	68.66	92.20	68.70	85.68	68.97	77.22	90.03	68.76	76.96	72.59	65.97	53.82	79.08	61.56	70.19
Cu	22.47	23.47	24.54	23.51	33.41	25.21	29.50	32.93	19.52	22.39	26.14	19.64	19.19	20.31	19.96	28.00
W	-	40.62	-	-	-	-	-	-	43.81	-	-	-	-	-	-	-
Zn	47.60	45.62	73.15	41.68	44.26	35.48	37.43	53.27	31.29	53.25	47.61	33.64	18.87	25.28	22.23	29.28
As	5.57	14.12	8.14	8.23	8.55	11.74	9.80	10.25	8.03	8.70	10.22	14.77	7.36	13.59	6.02	6.50
Se	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Rb	216.61	224.47	241.57	172.21	223.43	223.15	210.57	266.11	209.48	259.48	291.38	319.12	277.41	345.63	269.56	266.04
Sr	48.54	31.96	43.03	11.04	8.72	11.37	10.70	19.96	10.67	20.32	15.45	10.43	10.55	19.10	9.86	7.10
Zr	131.54	75.60	297.53	61.98	240.53	209.16	273.91	238.75	123.79	189.09	104.41	95.49	23.71	105.52	71.91	104.33
Mo	3.92	-	7.83	-	-	-	-	-	-	-	-	-	-	3.72	-	-
Pd	-	-	-	-	-	-	-	13.15	12.37	16.77	-	12.95	-	-	16.82	15.35
Ag	10.59	9.68	-	-	8.58	9.39	-	9.79	-	-	-	-	9.65	13.75	10.73	9.51
Cd	15.52	19.97	13.66	19.10	13.74	15.04	21.45	18.92	13.53	15.84	15.23	16.90	15.94	22.45	20.07	17.65
Sn	31.55	36.53	40.54	28.15	27.13	32.94	33.43	35.46	29.25	36.98	29.60	39.01	32.47	28.66	35.28	40.99
Sb	45.62	46.23	43.14	36.53	38.28	44.05	39.08	41.10	42.16	45.08	40.16	49.39	49.35	43.14	49.98	42.61
Te	157.97	174.14	162.79	140.28	141.78	142.19	159.19	163.25	125.23	174.38	142.67	165.34	156.22	151.44	173.85	143.81
Cs	105.87	113.47	118.90	94.11	105.36	98.09	97.46	110.08	96.03	112.75	100.53	118.21	104.71	105.97	108.46	99.67
Ba	923.38	1055.63	997.08	549.47	523.75	493.04	475.14	629.54	470.62	593.94	488.26	491.53	462.05	453.50	455.59	398.58
Au	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Hg	-	-	-	-	-	-	9.18	-	-	-	-	-	-	10.13	11.10	-
Pb	96.45	14.38	30.75	17.92	21.49	16.69	12.86	23.43	20.23	25.50	27.11	16.24	14.52	17.51	18.46	24.10
Th	7.98	7.32	31.70	28.08	35.83	25.33	22.01	22.00	18.83	27.62	24.14	24.40	11.25	16.44	16.16	20.34
U	-	12.08	19.09	17.41	30.30	22.69	25.59	27.38	31.34	46.33	41.63	46.42	34.21	53.25	42.49	31.31

Appendix E-1: Continued.

t1-17	t1-18	t1-19	t1-20	t1-21	t1-22	t1-23	t1-24	t1-25	t1-26	t1-27	t1-28	t1-29	t1-30	t1-31	t1-32
5391.37	1519.42	1319.06	931.37	12226.34	1459.23	1434.28	1110.50	1233.22	1512.89	6105.19	1060.87	1244.71	1049.85	1312.55	1237.68
608.83	638.18	811.56	714.37	631.89	699.51	680.16	844.89	664.29	547.57	795.87	542.21	694.36	653.04	916.09	678.29
41438.81	60278.74	19847.23	32834.51	31280.91	40825.48	41231.99	37579.81	31397.80	47043.28	40204.67	36914.86	36282.15	41083.82	34412.70	43251.58
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
674.91	697.33	2062.92	580.08	1378.12	718.09	560.91	724.86	566.12	1925.42	552.25	714.62	1102.27	466.00	1227.31	1204.24
164.95	31.54	26.81	-	26.44	25.81	31.90	28.55	46.47	44.95	18.72	21.46	26.60	-	45.78	43.81
255.95	38.01	37.38	19.92	27.32	43.04	41.95	53.26	55.08	116.95	-	22.54	35.23	49.58	67.09	82.09
743.47	362.22	446.98	289.64	307.03	566.29	258.02	198.18	189.97	274.29	462.31	366.66	785.42	424.46	475.08	390.90
14276.99	14363.88	32871.28	6470.01	9067.58	10500.98	10184.05	9665.62	8091.92	12360.44	5325.89	9081.11	9449.75	10183.31	9222.56	21868.66
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
90.16	87.17	84.53	54.04	64.20	83.11	66.38	58.13	41.92	74.29	67.27	72.82	60.85	73.20	77.78	83.96
43.78	45.82	58.96	26.36	52.15	56.34	31.08	40.20	18.82	33.28	27.25	41.40	56.18	40.52	19.31	20.99
66.55	45.31	130.43	-	63.33	-	-	39.80	-	46.85	45.57	46.52	-	-	-	-
44.62	31.30	45.77	20.23	21.81	30.11	26.16	27.84	17.85	39.93	25.58	30.14	27.80	37.32	36.75	77.06
8.30	10.05	18.92	6.03	9.57	12.56	11.12	8.15	6.91	18.27	15.70	14.32	22.95	29.22	6.45	10.52
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
364.75	518.22	144.80	347.84	276.43	340.77	368.45	324.79	253.96	586.70	436.93	386.48	371.33	396.77	198.14	225.99
14.47	19.34	4.91	10.82	16.41	7.66	19.09	15.80	7.61	12.84	9.18	10.07	9.57	9.08	20.18	23.31
117.32	117.38	383.72	104.38	152.28	106.21	40.76	77.54	71.40	79.18	286.44	313.47	187.21	98.06	220.88	196.99
-	-	9.89	-	-	-	-	-	-	7.20	-	7.73	-	-	-	-
14.47	14.62	-	-	-	14.37	-	-	-	-	-	-	12.81	-	13.24	-
-	13.32	9.17	15.54	9.69	-	12.11	10.10	12.25	11.53	9.23	-	-	-	9.38	14.28
21.26	24.01	18.35	20.78	20.80	23.35	21.25	17.48	17.29	19.70	20.37	18.77	14.10	18.52	18.31	19.75
33.99	39.87	23.90	40.77	46.82	42.60	42.35	26.04	34.82	31.64	33.98	32.07	33.96	62.56	32.94	43.16
49.26	57.75	44.80	50.58	59.02	53.21	56.23	41.99	53.96	42.78	38.95	35.05	34.29	49.59	41.31	53.02
179.44	201.51	152.57	179.69	194.83	188.58	184.72	146.16	156.73	144.96	148.56	134.18	120.01	173.36	150.31	203.55
118.13	125.08	94.89	116.02	121.54	116.60	121.79	97.26	104.39	102.06	73.43	89.56	88.87	110.43	108.09	129.97
491.36	533.33	296.02	481.50	526.56	501.35	502.53	427.60	431.37	486.20	363.06	404.90	390.66	489.40	869.46	1083.92
-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.52	-
10.02	-	-	-	-	10.19	9.37	9.65	-	-	-	9.86	-	11.60	-	12.67
29.11	16.98	19.63	9.79	17.08	19.41	19.66	19.72	10.37	28.68	14.37	20.59	23.74	18.20	17.78	48.07
6.41	8.44	61.86	31.89	25.14	14.68	13.26	18.79	19.66	21.06	38.18	27.05	85.78	20.24	13.87	19.18
52.04	45.35	40.58	22.44	20.72	24.49	21.52	30.92	28.18	67.09	45.52	58.24	37.37	43.30	24.34	36.78

Appendix E-1: Continued.

t1-33	t2-1	t2-2	t2-3	t2-4	t2-5	t2-6	t2-7	t2-8	t2-9	t2-10	t2-11	t2-12	t2-37	t2-36	t2-35	t2-34
940.93	1046.14	1361.93	1421.28	1388.84	1599.05	2983.02	5957.84	1953.89	1392.39	1145.00	856.95	1340.71	2603.08	2472.81	2889.72	4095.96
-	700.67	827.68	289.68	834.27	817.95	919.31	663.60	623.09	495.70	709.67	822.91	749.49	881.09	928.70	847.08	3315.88
53524.0	40646.6	44046.9	32038.6	39435.6	41549.0	34626.1	47569.6	43732.8	36040.3	34306.3	40634.6	38098.5	21393.8	34376.4	24653.8	27860.2
9	5	8	7	3	9	2	5	5	9	5	4	4	4	2	1	5
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	311.87
1092.35	1116.64	1010.42	503.38	498.12	737.36	1279.33	871.19	796.04	524.64	1252.22	1543.06	1032.78	763.33	1105.69	1070.64	1149.71
36.98	42.54	-	24.32	28.82	43.46	34.67	30.15	-	45.97	28.14	66.57	43.45	27.92	45.70	27.70	128.89
-	96.67	43.48	27.21	71.13	46.61	50.02	20.67	-	40.92	41.50	101.88	68.15	47.02	64.94	53.47	220.08
234.27	200.73	205.76	168.06	236.65	306.84	298.61	346.81	570.99	391.37	346.89	359.07	664.41	202.85	838.01	226.16	1117.57
13670.0		11552.7	11608.7			10850.6	10605.4			14149.4	15895.5	10818.6		10290.1		
9	6754.42	4	6	6475.29	8708.80	2	4	8024.52	9550.99	2	0	3	5811.82	4	8923.02	7069.83
-	77.93	-	189.87	-	100.69	-	-	-	-	-	-	-	-	-	-	4736.56
76.57	60.42	73.92	60.27	60.62	75.90	52.60	88.14	77.13	60.83	68.62	65.78	73.71	63.80	69.14	55.86	598.09
21.31	31.23	24.31	-	22.13	22.48	26.77	46.45	77.68	43.37	21.90	54.65	28.99	39.46	20.37	26.38	267.04
-	-	-	-	-	-	-	-	-	55.36	-	57.98	-	49.12	-	-	-
92.76	34.96	47.34	28.09	42.23	54.96	64.82	26.78	31.45	25.29	14.04	28.12	15.77	22.69	22.61	35.80	85.41
7.59	11.32	9.10	8.13	-	10.39	6.77	12.82	13.51	19.72	12.04	14.91	9.69	6.54	16.46	21.60	26.97
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	20.47
271.38	181.12	203.21	189.56	172.93	199.71	196.74	441.75	538.31	426.62	382.68	388.18	325.13	160.17	345.47	273.10	109.46
29.48	46.89	33.05	21.62	18.33	63.46	31.36	11.46	11.21	25.63	15.25	8.46	30.08	6.20	11.17	10.61	115.46
434.01	211.73	286.03	181.46	187.34	175.91	314.59	278.48	205.94	207.92	117.05	285.98	175.40	186.85	87.61	66.18	113.11
-	6.41	-	-	5.13	-	-	-	-	-	-	-	-	-	-	-	13.93
-	-	-	-	-	15.38	-	-	13.33	-	-	-	-	-	-	-	-
-	11.40	10.94	9.28	9.09	12.05	11.95	10.00	-	-	11.12	10.30	11.43	9.30	14.04	12.10	20.72
15.59	17.25	18.34	24.53	16.87	20.75	17.50	13.27	-	-	14.89	21.80	13.55	13.32	23.52	21.08	32.43
30.12	34.53	29.32	35.00	37.52	28.37	30.62	39.34	30.31	42.36	39.01	24.18	27.77	33.28	34.98	35.93	39.56
52.08	50.57	45.10	42.21	41.98	41.30	47.43	37.83	32.29	31.04	45.15	24.73	41.27	40.91	53.10	51.11	48.84
178.86	188.27	147.30	156.31	161.73	155.84	160.23	140.62	100.05	105.25	149.50	82.15	132.18	150.50	160.52	182.31	131.79
116.94	128.10	109.93	107.03	105.91	106.89	106.71	100.30	81.91	80.28	106.41	77.09	94.74	95.30	109.36	110.28	109.23
1088.37	1010.36	1055.48	832.12	879.80	1058.36	917.60	518.83	410.35	394.50	441.16	352.50	430.32	382.06	472.76	468.97	522.79
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	13.13	10.13	-	10.31	-	11.03	-	-	-	46.10
16.22	24.97	19.96	19.68	56.27	46.24	24.56	16.90	20.20	33.82	25.18	16.14	27.85	6.57	9.05	7.70	48.63
17.54	27.81	24.41	18.61	19.80	12.44	10.33	33.01	100.38	23.85	24.55	54.07	24.95	16.57	11.42	17.33	42.90
47.07	13.20	16.18	13.23	18.72	25.38	28.31	82.25	94.33	58.19	35.35	32.02	24.75	41.25	42.14	25.27	313.57

Appendix E-1: Continued.

t2-33	t2-32	t2-31	t2-30	t2-29	t2-28	t2-27	t2-26	t2-25	t2-24	t2-23	t2-22	t2-21	t2-20	t2-19	t2-18	t2-17
4429.45	2518.48	2629.07	3574.86	3005.26	3907.60	3233.00	3760.73	5285.72	4092.43	3991.13	2943.74	5082.95	3055.71	4222.68	3347.72	3934.70
4299.85	1538.01	1380.12	2158.41	1481.36	3284.34	1607.18	1999.78	3562.65	3139.30	2030.91	1231.65	5280.06	1782.11	4395.38	3837.17	4289.92
22130.6	44993.2	25496.1	28025.4	34211.0	16713.6	36274.5	29869.2	24127.3	27313.4	38256.3	28789.2	18500.3	36698.2	23792.9	16783.7	22258.4
0	9	8	5	6	2	8	4	7	3	3	8	1	4	7	4	4
1238.34	-	-	-	-	120.66	-	-	387.88	718.79	72.37	-	441.02	26.59	497.87	408.75	644.60
1501.75	1025.00	946.74	1164.96	1412.23	1868.44	1601.15	1217.88	2177.88	2453.57	731.22	2764.88	1728.20	1427.47	1631.93	2011.20	1368.60
-	87.91	74.23	67.03	-	102.19	96.45	73.44	78.67	72.48	62.58	-	78.28	52.54	-	111.70	44.50
152.86	151.54	130.24	107.00	80.11	281.56	218.15	272.84	362.38	395.59	79.49	177.87	200.01	126.26	179.99	287.91	68.49
1054.58	992.88	1203.37	695.25	1627.25	2256.72	2140.50	1045.79	1831.33	1878.99	1232.57	1153.49	979.85	1059.34	1689.72	2036.26	2173.17
				13006.1	19311.4											
3325.73	7837.11	6516.67	7730.57	4	0	7357.78	4728.60	4459.77	6769.26	1921.79	5922.86	4517.57	8170.94	3298.15	3771.19	2089.53
2558.21	4326.39	3479.01	2898.96	5052.57	7068.21	8722.39	4428.09	8197.02	9238.16	3464.83	7971.46	4350.25	4138.33	4901.79	7673.90	3563.05
1207.15	314.80	243.19	116.54	838.67	413.91	1503.28	365.27	2587.30	1749.92	1023.60	3325.68	592.20	295.18	1482.75	3225.94	1459.86
568.35	159.94	201.83	131.10	1344.80	204.95	420.83	263.39	1053.83	691.04	536.45	418.69	296.14	220.79	1314.77	1698.82	1302.01
131.52	-	-	-	1525.70	-	-	-	-	-	200.20	-	-	-	1864.29	288.87	631.20
114.25	72.62	87.31	68.98	243.23	107.95	109.04	106.76	236.04	133.76	172.49	109.14	98.91	85.57	306.04	294.00	272.65
24.82	18.87	16.97	-	35.36	-	22.84	18.32	30.64	19.70	27.83	21.15	18.85	16.11	33.55	38.36	37.46
15.00	-	13.14	11.87	-	13.44	19.95	-	27.05	16.68	26.38	20.33	-	-	18.74	22.09	26.44
62.46	186.48	66.44	83.16	129.81	66.43	49.03	39.07	27.15	39.43	22.71	72.70	53.13	109.93	33.58	20.46	18.19
128.83	87.57	47.50	52.71	57.00	54.64	96.06	92.47	133.21	115.43	123.65	84.33	79.27	60.18	116.67	140.63	130.11
38.34	78.31	90.22	100.70	188.95	250.47	75.48	55.42	87.60	109.60	46.43	105.84	98.03	148.11	68.66	86.97	68.70
14.74	-	-	-	82.96	-	-	-	32.81	24.90	22.23	24.35	-	-	85.24	46.34	97.92
20.96	-	-	-	-	-	26.01	25.77	-	-	-	-	-	-	23.98	-	19.89
-	18.15	-	-	-	21.36	-	-	-	16.81	-	15.18	20.69	-	19.63	-	-
-	26.64	25.50	-	52.03	31.47	24.25	28.73	26.31	26.35	-	-	-	-	27.08	-	-
36.04	38.15	30.58	30.45	47.03	34.63	40.80	35.46	25.38	33.63	34.09	33.16	34.42	24.84	32.67	40.66	35.31
49.38	58.61	38.68	-	66.68	54.99	62.19	49.29	34.03	45.38	45.42	39.43	51.83	41.73	67.16	50.53	56.59
210.30	196.98	155.13	114.74	201.36	161.94	172.17	157.98	113.81	164.31	184.33	130.33	187.08	137.25	176.53	189.61	171.75
110.69	137.84	103.92	85.65	137.17	122.03	134.52	120.49	94.22	113.81	112.02	98.13	126.06	98.20	121.67	137.16	118.78
476.00	1075.43	727.93	819.32	1008.51	1101.64	1465.34	906.06	442.20	535.26	916.80	985.39	516.51	537.73	1419.48	770.55	533.95
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	29.73
38.99	33.22	37.53	42.65	31.23	46.80	68.54	44.07	75.42	58.26	37.51	74.91	42.78	42.57	57.09	66.92	47.94
22.95	24.97	15.08	19.05	26.17	43.33	24.23	22.16	22.07	27.65	22.42	22.03	18.52	20.34	29.38	31.94	41.02
26.82	41.36	27.38	19.12	28.11	27.05	26.28	27.65	36.20	44.27	31.21	23.74	23.15	25.00	32.45	37.81	39.57
196.59	332.22	119.39	143.66	139.01	129.58	182.70	177.04	194.77	234.28	171.01	182.44	179.28	166.53	169.55	169.95	137.27

Appendix E-1: Continued.

t2-16	t2-15	t2-13	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8	L-9	L-10	L-11	L-12	L-13	L-14
2612.50	2988.45	1071.31	2140.31	1581.24	1664.28	1786.60	1492.96	1698.80	1862.04	2674.63	2147.33	5059.32	1507.98	2871.87	2205.92	2501.90
2744.11	731.73	1132.73	821.85	892.37	1001.33	662.08	783.82	751.63	891.14	804.29	1036.05	1798.54	664.39	1421.10	1059.46	1569.79
5911.47	51451.88	37052.51	36916.41	35196.64	37701.10	40910.87	33050.65	36241.86	36525.40	34810.19	31600.04	31681.09	41959.07	29058.61	37307.51	36982.75
480.96	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2021.87	1873.77	656.15	2051.49	649.27	797.89	727.90	1334.56	982.22	911.12	685.66	1942.42	1065.62	629.74	1127.76	1651.47	1522.54
816.27	-	20.47	55.64	135.58	21.46	26.37	35.41	31.96	35.31	30.05	25.44	51.61	34.27	39.91	37.77	62.28
783.53	70.90	122.39	41.50	233.37	86.20	36.74	44.36	57.83	71.18	32.75	45.91	111.81	26.84	110.98	66.33	192.60
5016.60	623.12	193.70	253.48	1245.01	284.36	197.84	457.04	804.09	406.99	429.07	260.84	507.00	869.74	264.88	235.17	453.09
6765.44	13635.80	15167.69	11139.93	18062.78	8292.25	22919.28	16824.21	11848.58	15169.41	10674.91	12436.43	8506.03	8556.92	11070.93	15261.88	21865.02
4078.18	-	-	-	190.42	-	-	-	-	-	-	-	-	-	-	-	-
1507.57	65.78	54.24	74.30	98.60	68.97	83.31	83.16	75.61	91.35	70.95	69.26	86.24	65.46	83.72	72.68	72.46
3016.82	24.15	21.89	36.47	143.87	38.85	41.50	64.66	49.95	63.68	56.91	35.67	35.33	55.11	26.52	31.57	36.51
3523.09	-	-	-	61.17	-	43.01	57.42	-	-	54.01	40.36	-	49.48	-	-	-
1734.73	103.12	17.24	43.62	64.28	27.80	35.54	31.29	25.22	37.11	29.30	29.76	28.07	30.36	22.22	59.26	84.71
405.92	9.54	9.53	11.00	39.39	10.63	10.20	13.93	13.66	10.11	9.52	6.94	7.13	13.55	17.31	11.46	21.67
210.39	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
63.65	240.66	339.25	322.98	373.95	380.83	529.76	365.04	332.84	453.47	315.75	254.46	363.19	389.06	238.80	218.29	193.73
100.04	92.73	7.43	13.90	10.25	11.54	7.01	103.68	13.88	13.67	10.69	10.63	11.11	9.81	80.65	19.79	20.24
163.41	244.09	143.98	254.04	239.99	166.06	368.38	315.20	191.62	262.19	271.57	219.20	182.43	280.96	190.71	317.89	254.88
136.14	-	-	7.32	6.44	-	-	23.53	5.19	14.58	11.15	-	-	-	-	-	12.01
32.17	14.18	-	-	-	-	-	-	-	-	-	-	-	-	13.49	14.52	-
16.89	-	13.61	11.60	9.44	-	-	-	-	-	-	-	-	13.85	-	9.36	9.39
30.93	16.15	20.32	17.25	19.00	14.88	-	14.56	-	-	20.05	13.97	12.94	15.00	22.14	14.83	15.35
43.32	29.39	38.66	35.67	63.92	44.14	22.96	106.33	37.98	56.88	465.24	29.82	33.32	35.03	27.22	39.09	58.09
62.40	36.85	47.31	44.93	45.10	35.40	28.08	36.38	36.53	29.72	28.87	33.77	30.96	45.06	40.31	42.51	41.62
213.01	142.83	165.57	165.27	107.13	131.68	84.06	127.92	127.00	106.21	104.97	123.77	116.50	130.04	129.04	139.30	147.33
152.06	105.04	108.05	112.27	91.21	87.52	78.69	68.96	94.21	89.25	76.17	100.20	86.37	96.63	101.23	103.84	106.01
1213.01	1664.76	434.93	764.96	461.62	417.94	341.53	516.08	447.52	464.70	364.17	590.54	684.42	442.89	683.11	830.96	770.72
61.72	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3432.70	-	8.81	-	-	9.92	11.79	-	-	10.83	-	-	-	-	9.89	-	-
52.26	32.35	8.28	21.54	71.63	18.30	9.85	43.35	29.43	42.97	22.25	9.18	18.97	31.03	57.48	45.01	44.32
74.38	-	33.43	25.04	39.84	36.19	61.64	60.12	44.35	42.36	39.50	12.59	29.42	19.59	23.93	20.57	35.31
153.55	13.50	23.94	20.54	44.52	29.02	39.07	57.75	38.89	45.92	83.65	17.82	31.90	46.90	22.60	22.41	24.74

Appendix E-1: Continued.

L-15	L-16	L-17	L-18	L-19	L-20	L-21	L-22	L-23	L-24	L-25	L-26	L-27	L-28	L-29	B-1
1542.33	1861.10	2265.68	3719.49	3635.48	3047.92	57.17	62.11	31.88	1705.91	2902.59	2216.53	1762.62	1563.87	2863.75	78.72
1005.64	1143.39	1384.10	1372.18	1564.96	1616.17	-	-	-	818.40	1406.25	1250.40	1036.53	963.94	1342.01	-
39716.46	36913.35	43155.01	40578.04	40194.11	32360.46	-	-	-	33346.46	21976.81	35178.85	34232.04	38389.13	27440.07	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1166.82	1974.77	1594.30	1734.90	1795.89	1347.38	215.07	206.14	265.26	724.76	1175.51	1131.75	852.12	542.58	1158.52	130.66
25.47	42.80	47.37	43.28	41.03	94.10	-	-	-	30.38	-	26.11	-	20.72	43.62	-
46.16	68.75	58.33	140.51	135.12	149.87	-	-	-	66.84	86.32	48.96	36.67	109.74	78.55	-
192.33	701.46	277.67	1217.50	774.71	612.58	2717.21	1257.96	1527.23	233.30	223.92	730.24	484.31	833.74	448.11	974.15
7828.72	22786.80	10806.46	16601.45	13648.34	37951.37	10853.02	16572.08	16415.47	10437.82	9553.22	15283.97	17069.19	11991.34	12347.37	6739.58
-	-	-	-	-	783.80	1153.91	1485.45	1370.23	-	-	119.90	149.12	-	-	617.56
65.97	76.79	66.42	88.26	73.94	76.88	-	-	-	49.36	68.31	65.10	70.30	67.30	69.69	-
20.84	36.56	21.63	24.61	35.15	131.98	382.64	305.81	821.12	29.20	37.39	50.57	60.75	91.65	54.65	-
39.07	-	-	-	-	-	-	-	597.98	-	-	48.30	43.96	82.21	-	-
37.01	97.48	30.00	29.85	32.83	185.78	426.65	450.97	536.81	31.28	20.60	34.02	43.85	37.83	32.95	219.80
11.23	9.56	15.92	13.16	8.41	15.24	176.28	-	-	10.21	7.80	10.95	7.43	17.57	9.92	-
-	-	-	-	-	1372.49	1087.72	1233.49	945.11	-	-	-	-	-	-	822.17
204.94	191.93	227.17	288.55	341.89	332.75	540.23	569.22	617.05	337.76	285.85	425.22	440.26	434.15	400.01	551.01
21.80	34.94	31.67	45.60	11.13	923.00	1544.97	2209.79	1906.95	22.02	7.48	11.37	12.77	15.09	36.08	1112.21
185.62	468.42	180.20	216.19	514.48	1096.92	1729.42	2629.06	2175.90	109.42	193.68	253.01	281.16	399.73	201.60	895.50
7.79	-	-	-	-	161.33	471.01	250.34	350.03	6.38	-	9.99	6.57	11.42	22.20	342.46
-	-	-	13.56	-	534.99	1542.74	374.29	1727.95	-	-	-	-	-	-	1194.19
11.09	10.00	11.82	12.44	11.80	54.04	494.43	103.19	532.97	-	-	-	12.45	9.16	-	324.95
16.51	18.35	17.91	23.23	15.03	46.14	226.72	53.34	254.02	15.01	15.51	-	24.37	18.27	14.17	157.93
24.31	36.28	36.43	42.57	36.35	63.00	102.11	89.18	119.60	22.69	46.19	119.94	69.86	35.18	32.71	128.37
33.67	40.68	42.69	62.59	49.51	107.51	268.08	144.06	320.45	33.15	46.43	28.41	53.21	36.10	30.11	256.94
136.45	144.63	149.32	200.86	174.90	364.49	875.09	471.86	1039.60	124.84	139.73	90.29	168.69	118.00	130.24	883.06
96.65	108.96	107.17	135.57	112.30	220.92	582.35	299.90	690.46	74.50	95.76	58.52	85.54	51.44	88.61	561.87
778.99	1012.68	1024.44	929.55	872.53	1090.38	2304.99	1466.42	2736.84	360.65	456.06	311.83	397.19	297.96	522.27	1995.18
-	-	-	-	-	2564.44	1896.95	2453.64	1877.26	-	-	-	-	-	-	1591.96
-	-	-	-	-	622.44	873.64	981.33	884.71	-	-	-	10.39	-	-	621.95
21.78	34.90	24.59	60.87	17.47	915.35	2086.65	2614.98	2324.23	18.74	11.48	19.25	18.67	44.44	27.47	2018.92
10.79	19.66	12.91	24.68	6.64	764.56	1875.85	2308.25	2099.60	17.30	19.03	27.30	29.11	62.36	35.74	1629.98
17.32	38.45	31.70	33.26	44.26	1478.69	2634.71	3379.72	3201.19	27.58	-	43.03	41.80	29.76	19.07	1918.17

Appendix E-1: Continued.

B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	B-10	B-11	B-12	B-13	B-14	B-15	B-16	B-17
-	-	-	38.53	44.32	-	1730.50	2024.76	1990.49	8938.04	1611.30	1922.51	3215.10	2002.11	1917.12	2343.58
-	-	-	-	-	-	1531.27	1081.04	1430.03	715.07	1035.34	775.74	1210.63	1084.86	961.75	1115.27
-	-	-	-	-	-	47212.59	34207.81	46566.20	34703.17	36370.94	30610.04	42033.29	22245.74	29300.00	31523.94
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
134.15	67.58	153.55	163.94	74.17	115.95	495.70	1106.13	738.73	594.90	462.38	709.57	665.08	944.44	508.45	995.05
-	-	-	-	-	-	-	26.75	67.91	-	45.26	18.33	37.43	28.34	-	42.69
-	-	-	-	-	-	114.71	57.65	174.32	75.49	202.50	38.02	46.34	175.30	60.01	68.52
679.19	638.33	665.02	986.81	836.65	935.42	797.14	577.86	350.54	441.91	201.87	1151.68	277.43	190.66	316.52	2090.12
5179.76	3147.07	4661.85	6159.75	3994.14	6525.40	9101.30	13713.21	13828.27	10537.08	10528.39	11964.85	10115.41	8375.87	8054.17	9091.32
572.63	469.07	714.46	663.09	555.55	771.45	823.41	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	68.08	73.60	70.26	77.58	51.05	57.58	57.87	59.04	67.25
-	-	140.06	307.54	-	-	23.47	31.36	39.87	46.99	30.72	17.93	22.89	38.10	26.00	38.38
-	-	-	-	-	-	-	-	-	-	-	-	-	57.02	-	56.15
141.69	158.61	296.35	257.60	187.92	281.75	149.39	30.53	38.09	24.72	29.01	25.66	43.03	17.18	26.12	42.22
577.57	-	1050.80	419.37	-	-	117.28	7.23	10.96	6.58	11.23	5.89	18.62	10.75	-	23.77
1198.51	937.10	1056.18	827.17	660.68	1013.83	1281.58	-	-	-	-	-	-	-	-	-
323.10	557.63	414.13	435.34	472.04	541.16	393.88	322.74	459.01	296.08	297.69	225.33	334.73	212.44	284.00	290.29
1097.29	794.09	788.17	1065.02	822.85	886.32	881.26	9.81	11.94	18.35	8.91	9.57	8.98	5.97	8.22	8.77
574.58	351.88	679.20	744.30	430.13	721.40	998.93	85.27	271.71	73.17	87.13	50.68	118.93	383.17	53.39	424.94
-	324.40	30.20	546.36	384.62	459.86	-	5.24	13.75	-	-	9.05	-	-	-	-
326.54	568.48	784.10	1592.87	1930.22	807.23	795.59	-	-	-	-	14.74	-	12.78	-	17.13
78.34	145.12	228.42	515.96	622.47	216.06	197.51	11.11	-	11.76	9.22	11.83	12.32	9.59	19.44	-
48.90	87.33	122.89	227.56	292.77	109.54	92.30	15.73	12.76	20.61	16.81	19.15	15.40	16.40	21.10	18.75
85.37	119.40	103.46	75.37	98.63	127.05	91.67	43.73	29.07	64.90	27.04	36.10	30.22	29.80	37.52	22.73
136.97	218.17	193.83	171.06	270.54	242.05	168.71	38.17	42.47	54.48	35.41	49.14	44.60	43.79	47.65	42.41
466.74	705.37	653.55	666.50	1012.81	815.95	547.58	149.72	141.70	180.48	141.40	178.23	160.54	149.89	175.39	134.92
294.71	445.36	418.93	451.89	638.42	496.40	347.49	102.78	100.05	117.62	96.51	114.59	102.57	97.10	115.88	85.18
1123.61	1609.22	1520.45	1638.60	2319.10	1765.02	1301.68	449.10	454.70	474.36	438.20	501.09	419.11	384.32	489.76	385.66
1834.85	1750.89	1719.15	1332.70	1231.21	1992.27	2325.59	-	-	-	-	-	-	-	-	-
1206.36	679.32	1330.19	721.06	586.93	705.51	972.10	9.23	-	-	12.26	-	-	-	9.43	-
1322.83	2223.49	1404.89	1529.54	1638.09	2058.66	1372.90	16.81	20.05	23.82	13.81	10.88	7.50	9.68	16.74	13.77
1107.05	1791.41	1216.62	1340.76	1413.62	1711.13	1089.61	20.71	39.31	12.19	36.77	6.39	15.40	12.85	13.53	55.52
1675.24	1638.40	1546.38	1803.56	1571.33	1737.67	2073.94	26.17	59.91	-	24.16	19.86	34.28	23.90	39.88	56.90

Appendix E-1: Continued.

B-18	B-19	B-20	B-21	B-22	B-23	B-24	B-25	B-26	B-27	B-28	G-1	G-2	G-3
1658.46	1636.36	1904.15	1682.51	1662.17	4107.03	2060.73	2170.31	1892.80	2171.11	1917.05	90.75	129.24	44.48
824.71	515.81	884.49	512.26	519.79	1731.65	755.46	1656.77	862.86	670.35	1146.69	-	-	-
15745.00	45506.38	45099.87	45230.56	36814.72	30470.80	37873.93	22572.24	17766.45	38696.17	27705.19	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-
1459.51	1158.30	636.04	374.47	854.06	1353.45	328.56	471.54	651.57	488.62	447.78	139.02	118.64	119.42
43.33	102.40	29.87	-	-	25.66	17.81	16.97	-	-	33.69	-	-	-
68.04	263.08	47.38	-	61.26	154.91	17.76	152.97	58.95	-	57.96	-	-	-
738.58	216.35	243.45	157.51	240.47	380.84	183.26	175.58	144.46	154.75	142.05	1194.08	1072.02	961.04
15711.93	5292.58	6260.18	6188.74	7271.12	12136.72	8457.59	10291.19	6076.38	5301.18	7648.91	14662.62	8069.65	6476.91
-	-	-	-	-	-	-	-	-	-	-	1276.64	706.60	740.98
70.82	56.79	58.21	64.27	59.50	69.11	55.23	79.03	45.01	59.49	65.49	-	-	-
-	26.73	-	19.89	62.25	23.87	26.07	56.66	22.66	-	-	760.56	-	-
-	-	-	-	-	-	-	65.36	-	-	-	-	-	-
14.93	22.19	19.39	23.04	21.16	21.47	39.59	23.42	14.84	25.40	18.10	447.88	270.92	215.11
8.56	9.59	8.51	13.85	12.20	20.96	5.64	10.84	40.34	5.79	10.88	-	-	-
-	-	-	-	-	-	-	-	-	-	-	854.79	788.42	805.42
169.57	331.93	323.95	344.49	321.59	315.24	270.77	170.96	151.86	336.89	253.56	596.31	596.24	594.98
6.40	7.88	8.84	6.49	8.30	8.97	7.25	11.80	46.17	7.10	7.24	1709.04	1266.35	1149.78
178.62	334.19	61.04	35.05	92.06	128.90	79.35	230.06	78.17	87.44	43.86	1513.09	835.63	826.44
-	-	-	-	-	-	-	-	-	-	-	1650.07	930.66	863.77
-	-	15.70	13.54	14.58	-	-	-	-	-	-	1364.02	1040.82	720.24
-	12.78	11.03	-	10.14	14.57	-	9.27	9.57	10.54	-	401.40	296.63	181.05
12.45	16.39	19.45	13.61	18.47	19.26	16.87	14.83	17.58	16.71	19.31	193.45	141.02	94.18
26.76	41.53	39.54	29.81	33.55	38.99	30.39	28.18	27.30	35.25	25.22	127.84	118.17	95.28
34.70	48.37	49.69	48.59	43.76	62.24	40.16	41.14	37.08	50.77	35.92	274.90	239.19	183.38
113.68	154.19	166.77	178.58	154.11	208.72	153.04	150.24	121.55	162.03	131.84	930.08	772.01	593.74
64.22	111.49	109.15	114.28	103.83	126.16	99.92	95.37	87.66	112.80	94.87	599.78	514.96	392.84
291.01	463.93	491.69	505.45	465.04	511.78	431.85	416.38	404.82	507.25	426.92	2471.90	2175.86	1782.13
-	-	-	-	-	-	-	-	-	-	-	1655.81	1517.64	1522.38
-	14.17	9.47	9.18	10.18	-	-	8.80	-	9.83	-	736.18	643.03	672.02
11.98	7.64	8.52	7.50	8.61	8.27	8.46	18.14	15.87	5.73	8.24	2318.29	2148.44	2332.94
36.48	22.98	14.66	12.43	10.19	6.93	13.41	40.95	13.22	8.16	9.08	2120.50	1960.81	1936.97
30.29	66.86	61.00	61.62	54.42	56.81	54.81	59.06	23.62	55.55	46.40	2800.70	2289.02	2126.97

Appendix E-2: Portable XRF analyses outcrop locations in decimal degrees.

Outcrop	x	y	Outcrop	x	y	Outcrop	x	y
t1-1	28.78116	-24.05294	t2-11	28.78049	-24.07222	L-18	28.77443	-24.07260
t1-2	28.78108	-24.05281	t2-12	28.78056	-24.07177	L-19	28.77322	-24.07116
t1-3	28.78070	-24.05319	t2-13	28.78311	-24.07109	L-20	28.77215	-24.07049
t1-4	28.77984	-24.05374	t2-15	28.78346	-24.07031	L-21	28.77193	-24.06984
t1-5	28.77939	-24.05391	t2-16	28.78372	-24.06977	L-22	28.77084	-24.06864
t1-6	28.77900	-24.05415	t2-17	28.78376	-24.06910	L-23	28.76996	-24.06795
t1-7	28.77868	-24.05450	t2-18	28.78412	-24.06861	L-24	28.77626	-24.06811
t1-8	28.77866	-24.05501	t2-19	28.78467	-24.06795	L-25	28.77567	-24.06853
t1-9	28.77843	-24.05559	t2-20	28.78501	-24.06760	L-26	28.77497	-24.06886
t1-10	28.77817	-24.05588	t2-21	28.78549	-24.06782	L-27	28.77425	-24.06839
t1-11	28.77749	-24.05654	t2-22	28.78605	-24.06727	L-28	28.77389	-24.06737
t1-12	28.77700	-24.05674	t2-23	28.78667	-24.06698	L-29	28.77333	-24.06642
t1-13	28.77643	-24.05697	t2-24	28.78713	-24.06633	B-1	28.77262	-24.06350
t1-14	28.77595	-24.05769	t2-25	28.78751	-24.06593	B-2	28.77382	-24.06317
t1-15	28.77555	-24.05821	t2-26	28.78817	-24.06555	B-3	28.77452	-24.06310
t1-16	28.77523	-24.05899	t2-27	28.78843	-24.06513	B-4	28.77411	-24.06378
t1-17	28.77474	-24.05933	t2-28	28.78881	-24.06461	B-5	28.77395	-24.06480
t1-18	28.77394	-24.05990	t2-29	28.78883	-24.06451	B-6	28.77446	-24.06567
t1-19	28.77338	-24.06037	t2-30	28.78899	-24.06418	B-7	28.77534	-24.06589
t1-20	28.77273	-24.06071	t2-31	28.78927	-24.06373	B-8	28.77538	-24.06665
t1-21	28.77254	-24.06116	t2-32	28.78944	-24.06309	B-9	28.77535	-24.06710
t1-22	28.77214	-24.06143	t2-33	28.78982	-24.06247	B-10	28.77636	-24.06778
t1-23	28.77157	-24.06194	t2-34	28.79001	-24.06195	B-11	28.77404	-24.06084
t1-24	28.77122	-24.06229	t2-35	28.79061	-24.06137	B-12	28.77856	-24.06195
t1-25	28.77062	-24.06298	t2-36	28.79204	-24.06042	B-13	28.77808	-24.06286
t1-26	28.77037	-24.06330	t2-37	28.78073	-24.07145	B-14	28.77764	-24.06371
t1-27	28.76987	-24.06370	L-1	28.76866	-24.06616	B-15	28.77712	-24.06418
t1-28	28.76945	-24.06416	L-2	28.76925	-24.06600	B-16	28.77705	-24.06501
t1-29	28.76924	-24.06467	L-3	28.77015	-24.06554	B-17	28.77718	-24.06587
t1-30	28.76888	-24.06505	L-4	28.77208	-24.06570	B-18	28.77735	-24.06645
t1-31	28.76804	-24.06627	L-5	28.77161	-24.06725	B-19	28.77742	-24.06738
t1-32	28.76774	-24.06657	L-6	28.77178	-24.06838	B-20	28.77783	-24.06855
t1-33	28.76761	-24.06696	L-7	28.77299	-24.06885	B-21	28.77817	-24.06926
t2-1	28.77872	-24.07678	L-8	28.77418	-24.06911	B-22	28.77901	-24.06949
t2-2	28.77882	-24.07641	L-9	28.77431	-24.07064	B-23	28.78017	-24.06935
t2-3	28.77897	-24.07605	L-10	28.77534	-24.07136	B-24	28.78136	-24.06860
t2-4	28.77902	-24.07545	L-11	28.77559	-24.07246	B-25	28.78034	-24.06645
t2-5	28.77913	-24.07494	L-12	28.77576	-24.07318	B-26	28.77958	-24.06560
t2-6	28.77938	-24.07448	L-13	28.77666	-24.07393	B-27	28.77914	-24.06466
t2-7	28.77965	-24.07409	L-14	28.77770	-24.07326	B-28	28.77940	-24.06364
t2-8	28.78001	-24.07367	L-15	28.77878	-24.07409	G-1	28.76916	-24.06768
t2-9	28.78023	-24.07323	L-16	28.77749	-24.07394	G-2	28.76935	-24.06809
t2-10	28.78040	-24.07272	L-17	28.77659	-24.07330	G-3	28.77261	-24.06351

Appendix F: Electron Probe Micro-Analysis (EPMA) Compositions.

Appendix F-1: Tourmaline EPMA compositions

Lithology	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG
Species	Srl	Srl	Srl	Srl	Srl	Srl	Fot	Srl	Fot	Srl	Srl	Srl	Srl	Srl	Srl	Srl	Srl	Srl	Srl	Srl	Srl	Srl	Srl	Srl
Sample No.	67	67	67	69	70	70	67	67	69	69	70	67	67	69	67	69	67	69	67	69	70	67	69	67
Point	1a	1b	1c	1	1a	1b	2a	2b	2a	2b	2	3a	3b	3	4	4	5	5	5	6	6	7	7	8
SiO ₂	34.19	34.02	34.04	34.06	33.84	33.66	34.70	33.52	35.03	33.71	33.65	34.30	34.01	33.79	33.48	34.51	33.94	33.94	33.49	33.49	33.84	33.72	34.06	33.51
TiO ₂	0.02	0.01	0.06	0.08	0.04	0.02	0.02	BDL	0.06	0.05	0.03	0.12	0.25	0.05	0.01	0.04	BDL	0.03	BDL	0.23	0.04	0.05	0.02	0.27
Al ₂ O ₃	30.10	26.70	26.71	26.01	25.89	26.05	31.62	25.14	31.48	24.92	23.77	28.15	26.01	25.83	24.68	26.16	27.33	25.74	23.82	26.37	25.73	25.22	25.97	24.64
FeO ^{tot}	18.54	21.56	21.67	22.24	22.32	22.04	16.50	23.05	15.97	23.20	24.23	20.49	22.09	22.28	23.33	21.86	20.73	22.13	25.03	22.20	21.63	23.25	22.02	23.94
MgO	BDL	0.01	0.03	0.01	BDL	BDL	0.02	0.02	0.04	0.01	0.02	0.02	0.06	0.04	0.02	0.01	0.04	0.01	0.01	0.04	BDL	0.02	0.02	0.05
CaO	0.18	0.07	0.09	0.08	0.16	0.18	0.02	0.07	0.02	0.16	0.15	0.01	0.03	0.10	0.03	0.12	0.10	0.16	0.12	0.02	0.17	0.12	0.24	0.18
MnO	0.01	0.07	BDL	0.03	0.06	0.05	0.04	0.03	BDL	0.04	0.02	0.04	0.04	0.01	0.05	0.03	0.02	0.02	BDL	0.04	0.02	0.01	0.02	0.05
Na ₂ O	1.84	2.57	2.51	2.52	2.53	2.57	0.72	2.68	0.86	2.65	2.62	2.57	2.65	2.59	2.66	2.53	2.29	2.52	2.71	2.64	2.56	2.63	2.60	2.66
K ₂ O	0.05	0.08	0.07	0.07	0.07	0.06	0.04	0.09	0.04	0.08	0.07	0.07	0.11	0.06	0.09	0.07	0.06	0.06	0.06	0.09	0.07	0.09	0.06	0.09
F	0.05	0.53	0.62	0.44	0.04	0.14	0.10	BDL	0.01	0.35	0.03	0.24	0.67	0.03	BDL	0.47	0.36	0.24	0.07	0.68	0.75	0.54	0.56	0.44
H ₂ O*	3.38	3.08	3.05	3.11	3.29	3.23	3.38	3.27	3.44	3.11	3.23	3.28	3.01	3.29	3.25	3.13	3.16	3.19	3.22	2.99	2.94	3.03	3.06	3.07
B ₂ O ₃ *	9.88	9.66	9.67	9.62	9.58	9.56	9.94	9.48	9.98	9.50	9.41	9.82	9.64	9.57	9.43	9.70	9.66	9.57	9.42	9.59	9.54	9.53	9.63	9.50
Li ₂ O*	0.03	0.11	0.10	0.12	0.09	0.08	0.08	0.03	0.27	0.09	0.09	0.10	0.12	0.09	0.04	0.26	0.10	0.17	BDL	BDL	0.24	0.03	0.19	BDL
Total	98.28	98.48	98.61	98.38	97.91	97.65	97.16	97.38	97.20	97.88	97.32	99.21	98.69	97.72	97.09	98.88	97.78	97.77	97.95	98.36	97.52	98.24	98.43	98.40
O=F	0.02	0.22	0.26	0.19	0.01	0.06	0.04	-	-	0.15	0.01	0.10	0.28	0.01	-	0.20	0.15	0.10	0.03	0.29	0.32	0.23	0.23	0.19
Total	98.26	98.26	98.35	98.20	97.89	97.59	97.12	97.38	97.19	97.73	97.31	99.11	98.41	97.71	97.09	98.69	97.63	97.67	97.92	98.08	97.20	98.01	98.19	98.21
Structural formula based on 31 anions																								
T: Si	6.02	6.12	6.12	6.15	6.14	6.12	6.07	6.15	6.10	6.16	6.22	6.07	6.13	6.14	6.17	6.18	6.11	6.16	6.18	6.07	6.16	6.15	6.15	6.13
Al	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
B	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Z: Al	6	5.66	5.66	5.54	5.53	5.58	6	5.43	6	5.37	5.18	5.87	5.53	5.53	5.36	5.52	5.80	5.51	5.18	5.63	5.52	5.42	5.52	5.31
Mg	-	-	0.01	-	-	-	-	0.01	-	-	-	-	0.02	0.01	-	-	0.01	-	-	0.01	-	0.01	-	0.01
Y: Al	0.24	-	-	-	-	-	0.52	-	0.46	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ti	-	-	0.01	0.01	0.01	-	-	0.01	0.01	-	0.02	0.03	0.01	-	0.01	-	-	-	-	0.03	-	0.01	-	0.04
Mg	-	-	-	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mn	-	0.01	-	-	0.01	0.01	0.01	-	-	0.01	-	0.01	0.01	-	0.01	-	-	-	-	0.01	-	-	-	0.01
Fe2+	2.73	3.24	3.26	3.36	3.39	3.35	2.41	3.53	2.33	3.55	3.74	3.03	3.33	3.38	3.60	3.27	3.12	3.36	3.86	3.36	3.30	3.55	3.32	3.66
Li*	0.02	0.08	0.07	0.09	0.07	0.06	0.06	0.02	0.19	0.07	0.07	0.07	0.09	0.07	0.03	0.19	0.07	0.12	-	-	0.17	0.02	0.14	-
ΣY	3	3.34	3.33	3.46	3.47	3.42	3	3.56	3	3.63	3.82	3.13	3.46	3.46	3.63	3.47	3.20	3.49	3.86	3.40	3.48	3.57	3.47	3.71
X: Ca	0.03	0.01	0.02	0.01	0.03	0.03	-	0.01	-	0.03	0.03	-	0.01	0.02	0.01	0.02	0.02	0.03	0.02	-	0.03	0.02	0.05	0.03
Na	0.63	0.90	0.88	0.88	0.89	0.91	0.24	0.95	0.29	0.94	0.94	0.88	0.93	0.91	0.95	0.88	0.80	0.89	0.97	0.93	0.90	0.93	0.91	0.94
K	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.02
r	0.33	0.07	0.09	0.09	0.06	0.04	0.74	0.01	0.70	0.01	0.02	0.10	0.04	0.05	0.02	0.08	0.17	0.07	-	0.05	0.05	0.03	0.03	-
OH	3.97	3.70	3.65	3.75	3.98	3.92	3.95	4	4	3.80	3.98	3.87	3.62	3.98	4	3.74	3.80	3.86	3.96	3.61	3.57	3.69	3.68	3.74
F	0.03	0.30	0.35	0.25	0.02	0.08	0.05	-	-	0.20	0.02	0.13	0.38	0.02	-	0.26	0.20	0.14	0.04	0.39	0.43	0.31	0.32	0.26

Stoichiometrically calculated values denoted by (*); Abbreviations: Bobbejaankop Granite (BG); Bobbejaankop hydrothermal pipe (BP); Lease Granite (LG); Lease hydrothermal pipe (LP); Schorl (Srl); and Foitite (Fot); Below Detection Limit (BDL).

Appendix F-1: Tourmaline continued

LG Srl 69 8	LG Srl 70 8	LG Srl 67 9	LG Srl 70 9	LG Srl 67 10	LG Srl 69 10	LG Srl 70 11	LG Srl 67 12	LG Srl 70 12a	LG Srl 67 12b	LG Srl 69 13	LG Srl 67 13	LG Srl 69 15	LG Srl 67 15	LG Srl 70 15	LG Srl 67 16	LG Srl 67 16	LG Srl 69 16	LG Srl 70 16a	LG Srl 67 16b	LG Srl 69 17	LG Srl 69 18	LG Srl 70 18	LG Srl 67 19	LG Srl 69 19	LG Srl 70 19
35.06	34.28	34.13	34.80	33.72	33.91	33.29	33.51	33.69	35.37	33.63	33.94	33.64	33.63	33.61	34.31	33.83	33.79	35.28	33.80	33.97	34.46	33.90	33.66	35.03	34.21
0.09	0.16	0.11	0.11	0.06	0.04	0.01	BDL	0.04	0.01	0.03	0.09	0.23	BDL	BDL	BDL	BDL	0.01	0.06	0.04	0.02	0.05	BDL	BDL	BDL	0.06
26.81	28.19	26.86	28.83	26.82	25.47	23.70	24.83	24.28	31.35	26.74	25.81	25.52	23.63	24.48	28.92	25.32	23.57	31.35	24.97	26.22	26.80	27.79	25.36	32.05	28.13
21.76	19.12	21.22	18.04	20.92	21.93	24.59	23.22	23.76	15.97	21.19	22.12	23.05	24.10	23.48	19.26	23.45	25.15	16.37	23.23	21.61	21.28	20.41	22.71	15.57	19.54
0.09	0.01	0.02	0.02	0.07	BDL	0.02	BDL	BDL	0.02	0.04	BDL	0.05	BDL	0.02	0.03	0.02	0.02	0.05	0.02	0.04	0.02	0.01	0.05	0.08	0.03
0.12	0.27	0.01	0.28	0.03	0.12	0.11	0.05	0.04	0.01	0.12	0.30	0.15	0.49	0.04	0.14	0.07	0.31	0.02	0.07	0.28	0.10	0.18	0.12	0.02	0.08
0.01	0.07	0.03	0.01	0.01	0.02	0.03	0.01	0.01	0.02	0.02	0.07	0.02	0.07	0.04	0.04	0.04	0.06	BDL	BDL	0.05	0.03	0.03	0.02	0.02	0.06
2.32	1.98	2.60	1.88	2.55	2.49	2.64	2.66	2.54	0.80	2.25	2.62	2.53	2.63	2.62	2.17	2.61	2.71	0.84	2.61	2.41	2.44	2.17	2.47	0.62	2.22
0.04	0.04	0.06	0.04	0.08	0.08	0.07	0.05	0.06	0.02	0.07	0.07	0.07	0.07	0.07	0.05	0.05	0.06	0.02	0.06	0.05	0.04	0.05	0.07	0.03	0.04
0.40	BDL	0.22	0.08	0.04	0.20	BDL	0.09	0.03	0.02	0.33	0.46	0.33	BDL	BDL	0.08	0.02	BDL	BDL	0.07	0.19	0.37	0.11	0.29	0.10	BDL
3.21	3.37	3.24	3.36	3.29	3.19	3.23	3.22	3.24	3.45	3.14	3.10	3.14	3.25	3.25	3.35	3.29	3.27	3.46	3.25	3.23	3.18	3.29	3.14	3.40	3.36
9.86	9.75	9.69	9.85	9.60	9.53	9.35	9.44	9.43	10.01	9.56	9.61	9.56	9.41	9.43	9.83	9.56	9.47	10.02	9.51	9.61	9.73	9.68	9.50	10	9.74
0.25	0.27	0.16	0.46	0.11	0.23	BDL	0.05	0.08	0.37	0.05	0.18	BDL	0.17	0.07	0.15	BDL	0.03	0.28	0.09	0.17	0.23	0.07	0.05	0.21	0.20
100.03	97.52	98.35	97.75	97.30	97.20	97.03	97.12	97.18	97.41	97.17	98.36	98.29	97.46	97.13	98.32	98.26	98.44	97.75	97.71	97.85	98.73	97.69	97.45	97.11	97.67
0.17	-	0.09	0.03	0.02	0.09	-	0.04	0.01	0.01	0.14	0.19	0.14	-	-	0.03	0.01	-	-	0.03	0.08	0.15	0.05	0.12	0.04	-
99.87	97.52	98.26	97.72	97.28	97.11	97.03	97.08	97.17	97.40	97.03	98.17	98.15	97.46	97.13	98.29	98.25	98.44	97.75	97.68	97.77	98.58	97.65	97.32	97.06	97.67
6.18	6.11	6.12	6.14	6.10	6.19	6.19	6.17	6.21	6.14	6.11	6.14	6.12	6.21	6.19	6.07	6.15	6.20	6.12	6.18	6.14	6.15	6.08	6.16	6.09	6.10
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
5.57	5.92	5.68	5.99	5.72	5.48	5.19	5.39	5.27	6	5.73	5.50	5.47	5.14	5.32	6	5.43	5.10	6	5.38	5.59	5.64	5.88	5.47	6	5.91
0.02	-	-	0.01	0.02	-	-	-	-	-	0.01	-	0.01	-	0.01	-	-	0.01	-	-	0.01	0.01	-	0.01	-	0.01
-	-	-	-	-	-	-	-	-	0.41	-	-	-	-	-	0.03	-	-	0.41	-	-	-	-	-	0.57	-
0.01	0.02	0.01	0.01	0.01	0.01	-	-	0.01	-	-	0.01	0.03	-	-	-	-	-	0.01	0.01	-	0.01	-	-	-	0.01
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	-	-	0.01	-	-	-	-	-	0.02	-
-	0.01	0.01	-	-	-	-	-	-	-	-	0.01	-	0.01	0.01	0.01	0.01	0.01	-	-	0.01	-	-	-	-	0.01
3.21	2.85	3.18	2.66	3.17	3.35	3.82	3.57	3.66	2.32	3.22	3.35	3.51	3.72	3.62	2.85	3.57	3.86	2.37	3.55	3.27	3.18	3.06	3.47	2.26	2.92
0.18	0.20	0.11	0.33	0.08	0.17	-	0.04	0.06	0.26	0.04	0.13	-	0.13	0.05	0.11	-	0.02	0.20	0.06	0.12	0.16	0.05	0.04	0.15	0.15
3.40	3.08	3.32	3	3.26	3.52	3.83	3.61	3.73	3	3.26	3.50	3.54	3.86	3.68	3	3.57	3.89	3	3.62	3.40	3.35	3.12	3.52	3	3.08
0.02	0.05	-	0.05	0.01	0.02	0.02	0.01	0.01	-	0.02	0.06	0.03	0.10	0.01	0.03	0.01	0.06	-	0.01	0.05	0.02	0.03	0.02	-	0.01
0.79	0.69	0.91	0.64	0.90	0.88	0.95	0.95	0.91	0.27	0.79	0.92	0.89	0.94	0.93	0.74	0.92	0.96	0.28	0.92	0.84	0.84	0.76	0.88	0.21	0.77
0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	-	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	-	0.01	0.01	0.01	0.01	0.02	0.01	0.01
0.17	0.25	0.08	0.30	0.08	0.08	0.01	0.03	0.07	0.72	0.17	0.01	0.06	-	0.04	0.22	0.05	-	0.71	0.05	0.09	0.13	0.20	0.08	0.78	0.21
3.78	4	3.88	3.96	3.97	3.88	4	3.95	3.98	3.99	3.81	3.74	3.81	4	4	3.96	3.99	4	4	3.96	3.89	3.79	3.94	3.83	3.94	4
0.22	-	0.12	0.04	0.03	0.12	-	0.05	0.02	0.01	0.19	0.26	0.19	-	-	0.04	0.01	-	-	0.04	0.11	0.21	0.06	0.17	0.06	-

Appendix F-1: Tourmaline continued

LG Srl 67 20	LG Srl 67 20	LG Srl 70 20	LG Srl 67 21	LG Srl 69 21	LG Srl 70 21	LG Srl 67 22	LG Srl 70 22	LG Srl 69 23	LG Srl 70 23	LG Srl 67 24	LG Srl 69 24	LG Srl 70 24	LG Srl 67 25	LG Srl 69 25	LG Srl 70 25	LG Srl 67 26	LG Srl 69 26	LG Srl 67 27	LG Srl 69 27	LG Srl 67 28	LG Srl 69 28	LG Srl 70 28	LG Srl 67 29a		
33.66 BDL	33.75 0.01	33.74 0.05	34.12 0.02	34.72 BDL	34.28 BDL	33.59 0.07	33.59 BDL	34.44 0.04	34.33 BDL	34.09 0.02	35.13 0.13	33.53 BDL	34.69 0.06	34.19 0.10	34.24 0.06	33.95 BDL	34.10 0.11	33.67 0.09	33.91 0.50	33.91 0.39	33.50 BDL	33.84 0.02	33.74 0.01	34.08 0.10	33.79 BDL
28.26	26.55	25.14	25.80	25.71	29.15	25.66	24.69	25.56	29.13	27.10	26.56	24.73	29.32	26.65	26.20	28.48	27.81	25.64	25.46	25.72	22.91	26.01	25.82	26.74	29.45
19.71	21.73	23.21	22.59	22.91	18.78	22.72	23.70	23.21	18.77	21.45	22.26	23.68	18.73	21.83	22.51	19.59	20.19	22.18	22.17	22.73	25.50	22.34	22.54	20.96	18.85
BDL	0.02	0.02	0.02	0.03	0.03	0.08	0.01	0.02	0.01	0.03	0.01	0.02	0.04	0.04	BDL	0.02	0.02	0.01	0.06	0.06	0.01	0.04	0.06	0.02	0.01
0.09	0.12	0.16	0.12	0.27	0.13	0.02	0.07	0.17	0.13	0.12	0.14	0.08	0.02	BDL	0.14	0.21	BDL	0.10	0.01	0.15	0.42	0.09	0.34	0.05	0.18
0.01	0.01	0.02	0.06	0.01	0.02	0.05	0.04	BDL	BDL	BDL	0.01	0.04	BDL	0.05	0.05	0.02	BDL	0.04	0.03	0.04	0.06	0.04	0.04	BDL	BDL
2.20	2.46	2.44	2.62	2.45	1.91	2.62	2.66	2.47	1.88	2.32	2.64	2.67	2.09	2.60	2.32	2.11	2.50	2.54	2.78	2.60	2.74	2.54	2.40	2.40	1.98
0.06	0.08	0.07	0.07	0.07	0.05	0.07	0.07	0.07	0.03	0.06	0.07	0.06	0.04	0.07	0.06	0.05	0.06	0.07	0.10	0.08	0.06	0.09	0.09	0.05	0.05
0.01	0.61	0.46	0.59	0.53	0.05	0.16	0.06	0.16	BDL	0.61	0.58	BDL	0.17	0.32	0.40	0.01	0.28	0.53	0.79	0.47	BDL	0.46	0.54	BDL	0.11
3.33	3.03	3.06	3.04	3.11	3.36	3.21	3.24	3.26	3.38	3.05	3.14	3.26	3.33	3.20	3.15	3.35	3.23	3.03	2.94	3.10	3.23	3.09	3.05	3.33	3.32
9.66	9.60	9.51	9.63	9.74	9.80	9.53	9.46	9.68	9.81	9.69	9.89	9.46	9.90	9.70	9.67	9.73	9.73	9.52	9.60	9.63	9.37	9.59	9.57	9.64	9.76
0.05	0.05	0.04	0.12	0.23	0.16	BDL	0.01	0.13	0.18	0.06	0.29	BDL	0.23	0.10	0.07	0.10	0.16	0.11	0.17	0.04	0.03	0.05	0.04	0.20	0.01
97.03	98.01	97.92	98.81	99.79	97.73	97.79	97.58	99.23	97.65	98.62	100.83	97.53	98.62	98.84	98.86	97.62	98.18	97.53	98.53	98.92	97.83	98.21	98.21	97.56	97.50
-	0.25	0.19	0.25	0.22	0.02	0.07	0.02	0.07	-	0.26	0.24	-	0.07	0.13	0.17	-	0.12	0.22	0.33	0.20	-	0.19	0.23	-	0.05
97.03	97.76	97.73	98.56	99.56	97.70	97.72	97.56	99.16	97.65	98.36	100.59	97.53	98.55	98.71	98.69	97.62	98.06	97.31	98.20	98.72	97.83	98.01	97.99	97.56	97.46
6.06	6.11	6.16	6.16	6.20	6.08	6.12	6.17	6.18	6.09	6.11	6.17	6.16	6.09	6.12	6.15	6.06	6.09	6.15	6.14	6.12	6.21	6.13	6.13	6.14	6.02
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
5.99	5.67	5.41	5.48	5.41	6	5.51	5.34	5.41	6	5.73	5.50	5.35	6	5.63	5.55	6	5.85	5.52	5.43	5.47	5.01	5.56	5.53	5.68	6
-	0.01	-	0.01	0.01	-	0.02	-	0.01	-	0.01	-	0.01	-	0.01	-	-	0.01	-	0.02	0.01	-	0.01	0.01	-	-
-	-	-	-	-	0.09	-	-	-	0.09	-	-	-	0.07	-	-	-	-	-	-	-	-	-	-	-	0.18
-	-	0.01	-	-	-	0.01	-	-	-	-	0.02	-	0.01	0.01	0.01	-	0.02	0.01	0.07	0.05	-	-	-	0.01	-
-	-	-	-	-	0.01	-	-	-	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	0.01	-	-	0.01	0.01	-	-	-	-	0.01	-	0.01	0.01	-	-	0.01	0.01	0.01	0.01	0.01	0.01	-	-
2.97	3.29	3.55	3.41	3.42	2.78	3.46	3.64	3.49	2.78	3.22	3.27	3.64	2.75	3.27	3.38	2.93	3.01	3.39	3.36	3.43	3.96	3.39	3.42	3.16	2.81
0.04	0.04	0.03	0.09	0.16	0.12	-	0.01	0.09	0.13	0.05	0.20	-	0.17	0.07	0.05	0.07	0.11	0.08	0.12	0.03	0.03	0.04	0.03	0.14	0.01
3.01	3.33	3.58	3.51	3.59	3	3.48	3.65	3.59	3	3.26	3.50	3.64	3	3.36	3.45	3	3.14	3.48	3.55	3.52	3.99	3.43	3.46	3.32	3
0.02	0.02	0.03	0.02	0.05	0.03	-	0.01	0.03	0.02	0.02	0.03	0.02	-	-	0.03	0.04	-	0.02	-	0.03	0.08	0.02	0.07	0.01	0.03
0.77	0.86	0.87	0.91	0.85	0.66	0.93	0.95	0.86	0.65	0.81	0.90	0.95	0.71	0.90	0.81	0.73	0.87	0.90	0.98	0.91	0.99	0.89	0.85	0.84	0.68
0.01	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.01	0.01
0.20	0.09	0.09	0.05	0.08	0.31	0.05	0.02	0.09	0.32	0.16	0.06	0.02	0.28	0.08	0.15	0.22	0.12	0.07	-	0.04	-	0.07	0.07	0.14	0.27
4	3.65	3.73	3.66	3.70	3.97	3.91	3.97	3.91	4	3.65	3.68	4	3.90	3.82	3.77	4	3.84	3.69	3.55	3.73	4	3.74	3.69	4	3.94
-	0.35	0.27	0.34	0.30	0.03	0.09	0.03	0.09	-	0.35	0.32	-	0.10	0.18	0.23	-	0.16	0.31	0.45	0.27	-	0.26	0.31	-	0.06

Appendix F-1: Tourmaline continued

LG Srl 67 29b	LG Srl 69 29	LG Srl 70 29	LG Srl 67 30a	LG Srl 67 30b	LG Srl 69 30c	LG Srl 70 30	LG Srl 67 31a	LG Srl 67 31b	LG Srl 70 31a	LG Srl 70 31b	LG Srl 67 32	LG Srl 69 32	LG Srl 70 32a	LG Srl 70 32b	LG Srl 67 33	LG Srl 69 33	LG Srl 70 33	LG Srl 70 33	LG Srl 67 34	LG Srl 69 34	LG Srl 70 34	LG Srl 67 35	LG Srl 69 35	LG Srl 67 36	LG Srl 69 36
33.70	33.86	34.25	34.43	33.82	35.30	35.68	34.07	34.14	34.54	33.51	33.36	34.22	34.63	35.33	34.02	33.84	34.25	33.80	33.20	33.93	33.84	34.43	34.23	33.79	34.56
BDL	0.06	0.05	BDL	BDL	BDL	0.08	0.09	0.04	BDL	BDL	0.14	0.01	BDL	0.03	0.01	BDL	0.02	0.02	BDL	0.05	0.04	0.12	0.03	BDL	0.01
25.04	26.10	28.24	28.72	26.03	28.03	30.22	29.89	27.01	26.27	23.11	25.93	24.59	27.54	26.22	27.12	25.76	27.31	24.38	24.51	24.75	25.44	29.15	25.90	24.74	29.01
23.23	21.99	19.50	20.02	22.11	20.25	18.17	17.71	21.22	22.38	25.47	22.12	23.58	20.38	22.58	21.15	22.10	20.59	23.63	24.05	23.90	22.46	19.07	22.21	23.90	18.96
BDL	0.01	0.05	BDL	0.02	0.01	0.05	0.09	0.05	0.03	0.03	0.06	0.02	BDL	BDL	0.03	0.03	0.02	0.04	BDL	0.04	0.02	0.03	0.02	0.01	0.01
0.11	0.16	0.02	0.18	0.14	0.10	BDL	0.04	0.03	0.20	0.14	0.02	0.36	0.12	0.06	0.11	0.18	0.05	0.04	0.04	0.11	0.10	0.01	0.14	0.06	0.32
0.02	0.01	BDL	0.03	0.01	0.05	0.03	0.06	0.02	0.02	0.02	0.04	0.10	0.02	0.02	0.07	0.02	0.01	0.03	0.01	BDL	0.02	BDL	0.03	0.07	0.03
2.62	2.51	1.79	2.19	2.48	2.52	1.53	1.83	2.42	2.50	2.67	2.58	2.72	2.35	2.68	2.41	2.75	2.45	2.61	2.55	2.59	2.51	2.21	2.53	2.77	2.07
0.07	0.06	0.04	0.04	0.06	0.05	0.04	0.05	0.06	0.08	0.08	0.12	0.08	0.07	0.06	0.06	0.08	0.06	0.07	0.06	0.06	0.08	0.07	0.07	0.06	0.04
BDL	0.43	BDL	BDL	0.37	0.06	0.12	0.31	0.08	0.01	0.05	0.39	0.06	0.11	0.04	0.46	0.55	0.08	BDL	0.01	0.13	BDL	0.25	0.49	0.08	0.03
3.28	3.10	3.35	3.40	3.13	3.41	3.43	3.24	3.30	3.36	3.21	3.10	3.28	3.33	3.39	3.12	3.05	3.31	3.27	3.24	3.23	3.29	3.29	3.10	3.25	3.39
9.50	9.59	9.72	9.86	9.57	9.97	10.10	9.80	9.69	9.74	9.37	9.51	9.59	9.79	9.88	9.68	9.58	9.71	9.46	9.39	9.54	9.53	9.87	9.64	9.52	9.87
0.06	0.11	0.15	0.11	0.09	0.40	0.33	0.12	0.12	0.18	BDL	BDL	0.22	0.30	0.34	0.09	0.17	0.21	0.10	BDL	0.04	0.13	0.16	0.19	0.02	0.26
97.64	98	97.15	98.97	97.84	100.14	99.78	97.28	98.17	99.32	97.66	97.36	98.81	98.62	100.63	98.31	98.09	98.07	97.46	97.05	98.35	97.45	98.66	98.56	98.27	98.55
-	0.18	-	-	0.16	0.03	0.05	0.13	0.03	0.01	0.02	0.16	0.02	0.05	0.02	0.20	0.23	0.03	-	-	0.05	-	0.10	0.20	0.03	0.01
97.64	97.82	97.15	98.97	97.68	100.11	99.73	97.15	98.13	99.31	97.64	97.20	98.78	98.57	100.62	98.12	97.86	98.04	97.46	97.05	98.30	97.45	98.55	98.36	98.23	98.54
6.16	6.13	6.13	6.07	6.14	6.15	6.14	6.04	6.12	6.16	6.22	6.10	6.20	6.15	6.21	6.11	6.14	6.13	6.21	6.14	6.18	6.17	6.06	6.17	6.17	6.08
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
5.40	5.57	5.95	5.97	5.57	5.76	6	6	5.71	5.52	5.05	5.59	5.25	5.76	5.43	5.74	5.51	5.76	5.28	5.35	5.31	5.47	6	5.50	5.32	6
-	-	0.01	-	-	-	-	-	0.01	0.01	0.01	0.02	-	-	-	0.01	0.01	-	0.01	-	0.01	-	-	0.01	-	-
-	-	-	-	-	-	0.13	0.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	-	-	0.02
-	0.01	0.01	-	-	-	0.01	0.01	0.01	-	-	0.02	-	-	-	-	-	-	-	-	0.01	0.01	0.02	-	-	-
-	-	-	-	-	-	0.01	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	-	-	-
-	-	-	-	-	0.01	-	0.01	-	-	-	0.01	0.01	-	-	0.01	-	-	-	-	-	-	-	0.01	0.01	-
3.55	3.33	2.92	2.95	3.36	2.95	2.62	2.63	3.18	3.34	3.95	3.38	3.57	3.02	3.32	3.18	3.35	3.08	3.63	3.72	3.64	3.42	2.81	3.35	3.65	2.79
0.05	0.08	0.11	0.08	0.07	0.28	0.23	0.08	0.08	0.13	-	-	0.16	0.21	0.24	0.07	0.13	0.15	0.08	-	0.03	0.10	0.12	0.14	0.01	0.18
3.60	3.42	3.03	3.03	3.43	3.24	3	3	3.28	3.47	3.96	3.41	3.75	3.24	3.57	3.25	3.48	3.24	3.71	3.72	3.68	3.53	3	3.49	3.67	3
0.02	0.03	-	0.03	0.03	0.02	-	0.01	0.01	0.04	0.03	-	0.07	0.02	0.01	0.02	0.03	0.01	0.01	0.01	0.02	0.02	-	0.03	0.01	0.06
0.93	0.88	0.62	0.75	0.87	0.85	0.51	0.63	0.84	0.86	0.96	0.92	0.95	0.81	0.91	0.84	0.97	0.85	0.93	0.91	0.91	0.89	0.76	0.88	0.98	0.71
0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.03	0.02	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.02	0.02	0.01	0.01	0.01
0.03	0.07	0.37	0.21	0.08	0.12	0.48	0.35	0.14	0.08	-	0.05	-	0.16	0.06	0.13	-	0.13	0.05	0.06	0.05	0.08	0.23	0.07	-	0.22
4	3.75	4	4	3.79	3.97	3.93	3.83	3.95	3.99	3.97	3.78	3.97	3.94	3.98	3.74	3.69	3.95	4	4	3.93	4	3.86	3.72	3.95	3.98
-	0.25	-	-	0.21	0.03	0.07	0.17	0.05	0.01	0.03	0.22	0.03	0.06	0.02	0.26	0.31	0.05	-	-	0.07	-	0.14	0.28	0.05	0.02

Appendix F-1: Tourmaline continued

LG Srl 67 37	LG Srl 69 37a	LG Srl 69 37b	LG Srl 67 38a	LG Srl 67 38b	LG Srl 69 38	LG Srl 67 39a	LG Srl 69 39b	LG Fot 70 39a	LG Srl 70 39b	LG Srl 67 40a	LG Srl 67 40b	LG Srl 69 40	LG Srl 70 40	LG Srl 67 41	LG Srl 70 41	LG Srl 67 42	LG Srl 67 43	LG Srl 69 43	LG Srl 70 43	LG Srl 69 44	LG Srl 69 45	LG Srl 70 45	LG Srl 69 46	LG Fot 70 46	LG Srl 70 47
34.55	34.54	34.40	34.02	33.57	34.72	33.72	33.82	35.55	33.71	34.16	34.10	34.28	34.28	33.72	35.16	33.81	34.31	35.13	33.65	34.30	34.03	34.66	33.85	35.59	34.53
0.05	0.03	0.27	BDL	BDL	0.13	0.01	0.03	BDL	0.04	BDL	0.04	BDL	BDL	0.04	BDL	0.02	BDL	0.02	0.05	BDL	0.04	0.01	BDL	0.06	0.04
27.12	28.75	26.05	28.92	24.87	29.52	25.25	25.44	31.83	24.58	29.66	27.64	26.43	29.12	25.25	30.20	26.26	26.47	26.61	24.37	26.31	25.82	29.17	25.99	30.51	29.12
21.51	19.01	22.13	18.75	23.39	18.16	23.03	22.81	16.19	23.96	17.71	20.43	21.84	18.35	22.95	18.65	22.60	22.74	21.79	23.90	22.17	22.41	18.44	21.72	18.15	18.25
0.05	0.05	0.03	0.02	BDL	0.09	BDL	0.02	0.05	0.01	0.09	0.05	0.03	0.02	0.04	0.01	0.03	BDL	BDL	0.02	0.02	0.03	BDL	BDL	0.08	BDL
0.13	0.08	0.09	0.17	0.04	BDL	0.06	0.26	0.05	0.08	0.05	0.01	0.25	0.10	0.06	0.13	0.14	0.07	0.47	0.07	0.10	0.14	0.11	0.16	0.01	0.02
BDL	0.01	0.01	BDL	0.02	0.01	0.02	0.02	0.01	0.01	0.04	0.02	BDL	BDL	0.04	0.03	0.03	0.04	0.07	0.01	0.01	0.04	0.04	0.08	0.04	0.03
2.53	1.92	2.67	1.91	2.63	1.64	2.58	2.62	1	2.68	1.87	2.48	2.48	1.95	2.55	2.01	2.49	2.59	2.73	2.57	2.60	2.45	1.96	2.57	1.48	1.74
0.06	0.05	0.06	0.05	0.06	0.04	0.04	0.09	0.03	0.07	0.04	0.05	0.06	0.03	0.04	0.05	0.07	0.06	0.08	0.05	0.06	0.07	0.05	0.06	0.03	0.04
0.53	BDL	0.62	0.13	0.11	0.07	BDL	0.57	0.15	0.01	0.16	0.14	0.38	0.07	0.01	0.08	0.20	BDL	0.36	0.02	0.34	0.18	0.12	0.67	0.04	0.03
3.13	3.39	3.06	3.30	3.21	3.37	3.28	3.03	3.42	3.27	3.30	3.29	3.16	3.34	3.28	3.44	3.23	3.36	3.25	3.25	3.19	3.23	3.34	2.98	3.47	3.37
9.80	9.82	9.71	9.74	9.46	9.88	9.51	9.57	10.12	9.49	9.79	9.72	9.70	9.78	9.51	10.07	9.62	9.73	9.91	9.44	9.69	9.60	9.86	9.57	10.11	9.80
0.17	0.24	0.21	0.16	0.03	0.23	0.05	0.10	0.32	0.02	0.19	0.14	0.19	0.24	0.05	0.22	BDL	0.03	0.41	0.03	0.15	0.11	0.30	0.17	0.25	0.28
99.64	97.88	99.29	97.16	97.37	97.86	97.56	98.38	98.72	97.94	97.07	98.12	98.80	97.28	97.53	100.04	98.49	99.40	100.83	97.44	98.95	98.14	98.06	97.84	99.80	97.24
0.22	-	0.26	0.05	0.04	0.03	-	0.24	0.06	-	0.07	0.06	0.16	0.03	-	0.03	0.08	-	0.15	0.01	0.14	0.08	0.05	0.28	0.02	0.01
99.41	97.88	99.03	97.10	97.32	97.83	97.56	98.14	98.66	97.94	97	98.06	98.64	97.25	97.53	100	98.41	99.40	100.68	97.43	98.80	98.06	98.01	97.56	99.79	97.23
6.13	6.12	6.15	6.07	6.17	6.11	6.16	6.14	6.10	6.17	6.06	6.10	6.14	6.09	6.16	6.07	6.11	6.13	6.16	6.19	6.15	6.16	6.11	6.15	6.12	6.12
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
5.67	6	5.49	6	5.38	6	5.44	5.45	6	5.30	6	5.82	5.58	6	5.44	6	5.59	5.57	5.50	5.28	5.56	5.51	6	5.56	6	6
0.01	-	0.01	-	-	-	-	0.01	-	-	-	0.01	0.01	-	0.01	-	0.01	-	-	0.01	0.01	0.01	-	-	-	-
-	-	-	0.08	-	0.12	-	-	0.44	-	0.20	-	-	0.10	-	0.15	-	-	-	-	-	-	0.06	-	0.18	0.09
0.01	-	0.04	-	-	0.02	-	-	-	0.01	-	0.01	-	-	0.01	-	-	-	-	0.01	-	0.01	-	-	0.01	0.01
-	0.01	-	-	-	0.02	-	-	0.01	-	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	0.02	-
-	-	-	-	-	-	-	-	-	-	0.01	-	-	-	0.01	-	-	0.01	0.01	-	-	0.01	0.01	0.01	0.01	-
3.19	2.81	3.31	2.80	3.59	2.67	3.52	3.47	2.33	3.67	2.63	3.05	3.27	2.73	3.51	2.69	3.41	3.40	3.20	3.68	3.32	3.39	2.72	3.30	2.61	2.71
0.12	0.17	0.15	0.11	0.02	0.16	0.04	0.08	0.22	0.01	0.13	0.10	0.13	0.17	0.03	0.16	-	0.02	0.29	0.02	0.11	0.08	0.22	0.13	0.17	0.20
3.32	3	3.50	3	3.62	3	3.56	3.55	3	3.69	3	3.16	3.41	3	3.55	3	3.42	3.43	3.50	3.71	3.44	3.49	3	3.44	3	3
0.02	0.01	0.02	0.03	0.01	-	0.01	0.05	0.01	0.02	0.01	-	0.05	0.02	0.01	0.02	0.03	0.01	0.09	0.01	0.02	0.03	0.02	0.03	-	-
0.87	0.66	0.92	0.66	0.94	0.56	0.91	0.92	0.33	0.95	0.64	0.86	0.86	0.67	0.90	0.67	0.87	0.90	0.93	0.92	0.90	0.86	0.67	0.90	0.49	0.60
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01
0.09	0.31	0.05	0.29	0.04	0.43	0.06	0.01	0.65	0.01	0.34	0.13	0.08	0.30	0.07	0.29	0.08	0.08	-	0.06	0.06	0.10	0.30	0.05	0.50	0.39
3.70	4	3.65	3.93	3.94	3.96	4	3.67	3.92	4	3.91	3.92	3.78	3.96	3.99	3.96	3.89	4	3.80	3.99	3.81	3.89	3.93	3.61	3.98	3.98
0.30	-	0.35	0.07	0.06	0.04	-	0.33	0.08	-	0.09	0.08	0.22	0.04	0.01	0.04	0.11	-	0.20	0.01	0.19	0.11	0.07	0.39	0.02	0.02

Appendix F-1: Tourmaline continued

LG Srl 69 48	LG Srl 69 49	LG Srl 70 49	LG Srl 70 50a	LG Srl 70 50b	BG Srl 97 1a	BG Srl 97 1b	BG Srl 97 2	BG Srl 97 3	BG Srl 97 5	BG Srl 97 6	BG Srl 97 7	BG Srl 97 8	BG Srl 97 9	BG Srl 97 10	BG Srl 97 11	BG Srl 97 12	BG Srl 97 13	BG Srl 97 14	BG Srl 97 15	BG Srl 97 17	BG Srl 97 18	BG Srl 97 19	BG Srl 97 20	BG Srl 97 22	BG Srl 97 23	BG Srl 97 24
34.06	34.14	34.01	34.79	33.70	35.11	34.90	35.39	34.57	34.72	35.18	35.10	35.19	34.67	35	34.80	34.79	34.65	34.36	34.67	34	35.19	35.30	34.78	35.01	34.77	34.79
BDL	BDL	BDL	BDL	0.01	0.48	0.45	0.12	0.18	0.03	0.12	0.02	0.05	0.01	0.09	0.05	0.13	0.11	0.09	0.07	0.10	0.07	0.01	0.03	0.04	0.07	0.23
26.14	26.03	29.04	30	24.16	27.09	27.20	28.89	28.60	29.81	29.14	30.20	30.48	30.47	29.91	29.07	29.01	29.36	27.93	28.78	28.87	29.71	30.56	29.46	29.83	29.93	28.20
22.05	21.88	19.11	18.25	24.41	20.55	20.77	19.24	19	17.85	18.97	17.58	17.36	17.07	17.66	18.46	18.80	18.77	19.35	18.56	19.35	19.13	17.46	19.04	18.30	17.97	20
0.03	0.02	0.02	0.01	0.02	0.17	0.17	0.11	0.17	0.06	0.10	0.02	0.06	0.04	0.07	0.11	0.13	0.11	0.14	0.12	0.13	0.15	0.03	0.06	0.12	0.12	0.09
0.20	0.58	0.17	0.14	0.13	0.03	0.03	BDL	0.04	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	BDL	0.01	0.03	0.02	0.01
0.04	0.07	0.03	0.01	0.05	BDL	BDL	0.01	0.03	0.01	BDL	0.03	BDL	BDL	0.01	0.01	BDL	BDL	BDL	0.01	0.01	BDL	BDL	0.01	BDL	BDL	0.01
2.66	2.40	1.94	1.82	2.58	2.61	2.53	1.58	2.05	1.21	1.72	1.17	1.22	1.20	1.45	1.42	1.66	1.90	1.82	1.68	1.83	1.65	1.22	1.58	1.48	1.45	2.03
0.07	0.05	0.04	0.05	0.05	0.07	0.07	0.04	0.04	0.04	0.04	0.05	0.03	0.03	0.04	0.06	0.05	0.04	0.04	0.04	0.05	0.06	0.05	0.05	0.04	0.05	0.06
0.45	0.21	0.08	BDL	0.06	0.23	0.13	0.05	0.26	BDL	BDL	0.07	0.06	BDL	BDL	0.04	BDL	0.11	0.09	BDL	BDL	0.06	BDL	0.02	0.08	0.08	0.10
3.12	3.23	3.33	3.43	3.23	3.31	3.35	3.41	3.27	3.40	3.43	3.40	3.41	3.41	3.43	3.37	3.40	3.36	3.31	3.38	3.36	3.43	3.45	3.40	3.40	3.38	3.36
9.65	9.66	9.76	9.95	9.45	9.91	9.88	9.96	9.84	9.85	9.96	9.94	9.98	9.87	9.93	9.83	9.87	9.89	9.71	9.81	9.75	10.01	10.01	9.90	9.95	9.90	9.86
0.16	0.23	0.07	0.22	BDL	0.39	0.29	0.30	0.23	0.20	0.28	0.27	0.28	0.22	0.30	0.25	0.22	0.17	0.22	0.28	BDL	0.14	0.29	0.12	0.21	0.19	0.20
98.62	98.51	97.62	98.67	97.84	99.95	99.75	99.10	98.28	97.18	98.95	97.87	98.15	97.01	97.90	97.48	98.07	98.48	97.07	97.42	97.45	99.61	98.37	98.46	98.47	97.93	98.93
0.19	0.09	0.03	-	0.03	0.10	0.06	0.02	0.11	-	-	0.03	0.03	-	-	0.02	-	0.05	0.04	-	-	0.02	-	0.01	0.03	0.03	0.04
98.44	98.42	97.59	98.67	97.81	99.86	99.69	99.07	98.17	97.18	98.95	97.84	98.12	97.01	97.90	97.46	98.07	98.44	97.03	97.42	97.45	99.59	98.37	98.45	98.44	97.89	98.89
6.14	6.14	6.05	6.08	6.20	6.16	6.14	6.17	6.11	6.13	6.14	6.14	6.13	6.10	6.13	6.15	6.13	6.09	6.15	6.14	6.06	6.11	6.13	6.11	6.12	6.10	6.13
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
5.55	5.52	6	6	5.23	5.60	5.64	5.94	5.96	6	6	6	6	6	6	6	6	6	5.89	6	6	6	6	6	6	6	5.86
0.01	0.01	-	-	-	0.04	0.04	0.03	0.04	-	-	-	-	-	-	-	-	-	0.04	-	-	-	-	-	-	-	0.02
-	-	0.09	0.17	-	-	-	-	-	0.20	-	0.22	0.25	0.32	0.17	0.06	0.02	0.08	-	0.01	0.07	0.08	0.25	0.10	0.14	0.19	-
-	-	-	-	-	0.06	0.06	0.02	0.02	-	0.02	-	0.01	-	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	-	-	0.01	0.01	0.03
-	-	-	-	-	-	-	-	-	0.02	0.02	0.01	0.02	0.01	0.02	0.03	0.03	0.03	-	0.03	0.03	0.04	0.01	0.02	0.03	0.03	-
0.01	0.01	-	-	0.01	-	-	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.32	3.29	2.85	2.67	3.75	3.02	3.05	2.81	2.81	2.63	2.77	2.57	2.53	2.51	2.59	2.73	2.77	2.76	2.90	2.75	2.89	2.78	2.54	2.80	2.67	2.64	2.95
0.11	0.17	0.05	0.16	-	0.28	0.20	0.21	0.16	0.14	0.19	0.19	0.20	0.15	0.21	0.18	0.16	0.12	0.16	0.20	-	0.10	0.20	0.09	0.15	0.13	0.14
3.44	3.47	3	3	3.76	3.35	3.32	3.03	3	3	3	3	3	3	3	3	3	3	3.07	3	3	3	3	3	3	3	3.12
0.04	0.11	0.03	0.03	0.03	0.01	0.01	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	-	-
0.93	0.84	0.67	0.61	0.92	0.89	0.86	0.53	0.70	0.42	0.58	0.40	0.41	0.41	0.49	0.49	0.57	0.65	0.63	0.58	0.63	0.56	0.41	0.54	0.50	0.49	0.69
0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.02	0.04	0.29	0.35	0.04	0.09	0.12	0.46	0.28	0.57	0.41	0.59	0.58	0.58	0.49	0.50	0.42	0.34	0.36	0.41	0.35	0.43	0.58	0.45	0.48	0.49	0.29
3.74	3.88	3.95	4	3.96	3.87	3.93	3.97	3.85	4	4	3.96	3.97	4	4	3.98	4	3.94	3.95	4	4	3.97	4	3.99	3.96	3.96	3.94
0.26	0.12	0.05	-	0.04	0.13	0.07	0.03	0.15	-	-	0.04	0.03	-	-	0.02	-	0.06	0.05	-	-	0.03	-	0.01	0.04	0.04	0.06

Appendix F-1: Tourmaline continued

BG Srl 97 25	BG Srl 97 26	BG Fot 97 27	BG Fot 97 29	BG Srl 97 30	BG Srl 97 31	BG Srl 97 32	BG Srl 97 33	BG Fot 97 34	BG Srl 97 35	BG Srl 97 36	BG Fot 97 43	BG Srl 97 45	BG Fot 97 46	BG Srl 97 47	BG Srl 97 48	BG Srl 97 49	BG Srl 97 50	BG Srl 97 52	BG Fot 97 53	BG Srl 97 54	BG Srl 97 55	LP Fot 71 1a	LP Srl 71 1b	LP Srl 71 1c	LP Srl 71 2
35.08	35.64	35.36	35.13	35.46	34.89	35.37	34.59	35.26	34.62	34.91	34.50	34.84	35.21	34.07	34.06	34.86	35.83	33.93	35.53	34.64	34.48	35.97	34.39	34.61	34.18
0.12	0.11	0.08	0.04	0.08	0.08	0.05	0.12	0.06	0.03	0.05	0.07	0.12	0.05	0.09	0.13	0.09	0.06	BDL	0.09	0.09	0.11	0.07	0.05	BDL	0.30
29.78	30.43	30.42	30.28	30.08	29.01	29.60	28.78	30.34	29.14	28.68	30.08	29.09	30.16	28.87	28.78	29.68	30.63	29.15	30.68	28.67	28.18	32.16	25.62	25.56	26.33
19.22	18.17	17.92	17.63	18.87	19.03	19.39	19.26	18.22	18.92	19.76	17.75	19.39	17.22	19.02	19.41	19.01	18.58	19.32	18.28	19.78	19.86	16.09	23.22	23.29	22.25
0.11	0.11	0.04	0.02	0.13	0.16	0.11	0.11	0.14	0.06	0.06	0.07	0.09	0.04	0.09	0.12	0.10	0.15	0.06	0.13	0.07	0.10	0.02	0.01	0.01	0.02
0.01	0.03	0.02	BDL	0.01	0.01	0.01	0.01	BDL	0.01	0.03	0.01	0.02	BDL	0.01	0.02	0.01	0.01	0.02	0.02	BDL	BDL	BDL	0.11	0.12	0.14
0.01	0.02	BDL	0.02	0.01	0.02	0.02	0.02	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.01	BDL	BDL	BDL	BDL	0.05	0.03	0.05	
1.72	1.54	1.25	1.23	1.64	1.81	1.74	1.52	1.45	1.50	1.71	1.32	1.75	1.21	1.73	1.80	1.69	1.64	1.54	1.47	1.53	1.89	0.87	2.79	2.65	2.45
0.05	0.04	0.04	0.03	0.04	0.06	0.04	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.04	0.04	0.05	0.03	0.06	0.06	0.07
BDL	0.01	BDL	BDL	0.03	0.02	0.04	0.03	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.01	BDL	0.09	0.02	0.03	0.56
3.45	3.49	3.46	3.44	3.47	3.41	3.45	3.37	3.46	3.39	3.41	3.40	3.42	3.43	3.36	3.36	3.43	3.52	3.36	3.49	3.39	3.37	3.48	3.34	3.34	3.08
10.01	10.13	10.03	9.96	10.09	9.90	10.04	9.81	10.04	9.83	9.88	9.85	9.91	9.95	9.73	9.75	9.95	10.20	9.73	10.13	9.82	9.78	10.21	9.70	9.72	9.70
0.11	0.27	0.25	0.27	0.18	0.21	0.18	0.13	0.18	0.15	0.18	0.14	0.15	0.36	0.07	0.01	0.11	0.22	BDL	0.18	0.09	0.15	0.36	0.13	0.17	0.07
99.66	100	98.86	98.04	100.08	98.62	100.02	97.79	99.19	97.68	98.70	97.23	98.82	97.66	97.06	97.49	98.96	100.88	97.17	100.05	98.12	97.96	99.36	99.49	99.59	99.21
-	-	-	-	0.01	0.01	0.02	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.04	0.01	0.01	0.23
99.66	99.99	98.86	98.04	100.07	98.62	100.01	97.77	99.19	97.68	98.70	97.23	98.82	97.66	97.06	97.49	98.96	100.88	97.17	100.04	98.12	97.96	99.32	99.49	99.58	98.98
6.09	6.12	6.13	6.13	6.11	6.12	6.12	6.13	6.11	6.12	6.14	6.09	6.11	6.15	6.08	6.07	6.09	6.11	6.06	6.10	6.13	6.13	6.12	6.16	6.19	6.12
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
6	6	6	6	6	6	6	6	6	6	5.95	6	6	6	6	6	6	6	6	6	5.98	5.90	6	5.41	5.39	5.56
-	-	-	-	-	-	-	-	-	-	0.02	-	-	-	-	-	-	-	-	-	0.02	0.03	-	-	-	0.01
0.09	0.16	0.21	0.23	0.11	-	0.04	0.01	0.19	0.08	-	0.26	0.01	0.21	0.08	0.05	0.11	0.15	0.14	0.20	-	-	0.45	-	-	-
0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	-	0.01	0.01	0.02	0.01	0.01	0.02	0.01	0.01	-	0.01	0.01	0.01	0.01	-	0.04	
0.03	0.03	0.01	0.01	0.03	0.04	0.03	0.03	0.04	0.02	-	0.02	0.02	0.01	0.02	0.03	0.03	0.04	0.02	0.03	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	-	-	0.01
2.79	2.61	2.60	2.57	2.72	2.79	2.80	2.85	2.64	2.80	2.91	2.62	2.84	2.52	2.84	2.89	2.78	2.65	2.89	2.62	2.93	2.95	2.29	3.48	3.48	3.33
0.07	0.19	0.17	0.19	0.13	0.15	0.12	0.09	0.13	0.11	0.12	0.10	0.10	0.26	0.05	0.01	0.08	0.15	-	0.13	0.06	0.11	0.25	0.09	0.12	0.05
3	3	3	3	3	3	3	3	3	3	3.04	3	3	3	3	3	3	3	3.04	3	3	3.07	3	3.59	3.61	3.43
-	0.01	-	-	-	-	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	0.02	0.02	0.03	0.03
0.58	0.51	0.42	0.42	0.55	0.62	0.58	0.52	0.49	0.51	0.58	0.45	0.60	0.41	0.60	0.62	0.57	0.54	0.53	0.49	0.52	0.65	0.29	0.97	0.92	0.85
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02
0.41	0.47	0.57	0.58	0.44	0.37	0.41	0.47	0.50	0.48	0.40	0.54	0.39	0.58	0.39	0.36	0.42	0.45	0.45	0.50	0.47	0.34	0.71	-	0.04	0.11
4	4	4	4	3.99	3.99	3.98	3.98	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3.95	3.99	3.98	3.68
-	-	-	-	0.01	0.01	0.02	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	0.01	0.02	0.32

Appendix F-1: Tourmaline continued

LP Srl 71 3	LP Fot 71 5a	LP Srl 71 5b	LP Srl 71 7	LP Srl 71 8	LP Srl 71 10	LP Srl 71 11a	LP Srl 71 11b	LP Srl 71 14	LP Srl 71 15	LP Srl 71 16	LP Srl 71 18	LP Srl 71 19	LP Srl 71 20	LP Srl 71 23	LP Srl 71 24	LP Srl 71 26	LP Srl 71 27	LP Srl 71 28	LP Srl 71 29	LP Srl 71 30	LP Srl 71 31	LP Srl 71 32	LP Srl 71 33	LP Srl 71 34	LP Srl 71 35
34.35	34.94	33.98	34.17	34.45	34.06	34.54	34.67	34.36	34.75	34.66	34.38	34.46	34.80	34.12	34.51	34.28	34.33	34.23	35.07	34.98	33.90	34.89	35.29	35.66	35.16
0.03	0.09	0.02	BDL	BDL	0.02	0.05	0.01	BDL	BDL	BDL	BDL	0.34	0.03	0.03	BDL	0.02	BDL	0.18	0.02	0.01	BDL	BDL	0.05	BDL	BDL
24.54	31.38	25.82	24.86	26.05	25.48	24.85	24.99	24.64	27.78	24.80	25.42	26.56	26.24	25.80	25.73	26.14	27.15	25.74	26.52	29.24	25.15	28.75	28.11	30.17	30.02
24.28	16.36	22.82	23.69	22.63	23.29	23.63	24.13	24.22	21	24	23.57	21.22	22.12	22.98	23.08	22	21.38	22.33	22.23	19.29	23.26	19.87	20.21	18.29	18.30
0.02	0.03	0.02	0.01	BDL	0.01	BDL	BDL	BDL	0.01	BDL	0.02	0.01	0.05	BDL	0.02	0.02	0.01	0.03	0.04	BDL	0.03	0.02	0.02	BDL	0.02
0.39	BDL	0.09	0.22	0.18	0.18	0.09	0.07	0.09	0.26	0.14	0.10	0.20	0.25	0.22	0.17	0.36	0.37	0.21	0.14	0.55	0.39	0.38	0.10	0.09	0.16
0.04	BDL	0.02	0.06	0.04	0.09	0.01	0.01	0.01	0.06	0.01	0.01	0.05	0.06	0.02	0.03	0.02	0.06	0.08	0.05	0.09	0.02	0.04	0.05	0.06	0.01
2.73	0.89	2.63	2.67	2.45	2.60	2.64	2.79	2.73	2.28	2.71	2.75	2.40	2.65	2.58	2.61	2.53	2.39	2.56	2.54	2.05	2.54	2.35	2.50	2.06	1.86
0.07	0.01	0.07	0.06	0.11	0.09	0.05	0.06	0.07	0.05	0.07	0.07	0.04	0.06	0.07	0.06	0.05	0.05	0.06	0.06	0.05	0.08	0.06	0.06	0.05	0.04
BDL	BDL	0.39	0.02	0.23	0.27	BDL	0.06	0.08	BDL	0.02	0.05	0.55	0.58	0.40	0.44	0.56	0.18	0.54	0.40	0.02	BDL	0.13	0.05	0.01	0.05
3.33	3.44	3.13	3.30	3.24	3.19	3.33	3.32	3.28	3.41	3.33	3.32	3.10	3.11	3.14	3.14	3.08	3.28	3.08	3.21	3.44	3.30	3.38	3.42	3.49	3.44
9.64	9.97	9.62	9.60	9.71	9.62	9.65	9.71	9.62	9.87	9.68	9.68	9.74	9.80	9.65	9.71	9.69	9.77	9.66	9.85	10.01	9.57	9.97	9.98	10.14	10.02
0.15	0.21	0.06	0.13	0.15	0.05	0.21	0.16	0.13	0.18	0.21	0.11	0.27	0.29	0.08	0.15	0.22	0.16	0.19	0.27	0.28	0.10	0.26	0.38	0.40	0.30
99.57	97.31	98.68	98.77	99.22	98.95	99.05	99.98	99.22	99.67	99.62	99.47	98.93	100.02	99.10	99.67	98.97	99.13	98.89	100.39	99.99	98.35	100.12	100.22	100.42	99.36
-	-	0.16	0.01	0.10	0.11	-	0.03	0.03	-	0.01	0.02	0.23	0.24	0.17	0.19	0.24	0.08	0.23	0.17	0.01	-	0.06	0.02	-	0.02
99.57	97.31	98.51	98.76	99.12	98.84	99.05	99.95	99.18	99.67	99.62	99.44	98.70	99.78	98.93	99.48	98.74	99.06	98.66	100.22	99.98	98.35	100.06	100.19	100.42	99.34
6.19	6.09	6.14	6.19	6.17	6.15	6.22	6.21	6.21	6.12	6.22	6.17	6.15	6.17	6.14	6.17	6.15	6.11	6.16	6.18	6.08	6.16	6.08	6.15	6.11	6.10
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
5.21	6	5.50	5.31	5.50	5.42	5.28	5.27	5.25	5.77	5.25	5.38	5.59	5.49	5.48	5.43	5.53	5.69	5.46	5.51	5.99	5.38	5.91	5.77	6	6
0.01	-	0.01	-	-	-	-	-	-	-	-	-	-	0.01	-	0.01	0.01	-	0.01	0.01	-	0.01	0.01	-	-	-
-	0.45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.10	0.13
-	0.01	-	-	-	-	0.01	-	-	-	-	-	0.05	-	-	-	-	-	0.02	-	-	-	-	0.01	-	-
-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.01	-	-	0.01	0.01	0.01	-	-	-	0.01	-	-	0.01	0.01	-	-	-	0.01	0.01	0.01	0.01	-	0.01	0.01	0.01	-
3.66	2.39	3.45	3.59	3.39	3.52	3.56	3.61	3.66	3.09	3.60	3.54	3.17	3.28	3.46	3.45	3.30	3.18	3.36	3.28	2.80	3.53	2.90	2.94	2.62	2.65
0.11	0.15	0.04	0.09	0.11	0.04	0.15	0.11	0.09	0.13	0.15	0.08	0.19	0.21	0.06	0.11	0.16	0.11	0.14	0.19	0.20	0.07	0.18	0.27	0.27	0.21
3.78	3	3.50	3.69	3.50	3.57	3.72	3.73	3.75	3.23	3.75	3.62	3.41	3.50	3.52	3.57	3.47	3.30	3.53	3.48	3.01	3.61	3.09	3.22	3	3
0.08	-	0.02	0.04	0.03	0.03	0.02	0.01	0.02	0.05	0.03	0.02	0.04	0.05	0.04	0.03	0.07	0.07	0.04	0.03	0.10	0.08	0.07	0.02	0.02	0.03
0.96	0.30	0.92	0.94	0.85	0.91	0.92	0.97	0.96	0.78	0.94	0.96	0.83	0.91	0.90	0.91	0.88	0.83	0.89	0.87	0.69	0.89	0.80	0.84	0.68	0.62
0.02	-	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01
-	0.70	0.04	0.01	0.09	0.03	0.05	-	0.01	0.16	0.01	0.01	0.12	0.03	0.04	0.05	0.04	0.09	0.05	0.09	0.20	0.01	0.12	0.13	0.29	0.34
4	4	3.78	3.99	3.87	3.85	4	3.97	3.96	4	3.99	3.97	3.69	3.68	3.77	3.75	3.68	3.90	3.69	3.78	3.99	4	3.93	3.97	4	3.97
-	-	0.22	0.01	0.13	0.15	-	0.03	0.04	-	0.01	0.03	0.31	0.32	0.23	0.25	0.32	0.10	0.31	0.22	0.01	-	0.07	0.03	-	0.03

Appendix F-1: Tourmaline continued

LP Srl 71 36	LP Srl 71 37	LP Srl 71 38	LP Srl 71 39	LP Srl 71 40	LP Srl 71 41	LP Srl 71 42	LP Srl 71 43	LP Srl 71 45	LP Srl 71 47	BP Srl 79 1	BP Srl 79 2	BP Srl 79 5	BP Srl 79 6	BP Srl 79 7	BP Srl 79 11	BP Srl 79 12	BP Srl 79 14	BP Srl 79 15a	BP Srl 79 15b	BP Fot 79 16a	BP Srl 79 16b	BP Srl 79 17	BP Srl 79 20	BP Srl 79 25	BP Srl 79 26
34.90	34.75	33.67	35	34.12	33.82	33.96	34.59	34.50	33.51	34.14	34.01	34.01	34.07	34.10	33.96	34.09	33.56	33.95	33.91	34.50	34.12	33.94	33.60	33.68	33.81
0.02	0.01	0.14	0.02	0.01	BDL	0.02	0.03	0.02	0.03	0.06	0.03	0.03	0.17	0.03	BDL	BDL	BDL	0.04	0.01	BDL	0.04	0.09	0.05	0.07	0.06
29.70	26.60	25.05	25.78	25.32	25.85	24.62	26.66	25.24	23.10	29.87	28.64	27.15	26.72	27.04	30.01	30.72	26.70	28.86	26.19	31.25	26.66	27.26	26.67	26.44	26.02
18.19	22.08	22.93	23.34	23.59	22.34	23.59	22.37	23.59	25.55	18.26	19.94	21.39	20.98	21.07	18.24	17.32	21.32	19.10	21.84	17.28	21.87	21	21.40	21.47	21.96
0.03	0.01	0.04	0.02	0.01	0.01	BDL	0.01	BDL	0.01	BDL	0.02	BDL	0.03	BDL	BDL	BDL	0.01	BDL	BDL	0.02	0.02	BDL	0.02	0.01	0.02
0.15	0.06	0.08	0.09	0.12	0.14	0.07	0.04	0.08	0.39	0.11	0.06	0.04	0.04	0.02	0.13	0.19	0.02	0.08	0.03	0.17	0.05	0.02	0.04	0.04	0.04
0.04	0.02	0.04	0.01	0.06	0.01	0.02	0.06	0.03	0.03	0.01	BDL	0.06	0.02	0.04	0.02	0.03	0.06	0.01	0.06	0.01	0.04	0.01	0.07	0.06	0.01
1.85	2.63	2.71	2.76	2.74	2.38	2.72	2.72	2.58	2.66	1.59	2.13	2.21	2.13	2.15	1.58	1.40	2.45	2.18	2.49	1.35	2.37	2.22	2.28	2.33	2.37
0.04	0.06	0.10	0.06	0.04	0.06	0.06	0.06	0.07	0.07	0.05	0.05	0.05	0.06	0.04	0.03	0.03	0.06	0.06	0.05	0.04	0.04	0.04	0.04	0.07	0.06
0.03	0.07	0.58	0.01	BDL	0.07	BDL	0.02	0.01	0.04	BDL	BDL	BDL	BDL	BDL	0.01	0.07	BDL	0.05	BDL	BDL	0.05	0.04	0.04	0.04	BDL
3.42	3.35	3	3.39	3.32	3.26	3.29	3.37	3.33	3.22	3.38	3.37	3.34	3.32	3.33	3.37	3.36	3.30	3.34	3.31	3.43	3.31	3.31	3.28	3.28	3.30
9.94	9.80	9.51	9.82	9.63	9.56	9.52	9.80	9.67	9.39	9.81	9.76	9.67	9.63	9.65	9.79	9.84	9.56	9.75	9.59	9.96	9.67	9.65	9.55	9.56	9.55
0.30	0.22	0.09	0.22	0.06	0.08	0.13	0.13	0.14	BDL	0.06	0.02	0.02	0.15	0.11	0.01	0.06	0.03	0.11	0.11	0.06	0.07	0.06	0.01	0.06	0.09
98.60	99.65	97.96	100.52	99.02	97.58	98.02	99.85	99.24	97.99	97.35	98.02	97.97	97.33	97.57	97.16	97.10	97.06	97.52	97.58	98.08	98.31	97.64	97.04	97.10	97.30
0.01	0.03	0.25	-	-	0.03	-	0.01	-	0.02	-	-	-	-	-	0.01	0.03	-	0.02	-	-	0.02	0.02	0.02	0.02	-
98.58	99.62	97.71	100.51	99.01	97.55	98.02	99.85	99.24	97.97	97.35	98.02	97.97	97.33	97.57	97.15	97.07	97.06	97.50	97.58	98.07	98.29	97.62	97.03	97.08	97.30
6.10	6.16	6.15	6.19	6.16	6.15	6.20	6.14	6.20	6.20	6.05	6.06	6.11	6.15	6.14	6.03	6.02	6.10	6.05	6.15	6.02	6.13	6.11	6.11	6.13	6.15
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
6	5.56	5.40	5.38	5.39	5.54	5.30	5.57	5.35	5.04	6	6	5.75	5.69	5.74	6	6	5.72	6	5.59	6	5.65	5.78	5.72	5.67	5.58
-	-	0.01	0.01	-	-	-	-	-	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	0.01
0.12	-	-	-	-	-	-	-	-	-	0.24	0.01	-	-	-	0.28	0.40	-	0.06	-	0.43	-	-	-	-	-
-	-	0.02	-	-	-	-	-	-	-	0.01	-	-	0.02	-	-	-	-	0.01	-	-	-	0.01	0.01	0.01	0.01
0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.01	-	0.01	-	0.01	-	-	0.01	-	0.01	-	-	0.01	-	0.01	-	-	0.01	-	0.01	-	0.01	-	0.01	0.01	-
2.66	3.27	3.50	3.45	3.56	3.40	3.60	3.32	3.55	3.96	2.71	2.97	3.22	3.17	3.17	2.71	2.56	3.24	2.85	3.31	2.52	3.29	3.16	3.26	3.27	3.34
0.21	0.16	0.07	0.16	0.04	0.06	0.10	0.09	0.10	-	0.05	0.01	0.02	0.11	0.08	0.01	0.04	0.02	0.08	0.08	0.04	0.05	0.04	0.01	0.04	0.06
3	3.44	3.59	3.62	3.61	3.46	3.70	3.42	3.65	3.96	3	3	3.25	3.31	3.26	3	3	3.27	3	3.40	3	3.35	3.22	3.28	3.33	3.41
0.03	0.01	0.02	0.02	0.02	0.03	0.01	0.01	0.02	0.08	0.02	0.01	0.01	0.01	-	0.03	0.04	-	0.01	0.01	0.03	0.01	-	0.01	0.01	0.01
0.63	0.90	0.96	0.95	0.96	0.84	0.96	0.93	0.90	0.96	0.55	0.74	0.77	0.75	0.75	0.54	0.48	0.87	0.75	0.87	0.46	0.83	0.77	0.80	0.82	0.84
0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
0.34	0.07	-	0.02	0.01	0.12	0.01	0.04	0.07	-	0.42	0.24	0.21	0.23	0.24	0.42	0.48	0.12	0.22	0.11	0.50	0.15	0.21	0.18	0.15	0.14
3.98	3.96	3.66	4	4	3.96	4	3.99	3.99	3.97	4	4	4	4	4	3.99	3.96	4	3.97	4	4	3.97	3.98	3.98	3.98	4
0.02	0.04	0.34	-	-	0.04	-	0.01	0.01	0.03	-	-	-	-	-	0.01	0.04	-	0.03	-	-	0.03	0.02	0.02	0.02	-

Appendix F-1: Tourmaline continued

BP Srl 79 28	BP Srl 79 30a	BP Srl 79 30b	BP Srl 79 31	BP Srl 79 33	BP Fot 79 34a	BP Srl 79 34b	BP Srl 79 35	BP Srl 79 36	BP Srl 79 37	BP Srl 79 38	BP Srl 79 39	BP Srl 79 40	BP Srl 79 41a	BP Srl 79 41b	BP Srl 79 42	BP Srl 79 43a	BP Srl 79 43b	BP Srl 79 44a	BP Srl 79 44b	BP Srl 79 45	BP Srl 79 46	BP Srl 79 47	BP Srl 79 50
34.18	34.21	33.93	33.79	33.78	35.37	33.65	33.97	33.74	33.69	33.73	34.1 1	33.76	34.46	34.02	34.74	34.17	33.52	34.15	33.86	33.76	33.99	34.12	34.04
0.07	0.01	0.05	0.12	0.05	BDL	0.01	0.05	0.06	BDL	0.03	0.08	0.02	BDL	0.05	0.06	0.04	0.04	0.01	0.04	0.05	BDL	0.01	BDL
26.91	30.27	27.21	26.76	26.26	31.82	25.16	26.95	26.59	25.49	25.84	27.3 6	26.35	29.37	26.35	27.24	30.80	26.01	31.04	26.12	25.97	26.67	26.98	26.29
21.40	17.79	21.07	21.13	21.78	15.93	22.92	21.27	21.39	22.69	22.08	20.9 1	22.24	18.73	21.97	21.25	17.52	22.48	17.43	22.62	21.84	21.30	21.04	21.88
BDL	BDL	0.01	BDL	BDL	0.07	BDL	0.03	0.01	0.01	BDL	BDL	BDL	BDL	BDL	0.01	0.02	BDL	BDL	0.08	BDL	BDL	BDL	0.02
0.05	0.14	0.04	0.09	0.06	0.02	0.05	0.03	0.04	0.03	0.04	0.03	0.02	0.07	0.03	0.04	0.18	0.04	0.20	0.05	0.02	0.03	0.04	0.02
BDL	0.06	BDL	0.03	BDL	BDL	0.03	0.03	0.03	0.03	0.02	0.05	BDL	BDL	0.03	0.02	0.03	0.04	0.03	0.01	0.04	0.01	0.02	BDL
2.15	1.49	2.13	2.27	2.31	0.75	2.52	2.23	2.22	2.51	2.35	2.27	2.38	1.81	2.48	2.24	1.41	2.36	1.53	2.45	2.39	2.28	2.28	2.46
0.06	0.05	0.05	0.06	0.08	0.03	0.06	0.06	0.06	0.07	0.05	0.05	0.05	0.06	0.07	0.08	0.04	0.07	0.02	0.07	0.07	0.05	0.05	0.07
0.02	0.01	BDL	0.15	BDL	BDL	BDL	0.11	0.14	BDL	BDL	BDL	BDL	0.01	0.03	0.01	0.05	BDL	BDL	BDL	BDL	0.02	0.01	0.02
3.33	3.39	3.33	3.24	3.30	3.47	3.27	3.27	3.23	3.28	3.28	3.35	3.31	3.39	3.31	3.38	3.38	3.29	3.42	3.32	3.29	3.31	3.33	3.31
9.67	9.84	9.64	9.60	9.56	10.06	9.48	9.64	9.57	9.51	9.52	9.70	9.58	9.84	9.63	9.80	9.87	9.53	9.90	9.61	9.53	9.61	9.66	9.62
0.10	0.08	0.05	0.09	0.08	0.29	0.06	0.07	0.06	0.05	0.08	0.10	BDL	0.17	0.10	0.20	0.02	BDL	0.02	BDL	0.11	0.13	0.15	0.13
97.94	97.33	97.48	97.33	97.25	97.79	97.20	97.70	97.14	97.36	97.02	98	97.70	97.91	98.06	99.06	97.53	97.37	97.74	98.25	97.06	97.39	97.67	97.85
0.01	-	-	0.06	-	-	-	0.05	0.06	-	-	-	-	-	-	0.01	-	0.02	-	-	-	0.01	-	0.01
97.9 4	97.3 3	97.4 8	97.2 6	97.2 5	97.7 9	97.2 0	97.6 6	97.0 8	97.3 6	97.0 2	98	97.7 0	97.9 1	98.0 4	99.0 6	97.5 1	97.3 7	97.7 4	98.2 5	97.0 6	97.3 8	97.6 7	97.8 4
6.14	6.04	6.12	6.12	6.14	6.11	6.17	6.13	6.13	6.16	6.16	6.11	6.12	6.09	6.14	6.16	6.02	6.12	6	6.12	6.16	6.15	6.14	6.15
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
5.70	6	5.78	5.71	5.63	6	5.44	5.73	5.69	5.49	5.56	5.78	5.63	6	5.60	5.69	6	5.59	6	5.57	5.58	5.68	5.72	5.60
-	-	-	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	0.02	-	-	-	-
-	0.30	-	-	-	0.48	-	-	-	-	-	-	-	0.11	-	-	0.39	-	0.42	-	-	-	-	-
0.01	-	0.01	0.02	0.01	-	-	0.01	0.01	-	-	0.01	-	-	0.01	0.01	0.01	-	-	0.01	0.01	-	-	-
-	-	-	-	-	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	0.01	-	-	-	-	-	-	-	-	-	0.01	-	-	-	-	-	0.01	-	-	0.01	-	-	-
3.22	2.63	3.18	3.20	3.31	2.30	3.51	3.21	3.25	3.47	3.37	3.13	3.37	2.77	3.32	3.15	2.58	3.43	2.56	3.42	3.33	3.22	3.17	3.31
0.07	0.06	0.03	0.07	0.06	0.20	0.04	0.05	0.04	0.03	0.06	0.07	-	0.12	0.07	0.14	0.02	-	0.02	-	0.08	0.09	0.11	0.09
3.30	3	3.22	3.29	3.37	3	3.56	3.27	3.30	3.51	3.44	3.22	3.38	3	3.40	3.31	3	3.44	3	3.43	3.42	3.32	3.28	3.40
0.01	0.03	0.01	0.02	0.01	-	0.01	-	0.01	0.01	0.01	0.01	-	0.01	0.01	0.01	0.03	0.01	0.04	0.01	-	0.01	0.01	-
0.75	0.51	0.74	0.80	0.81	0.25	0.89	0.78	0.78	0.89	0.83	0.79	0.84	0.62	0.87	0.77	0.48	0.84	0.52	0.86	0.84	0.80	0.79	0.86
0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.02	-	0.02	0.02	0.01	0.01	0.02
0.23	0.45	0.24	0.17	0.16	0.74	0.08	0.20	0.20	0.09	0.15	0.19	0.15	0.35	0.11	0.21	0.48	0.14	0.44	0.12	0.14	0.18	0.19	0.12
3.99	3.99	4	3.92	4	4	4	3.94	3.92	4	4	4	4	4	3.98	4	3.97	4	4	4	4	3.99	4	3.99
0.01	0.01	-	0.08	-	-	-	0.06	0.08	-	-	-	-	-	0.02	-	0.03	-	-	-	-	0.01	-	0.01

Appendix F-2: Cassiterite EPMA compositions

Sample Point	67 26 Vug	67 16 Vug	67 17 Vug	67 19 Vug	67 20 Vug	67 22 Vug	67 23 Vug	67 25 Vug	67 27 Vug	67 29 Vug	67 30 Vug	67 31 Vug	67 32 Vug	67 33 Vug	67 34 Vug	67 36 Vug	67 37 Vug	67 39 Vug	67 40 Vug	67 43 Vug	67 44 Vug	67 46 Vug
SnO ₂	100.71	99.25	100.34	99.53	99.95	100.69	100.39	100.20	99.92	100.07	99.49	100.06	99.41	100.21	99.88	98.76	100.35	100.15	100.30	99.99	100.10	99.15
Nb ₂ O ₅	BDL	0.11	0.02	0.06	0.02	0.02	0.03	0.04	0.02	0.02	0.03	0.02	0.02	0.05	0.01	0.05	BDL	0.04	BDL	BDL	BDL	0.01
FeO ^{tot}	0.85	0.62	1.03	0.97	0.97	0.27	0.46	0.33	0.85	0.90	0.74	0.47	0.42	0.55	0.61	0.90	0.36	0.73	0.27	0.72	0.90	0.76
MnO	BDL	BDL	BDL	BDL	BDL	0.02	BDL	BDL	BDL	0.02	BDL	BDL	0.03	BDL	BDL	0.02	BDL	0.01	BDL	0.03	BDL	0.05
Ta ₂ O ₅	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
WO ₃	BDL	0.01	0.01	BDL	0.04	BDL	BDL	0.23	0.02	BDL	BDL	BDL	0.14	0.01	BDL	BDL	BDL	BDL	0.10	0.04	0.01	BDL
TiO ₂	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Total	101.56	99.99	101.40	100.56	100.98	101	100.88	100.78	100.81	101	100.26	100.54	100.03	100.82	100.49	99.74	100.71	100.93	100.67	100.77	101.02	99.97
Cations based on 2 anions																						
Sn	0.99	0.98	0.99	0.98	0.98	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.99	0.98	0.97	0.99	0.99	0.99	0.98	0.99	0.98
Nb	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fe ²⁺	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.02	0.02
Mn	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ta	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
W	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ti	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	1.01	0.99	1.01	1	1	1	1	0.99	1	1	0.99	0.99	0.99	1	1	0.99	1	1	0.99	1	1	0.99
	67 47 1 Vug	67 48 1 Vug	67 49 1 Vug	67 50 1 Vug	67 1 1 Vug	67 2 1 Vug	67 3 1 Vug	67 4 1 Vug	67 6 1 Vug	67 7 1 Vug	67 8 1 Vug	67 9 1 Vug	67 10 1 Vug	67 11 1 Vug	67 12 1 Vug	67 13 1 Vug	67 14 1 Vug	67 15 1 Vug	69 46 1 Grsn	69 23 1 Grsn	69 22 1 Grsn	69 13 1 Grsn
	99.80	99.20	100.03	99.64	99.44	99.51	100.78	101.09	100.40	100.11	98.87	99.94	100.09	99.94	100.87	99.86	99.94	100.17	101.10	100.82	100.40	100.13
	0.01	0.03	0.06	0.04	BDL	0.01	0.01	0.02	BDL	BDL	0.05	0.10	0.03	0.05	BDL	0.05	0.02	0.06	0.03	BDL	BDL	BDL
	0.34	0.64	0.84	0.82	0.58	0.51	0.33	0.45	0.20	0.71	0.90	0.95	0.60	0.99	0.27	0.86	0.71	0.33	0.49	0.54	1.02	1.07
	BDL	BDL	BDL	BDL	BDL	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.02	BDL	BDL	BDL	BDL	BDL	0.01	0.05	0.04	BDL	BDL	BDL	BDL	BDL
	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
	100.15	99.86	100.93	100.49	100.03	100.03	101.11	101.56	100.62	100.82	99.82	100.98	100.72	100.99	101.15	100.82	100.72	100.57	101.62	101.35	101.42	101.20
	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.99	0.97	0.98	0.99	0.98	0.99	0.98	0.98	0.99	1	0.99	0.99	0.99
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	-	0.01	0.02	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.02
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	0.99	0.99	1	1.00	0.99	0.99	1.00	1.00	0.99	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.01	1.00	1.01	1.01

Appendix F-2: Cassiterite continued

69 7 Grsn	69 Grsn	69 1 Grsn	69 44 Grsn	69 1 Grsn	69 22 Grsn	69 13 Grsn	69 49 Grsn	69 45 Grsn	69 42 Grsn	69 40 Grsn	69 34 Grsn	69 31 Grsn	69 28 Grsn	69 27 Grsn	69 26 Grsn	69 20 Grsn	69 19 Grsn
100.87	100.85	100.26	100.54	100.72	100.38	100.70	100.35	100.88	100.47	100.50	100.53	100.21	100.44	100.38	100.61	99.90	100.61
BDL	0.03	0.02	BDL	0.08	0.03	BDL	0.06	BDL	0.05	0.04	0.07	BDL	0.04	BDL	BDL	0.04	0.04
0.95	0.84	1.08	0.76	0.58	1.10	1.06	0.97	0.93	1.00	0.95	1.25	0.93	1.06	0.86	0.96	0.94	0.90
BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.03	BDL	0.01	BDL	BDL	0.01	BDL	BDL	0.01	BDL	BDL
BDL	BDL	BDL	0.02	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.11	BDL	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
101.82	101.71	101.36	101.33	101.38	101.51	101.76	101.41	101.81	101.53	101.48	101.85	101.14	101.54	101.35	101.58	100.88	101.55
0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.01	1.01	1.01	1.01	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.02	1.01	1.01	1.01	1.01	1.00	1.01
69 18 1 Grsn	69 15 1 Grsn	69 14 1 Grsn	69 12 1 Grsn	69 10 1 Grsn	69 8 1 Grsn	69 6 1 Grsn	69 5 1 Grsn	69 4 1 Grsn	69 3 1 Grsn	69 2 1 Grsn	72 42 1 Grsn	72 33 1 Grsn	72 30 1 Grsn	72 25 1 Grsn	72 7 1 Grsn	72 4 1 Grsn	72 1 1 Grsn
100.84	100.64	100.81	100.76	100.32	100.71	100.95	101.08	100.57	100.28	100.41	99.36	100.32	100.39	99.05	101.14	100.07	99.87
0.02	BDL	0.02	BDL	0.01	0.03	BDL	0.07	0.01	0.02	0.02	0.05	BDL	0.02	0.25	0.03	0.10	0.04
0.39	0.87	0.96	0.82	1.06	0.81	0.83	0.73	0.77	0.93	1.02	1.55	1.08	0.92	1.61	0.67	1.64	1.58
BDL	0.01	BDL	0.01	0.04	0.01	BDL	BDL	0.01	0.01	0.01	0.03	BDL	BDL	BDL	0.01	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
BDL	BDL	BDL	BDL	0.10	BDL	BDL	BDL	BDL	BDL	BDL	0.11	BDL	BDL	BDL	BDL	0.03	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
101.25	101.52	101.79	101.59	101.52	101.57	101.78	101.89	101.35	101.25	101.46	101.10	101.41	101.34	100.91	101.84	101.84	101.49
0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.97	1.00	0.98	0.98
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.01	0.03	0.03
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.02	1.02

Appendix F-2: Cassiterite continued

72 30 Grsn	72 7 Grsn	72 14 Grsn	72 46 Grsn	72 47 Grsn	72 48 Grsn	72 49 Grsn	72 44 Grsn	72 43 Grsn	72 41 Grsn	72 40 Grsn	72 39 Grsn	72 38 Grsn	72 37 Grsn	72 36 Grsn	72 32 Grsn	72 31 Grsn	72 29 Grsn
100.20	99.67	100.24	99.94	99.08	99.84	99.85	99.60	99.23	100.12	99.31	99.55	100.13	99.62	100.15	99.14	100.13	99.41
BDL	BDL	0.08	0.08	BDL	0.05	0.01	BDL	BDL	0.17	0.15	0.05	0.01	0.02	0.02	0.01	0.02	0.39
1.06	1.38	1.00	1.28	1.64	1.01	1.44	1.47	1.57	0.99	1.64	1.37	0.85	1.50	1.56	1.47	0.93	1.04
BDL	0.01	BDL	BDL	0.01	0.02	BDL	BDL	BDL	BDL	BDL	BDL	0.02	BDL	BDL	BDL	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
0.10	BDL	BDL	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
101.35	101.06	101.31	101.30	100.72	100.93	101.31	101.07	100.80	101.28	101.10	100.97	101.01	101.14	101.73	100.61	101.08	100.83
0.99	0.98	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.99	0.98	0.98	0.99	0.98	0.99	0.98	0.99	0.98
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.02	0.03	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.02	0.03	0.03	0.02	0.03	0.03	0.03	0.02	0.02
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.01	1.01	1.01	1.01	1.01	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.01	1.02	1.01	1.00	1.00
72 28 1 Grsn	72 27 1 Grsn	72 26 1 Grsn	72 23 1 Grsn	72 22 1 Grsn	72 21 1 Grsn	72 20 1 Grsn	72 19 1 Grsn	72 18 1 Grsn	72 17 1 Grsn	72 16 1 Grsn	72 15 1 Grsn	72 13 1 Grsn	72 13 1 Grsn	72 11 1 Grsn	72 10 1 Grsn	72 8 1 Grsn	72 6 1 Grsn
99.70	99.13	98.95	98.97	100.30	99.22	101.08	99.43	100.07	99.82	100.76	99.83	99.41	99.70	98.65	99.91	100.40	100.75
0.07	BDL	BDL	0.17	0.10	0.05	0.08	0.30	0.06	0.04	BDL	0.37	0.16	0.19	0.85	0.08	BDL	0.05
1.16	1.37	1.35	1.65	1.10	1.58	0.65	1.77	1.57	1.01	1.12	1.49	1.55	1.50	1.87	1.37	1.00	0.83
0.01	BDL	0.02	BDL	0.01	BDL	BDL	BDL	0.01	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.01
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
0.09	BDL	0.01	BDL	BDL	0.11	BDL	BDL	0.16	0.12	BDL	BDL	BDL	BDL	BDL	0.21	BDL	0.06
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
101.02	100.50	100.33	100.79	101.52	100.96	101.81	101.50	101.88	100.99	101.88	101.69	101.12	101.39	101.37	101.58	101.40	101.69
0.98	0.98	0.97	0.97	0.99	0.98	0.99	0.98	0.98	0.98	0.99	0.98	0.98	0.98	0.97	0.98	0.99	0.99
-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	-	-	-
0.02	0.03	0.03	0.03	0.02	0.03	0.01	0.04	0.03	0.02	0.02	0.03	0.03	0.03	0.04	0.03	0.02	0.02
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.01	1.00	1.00	1.01	1.01	1.01	1.01	1.02	1.02	1.00	1.01	1.02	1.01	1.01	1.01	1.01	1.01	1.01

Appendix F-2: Cassiterite continued

72 3 Grsn	72 2 Grsn	85 50 Vug	85 47 Vug	85 46 Vug	85 45 Vug	85 43 Vug	85 42 Vug	85 41 Vug	85 39 Vug	85 38 Vug	85 37 Vug	85 36 Vug	85 35 Vug	85 34 Vug	85 33 Vug	85 32 Vug	85 30 Vug	85 29 Vug	85 27 Vug	85 26 Vug	85 25 Vug
100.66	99.37	100.81	100.54	100.16	100.77	100.58	100.99	100.57	101.08	100.15	100.05	100.70	98.50	100.96	100.27	99.76	101.52	100.56	101.32	100.51	101.48
0.02	0.08	0.02	0.01	BDL	BDL	BDL	BDL	BDL	0.03	0.02	BDL	0.04	0.04	BDL	0.08	0.04	0.02	0.02	0.04	BDL	0.03
0.90	1.50	0.80	0.75	1.12	1.02	0.97	0.82	0.98	0.62	1.02	0.73	1.06	0.82	0.92	1.14	1.26	0.27	0.37	0.49	0.88	0.23
BDL	0.02	BDL	0.01	BDL	BDL	BDL	0.03	BDL	BDL	BDL	0.01	BDL	BDL	BDL	0.01	0.01	0.01	BDL	BDL	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
BDL	0.04	BDL	0.12	BDL	BDL	BDL	BDL	0.08	0.08	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.11	BDL	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
101.57	101.01	101.63	101.44	101.27	101.79	101.55	101.84	101.63	101.81	101.18	100.79	101.80	99.36	101.88	101.49	101.07	101.81	101.06	101.85	101.39	101.75
0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.99	0.97	0.99	0.99	0.98	1.00	0.99	1.00	0.99	1.00
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.01	0.01	0.01	0.02	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.00	1.01	0.99	1.01	1.01	1.01	1.01	1.00	1.01	1.01	1.00
85 24 1 Vug	85 23 1 Vug	85 22 1 Vug	85 21 1 Vug	85 20 1 Vug	85 19 1 Vug	85 18 1 Vug	85 16 1 Vug	85 15 1 Vug	85 13 1 Vug	85 11 1 Vug	85 10 1 Vug	85 8 1 Vug	85 7 1 Vug	85 5 1 Vug	85 4 1 Vug	85 3 1 Vug	85 2 1 Vug	85 1 1 Vug	85 1 1 Vug	94 6 1 Diss.	94 5 1 Diss.
101.01	100.41	100.33	99.95	100.48	100.48	100.68	100.41	99.99	100.16	100.18	100.36	100.60	100.35	101.30	100.45	100.82	100.56	100.47	101	99.37	99
0.03	0.05	0.01	0.02	0.04	0.04	0.01	0.05	0.01	0.05	BDL	0.01	0.02	BDL	0.01	0.03	0.13	0.03	BDL	BDL	0.01	0.09
0.35	0.94	0.88	0.86	0.68	0.75	0.93	0.78	0.92	1.11	1.04	0.40	1.06	0.91	0.33	0.73	0.80	0.82	0.65	0.66	1.44	0.95
BDL	BDL	0.02	BDL	0.01	0.01	BDL	BDL	BDL	0.01	BDL	BDL	0.03	BDL	BDL	0.01	BDL	BDL	BDL	BDL	BDL	0.01
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
BDL	0.04	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.01	BDL	BDL	BDL	BDL	0.06	0.01	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
101.39	101.45	101.23	100.83	101.21	101.28	101.61	101.24	100.92	101.32	101.22	100.77	101.71	101.27	101.63	101.23	101.75	101.41	101.18	101.68	100.82	100.04
0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.99	1	0.99	0.99	0.99	0.99	0.99	0.98	0.97
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.03	0.02
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	1.01	1.01	1	1	1	1.01	1	1	1.01	1.01	1	1.01	1.01	1	1	1.01	1.01	1	1.01	1.01	0.99

Appendix F-2: Cassiterite continued

94 4 Diss.	94 3 Diss.	94 2 Diss.	94 1 Diss.	94 1 Diss.	67 38 Diss.	67 42 Diss.	94 13 Diss.	94 48 Diss.	94 44 Diss.	94 43 Diss.	94 41 Diss.	94 39 Diss.	94 37 Diss.	94 36 Diss.	94 35 Diss.	94 33 Diss.	94 30 Diss.	94 29 Diss.	94 28 Diss.	94 26 Diss.	94 25 Diss.
99.49	100.52	99.75	99.70	99.50	100.07	98.97	98.25	100.01	101.01	100.44	100.40	100.27	100.41	100.17	99.84	99.76	100.25	100.59	100.38	99.79	100.57
0.07	0.04	BDL	0.52	0.51	0.09	0.10	0.56	0.38	0.03	BDL	0.02	0.13	0.21	0.17	0.08	0.07	0.01	0.02	0.10	0.08	0.06
1.07	1.03	1.07	0.97	0.95	0.56	1.25	1.90	1.05	0.80	1.24	1.27	0.69	0.87	1.31	1.26	1.48	0.99	0.71	0.87	1.32	0.97
BDL	BDL	BDL	BDL	BDL	BDL	0.03	BDL	0.02	BDL	BDL	0.01	0.03	BDL	BDL	BDL	BDL	BDL	BDL	0.02	0.03	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.02	BDL	BDL	BDL	BDL	BDL	0.07	BDL	BDL	BDL	0.06	BDL	0.01	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
100.63	101.59	100.82	101.19	100.96	100.72	100.35	100.72	101.46	101.84	101.68	101.70	101.13	101.57	101.65	101.18	101.30	101.32	101.32	101.39	101.22	101.60
0.98	0.99	0.98	0.98	0.98	0.98	0.97	0.97	0.98	0.99	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.99	0.99	0.99	0.98	0.99
-	-	-	0.01	0.01	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.02	0.02	0.02	0.02	0.02	0.01	0.03	0.04	0.02	0.02	0.03	0.03	0.01	0.02	0.03	0.03	0.03	0.02	0.01	0.02	0.03	0.02
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	1.01	1	1	1	1	1	1.01	1.01	1.01	1.01	1.01	1	1.01	1.01	1.01	1.01	1.01	1	1.01	1.01	1.01
94 23 1 Diss.	94 22 1 Diss.	94 21 1 Diss.	94 20 1 Diss.	94 19 1 Diss.	94 18 1 Diss.	94 17 1 Diss.	94 14 1 Diss.	94 12 1 Diss.	94 11 1 Diss.	94 10 1 Diss.	94 9 1 Diss.	94 8 1 Diss.	94 7 1 Diss.	72 45 2 Grsn	72 34 2 Grsn	72 34 2 Grsn	72 24 2 Grsn	67 26 2 Vug	67 18 2 Vug	67 21 2 Vug	67 24 2 Vug
99.98	99.94	100.12	99.59	98.65	100.40	100.23	100.03	99.24	99.07	98.89	100.14	99.78	98.76	98.66	98.84	98.77	93.92	98.81	98.65	99.12	99.70
0.11	0.14	0.05	0.65	0.23	0.16	0.03	0.04	0.06	0.05	0.07	0.13	0.04	0.06	0.03	0.02	0.06	3.69	0.18	0.18	0.10	0.11
1.28	1.31	1.23	1.28	1.84	0.97	1.39	1.05	1.49	0.91	1.26	0.95	0.94	1.41	0.76	0.80	0.85	1.43	0.33	0.30	0.35	0.27
0.01	BDL	BDL	BDL	BDL	0.02	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.01	BDL	0.02	BDL	0.04
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
0.09	BDL	BDL	0.11	BDL	0.11	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	1.77	1.71	1.70	0.85	0.89	0.77	0.65	0.72
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
101.46	101.39	101.40	101.63	100.72	101.66	101.65	101.13	100.80	100.03	100.22	101.22	100.76	100.23	101.22	101.36	101.38	99.90	100.22	99.91	100.22	100.84
0.98	0.98	0.99	0.98	0.97	0.99	0.99	0.98	0.98	0.98	0.97	0.99	0.98	0.97	0.97	0.97	0.97	0.92	0.97	0.97	0.98	0.98
-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	0.04	-	-	-	-
0.03	0.03	0.03	0.03	0.04	0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.02	0.03	0.01	0.01	0.01	0.01
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	0.01	0.01	0.01	0.01	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.01	1.01	1.01	1.01	1.01	1.01	1.02	1.01	1.01	0.99	1	1.01	1	1	1	1	1	0.98	0.99	0.98	0.99	0.99

Appendix F-2: Cassiterite continued

67 28 Vug	67 35 Vug	67 41 Vug	67 45 Vug	67 5 Vug	69 9 Grsn	69 39 Grsn	69 46 Grsn	69 25 Grsn	69 23 Grsn	69 7 Grsn	69 41 Grsn	72 42 Grsn	72 25 Grsn	72 4 Grsn	72 1 Grsn	72 2 Grsn	85 44 Vug	85 17 Vug	85 14 Vug
100.54	99.46	99.39	98.93	100.18	99.03	99.90	100.12	99.45	99.81	100.08	99.92	98.54	96.43	99	99.57	99.91	100.79	100.69	99.50
0.10	0.05	BDL	0.10	0.01	0.77	0.12	0.14	0.09	0.18	0.08	0.11	BDL	0.91	0.15	0.04	BDL	0.06	0.06	0.17
0.21	0.31	0.21	0.29	0.17	0.28	0.41	0.35	0.43	0.47	0.50	0.50	0.68	0.93	0.84	0.40	0.35	0.21	0.23	0.30
BDL	0.01	0.01	0.01	BDL	BDL	BDL	0.02	BDL	BDL	0.01	BDL	BDL	BDL	0.01	BDL	0.01	BDL	BDL	BDL
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.08
0.60	0.66	0.64	0.70	0.55	0.48	1	0.91	1.06	0.97	0.91	0.90	1.55	1.53	1.88	1.30	1.08	0.44	0.71	0.56
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
101.46	100.48	100.25	100.03	100.91	100.56	101.43	101.53	101.02	101.43	101.58	101.43	100.77	99.81	101.88	101.31	101.35	101.50	101.69	100.61
0.99	0.98	0.98	0.97	0.99	0.97	0.98	0.99	0.98	0.98	0.99	0.98	0.97	0.95	0.97	0.98	0.98	0.99	0.99	0.98
-	-	-	-	-	0.01	-	-	-	-	-	-	-	0.01	-	-	-	-	-	-
-	0.01	-	0.01	-	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	-	-	0.01
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1	0.99	0.99	0.98	0.99	0.99	1	1	0.99	1	1	1	0.99	0.98	1	1	1	1	1	0.99

85 12 2 Vug	85 6 2 Vug	94 50 2 Diss.	94 40 2 Diss.	94 24 2 Diss.	94 16 2 Diss.	94 15 2 Diss.
100.42	100.32	99.59	100.12	99.37	99.66	98.98
0.10	0.08	0.59	0.34	1.14	0.02	0.24
0.28	0.17	0.50	0.45	0.59	0.48	0.50
BDL	BDL	BDL	BDL	BDL	0.02	0.01
BDL	BDL	BDL	BDL	BDL	BDL	BDL
0.80	0.70	0.58	0.76	0.39	1.54	0.65
BDL	BDL	BDL	BDL	BDL	BDL	BDL
101.60	101.26	101.26	101.66	101.49	101.72	100.38
0.99	0.99	0.98	0.99	0.98	0.98	0.97
-	-	0.01	-	0.01	-	-
0.01	-	0.01	0.01	0.01	0.01	0.01
-	-	-	-	-	-	-
-	-	-	-	-	-	-
0.01	-	-	-	-	0.01	-
-	-	-	-	-	-	-
1	1	1	1	1	1	0.99

Abbreviations: Disseminated (Diss.); and Greisen Related (Grsn).

Appendix F-3a: Mica EPMA compositions from the Lebowa Granite Suite.

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Granite	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG
SiO ₂	34.42	33.88	34.50	32.72	32.75	34.79	33.92	32.95	34.48	34.05	33.04	33.45	33.81	33.21	34.19	33.60	32.80
TiO ₂	1.53	0.97	2.50	1.72	1.60	2.12	2.13	1.94	1.70	1.98	1.19	1.20	1.34	1.06	1.57	2.58	2.46
Al ₂ O ₃	13.51	13.85	13.62	14.02	13.87	13.19	13.81	14.18	13.81	12.89	13.97	13.52	13.67	13.58	13.24	13.96	14.24
MgO	0.54	0.85	1.20	1.40	1.20	1.20	1.38	1.54	1.07	1.14	1.45	1.22	0.99	1.01	0.66	1.81	1.70
CaO	0.01	0.02	BDL	0.02	0.01	0.10	0.03	0.04	0.07	0.37	0.01	0.03	0.02	0.09	0.01	0.08	0.09
MnO	0.39	0.38	0.37	0.44	0.47	0.40	0.36	0.43	0.38	0.40	0.40	0.36	0.41	0.37	0.38	0.34	0.40
FeO ^{tot}	34.90	35.60	33.32	35.37	35.76	33.43	33.73	34.66	34.05	33.99	35.86	34.84	34.48	35.27	34.84	33.10	34.03
Na ₂ O	0.04	0.20	BDL	BDL	0.11	0.07	0.15	0.10	0.19	0.10	0.09	0.10	0.08	0.29	0.04	0.23	0.13
K ₂ O	7.82	6.77	7.43	5.70	5.79	6.77	6.92	6.14	7.28	5.60	6.17	6.29	7.30	6.66	7.67	6.81	6.23
F	0.17	BDL	0.04	0.02	0.04	0.05	0.03	0.06	0.08	0.05	0.10	BDL	0.05	BDL	0.08	0.28	BDL
Cl	1.68	1.64	1.61	1.04	1.31	1.27	1.51	1.41	1.46	1.33	1.44	1.57	1.74	1.73	1.91	1.64	1.48
Li ₂ O**	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.02	BDL
H ₂ O*	3.14	3.19	3.23	3.29	3.22	3.28	3.24	3.22	3.24	3.21	3.19	3.17	3.15	3.14	3.11	3.12	3.24
Total	98.17	97.35	97.83	95.75	96.15	96.68	97.21	96.66	97.82	95.11	96.93	95.76	97.05	96.42	97.71	97.56	96.80
O≡F,Cl*	0.45	0.37	0.38	0.24	0.31	0.31	0.35	0.34	0.36	0.32	0.37	0.36	0.41	0.39	0.46	0.49	0.33
Total	97.71	96.98	97.44	95.51	95.84	96.37	96.86	96.32	97.46	94.79	96.57	95.41	96.64	96.03	97.24	97.08	96.46
Cations Proportions Based on 22 Oxygens (apfu)																	
Tetrahedral Site																	
Si	5.66	5.57	5.67	5.38	5.39	5.72	5.58	5.42	5.67	5.60	5.43	5.50	5.56	5.46	5.62	5.52	5.39
Al ^{IV}	2.34	2.43	2.33	2.62	2.61	2.28	2.42	2.58	2.33	2.40	2.57	2.50	2.44	2.54	2.38	2.48	2.61
Fe ^{3+*}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Z Sum	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Octahedral Site																	
Al ^{VI}	0.28	0.25	0.31	0.10	0.07	0.28	0.25	0.16	0.35	0.10	0.14	0.12	0.21	0.09	0.19	0.23	0.15
Ti	0.19	0.12	0.31	0.21	0.20	0.26	0.26	0.24	0.21	0.24	0.15	0.15	0.17	0.13	0.19	0.32	0.30
Mg	0.13	0.21	0.29	0.34	0.30	0.29	0.34	0.38	0.26	0.28	0.36	0.30	0.24	0.25	0.16	0.44	0.42
Fe ^{tot}	4.80	4.89	4.58	4.86	4.92	4.60	4.64	4.77	4.68	4.67	4.93	4.79	4.74	4.85	4.79	4.55	4.68
Mn	0.05	0.05	0.05	0.06	0.07	0.06	0.05	0.06	0.05	0.06	0.06	0.05	0.06	0.05	0.05	0.05	0.06
Ca	-	-	-	-	-	0.02	-	-	0.01	0.06	-	-	-	0.02	-	0.01	0.02
Li*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Y Sum	5.46	5.53	5.55	5.58	5.55	5.50	5.55	5.61	5.56	5.42	5.63	5.41	5.42	5.39	5.39	5.60	5.62
Interlayer																	
K	1.64	1.42	1.56	1.20	1.21	1.42	1.45	1.29	1.53	1.18	1.30	1.32	1.53	1.40	1.61	1.43	1.31
Na	0.01	0.06	-	-	0.04	0.02	0.05	0.03	0.06	0.03	0.03	0.03	0.03	0.09	0.01	0.07	0.04
X Sum	1.65	1.48	1.56	1.20	1.25	1.44	1.50	1.32	1.59	1.21	1.33	1.35	1.56	1.49	1.62	1.50	1.35
Anion Site																	
F	0.09	-	0.02	0.01	0.02	0.03	0.01	0.03	0.04	0.02	0.05	-	0.02	-	0.04	0.15	-
Cl	0.47	0.46	0.45	0.29	0.37	0.35	0.42	0.39	0.41	0.37	0.40	0.44	0.49	0.48	0.53	0.46	0.41
OH*	3.44	3.54	3.53	3.70	3.61	3.62	3.56	3.58	3.55	3.61	3.54	3.56	3.49	3.52	3.43	3.40	3.59
A Sum	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Sum	19.11	19.01	19.11	18.78	18.80	18.95	19.05	18.93	19.15	18.62	18.96	18.76	18.98	18.88	19.01	19.10	18.97

Appendix F-3a: Mica continued

18 NG	19 NG	20 NG	21 NG	22 NG	23 NG	24 NG	25 NG	26 NG	27 NG	28 NG	29 NG	30 NG	31 NG	32 NG	33 NG	34 NG	35 NG
33.40	33.92	30.14	32.30	32.21	31.76	33.09	32.29	27.44	27.82	27.27	33.30	31.10	32.43	31.82	31.57	30.71	30.79
2.48	2.88	1.44	1.35	1.38	1.82	0.02	0.06	0.17	0.33	0.09	0.38	0.50	0.40	1.52	0.96	2.03	2.11
13.57	13.42	13.04	13.22	13.06	13.57	13.28	13.34	11.99	12.28	11.95	12.92	13.73	13.03	13.35	13.43	13.26	13.18
1.54	1.43	0.94	0.92	0.78	1.32	0.49	0.44	0.56	0.52	0.45	1.03	1.55	0.80	0.92	1.09	1.20	1.24
0.10	0.30	0.14	0.18	0.08	0.04	0.08	0.07	0.11	0.11	0.06	0.07	0.05	0.08	BDL	0.02	0.20	0.11
0.36	0.41	0.40	0.39	0.40	0.48	0.53	0.51	0.44	0.41	0.37	0.52	0.52	0.53	0.39	0.46	0.36	0.39
33.07	32.58	34.87	33.99	34.60	34.57	35.91	36.95	34.68	34.56	35.41	34.96	35.93	35.51	34.51	35.04	34.38	33.91
0.11	0.12	0.06	0.09	0.07	0.05	0.07	0.09	0.15	0.27	0.22	0.18	0.04	0.20	0.09	BDL	0.14	0.25
6.57	5.76	5.75	6.05	6.53	5.63	5.82	5.72	5.55	5.61	6.28	5.88	5.63	5.83	7.13	6.34	6.14	6.72
0.10	BDL	0.05	0.16	0.03	BDL	0.05	BDL	0.13	0.05	0.02	0.08	0.06	0.08	0.02	BDL	BDL	BDL
1.37	1.23	1.71	1.77	1.87	1.60	2.13	2.11	1.81	2.05	2.37	2.04	1.88	1.83	1.73	1.41	1.50	1.62
BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
3.21	3.29	2.94	2.98	3.01	3.10	2.96	2.97	2.66	2.68	2.60	2.98	2.98	2.99	3.05	3.10	3.06	3.04
95.88	95.33	91.49	93.39	94.01	93.93	94.43	94.55	85.69	86.68	87.10	94.35	93.98	93.70	94.53	93.43	92.97	93.36
0.35	0.28	0.41	0.47	0.43	0.36	0.50	0.48	0.46	0.48	0.54	0.49	0.45	0.44	0.40	0.32	0.34	0.37
95.53	95.05	91.09	92.93	93.58	93.56	93.93	94.07	85.23	86.20	86.56	93.86	93.53	93.26	94.13	93.10	92.63	93
5.49	5.58	4.96	5.31	5.29	5.22	5.44	5.31	4.51	4.57	4.48	5.48	5.11	5.33	5.23	5.19	5.05	5.06
2.51	2.42	2.53	2.56	2.53	2.63	2.56	2.58	2.32	2.38	2.31	2.50	2.66	2.52	2.59	2.60	2.57	2.55
-	-	0.52	0.13	0.17	0.15	-	0.11	1.17	1.05	1.20	0.02	0.23	0.14	0.18	0.21	0.38	0.38
8	8	7.48	7.87	7.83	7.85	8	7.89	6.83	6.95	6.80	7.98	7.77	7.86	7.82	7.79	7.62	7.62
0.12	0.18	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-
0.31	0.36	0.18	0.17	0.17	0.22	-	-	0.02	0.04	0.01	0.05	0.06	0.05	0.19	0.12	0.25	0.26
0.38	0.35	0.23	0.23	0.19	0.32	0.12	0.11	0.14	0.13	0.11	0.25	0.38	0.20	0.23	0.27	0.29	0.30
4.55	4.48	4.79	4.67	4.76	4.75	4.94	5.08	4.77	4.75	4.87	4.81	4.94	4.88	4.74	4.82	4.73	4.66
0.05	0.06	0.06	0.05	0.06	0.07	0.07	0.07	0.06	0.06	0.05	0.07	0.07	0.07	0.05	0.06	0.05	0.05
0.02	0.05	0.03	0.03	0.01	-	0.01	0.01	0.02	0.02	0.01	0.01	-	0.01	-	-	0.04	0.02
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5.42	5.47	5.28	5.15	5.19	5.37	5.16	5.28	5.01	5	5.05	5.19	5.46	5.21	5.21	5.27	5.36	5.30
1.38	1.21	1.21	1.27	1.37	1.18	1.22	1.20	1.16	1.18	1.32	1.23	1.18	1.22	1.50	1.33	1.29	1.41
0.03	0.04	0.02	0.03	0.02	0.01	0.02	0.03	0.05	0.09	0.07	0.06	0.01	0.06	0.03	-	0.04	0.08
1.41	1.24	1.22	1.30	1.39	1.19	1.24	1.23	1.21	1.26	1.39	1.29	1.19	1.29	1.52	1.33	1.33	1.49
0.05	-	0.03	0.08	0.02	-	0.02	-	0.07	0.02	0.01	0.04	0.03	0.04	0.01	-	-	-
0.38	0.34	0.48	0.49	0.52	0.45	0.59	0.59	0.50	0.57	0.66	0.57	0.52	0.51	0.48	0.39	0.42	0.45
3.57	3.66	3.50	3.42	3.46	3.55	3.38	3.41	3.43	3.41	3.33	3.39	3.44	3.45	3.51	3.60	3.58	3.54
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
18.83	18.72	17.99	18.32	18.41	18.42	18.40	18.40	17.05	17.21	17.24	18.46	18.43	18.36	18.55	18.39	18.30	18.40

Appendix F-3a: Mica continued

36 NG	37 NG	38 NG	39 NG	40 NG	41 NG	42 NG	10 BG	11 BG	12 BG	13 BG	14 BG	15 BG	35 BG	37 BG	39 BG	40 BG	41 BG
31.24	33.85	32.91	34.32	32.87	33.04	33.02	49.52	47.24	47.45	49.69	48.72	48.44	51.37	51.03	49.97	48.50	48.76
1.04	1.49	2.11	2.58	1.51	1.01	2.30	0.13	0.09	0.11	0.12	0.13	0.10	0.15	0.16	0.14	0.11	0.21
13.47	13.41	13.85	13.57	13.54	13.54	14.20	30.05	29.15	29.33	30.67	29.60	29.16	30.41	30.47	30.30	29.41	29.58
1.20	1.08	1.83	1.01	0.57	0.71	1.74	0.74	0.70	0.64	0.58	0.68	0.65	0.76	0.73	0.72	0.69	0.69
0.03	0.02	0.04	BDL	0.03	0.03	0.03	0.17	0.17	0.18	0.23	0.17	0.11	0.16	0.17	0.17	0.12	0.10
0.41	0.49	0.41	0.37	0.41	0.36	0.43	0.06	0.07	0.10	0.05	0.06	0.03	0.05	0.08	0.08	0.09	0.08
35.37	34.81	34.03	33.23	35.16	35.32	34.27	5.25	4.76	7.55	5.01	4.89	5.09	5.08	4.86	5.07	5.14	5.16
0.12	0.26	BDL	0.08	1.55	0.16	1.66	BDL	0.04	0.09	0.18	0.04	0.06	BDL	0.24	0.10	BDL	0.09
6.22	6.49	5.81	8.17	7.22	6.70	6.21	9.02	8.93	8.42	8.91	8.97	8.58	8.87	8.98	9.25	8.68	9.03
BDL	BDL	BDL	0.07	0.03	0.08	0.06	0.11	0.27	0.26	0.30	0.33	0.28	0.32	0.35	0.26	0.25	0.19
1.33	1.37	1.04	1.92	1.87	1.48	1.34	BDL	0.02	BDL	0.01	BDL	0.01	0.02	0.01	0.01	0.02	0.01
BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.02	0.07	0.07	0.08	0.09	0.07	0.09	0.10	0.07	0.06	0.04
3.12	3.24	3.30	3.15	3.11	3.13	3.29	4.42	4.18	4.26	4.38	4.27	4.24	4.45	4.43	4.40	4.27	4.33
93.53	96.51	95.33	98.47	97.89	95.56	98.53	99.52	95.69	98.46	100.20	97.94	96.83	101.72	101.61	100.55	97.34	98.28
0.30	0.31	0.24	0.46	0.44	0.37	0.33	0.05	0.12	0.11	0.13	0.14	0.12	0.14	0.15	0.11	0.11	0.08
93.23	96.20	95.09	98	97.45	95.20	98.20	99.47	95.58	98.35	100.07	97.81	96.72	101.58	101.46	100.44	97.23	98.20
5.14	5.57	5.41	5.64	5.40	5.43	5.43	6.63	6.33	6.35	6.65	6.53	6.49	6.88	6.83	6.69	6.49	6.53
2.61	2.43	2.59	2.36	2.60	2.57	2.57	1.37	1.67	1.65	1.35	1.47	1.51	1.12	1.17	1.31	1.51	1.47
0.25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7.75	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
-	0.16	0.09	0.27	0.03	0.06	0.18	3.38	2.93	2.98	3.49	3.20	3.09	3.68	3.64	3.47	3.14	3.20
0.13	0.18	0.26	0.32	0.19	0.12	0.28	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.02
0.29	0.26	0.45	0.25	0.14	0.17	0.43	0.15	0.14	0.13	0.11	0.14	0.13	0.15	0.15	0.14	0.14	0.14
4.86	4.79	4.68	4.57	4.83	4.86	4.71	0.59	0.53	0.85	0.56	0.55	0.57	0.57	0.54	0.57	0.58	0.58
0.06	0.07	0.06	0.05	0.06	0.05	0.06	-	-	0.01	-	-	-	-	0.01	-	0.01	0.01
-	-	-	-	-	-	-	0.02	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.01
-	-	-	-	-	-	-	-	0.02	0.02	0.02	0.02	0.02	-	-	0.01	0.03	0.02
5.35	5.47	5.55	5.46	5.25	5.27	5.66	4.16	3.64	4	4.22	3.92	3.82	4.44	4.38	4.23	3.89	3.96
1.30	1.36	1.22	1.71	1.51	1.41	1.30	1.54	1.53	1.44	1.52	1.53	1.47	1.52	1.53	1.58	1.48	1.54
0.04	0.08	-	0.03	0.49	0.05	0.53	-	0.01	0.02	0.05	0.01	0.01	-	0.06	0.03	-	0.02
1.34	1.45	1.22	1.74	2.01	1.46	1.83	1.54	1.54	1.46	1.57	1.54	1.48	1.52	1.60	1.61	1.48	1.56
-	-	-	0.04	0.02	0.04	0.03	0.05	0.11	0.11	0.13	0.14	0.12	0.14	0.15	0.11	0.11	0.08
0.37	0.38	0.29	0.53	0.52	0.41	0.37	-	-	-	-	-	-	-	-	-	-	-
3.63	3.62	3.71	3.43	3.46	3.55	3.60	3.95	3.88	3.89	3.87	3.86	3.88	3.86	3.85	3.89	3.89	3.92
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
18.43	18.91	18.76	19.20	19.26	18.72	19.50	17.70	17.18	17.47	17.79	17.47	17.30	17.96	17.98	17.84	17.37	17.52

Appendix F-3a: Mica continued

42 BG	44 BG	45 BG	46 BG	48 BG	49 BG	51 BG	52 BG	53 BG	56 BG	58 BG	61 BG	66 BG	67 BG	68 BG	69 BG	77 BG	84 BG
47.08	50	46.82	48.49	49.77	47.87	46.97	45.31	45.01	45.95	44.82	40.84	43.99	46.73	43.69	47.46	47	45.88
0.13	0.09	0.08	0.14	0.11	0.11	0.11	0.16	0.16	0.11	0.23	0.42	3.42	0.12	0.28	0.10	0.14	0.23
29.12	30.43	28.79	28.73	30.18	29.63	27.90	25.71	26.96	26.98	26.38	24.27	26.05	27.39	26.52	28.02	27.34	26.45
0.60	0.72	0.69	0.84	0.74	0.69	1.15	1.44	1.16	1.18	1.15	1.52	1.05	0.79	1.07	0.77	0.98	1.02
0.06	0.12	0.12	0.14	0.12	0.12	0.07	0.10	0.06	0.07	0.07	0.13	0.07	0.03	0.08	0.02	0.13	0.11
0.10	0.08	0.06	0.06	0.04	0.06	0.05	0.09	0.08	0.07	0.07	0.13	0.08	0.05	0.10	0.04	0.02	0.07
4.98	4.97	5.27	6.02	5.26	4.93	6.25	10.48	9.43	7.62	10.19	16.85	7.92	6	11.47	5.61	5.74	8.12
0.06	0.03	0.36	0.11	0.13	0.10	0.03	0.04	0.06	BDL	BDL	0.03	BDL	0.06	BDL	0.05	0.11	0.07
9.10	8.85	8.80	8.35	8.70	9.06	9.22	7.98	8.41	8.84	8.55	6.82	8.49	9.57	8.31	9.94	9.54	9.42
0.28	0.22	0.31	0.27	0.23	0.22	0.21	0.26	0.19	0.29	0.32	BDL	0.34	0.16	0.20	0.06	0.32	0.14
BDL	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02	0.03	0.03	0.04	0.04	0.03	0.01	0.04	0.12
0.07	0.05	0.08	0.07	0.06	0.05	0.05	0.06	0.04	0.08	0.09	BDL	0.09	0.04	0.05	0.01	0.09	0.03
4.17	4.41	4.15	4.26	4.39	4.26	4.18	4.06	4.10	4.09	4.04	3.98	4.04	4.15	4.05	4.25	4.11	4.11
95.77	99.99	95.54	97.50	99.76	97.12	96.20	95.74	95.69	95.30	95.94	95.02	95.59	95.13	95.84	96.35	95.55	95.77
0.12	0.10	0.13	0.12	0.10	0.10	0.09	0.11	0.09	0.13	0.14	0.01	0.15	0.08	0.09	0.03	0.15	0.09
95.65	99.90	95.41	97.39	99.65	97.03	96.11	95.63	95.60	95.17	95.80	95.02	95.44	95.05	95.75	96.32	95.41	95.68
6.30	6.70	6.27	6.49	6.67	6.41	6.29	6.07	6.03	6.15	6	5.47	5.89	6.26	5.85	6.36	6.29	6.14
1.70	1.30	1.73	1.51	1.33	1.59	1.71	1.93	1.97	1.85	2	2.53	2.11	1.74	2.15	1.64	1.71	1.86
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.90	3.50	2.81	3.03	3.43	3.09	2.69	2.13	2.28	2.41	2.17	1.30	2	2.58	2.04	2.78	2.61	2.32
0.01	-	-	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.04	0.34	0.01	0.03	0.01	0.01	0.02
0.12	0.14	0.14	0.17	0.15	0.14	0.23	0.29	0.23	0.23	0.23	0.30	0.21	0.16	0.21	0.15	0.19	0.20
0.56	0.56	0.59	0.67	0.59	0.55	0.70	1.17	1.06	0.85	1.14	1.89	0.89	0.67	1.28	0.63	0.64	0.91
0.01	0.01	-	-	-	-	-	0.01	0.01	-	-	0.02	-	-	0.01	-	-	-
-	0.02	0.02	0.02	0.02	0.02	0.01	0.01	-	0.01	0.01	0.02	0.01	-	0.01	-	0.02	0.02
0.03	0.03	-	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.01	-	0.01	0.02	0.01
3.61	4.23	3.57	3.91	4.20	3.81	3.65	3.63	3.60	3.53	3.58	3.57	3.46	3.43	3.59	3.58	3.48	3.48
1.55	1.51	1.50	1.43	1.49	1.55	1.58	1.36	1.44	1.51	1.46	1.17	1.45	1.64	1.42	1.70	1.63	1.61
0.02	-	0.09	0.03	0.03	0.03	-	0.01	0.02	-	-	-	-	0.02	-	0.01	0.03	0.02
1.57	1.52	1.60	1.45	1.52	1.57	1.58	1.37	1.45	1.51	1.46	1.17	1.45	1.65	1.42	1.71	1.66	1.63
0.12	0.09	0.13	0.11	0.10	0.09	0.09	0.11	0.08	0.12	0.13	-	0.14	0.07	0.08	0.03	0.14	0.06
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	0.03
3.88	3.90	3.87	3.88	3.90	3.90	3.91	3.88	3.91	3.87	3.86	3.99	3.85	3.92	3.91	3.97	3.85	3.91
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
17.18	17.75	17.17	17.37	17.72	17.39	17.23	17	17.06	17.04	17.04	16.74	16.91	17.08	17	17.29	17.14	17.11

Appendix F-3a: Mica continued

85 BG	87 BG	91 BG	92 BG	93 BG	94 BG	95 BG	97 BG	98 BG	99 BG	101 BG	102 BG	103 BG	104 BG	105 BG	110 BG	115 BG	121 BG
45.41	46.29	47.44	47.92	47.90	47.56	47.85	47.49	47.44	47.16	48.72	47.62	47.05	47.92	48.74	46.78	47.54	46.62
0.22	0.10	0.10	0.08	0.06	0.17	0.07	0.15	0.35	0.11	0.10	0.12	0.13	0.13	0.08	0.31	0.27	0.33
26.49	25.96	25.88	25.91	26.15	25.84	26.29	27.95	27.02	27.94	29.12	28.02	28.04	27.46	28.74	25.35	25.05	25.17
1.07	1.44	1.35	1.40	1.33	1.35	1.38	0.66	0.79	0.89	0.91	1.16	0.82	1.23	1.04	0.58	0.57	0.58
0.16	0.14	0.13	0.18	0.15	0.14	0.11	0.26	0.08	0.18	0.17	0.23	0.10	0.14	0.15	0.05	0.05	0.03
0.07	0.09	0.03	0.06	0.04	0.06	0.02	0.02	0.04	0.02	0.03	0.04	0.04	0.05	0.02	0.01	0.03	0.04
8.50	9.27	6.49	6.82	6.51	6.89	6.64	5.63	6.93	5.38	4.81	6.51	5.59	6.07	4.96	7.90	7.46	8.69
0.27	0.05	0.08	0.13	0.08	BDL	0.12	0.20	0.20	0.09	0.08	0.05	0.09	0.03	0.10	0.07	0.10	0.12
8.88	8.45	9.64	9.49	9.49	9.45	9.65	10.08	10.09	9.60	9.90	9.21	9.90	9.89	9.74	9.90	9.88	9.35
0.26	0.41	0.20	0.24	0.02	0.18	0.15	0.38	0.34	0.26	0.18	0.29	0.16	0.33	0.18	0.29	0.32	0.40
0.09	0.02	0.02	0.01	0.02	0.05	BDL	0.04	0.11	0.02	0.02	0.03	0.03	BDL	BDL	0.05	0.07	0.06
0.07	0.12	0.05	0.06	BDL	0.04	0.03	0.11	0.09	0.07	0.04	0.08	0.03	0.09	0.04	0.08	0.09	0.12
4.06	4.06	4.14	4.16	4.24	4.16	4.21	4.14	4.14	4.16	4.32	4.21	4.20	4.19	4.31	4.05	4.06	4.01
95.53	96.40	95.55	96.47	95.98	95.89	96.53	97.11	97.62	95.87	98.39	97.56	96.19	97.54	98.09	95.43	95.48	95.52
0.13	0.18	0.09	0.10	0.01	0.09	0.07	0.17	0.17	0.11	0.08	0.13	0.07	0.14	0.08	0.13	0.15	0.18
95.40	96.22	95.46	96.37	95.96	95.80	96.46	96.94	97.45	95.75	98.31	97.44	96.11	97.40	98.02	95.30	95.33	95.33
6.08	6.20	6.35	6.42	6.41	6.37	6.41	6.36	6.35	6.32	6.52	6.38	6.30	6.42	6.53	6.26	6.37	6.24
1.92	1.80	1.65	1.58	1.59	1.63	1.59	1.64	1.65	1.68	1.48	1.62	1.70	1.58	1.47	1.74	1.63	1.76
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.26	2.30	2.44	2.51	2.54	2.45	2.56	2.77	2.62	2.73	3.12	2.80	2.73	2.75	3.06	2.27	2.32	2.22
0.02	0.01	0.01	-	-	0.02	-	0.02	0.04	0.01	0.01	0.01	0.01	0.01	-	0.03	0.03	0.03
0.21	0.29	0.27	0.28	0.27	0.27	0.28	0.13	0.16	0.18	0.18	0.23	0.16	0.25	0.21	0.12	0.11	0.12
0.95	1.04	0.73	0.76	0.73	0.77	0.74	0.63	0.78	0.60	0.54	0.73	0.63	0.68	0.56	0.88	0.84	0.97
-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.04	0.01	0.03	0.02	0.03	0.01	0.02	0.02	-	-	-
0.01	0.01	0.02	0.01	0.02	0.01	0.01	-	0.03	0.01	0.01	-	0.02	-	-	0.02	-	0.01
3.48	3.66	3.47	3.59	3.57	3.53	3.60	3.59	3.60	3.54	3.88	3.81	3.55	3.72	3.86	3.31	3.31	3.35
1.52	1.44	1.65	1.62	1.62	1.61	1.65	1.72	1.72	1.64	1.69	1.57	1.69	1.69	1.66	1.69	1.69	1.60
0.07	0.01	0.02	0.03	0.02	-	0.03	0.05	0.05	0.02	0.02	0.01	0.02	-	0.03	0.02	0.02	0.03
1.59	1.46	1.67	1.66	1.64	1.61	1.68	1.77	1.78	1.66	1.71	1.59	1.71	1.70	1.69	1.71	1.71	1.63
0.11	0.17	0.08	0.10	-	0.07	0.06	0.16	0.14	0.11	0.08	0.12	0.07	0.14	0.08	0.12	0.13	0.17
0.02	-	-	-	-	0.01	-	0.01	0.02	-	-	-	-	-	-	0.01	0.02	0.01
3.87	3.82	3.91	3.90	3.99	3.91	3.93	3.83	3.83	3.88	3.92	3.87	3.93	3.86	3.92	3.86	3.85	3.82
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
17.07	17.12	17.14	17.25	17.21	17.15	17.28	17.36	17.38	17.21	17.59	17.40	17.26	17.41	17.55	17.02	17.02	16.98

Appendix F-3a: Mica continued

122 BG	123 BG	124 BG	125 BG	126 BG	128 BG	129 BG	130 BG	136 BG	147 BG	148 BG	149 BG	150 BG	151 BG	159 BG	161 BG	162 BG	163 BG
46.08	47.96	47.78	47.47	48.05	47.25	47.14	46.87	47.47	47.37	47.33	47.20	47.31	47.43	48.10	48.30	48.09	47.82
0.24	0.19	0.24	0.31	0.29	0.34	0.31	0.27	0.25	0.43	0.20	0.28	0.23	0.30	0.17	0.06	0.06	0.13
24.95	25.74	26.12	25.65	25.46	25.39	25.39	26.30	25.64	25.36	26.20	25.89	26.01	25.15	26.03	29.74	29.47	29.09
0.62	0.68	0.56	0.51	0.49	0.57	0.51	0.53	0.49	0.52	0.65	0.49	0.48	0.52	0.54	0.75	0.78	0.82
0.04	0.04	0.03	0.04	0.03	0.05	0.04	0.04	0.04	0.02	0.06	0.03	0.02	0.03	0.04	0.17	0.12	0.13
0.06	0.02	0.01	0.04	0.02	BDL	0.01	0.03	0.03	0.04	0.03	0.02	0.04	0.02	0.03	0.02	BDL	0.02
9.71	6.87	7.18	7.49	7.68	7.68	7.50	7.58	7.74	7.94	6.93	7.42	7.37	7.69	6.97	4.56	4.68	5.02
BDL	BDL	0.10	0.02	0.09	0.16	0.01	0.10	0.04	0.09	0.10	0.03	0.15	0.18	0.12	0.08	0.21	0.17
9.21	9.60	10.03	10.09	9.93	10.17	9.89	10.11	9.95	9.88	9.66	9.98	9.87	9.70	9.67	9.37	9.54	9.42
0.44	0.26	0.39	0.32	0.36	0.40	0.39	0.33	0.39	0.44	0.38	0.19	0.18	0.54	0.35	0.07	0.22	0.21
0.05	0.03	0.04	0.06	0.05	0.06	0.05	0.03	0.03	0.07	0.04	0.04	0.02	0.03	0.01	BDL	BDL	0.01
0.13	0.07	0.11	0.09	0.10	0.12	0.11	0.09	0.11	0.13	0.11	0.04	0.04	0.17	0.10	0.01	0.05	0.05
3.97	4.12	4.09	4.08	4.09	4.04	4.03	4.09	4.07	4.03	4.07	4.12	4.14	3.99	4.11	4.35	4.28	4.26
95.49	95.56	96.69	96.17	96.62	96.24	95.37	96.38	96.24	96.32	95.77	95.73	95.87	95.76	96.26	97.49	97.52	97.15
0.20	0.12	0.17	0.15	0.16	0.18	0.17	0.14	0.17	0.20	0.17	0.09	0.08	0.23	0.15	0.03	0.09	0.09
95.29	95.45	96.52	96.03	96.45	96.05	95.19	96.24	96.07	96.12	95.60	95.64	95.78	95.52	96.11	97.46	97.42	97.06
6.17	6.42	6.40	6.36	6.43	6.33	6.31	6.28	6.36	6.34	6.34	6.32	6.34	6.35	6.44	6.47	6.44	6.40
1.83	1.58	1.60	1.64	1.57	1.67	1.69	1.72	1.64	1.66	1.66	1.68	1.66	1.65	1.56	1.53	1.56	1.60
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.11	2.48	2.52	2.41	2.45	2.34	2.32	2.43	2.40	2.35	2.47	2.41	2.44	2.32	2.55	3.16	3.09	3
0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.04	0.02	0.03	0.02	0.03	0.02	-	-	0.01
0.12	0.14	0.11	0.10	0.10	0.11	0.10	0.11	0.10	0.10	0.13	0.10	0.10	0.10	0.11	0.15	0.16	0.16
1.09	0.77	0.80	0.84	0.86	0.86	0.84	0.85	0.87	0.89	0.78	0.83	0.83	0.86	0.78	0.51	0.52	0.56
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.02	0.02	0.02
0.02	-	0.02	0.02	0.03	0.02	0.02	0.01	0.02	-	0.01	-	-	0.03	0.03	0.02	0.01	0.01
3.35	3.42	3.47	3.39	3.44	3.35	3.30	3.42	3.40	3.39	3.41	3.37	3.39	3.32	3.47	3.86	3.80	3.75
1.57	1.64	1.71	1.72	1.70	1.74	1.69	1.73	1.70	1.69	1.65	1.70	1.69	1.66	1.65	1.60	1.63	1.61
-	-	0.03	-	0.02	0.04	-	0.02	0.01	0.02	0.03	-	0.04	0.05	0.03	0.02	0.05	0.04
1.57	1.64	1.74	1.73	1.72	1.78	1.69	1.75	1.71	1.71	1.68	1.71	1.73	1.71	1.68	1.62	1.68	1.65
0.19	0.11	0.16	0.13	0.15	0.17	0.16	0.14	0.16	0.19	0.16	0.08	0.08	0.23	0.15	0.03	0.09	0.09
0.01	-	-	0.01	0.01	0.01	0.01	-	-	0.02	0.01	-	-	-	-	-	-	-
3.80	3.88	3.83	3.85	3.84	3.82	3.82	3.86	3.83	3.80	3.83	3.91	3.92	3.77	3.85	3.97	3.91	3.91
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
16.93	17.06	17.21	17.12	17.16	17.13	16.99	17.17	17.11	17.10	17.09	17.08	17.12	17.03	17.15	17.48	17.48	17.41

Appendix F-3a: Mica continued

164 BG	165 BG	166 BG	167 BG	168 BG	170 BG	171 BG	172 BG	173 BG	174 BG	176 BG	178 BG	179 BG	181 BG	184 BG	185 BG	187 BG	189 BG
48.18	48.42	48.43	49.08	48.59	49.17	47.32	47.44	47.32	47.19	48.08	45.57	44.34	47.77	47.90	47.92	48.20	49.32
0.06	0.07	0.05	0.05	0.06	0.06	0.08	0.04	0.06	0.06	0.06	0.08	0.22	0.05	0.05	0.05	0.05	0.07
30.31	28.94	29.66	30.31	29.75	30.33	28.51	29.36	29.17	28.72	30.46	26.90	26.32	29.91	29.95	29.41	29.40	29.94
0.64	0.91	0.76	0.70	0.81	0.69	0.99	0.72	0.70	0.74	0.66	1.33	1.11	0.70	0.75	0.66	0.65	0.78
0.15	0.18	0.12	0.21	0.13	0.18	0.12	0.17	0.17	0.19	0.16	0.09	0.34	0.17	0.08	0.24	0.33	0.19
BDL	0.02	0.03	0.03	BDL	0.04	BDL	0.01	BDL	BDL	0.03	0.02	0.06	0.03	0.02	0.02	0.02	BDL
4.31	4.77	4.67	4.32	4.64	4.64	4.88	4.53	4.78	4.29	4.43	6.45	10.61	4.49	4.63	4.46	4.58	4.53
0.28	0.21	0.13	0.19	0.15	0.27	0.20	0.12	0.16	0.52	3.13	3.53	0.19	2.58	4.07	2.59	0.18	0.17
9.43	9.51	9.61	9.41	9.54	9.40	9.41	9.35	9.42	9.17	9.35	8.96	8.48	9.28	9.39	7.97	9.13	9.31
BDL	0.20	0.14	0.01	0.21	0.09	0.25	0.18	0.19	0.14	0.20	0.11	0.17	0.12	0.19	0.18	0.11	0.13
BDL	0.01	BDL	BDL	0.01	BDL	0.01	BDL	BDL	0.01	BDL	0.05	0.02	BDL	BDL	0.01	0.02	0.02
BDL	0.05	0.03	BDL	0.05	0.02	0.06	0.04	0.04	0.03	0.05	0.02	0.04	0.02	0.04	0.04	0.02	0.03
4.39	4.28	4.33	4.43	4.32	4.42	4.19	4.24	4.23	4.21	4.40	4.19	4.08	4.37	4.39	4.31	4.31	4.39
97.76	97.56	97.98	98.76	98.26	99.31	96.03	96.21	96.24	95.27	101.01	97.31	95.98	99.50	101.47	97.83	96.99	98.88
-	0.09	0.06	0.01	0.09	0.04	0.11	0.08	0.08	0.06	0.08	0.06	0.08	0.05	0.08	0.08	0.05	0.06
97.76	97.47	97.92	98.75	98.17	99.27	95.92	96.13	96.16	95.21	100.92	97.25	95.90	99.44	101.39	97.76	96.94	98.83
6.45	6.48	6.49	6.57	6.51	6.59	6.34	6.35	6.34	6.32	6.44	6.10	5.94	6.40	6.42	6.42	6.46	6.61
1.55	1.52	1.51	1.43	1.49	1.41	1.66	1.65	1.66	1.68	1.56	1.90	2.06	1.60	1.58	1.58	1.54	1.39
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
3.24	3.05	3.17	3.36	3.20	3.37	2.84	2.99	2.94	2.85	3.25	2.35	2.09	3.12	3.14	3.06	3.10	3.33
-	-	-	-	-	-	-	-	-	-	-	-	0.02	-	-	-	-	-
0.13	0.18	0.15	0.14	0.16	0.14	0.20	0.14	0.14	0.15	0.13	0.27	0.22	0.14	0.15	0.13	0.13	0.16
0.48	0.53	0.52	0.48	0.52	0.52	0.55	0.51	0.53	0.48	0.50	0.72	1.19	0.50	0.52	0.50	0.51	0.51
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.02	0.03	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.03	0.02	0.01	0.05	0.02	0.01	0.03	0.05	0.03
0.02	0.01	0.02	0.01	0.02	-	0.02	0.03	0.02	0.02	0.03	0.03	0.04	0.02	0.03	0.04	0.02	0.03
3.88	3.80	3.87	4.02	3.91	4.06	3.61	3.67	3.65	3.51	3.91	3.36	3.58	3.79	3.83	3.73	3.79	4.03
1.61	1.62	1.64	1.61	1.63	1.61	1.61	1.60	1.61	1.57	1.60	1.53	1.45	1.59	1.60	1.36	1.56	1.59
0.07	0.05	0.03	0.05	0.04	0.07	0.05	0.03	0.04	0.14	0.81	0.92	0.05	0.67	1.06	0.67	0.05	0.05
1.68	1.68	1.68	1.66	1.67	1.68	1.66	1.63	1.65	1.70	2.41	2.45	1.50	2.26	2.66	2.03	1.61	1.64
-	0.09	0.06	-	0.09	0.04	0.10	0.08	0.08	0.06	0.08	0.05	0.07	0.05	0.08	0.08	0.05	0.05
-	-	-	-	-	-	-	-	-	-	-	0.01	-	-	-	-	-	-
4	3.91	3.94	3.99	3.91	3.96	3.89	3.92	3.92	3.94	3.92	3.94	3.92	3.95	3.92	3.92	3.95	3.94
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
17.56	17.48	17.55	17.68	17.58	17.74	17.27	17.30	17.30	17.22	18.32	17.81	17.08	18.05	18.49	17.76	17.40	17.66

Appendix F-3a: Mica continued

190 BG	192 BG	195 BG	196 BG	198 BG	200 BG	205 BG	206 BG	207 BG	208 BG	209 BG	210 BG	213 BG	214 BG	215 BG	217 BG	218 BG	220 BG
48.45	47.50	48.67	48.18	46.15	48.66	43.69	49.09	49.14	48.20	48.60	47.12	48.70	47.80	45.85	48.90	49	48.48
0.06	0.05	0.07	0.13	0.07	0.12	0.08	0.07	0.06	0.05	0.07	0.09	0.05	0.10	0.10	0.05	0.05	0.09
29.79	29.27	28.23	27.70	26.82	27.77	27.01	30.02	30.02	29.30	29.75	28.70	29.63	27.65	26.47	29.77	30.10	28.01
0.71	0.71	1.48	1.46	1.58	1.34	1.62	0.71	0.68	0.71	0.66	0.75	0.68	1.28	1.56	0.65	0.67	1.42
0.11	0.27	0.24	0.20	0.21	0.21	0.10	0.10	0.09	0.10	0.17	0.22	0.06	0.18	0.15	0.19	0.12	0.10
BDL	0.02	0.06	0.05	0.07	0.02	0.11	BDL	BDL	BDL	0.03	0.05	0.03	0.02	0.08	0.02	0.02	0.05
4.62	4.45	6.53	5.53	7.74	5.46	12.74	4.52	4.45	4.41	4.44	4.56	4.52	5.77	8.89	4.44	4.59	5.21
0.13	2.04	0.18	0.50	0.14	0.18	0.35	0.21	0.17	0.43	0.35	0.19	0.18	0.26	0.19	0.17	0.24	0.25
9.41	9.16	9.19	9.50	8.63	9.46	7.19	9.66	9.72	9.42	9.61	9.36	9.69	9.17	8.17	9.37	9.50	9.62
0.07	0.09	0.22	0.37	0.26	0.25	0.14	0.24	0.28	0.18	BDL	0.13	0.10	0.20	0.31	0.14	0.18	0.39
BDL	0.03	0.02	0.02	0.04	0.02	0.03	BDL	BDL	0.01	0.01	0.01	BDL	0.02	0.02	BDL	BDL	0.02
0.01	0.02	0.05	0.11	0.07	0.06	0.03	0.06	0.07	0.04	BDL	0.03	0.02	0.05	0.08	0.03	0.04	0.11
4.36	4.31	4.31	4.20	4.11	4.26	4.13	4.34	4.33	4.28	4.39	4.22	4.35	4.22	4.09	4.35	4.36	4.21
97.74	97.90	99.27	97.94	95.89	97.81	97.20	99.03	99.02	97.14	98.09	95.42	98.02	96.72	95.96	98.09	98.87	97.98
0.03	0.05	0.10	0.16	0.12	0.11	0.07	0.10	0.12	0.08	-	0.06	0.04	0.09	0.13	0.06	0.08	0.17
97.71	97.86	99.17	97.78	95.77	97.70	97.14	98.93	98.90	97.06	98.09	95.36	97.98	96.64	95.83	98.03	98.79	97.81
6.49	6.36	6.52	6.45	6.18	6.52	5.85	6.57	6.58	6.46	6.51	6.31	6.52	6.40	6.14	6.55	6.56	6.49
1.51	1.64	1.48	1.55	1.82	1.48	2.15	1.43	1.42	1.54	1.49	1.69	1.48	1.60	1.86	1.45	1.44	1.51
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
3.19	2.98	2.97	2.82	2.41	2.90	2.11	3.31	3.32	3.08	3.20	2.84	3.20	2.77	2.32	3.25	3.31	2.91
-	-	-	0.01	-	0.01	-	-	-	-	-	-	-	0.01	0.01	-	-	0.01
0.14	0.14	0.30	0.29	0.32	0.27	0.32	0.14	0.14	0.14	0.13	0.15	0.14	0.26	0.31	0.13	0.13	0.28
0.52	0.50	0.73	0.62	0.87	0.61	1.43	0.51	0.50	0.49	0.50	0.51	0.51	0.65	1	0.50	0.51	0.58
-	-	-	-	-	-	0.01	-	-	-	-	-	-	-	0.01	-	-	-
0.02	0.04	0.03	0.03	0.03	0.03	0.01	0.01	0.01	0.01	0.02	0.03	0.01	0.03	0.02	0.03	0.02	0.01
0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.01	0.04	0.03	0.01	0.01	0.05	0.01	0.01	0.04	0.03	-
3.87	3.66	4.05	3.78	3.64	3.82	3.90	3.98	3.97	3.73	3.87	3.55	3.86	3.71	3.67	3.91	3.98	3.81
1.61	1.56	1.57	1.62	1.47	1.62	1.23	1.65	1.66	1.61	1.64	1.60	1.65	1.57	1.40	1.60	1.62	1.64
0.03	0.53	0.05	0.13	0.04	0.05	0.09	0.06	0.04	0.11	0.09	0.05	0.05	0.07	0.05	0.05	0.06	0.07
1.64	2.09	1.62	1.75	1.51	1.66	1.32	1.71	1.71	1.72	1.73	1.65	1.70	1.63	1.44	1.65	1.68	1.71
0.03	0.04	0.09	0.16	0.11	0.11	0.06	0.10	0.12	0.08	-	0.06	0.04	0.08	0.13	0.06	0.08	0.16
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.97	3.95	3.90	3.84	3.88	3.89	3.93	3.90	3.88	3.92	4	3.94	3.96	3.91	3.87	3.94	3.92	3.83
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
17.51	17.76	17.67	17.53	17.15	17.49	17.22	17.69	17.68	17.46	17.60	17.19	17.56	17.34	17.11	17.55	17.67	17.52

Appendix F-3a: Mica continued

221 BG	224 BG	225 BG	226 BG	231 BG	234 BG	235 BG	27 LG	28 LG	29 LG	30 LG	31 LG	32 LG	34 LG	35 LG	36 LG	43 LG	44 LG
48.72	47.97	46.68	49.63	47.92	47.18	47.31	50.24	45.09	43.44	45.17	44.56	44.60	43.74	43.62	44.73	43.65	43.24
0.07	0.09	0.08	0.06	0.06	0.06	0.06	0.07	0.10	0.16	0.14	0.12	0.14	0.06	0.03	0.15	0.17	0.18
29.65	27.98	26.26	30.12	29.98	29.42	29.43	31.90	30.37	29.56	30.37	29.53	30.50	31.47	30.98	30.23	29.58	28.02
0.68	1.26	1.63	0.69	0.63	0.72	0.72	0.01	0.02	0.05	0.01	0.02	0.04	0.02	0.04	0.02	0.08	0.10
0.09	0.21	0.12	0.39	0.15	0.11	0.07	BDL	BDL	0.05	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
0.02	0.04	0.05	0.03	BDL	0.05	0.05	BDL	BDL	0.03	BDL	BDL	0.03	0.01	BDL	BDL	BDL	BDL
4.63	5.52	7.85	4.53	4.39	4.44	4.47	5.37	5.91	6.18	5.80	6.25	5.71	4.87	4.85	6.15	6.31	7.87
0.26	0.16	0.22	0.21	0.21	0.21	0.28	BDL	0.07	0.10	BDL	0.02	0.03	0.01	0.03	0.01	BDL	0.01
9.66	9.57	8.57	9.12	9.39	9.45	9.50	7.85	10.35	9.94	10.44	10.29	10.31	10.63	10.27	10.38	10.40	10.15
BDL	0.32	0.26	0.20	0.13	0.23	0.08	0.35	0.92	0.38	0.42	0.43	0.62	0.37	0.20	0.54	0.49	0.46
BDL	0.03	0.03	0.02	BDL	BDL	BDL	BDL	0.01	BDL	BDL	BDL	BDL	BDL	0.01	BDL	0.02	0.16
BDL	0.09	0.06	0.05	0.03	0.05	0.01	0.10	0.35	0.11	0.13	0.13	0.21	0.11	0.05	0.17	0.15	0.14
4.40	4.20	4.12	4.39	4.31	4.21	4.28	4.41	3.93	3.99	4.10	4.04	4.01	4.08	4.10	4.04	3.98	3.90
98.21	97.45	95.93	99.41	97.21	96.14	96.26	100.31	97.12	94	96.60	95.39	96.20	95.36	94.18	96.43	94.82	94.22
-	0.14	0.11	0.09	0.05	0.10	0.03	0.15	0.39	0.16	0.18	0.18	0.26	0.16	0.09	0.23	0.21	0.23
98.21	97.31	95.81	99.32	97.16	96.04	96.23	100.16	96.73	93.83	96.42	95.21	95.94	95.21	94.10	96.20	94.61	93.99
6.53	6.42	6.25	6.65	6.42	6.32	6.34	6.59	5.91	5.70	5.92	5.84	5.85	5.73	5.72	5.86	5.72	5.67
1.47	1.58	1.75	1.35	1.58	1.68	1.66	1.41	2.09	2.30	2.08	2.16	2.15	2.27	2.28	2.14	2.28	2.33
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
3.21	2.84	2.40	3.40	3.15	2.96	2.98	3.51	2.60	2.26	2.61	2.40	2.56	2.60	2.51	2.53	2.29	2
-	0.01	-	-	-	-	-	-	0.01	0.02	0.01	0.01	0.01	-	-	0.01	0.02	0.02
0.14	0.25	0.33	0.14	0.13	0.14	0.14	-	-	-	-	-	-	-	-	-	0.02	0.02
0.52	0.62	0.88	0.51	0.49	0.50	0.50	0.59	0.65	0.68	0.64	0.68	0.63	0.53	0.53	0.67	0.69	0.86
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.01	0.03	0.02	0.06	0.02	0.02	0.01	-	-	-	-	-	-	-	-	-	-	-
0.01	0.01	-	0.01	-	-	0.01	0.03	0.09	0.03	0.03	0.03	0.06	0.03	0.01	0.05	0.04	0.04
3.88	3.75	3.63	4.11	3.80	3.63	3.65	4.14	3.27	2.97	3.27	3.10	3.21	3.14	3.05	3.23	3.02	2.90
1.65	1.64	1.46	1.56	1.60	1.61	1.62	1.31	1.73	1.66	1.75	1.72	1.72	1.78	1.72	1.74	1.74	1.70
0.07	0.04	0.06	0.05	0.05	0.06	0.07	-	0.02	0.03	-	-	-	-	-	-	-	-
1.72	1.68	1.52	1.61	1.66	1.67	1.69	1.31	1.75	1.69	1.75	1.73	1.73	1.78	1.73	1.74	1.74	1.70
-	0.14	0.11	0.08	0.05	0.10	0.03	0.14	0.38	0.16	0.18	0.18	0.26	0.15	0.08	0.22	0.20	0.19
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.04
4	3.86	3.88	3.91	3.95	3.90	3.97	3.85	3.62	3.84	3.82	3.82	3.74	3.85	3.92	3.77	3.79	3.77
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
17.60	17.43	17.15	17.72	17.46	17.30	17.34	17.45	17.01	16.66	17.01	16.83	16.94	16.92	16.77	16.97	16.76	16.60

Appendix F-3a: Mica continued

45 LG	47 LG	48 LG	49 LG	50 LG	54 LG	55 LG	56 LG	57 LG	58 LG	60 LG	61 LG	62 LG	63 LG	64 LG	65 LG	66 LG	67 LG
43.28	43.85	43.74	43.41	44.05	43.97	43.22	43.91	43.63	44.02	43.28	43.15	46.61	46.60	45.54	45.63	45.29	46.21
0.15	0.10	0.03	0.03	0.04	0.12	0.25	0.20	0.12	0.20	0.20	0.23	0.08	0.11	0.12	0.08	0.07	0.10
29.53	29.08	31.11	31.29	31.51	30.37	27.49	25.26	28.84	28.97	26.15	27.94	30.76	29.93	30.97	31.27	29.90	30.53
0.04	0.04	0.05	0.22	0.08	0.04	0.34	0.22	0.21	0.05	0.20	0.08	0.09	0.08	0.08	0.19	0.14	0.02
BDL	0.05	0.02	0.06	0.01	BDL	0.01	BDL	BDL	BDL	0.03	BDL	0.03	BDL	0.02	0.03	0.01	BDL
0.01	BDL	0.01	BDL	BDL	BDL	0.02	0.02	BDL	0.02	0.01	BDL	BDL	0.01	BDL	0.02	0.03	BDL
6.45	6.07	4.28	4.16	4.21	5.38	7.66	9.63	6.07	6.41	10.08	7.59	5.48	5.95	5.47	5.16	5.53	6.17
BDL	0.29	BDL	0.07	0.05	0.31	0.03	0.06	0.03	0.04	BDL	0.44	BDL	BDL	0.07	0.11	BDL	0.10
10.49	10.04	10.19	9.65	10.21	10.39	10	9.95	10.18	10.47	9.83	10.35	10.29	10.13	10.33	10.35	10.09	10.26
0.42	0.51	0.36	0.27	0.40	0.37	0.39	0.38	0.28	0.27	0.39	0.38	0.31	0.49	0.40	0.41	0.53	0.46
BDL	0.05	0.01	0.04	0.01	BDL	0.02	0.02	0.02	BDL	0.03	0.02	BDL	BDL	0.01	0.02	0.03	0.01
0.12	0.16	0.10	0.07	0.12	0.10	0.11	0.11	0.07	0.07	0.11	0.11	0.08	0.15	0.12	0.12	0.17	0.14
3.98	3.94	4.04	4.05	4.06	4.06	3.93	3.90	4	4.05	3.91	3.95	4.22	4.13	4.15	4.16	4.04	4.16
94.49	94.18	93.96	93.31	94.76	95.13	93.48	93.67	93.45	94.57	94.23	94.24	97.98	97.59	97.27	97.54	95.84	98.17
0.18	0.23	0.15	0.12	0.17	0.16	0.17	0.17	0.12	0.11	0.17	0.16	0.13	0.21	0.17	0.18	0.23	0.19
94.31	93.96	93.80	93.19	94.59	94.97	93.32	93.50	93.33	94.45	94.06	94.08	97.85	97.38	97.10	97.36	95.61	97.97
5.67	5.75	5.73	5.69	5.78	5.76	5.67	5.76	5.72	5.77	5.67	5.66	6.11	6.11	5.97	5.98	5.94	6.06
2.33	2.25	2.27	2.31	2.22	2.24	2.33	2.24	2.28	2.23	2.33	2.34	1.89	1.89	2.03	2.02	2.06	1.94
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.24	2.24	2.54	2.53	2.64	2.46	1.91	1.66	2.18	2.25	1.71	1.97	2.86	2.73	2.76	2.81	2.56	2.78
0.01	0.01	-	-	-	0.01	0.02	0.02	0.01	0.02	0.02	0.02	-	0.01	0.01	-	-	0.01
-	-	0.01	0.04	0.02	-	0.07	0.04	0.04	0.01	0.04	0.02	0.02	0.02	0.01	0.04	0.03	-
0.71	0.66	0.47	0.46	0.46	0.59	0.84	1.06	0.67	0.70	1.11	0.83	0.60	0.65	0.60	0.57	0.61	0.68
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.03	0.04	0.03	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.03	0.02	0.04	0.03	0.03	0.04	0.04
2.97	2.93	3.03	3.04	3.13	3.07	2.85	2.78	2.89	2.98	2.88	2.85	3.49	3.41	3.38	3.43	3.20	3.47
1.75	1.68	1.70	1.61	1.71	1.74	1.67	1.66	1.70	1.75	1.64	1.73	1.72	1.69	1.73	1.73	1.69	1.72
-	0.07	-	0.02	0.01	0.08	-	0.02	-	0.01	-	0.11	-	-	0.02	0.03	-	0.03
1.75	1.75	1.70	1.63	1.72	1.82	1.68	1.68	1.71	1.76	1.64	1.84	1.72	1.69	1.75	1.76	1.69	1.74
0.17	0.21	0.15	0.11	0.17	0.15	0.16	0.16	0.12	0.11	0.16	0.16	0.13	0.20	0.16	0.17	0.22	0.19
-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.83	3.78	3.85	3.88	3.83	3.85	3.83	3.84	3.88	3.89	3.83	3.84	3.87	3.80	3.83	3.82	3.77	3.81
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
16.72	16.68	16.73	16.67	16.85	16.88	16.53	16.46	16.60	16.74	16.53	16.69	17.22	17.11	17.13	17.19	16.89	17.21

Appendix F-3a: Mica continued

68 LG	69 LG	70 LG	84 LG	89 LG	90 LG	91 LG	92 LG	93 LG	94 LG	95 LG	96 LG	97 LG	98 LG	99 LG	100 LG	101 LG	102 LG
46.19	45.22	45.67	42.17	47.99	48.88	45.49	44.54	46.46	45.15	45.09	47.86	43.61	45.40	48.41	45.12	44.05	45.15
0.11	0.17	0.07	0.28	0.11	0.15	0.24	0.36	0.21	0.33	0.31	0.09	1.03	0.03	0.07	0.25	0.05	0.02
29.60	29.30	31.09	26.54	27.46	26.74	24.48	25.60	24.45	25.62	25.60	28.12	25.01	30.20	29.49	27.09	32.19	32.26
0.02	0.04	0.04	0.25	2.53	3	0.23	0.25	0.19	0.20	0.22	1.71	0.18	0.50	1.06	0.19	0.01	0.42
0.01	0.03	0.10	0.05	0.02	0.03	0.01	0.02	0.01	0.03	0.02	0.05	0.13	0.08	0.03	0.07	BDL	0.04
BDL	BDL	0.04	0.15	0.06	0.03	0.03	0.02	BDL	0.04	0.08	0.59	0.52	0.12	0.04	0.42	BDL	0.01
6.44	7.63	5.45	10.35	4.43	5.02	11.69	11.98	11.03	10.76	11.05	5.42	9.43	3.71	4.40	8.97	3.25	2.78
0.02	0.02	0.23	0.14	BDL	BDL	BDL	BDL	BDL	BDL	0.04	BDL	BDL	0.03	BDL	BDL	BDL	BDL
10.25	10.41	10.34	9.26	9.63	9.64	9.20	9.17	9.76	9.37	9.34	9.59	9.47	9.24	10.32	9.08	10.01	9.49
0.40	0.51	0.27	0.35	1.08	0.86	0.29	0.79	0.52	0.46	0.46	0.39	0.45	0.48	0.69	0.46	0.56	0.18
0.01	0.02	BDL	0.08	BDL	BDL	0.04	0.05	0.03	0.03	0.04	BDL	0.02	0.02	BDL	0.03	BDL	BDL
0.12	0.16	0.07	0.10	0.44	0.32	0.08	0.29	0.16	0.14	0.14	0.11	0.14	0.15	0.24	0.14	0.18	0.04
4.13	4.06	4.21	3.88	3.94	4.06	4.01	3.85	3.97	3.97	3.97	4.21	3.88	4.04	4.14	4	4.01	4.20
97.30	97.58	97.58	93.59	97.68	98.73	95.78	96.91	96.79	96.11	96.35	98.15	93.87	94.01	98.89	95.82	94.31	94.60
0.17	0.22	0.11	0.16	0.46	0.37	0.13	0.34	0.22	0.20	0.20	0.16	0.20	0.21	0.29	0.20	0.24	0.08
97.13	97.36	97.46	93.43	97.23	98.37	95.65	96.57	96.57	95.91	96.15	97.99	93.68	93.80	98.60	95.62	94.08	94.52
6.06	5.93	5.99	5.53	6.29	6.41	5.96	5.84	6.09	5.92	5.91	6.27	5.72	5.95	6.35	5.91	5.77	5.92
1.94	2.07	2.01	2.47	1.71	1.59	2.04	2.16	1.91	2.08	2.09	1.73	2.28	2.05	1.65	2.09	2.23	2.08
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.63	2.45	2.79	1.63	2.53	2.54	1.75	1.79	1.87	1.88	1.87	2.62	1.58	2.62	2.90	2.10	2.75	2.90
0.01	0.02	-	0.03	0.01	0.01	0.02	0.04	0.02	0.03	0.03	0.01	0.10	-	-	0.02	-	-
-	-	-	0.05	0.49	0.59	0.05	0.05	0.04	0.04	0.04	0.33	0.04	0.10	0.21	0.04	-	0.08
0.71	0.84	0.60	1.13	0.49	0.55	1.28	1.31	1.21	1.18	1.21	0.59	1.03	0.41	0.48	0.98	0.36	0.30
-	-	-	0.02	-	-	-	-	-	-	-	0.07	0.06	0.01	-	0.05	-	-
-	-	0.01	-	-	-	-	-	-	-	-	-	0.02	0.01	-	0.01	-	-
0.03	0.04	0.02	0.03	0.12	0.09	0.02	0.08	0.04	0.04	0.04	0.03	0.04	0.04	0.06	0.04	0.05	0.01
3.35	3.32	3.42	2.86	3.53	3.70	3.10	3.20	3.14	3.14	3.16	3.63	2.83	3.15	3.61	3.20	3.11	3.30
1.71	1.74	1.73	1.55	1.61	1.61	1.54	1.53	1.63	1.57	1.56	1.60	1.58	1.55	1.73	1.52	1.67	1.59
-	-	0.06	0.03	-	-	-	-	-	-	0.01	-	-	-	-	-	-	-
1.72	1.75	1.79	1.58	1.61	1.61	1.54	1.53	1.63	1.57	1.57	1.60	1.58	1.55	1.73	1.52	1.67	1.59
0.17	0.21	0.11	0.14	0.45	0.36	0.12	0.33	0.21	0.19	0.19	0.16	0.19	0.20	0.29	0.19	0.23	0.07
-	-	-	0.02	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-
3.83	3.78	3.89	3.84	3.55	3.64	3.87	3.66	3.78	3.80	3.80	3.84	3.81	3.79	3.71	3.80	3.77	3.93
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
17.07	17.07	17.21	16.45	17.14	17.31	16.64	16.73	16.77	16.71	16.73	17.23	16.41	16.70	17.33	16.72	16.78	16.89

Appendix F-3a: Mica continued

103 LG	104 LG	105 LG	106 LG	107 LG	109 LG	110 LG	111 LG	112 LG	113 LG	114 LG	115 LG	117 LG	119 LG	120 LG	121 LG	122 LG	123 LG
43.72	44.58	44.27	43.38	44.82	43.13	43.75	45.37	46.06	44.75	46.49	45.81	43.48	45.52	44.34	44.81	45.41	45.51
0.03	0.03	0.02	0.29	0.41	0.26	0.22	0.05	0.06	0.05	0.03	0.05	0.31	0.29	0.38	0.40	0.24	0.34
32.45	32.24	31.99	26.91	26.54	26.17	27.48	32.20	32.95	32.07	32.43	33.05	27.23	28.55	27.09	27	27.62	27.07
0.39	0.11	0.32	0.21	0.14	0.19	0.19	0.07	0.04	0.31	0.37	0.08	0.29	0.17	0.17	0.39	0.29	0.23
0.03	BDL	0.03	0.02	BDL	0.02	BDL	0.05	0.03	0.11	0.07	0.03	0.04	0.01	0.02	0.11	0.02	0.01
0.02	0.02	0.03	BDL	0.03	BDL	BDL	0.02	0.02	0.02	0.02	BDL	0.01	BDL	BDL	BDL	0.02	0.02
2.59	2.86	2.91	8.50	10.78	9.62	8.97	3.61	3.50	2.72	3.17	3.23	7.63	8.06	9.28	8.49	8.79	10.74
BDL	BDL	BDL	0.06	0.06	0.16	0.15	0.16	BDL	0.07	0.10	0.07	0.02	0.06	0.02	0.28	0.05	0.07
9.76	9.83	9.66	9.82	9.76	9.98	9.99	9.89	9.94	9.47	9.80	9.92	10	9.90	9.57	9.84	9.95	9.82
0.11	0.26	0.18	1.53	0.33	0.38	0.25	0.36	0.31	0.26	0.03	0.21	0.54	0.26	0.65	0.36	0.12	0.36
0.01	BDL	BDL	0.03	0.05	0.05	0.04	0.02	BDL	0.02	0.01	BDL	0.03	0.05	0.05	0.07	0.05	0.10
0.02	0.07	0.04	0.69	0.09	0.11	0.06	0.10	0.08	0.07	BDL	0.05	0.17	0.07	0.22	0.10	0.02	0.10
4.16	4.14	4.14	3.54	4.04	3.90	4.02	4.16	4.25	4.14	4.35	4.27	3.88	4.14	3.90	4.02	4.15	4.09
93.28	94.14	93.59	94.99	97.06	93.97	95.13	96.07	97.24	94.06	96.87	96.76	93.63	97.08	95.70	95.87	96.74	98.47
0.05	0.11	0.08	0.65	0.15	0.17	0.11	0.16	0.13	0.11	0.02	0.09	0.23	0.12	0.29	0.17	0.06	0.17
93.23	94.03	93.51	94.34	96.91	93.80	95.01	95.91	97.11	93.94	96.86	96.68	93.40	96.96	95.42	95.70	96.68	98.30
5.73	5.84	5.80	5.69	5.88	5.65	5.73	5.95	6.04	5.87	6.09	6.01	5.70	5.97	5.81	5.87	5.95	5.97
2.27	2.16	2.20	2.31	2.12	2.35	2.27	2.05	1.96	2.13	1.91	1.99	2.30	2.03	2.19	2.13	2.05	2.03
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.75	2.83	2.75	1.84	1.98	1.70	1.98	2.92	3.13	2.82	3.10	3.11	1.91	2.38	2	2.05	2.22	2.15
-	-	-	0.03	0.04	0.03	0.02	-	-	-	-	-	0.03	0.03	0.04	0.04	0.02	0.03
0.08	0.02	0.06	0.04	0.03	0.04	0.04	0.01	-	0.06	0.07	0.02	0.06	0.03	0.03	0.08	0.06	0.04
0.28	0.31	0.32	0.93	1.18	1.05	0.98	0.40	0.38	0.30	0.35	0.35	0.84	0.88	1.02	0.93	0.96	1.18
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	0.02	0.01	-	-	-	-	0.01	-	-
-	0.02	0.01	0.18	0.02	0.03	0.02	0.03	0.02	0.02	-	0.01	0.05	0.02	0.06	0.03	-	0.03
3.11	3.17	3.14	2.85	3.23	2.82	3.02	3.35	3.53	3.20	3.54	3.49	2.84	3.33	3.09	3.11	3.27	3.41
1.63	1.64	1.62	1.64	1.63	1.67	1.67	1.65	1.66	1.58	1.64	1.66	1.67	1.66	1.60	1.65	1.66	1.64
-	-	-	0.01	0.02	0.04	0.04	0.04	-	0.02	0.03	0.02	-	0.02	-	0.07	0.01	0.02
1.63	1.64	1.62	1.66	1.65	1.71	1.71	1.69	1.66	1.60	1.66	1.68	1.68	1.67	1.61	1.72	1.68	1.66
0.04	0.11	0.08	0.63	0.14	0.16	0.10	0.15	0.13	0.11	0.01	0.09	0.22	0.11	0.27	0.15	0.05	0.15
-	-	-	-	0.01	0.01	0.01	-	-	-	-	-	-	0.01	0.01	0.01	0.01	0.02
3.95	3.89	3.92	3.36	3.85	3.83	3.89	3.84	3.87	3.89	3.98	3.91	3.77	3.88	3.72	3.84	3.94	3.83
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
16.75	16.81	16.75	16.51	16.88	16.53	16.73	17.04	17.19	16.80	17.20	17.17	16.51	17	16.70	16.83	16.95	17.07

Appendix F-3a: Mica continued

124 LG	125 LG	126 LG	127 LG	128 LG	129 LG	130 LG	131 LG	132 LG	133 LG	134 LG	135 LG	136 LG	137 LG	139 LG	140 LG	141 LG	143 LG
46.21	45.13	44.86	45.66	46.07	44.33	43.26	46.17	46.41	45.14	45.96	46.25	44.68	47.19	46.50	46.60	47.59	45.55
0.19	0.17	0.20	0.05	0.08	0.03	0.33	0.31	0.31	0.35	0.25	0.31	0.04	0.07	0.24	0.41	0.11	0.05
30.43	28.31	29.50	32.36	31.60	30.93	25.94	28.72	28.69	27.61	28.14	27.93	32.78	32.98	27.68	28.29	29.70	33.82
0.06	0.34	0.09	0.05	0.42	0.33	0.21	0.15	0.16	0.30	0.56	0.37	0.29	0.04	0.20	0.20	1.38	0.05
0.02	0.02	BDL	0.07	0.01	0.11	0.02	BDL	BDL	0.48	BDL	0.18	0.03	BDL	0.02	0.02	0.04	0.01
BDL	0.02	0.01	0.02	0.01	0.02	BDL	BDL	0.02	BDL	0.02	BDL	0.05	0.02	0.01	0.01	0.04	BDL
6.72	8.17	7	3.58	4.41	3.37	10.39	8.31	8.47	8.82	7.46	8	2.50	3.34	9.79	8.35	4.90	2.56
0.02	0.01	0.12	0.09	0.09	0.45	0.17	0.10	BDL	0.08	BDL	0.10	BDL	0.08	0.10	BDL	BDL	0.03
10.04	9.48	10.03	9.91	10.08	9.63	10.07	9.68	9.70	9.38	9.63	9.18	9.89	9.62	9.53	9.43	10.09	9.93
0.76	0.65	0.60	0.40	0.39	0.29	0.33	0.26	0.60	1.14	0.51	0.42	0.18	0.18	0.85	0.38	0.40	0.30
0.01	0.07	0.03	0.06	0.01	0.25	0.09	0.06	0.06	0.05	0.03	0.04	BDL	0.01	0.03	0.21	0.02	BDL
0.28	0.22	0.20	0.12	0.11	0.07	0.09	0.07	0.20	0.47	0.16	0.12	0.04	0.04	0.32	0.11	0.12	0.08
4.05	3.96	4.01	4.16	4.19	4.04	3.93	4.18	4.08	3.80	4.05	4.09	4.20	4.35	3.98	4.11	4.23	4.24
98.79	96.57	96.67	96.52	97.50	93.86	94.82	98	98.69	97.63	96.76	96.99	94.69	97.92	99.25	98.11	98.62	96.63
0.32	0.29	0.26	0.18	0.17	0.18	0.16	0.12	0.26	0.49	0.22	0.19	0.08	0.08	0.37	0.21	0.17	0.13
98.47	96.28	96.41	96.34	97.33	93.68	94.66	97.88	98.43	97.14	96.54	96.81	94.61	97.85	98.88	97.90	98.45	96.50
6.06	5.92	5.88	5.99	6.04	5.81	5.67	6.05	6.08	5.92	6.02	6.06	5.86	6.19	6.10	6.11	6.24	5.97
1.94	2.08	2.12	2.01	1.96	2.19	2.33	1.95	1.92	2.08	1.98	1.94	2.14	1.81	1.90	1.89	1.76	2.03
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.76	2.29	2.44	2.98	2.92	2.59	1.68	2.49	2.52	2.18	2.37	2.38	2.92	3.28	2.37	2.48	2.83	3.20
0.02	0.02	0.02	-	-	-	0.03	0.03	0.03	0.03	0.02	0.03	-	-	0.02	0.04	0.01	-
0.01	0.07	0.02	0.01	0.08	0.06	0.04	0.03	0.03	0.06	0.11	0.07	0.06	-	0.04	0.04	0.27	0.01
0.74	0.90	0.77	0.39	0.48	0.37	1.14	0.91	0.93	0.97	0.82	0.88	0.27	0.37	1.07	0.91	0.54	0.28
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	0.01	-	0.02	-	-	-	0.07	-	0.03	-	-	-	-	-	-
0.07	0.06	0.05	0.03	0.03	0.02	0.02	0.02	0.05	0.12	0.04	0.03	0.01	0.01	0.08	0.03	0.03	0.02
3.53	3.27	3.25	3.40	3.50	3.05	2.89	3.46	3.51	3.31	3.33	3.38	3.27	3.67	3.51	3.48	3.66	3.49
1.68	1.59	1.68	1.66	1.69	1.61	1.68	1.62	1.62	1.57	1.61	1.54	1.65	1.61	1.59	1.58	1.69	1.66
-	-	0.03	0.02	0.02	0.11	0.04	0.02	-	0.02	-	0.02	-	0.02	0.02	-	-	-
1.69	1.59	1.71	1.68	1.71	1.72	1.73	1.64	1.62	1.59	1.61	1.56	1.65	1.63	1.62	1.58	1.69	1.67
0.32	0.27	0.25	0.17	0.16	0.12	0.14	0.11	0.25	0.47	0.21	0.17	0.07	0.07	0.35	0.16	0.17	0.12
-	0.02	-	0.01	-	0.06	0.02	0.01	0.01	0.01	-	0.01	-	-	-	0.05	-	-
3.68	3.71	3.74	3.82	3.84	3.82	3.84	3.88	3.74	3.52	3.78	3.82	3.93	3.92	3.64	3.80	3.83	3.87
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
17.21	16.86	16.96	17.08	17.21	16.77	16.62	17.10	17.13	16.90	16.94	16.94	16.92	17.30	17.13	17.05	17.34	17.16

Appendix F-3a: Mica continued

144	145	146	147	148	150
LG	LG	LG	LG	LG	LG
45.56	46.62	46.83	47.98	47.02	46.10
0.04	0.02	0.04	0.03	0.02	0.06
33.70	33.48	33.92	33.16	33.81	33.11
0.13	0.30	0.22	0.26	0.26	0.08
0.03	0.06	0.06	0.04	0.05	0.03
0.02	BDL	BDL	0.03	0.02	BDL
2.33	2.29	2.68	3.19	2.56	3.59
BDL	BDL	0.06	0.10	0.03	BDL
9.77	9.40	9.48	9.37	9.55	9.69
0.32	0.18	0.20	0.25	0.23	0.23
0.02	BDL	0.02	0.01	BDL	0.02
0.09	0.04	0.05	0.06	0.06	0.06
4.22	4.32	4.35	4.37	4.35	4.28
96.23	96.71	97.90	98.84	97.96	97.24
0.14	0.08	0.09	0.11	0.10	0.10
96.09	96.64	97.82	98.74	97.86	97.14

**Stoichiometrically calculated; **Calculated according to Tischendorf et al. (1997).*

Abbreviations: Nebo Granite (NG); Bobbejaankop Granite (BG); Lease Granite (LG); and Below Detection Limit (BDL).

5.97	6.11	6.14	6.29	6.16	6.04
2.03	1.89	1.86	1.71	1.84	1.96
-	-	-	-	-	-
8	8	8	8	8	8
3.18	3.28	3.38	3.41	3.39	3.16
-	-	-	-	-	-
0.03	0.06	0.04	0.05	0.05	0.02
0.26	0.25	0.29	0.35	0.28	0.39
-	-	-	-	-	-
-	-	-	-	-	-
0.02	0.01	0.01	0.02	0.01	0.01
3.47	3.60	3.73	3.82	3.73	3.58
1.63	1.57	1.59	1.57	1.60	1.62
-	-	0.02	0.03	-	-
1.63	1.57	1.60	1.59	1.60	1.62
0.13	0.07	0.08	0.10	0.10	0.09
-	-	-	-	-	-
3.86	3.93	3.91	3.89	3.90	3.90
4	4	4	4	4	4
17.11	17.18	17.33	17.42	17.34	17.20

Appendix F-3b: Mica EPMA compositions from the Gaborone Granite Suite.

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Granite	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr
SiO ₂	32.53	34.40	33.61	33.24	34.22	32.17	31.87	34.18	33.99	34.84	33	34.12	33.93	34.75	34.28	34.29	33.39
TiO ₂	1.16	1.93	1.80	1.22	1.52	1.24	1.04	1.91	1.90	1.93	1.63	1.81	1.80	1.93	1.81	1.95	1.63
Al ₂ O ₃	17.20	15.79	15.47	15.86	15.86	16.13	15.95	15.78	15.80	15.51	15.65	15.73	15.33	15.27	15.74	15.46	15.62
MgO	3.92	3.73	3.50	3.85	3.91	4.05	4.06	3.60	3.60	3.80	4.10	3.89	3.90	3.83	3.69	3.64	3.99
CaO	BDL	BDL	0.01	BDL	BDL	0.14	0.02	0.02	BDL	BDL	BDL	BDL	0.01	BDL	BDL	0.01	0.01
MnO	0.27	0.27	0.26	0.30	0.30	0.30	0.33	0.34	0.32	0.31	0.30	0.31	0.27	0.28	0.28	0.31	0.29
FeO ^{tot}	31.69	30.04	30.82	30.79	30.87	32.71	32.59	30.01	30.48	29.96	31.66	30.56	31.12	30.26	30.77	29.96	31.57
Na ₂ O	BDL	0.22	BDL	0.21	BDL	BDL	0.15	0.14	0.02	0.07	0.03	BDL	BDL	0.10	BDL	BDL	BDL
K ₂ O	7.85	9.03	8.47	8.44	8.52	6.53	6.55	8.82	8.76	9	7.54	8.65	8.29	8.67	8.45	8.61	7.69
F	0.13	0.33	0.10	0.24	0.10	0.10	0.10	0.25	0.08	0.22	BDL	BDL	0.08	0.18	0.08	0.02	0.02
Cl	0.02	0.05	0.04	0.03	0.05	0.02	0.02	0.04	0.04	0.03	0.03	0.03	0.05	0.05	0.04	0.04	0.04
Li ₂ O**	BDL	0.03	BDL	0.02	BDL	BDL	BDL	0.02	BDL	0.01	BDL	BDL	BDL	0.01	BDL	BDL	BDL
H ₂ O*	3.62	3.58	3.60	3.55	3.66	3.57	3.54	3.59	3.65	3.64	3.64	3.70	3.64	3.64	3.67	3.66	3.65
Total	98.40	99.40	97.69	97.75	99.03	96.97	96.24	98.70	98.66	99.32	97.58	98.79	98.44	98.98	98.82	97.95	97.91
O≡F,Cl*	0.06	0.15	0.05	0.11	0.05	0.05	0.05	0.11	0.04	0.10	0.01	0.01	0.05	0.09	0.04	0.02	0.02
Total	98.34	99.25	97.64	97.64	98.97	96.93	96.19	98.59	98.61	99.22	97.58	98.78	98.39	98.90	98.78	97.94	97.89
Cations Proportions Based on 22 Oxygens (apfu)																	
Tetrahedral Site																	
Si	5.29	5.60	5.47	5.41	5.57	5.23	5.18	5.56	5.53	5.67	5.37	5.55	5.52	5.65	5.58	5.58	5.43
Al ^{IV}	2.71	2.40	2.53	2.59	2.43	2.77	2.82	2.44	2.47	2.33	2.63	2.45	2.48	2.35	2.42	2.42	2.57
Fe ^{3+*}	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Z Sum	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Octahedral Site																	
Al ^{VI}	0.59	0.62	0.43	0.45	0.61	0.33	0.24	0.59	0.56	0.64	0.37	0.57	0.46	0.58	0.59	0.54	0.43
Ti	0.14	0.24	0.22	0.15	0.19	0.15	0.13	0.23	0.23	0.24	0.20	0.22	0.22	0.24	0.22	0.24	0.20
Mg	0.95	0.90	0.85	0.93	0.95	0.98	0.98	0.87	0.87	0.92	0.99	0.94	0.95	0.93	0.89	0.88	0.97
Fe ^{tot}	4.31	4.09	4.19	4.19	4.20	4.45	4.43	4.08	4.15	4.08	4.31	4.16	4.23	4.12	4.19	4.08	4.29
Mn	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Ca	-	-	-	-	-	0.02	-	-	-	-	-	-	-	-	-	-	-
Li*	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Y Sum	6.03	5.89	5.73	5.76	5.98	5.97	5.84	5.82	5.86	5.92	5.91	5.93	5.90	5.90	5.93	5.78	5.93
Interlayer																	
K	1.63	1.87	1.76	1.75	1.77	1.35	1.36	1.83	1.82	1.87	1.56	1.79	1.72	1.80	1.75	1.79	1.60
Na	-	0.07	-	0.07	-	-	0.05	0.04	-	0.02	0.01	-	-	0.03	-	-	-
X Sum	1.63	1.94	1.76	1.82	1.77	1.35	1.41	1.87	1.82	1.89	1.58	1.79	1.72	1.83	1.75	1.79	1.60
Anion Site																	
F	0.07	0.17	0.05	0.12	0.05	0.05	0.05	0.13	0.04	0.11	-	-	0.04	0.09	0.04	0.01	0.01
Cl	-	0.01	0.01	-	0.01	-	-	0.01	0.01	-	-	0.01	0.01	0.01	0.01	0.01	0.01
OH*	3.93	3.81	3.94	3.87	3.94	3.94	3.94	3.86	3.95	3.88	3.99	3.99	3.94	3.89	3.95	3.98	3.98
A Sum	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Sum	19.66	19.83	19.49	19.58	19.75	19.33	19.24	19.70	19.68	19.81	19.48	19.72	19.62	19.73	19.69	19.57	19.53

Appendix F-3b: Mica continued

18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr
33.43	33.04	32.87	32.93	33.83	33.23	34.18	32.63	33.67	33.02	33.89	33.97	34.33	31.30	31.91	34.06	31.91	34.23
1.81	1.73	1.61	1.70	1.80	1.14	1.27	1.13	1.48	1.45	1.51	1.54	1.55	1.06	1.10	1.14	0.95	1.23
14.81	14.74	14.48	14.70	15.01	15.66	15.42	16.08	15.80	15.78	15.89	15.87	15.68	15.96	15.95	15.92	15.39	15.67
3.46	3.53	3.68	3.54	3.66	3.96	3.93	3.92	3.99	4.02	4.07	3.88	3.82	4.14	4.09	3.82	4.41	3.90
BDL	BDL	BDL	0.03	BDL	0.02	BDL	0.01	BDL	BDL	BDL	BDL	BDL	0.01	0.01	0.01	0.03	0.01
0.22	0.25	0.26	0.22	0.24	0.26	0.25	0.28	0.27	0.27	0.24	0.26	0.22	0.29	0.32	0.23	0.32	0.27
30.59	31.01	32.25	31.03	30.58	31.77	30.81	31.70	31.36	31.77	31.15	30.81	30.52	32.69	32.21	30.02	32.57	29.82
0.05	BDL	0.15	BDL	0.26	0.27	0.42	0.22	0.30	0.25	0.27	0.40	0.23	0.11	BDL	0.19	BDL	0.17
8.71	8.28	7.72	8.21	8.68	7.70	8.71	7.65	8.07	7.99	8.13	8.48	8.75	6.44	6.88	7.63	5.69	8.62
BDL	0.01	BDL	0.17	0.09	BDL	0.18	0.09	BDL	0.10	0.09	0.11	0.10	0.05	0.03	0.04	0.14	0.16
0.06	0.04	0.03	0.04	0.05	0.03	0.03	0.02	0.04	0.03	0.04	0.04	0.05	0.03	0.03	0.06	0.06	0.06
BDL	BDL	BDL	0.01	BDL	BDL	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.01
3.59	3.57	3.58	3.50	3.61	3.64	3.61	3.59	3.68	3.61	3.66	3.65	3.66	3.53	3.57	3.63	3.49	3.60
96.76	96.22	96.64	96.07	97.80	97.67	98.82	97.31	98.65	98.31	98.94	99.02	98.90	95.61	96.10	96.74	94.95	97.76
0.02	0.01	0.01	0.08	0.05	0.01	0.08	0.04	0.01	0.05	0.04	0.05	0.05	0.03	0.02	0.03	0.07	0.08
96.74	96.21	96.63	95.99	97.75	97.67	98.73	97.27	98.64	98.26	98.90	98.96	98.85	95.59	96.08	96.71	94.88	97.68
5.44	5.38	5.35	5.36	5.50	5.40	5.56	5.31	5.48	5.37	5.51	5.53	5.58	5.09	5.19	5.54	5.19	5.57
2.56	2.62	2.65	2.64	2.50	2.60	2.44	2.69	2.52	2.63	2.49	2.47	2.42	2.91	2.81	2.46	2.81	2.43
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
0.28	0.20	0.12	0.17	0.38	0.41	0.51	0.39	0.51	0.40	0.56	0.57	0.59	0.15	0.25	0.59	0.14	0.57
0.22	0.21	0.20	0.21	0.22	0.14	0.16	0.14	0.18	0.18	0.18	0.19	0.19	0.13	0.13	0.14	0.12	0.15
0.84	0.86	0.89	0.86	0.89	0.96	0.95	0.95	0.97	0.98	0.99	0.94	0.93	1	0.99	0.93	1.07	0.95
4.16	4.22	4.39	4.22	4.16	4.32	4.19	4.31	4.27	4.32	4.24	4.19	4.15	4.45	4.38	4.08	4.43	4.06
0.03	0.03	0.04	0.03	0.03	0.04	0.03	0.04	0.04	0.04	0.03	0.04	0.03	0.04	0.04	0.03	0.04	0.04
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5.53	5.52	5.64	5.49	5.68	5.87	5.85	5.83	5.96	5.91	6	5.92	5.89	5.77	5.80	5.77	5.80	5.76
1.81	1.72	1.60	1.70	1.80	1.60	1.81	1.59	1.67	1.66	1.69	1.76	1.82	1.34	1.43	1.58	1.18	1.79
0.02	-	0.05	-	0.08	0.08	0.13	0.07	0.09	0.08	0.08	0.13	0.07	0.03	-	0.06	-	0.05
1.82	1.72	1.65	1.70	1.88	1.68	1.94	1.66	1.77	1.74	1.77	1.89	1.89	1.37	1.43	1.64	1.18	1.84
-	-	-	0.09	0.05	-	0.09	0.05	-	0.05	0.04	0.06	0.05	0.03	0.01	0.02	0.07	0.08
0.02	0.01	-	0.01	0.01	0.01	0.01	-	0.01	-	0.01	0.01	0.01	-	-	0.02	0.02	0.02
3.98	3.98	3.99	3.90	3.94	3.99	3.90	3.95	3.99	3.94	3.95	3.93	3.93	3.97	3.98	3.96	3.91	3.90
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
19.35	19.24	19.29	19.20	19.56	19.55	19.79	19.49	19.72	19.65	19.77	19.81	19.77	19.14	19.23	19.42	18.99	19.61

Appendix F-3b: Mica continued

36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr
34.25	34.19	33.72	33.98	32.97	33.30	34.03	34.12	33.67	34.36	33.59	33.94	34.30	34.04	34.16	33.97	34.01	34.65
1.25	1.21	1.23	1.51	1.41	1.47	1.80	1.89	1.86	1.98	1.91	1.89	1.78	1.87	1.95	1.71	1.95	2.14
15.60	15.54	15.65	16.12	16.19	16.22	15.88	16.03	16.04	16.48	16.56	16.40	16.35	16.08	15.77	16.35	15.45	16.57
3.80	3.85	3.83	3.88	3.91	3.77	6.41	6.17	6.14	6.13	6.32	6.06	6.47	6.33	6.38	6.25	6.44	6.42
BDL	0.03	0.01	0.08	0.02	0.03	BDL	BDL	BDL	BDL	0.06	BDL	BDL	BDL	BDL	BDL	0.07	BDL
0.25	0.24	0.28	0.27	0.30	0.24	0.22	0.20	0.20	0.19	0.26	0.20	0.24	0.18	0.21	0.23	0.22	0.19
30.22	29.98	30.17	30.66	31.64	31.16	26.51	27.10	26.67	26.33	26.91	26.41	26.62	26.75	27.06	27.17	26.98	26.63
0.10	0.20	0.07	BDL	0.08	0.09	BDL	0.07	0.13	0.23	0.15	0.13	2.38	BDL	BDL	BDL	BDL	BDL
8.71	8.66	8.40	8.50	7.03	7.57	9.24	8.75	9.14	9.08	7.95	8.97	9.06	9.09	8.93	8.83	8.37	8.96
0.24	0.23	0.18	0.14	BDL	0.26	0.08	0.10	0.01	0.28	BDL	0.23	0.07	0.23	0.19	0.19	0.21	0.29
0.07	0.07	0.05	0.05	0.03	0.04	0.03	0.02	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.03	0.02	0.02
0.02	0.02	0.01	BDL	BDL	0.02	BDL	BDL	BDL	BDL	0.02	BDL	0.02	BDL	0.02	0.01	0.01	0.02
3.57	3.56	3.56	3.64	3.64	3.55	3.69	3.69	3.70	3.65	3.73	3.64	3.79	3.64	3.66	3.66	3.62	3.68
98.08	97.79	97.19	98.84	97.22	97.72	97.87	98.15	97.60	98.76	97.46	97.90	101.10	98.26	98.35	98.39	97.36	99.58
0.12	0.11	0.09	0.07	0.01	0.12	0.04	0.05	0.01	0.12	-	0.10	0.04	0.10	0.09	0.09	0.09	0.12
97.96	97.68	97.10	98.77	97.21	97.60	97.83	98.10	97.59	98.64	97.45	97.80	101.06	98.15	98.26	98.31	97.27	99.45
5.57	5.56	5.49	5.53	5.36	5.42	5.54	5.55	5.48	5.59	5.46	5.52	5.58	5.54	5.56	5.52	5.53	5.64
2.43	2.44	2.51	2.47	2.64	2.58	2.46	2.45	2.52	2.41	2.54	2.48	2.42	2.46	2.44	2.48	2.47	2.36
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
0.56	0.54	0.49	0.62	0.47	0.53	0.58	0.62	0.55	0.75	0.64	0.66	0.71	0.62	0.58	0.66	0.49	0.81
0.15	0.15	0.15	0.18	0.17	0.18	0.22	0.23	0.23	0.24	0.23	0.23	0.22	0.23	0.24	0.21	0.24	0.26
0.92	0.93	0.93	0.94	0.95	0.91	1.55	1.50	1.49	1.49	1.53	1.47	1.57	1.53	1.55	1.52	1.56	1.56
4.11	4.08	4.10	4.17	4.30	4.24	3.61	3.69	3.63	3.58	3.66	3.59	3.62	3.64	3.68	3.70	3.67	3.62
0.03	0.03	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.03	0.02	0.03	0.03	0.03	0.03
-	-	-	0.01	-	-	-	-	-	-	0.01	-	-	-	-	-	0.01	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5.78	5.74	5.71	5.96	5.94	5.90	5.99	6.06	5.92	6.09	6.11	5.98	6.15	6.05	6.08	6.11	6.01	6.28
1.81	1.80	1.74	1.76	1.46	1.57	1.92	1.81	1.90	1.88	1.65	1.86	1.88	1.89	1.85	1.83	1.74	1.86
0.03	0.06	0.02	-	0.02	0.03	-	0.02	0.04	0.07	0.05	0.04	0.75	-	-	-	-	-
1.84	1.86	1.77	1.77	1.48	1.60	1.92	1.84	1.94	1.96	1.70	1.90	2.63	1.89	1.85	1.83	1.74	1.86
0.12	0.12	0.09	0.07	-	0.13	0.04	0.05	-	0.14	-	0.12	0.04	0.12	0.10	0.10	0.11	0.15
0.02	0.02	0.01	0.01	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-
3.86	3.86	3.89	3.91	3.99	3.86	3.95	3.94	3.99	3.85	4	3.88	3.96	3.87	3.89	3.90	3.89	3.85
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
19.62	19.60	19.48	19.73	19.42	19.50	19.91	19.90	19.86	20.04	19.81	19.89	20.79	19.93	19.93	19.94	19.74	20.14

Appendix F-3b: Mica continued

54 Th Gr	55 Th Gr	56 Th Gr	57 Th Gr	58 Th Gr	59 Th Gr	60 Th Gr	61 Th Gr	62 Th Gr	63 Th Gr	64 Th Gr	65 Th Gr	66 Th Gr	67 Th Gr	68 Th Gr	69 Th Gr	70 Th Gr	71 Th Gr
34.49	34.49	33.15	35.10	33.68	33.34	33.51	33.66	33.88	31.80	32.38	34.54	34.74	34.31	34.45	33.84	33.73	33.97
2.26	2.21	1.96	2.28	2.30	2.20	2.42	2.21	2.21	1.50	1.51	2.22	2.10	2.09	2.10	8.89	2.01	2.01
16.64	16.78	17.09	16.59	16.70	16.82	16.59	16.86	16.88	17.22	16.24	15.21	15.43	15.34	15.78	12.08	15.65	16
6.22	6.18	6.30	6.06	5.97	6.08	6.41	6.12	6.25	7.38	7.33	6.33	6.35	6.07	6.21	4.91	6.40	6.10
BDL	BDL	BDL	BDL	BDL	BDL	0.08	BDL	BDL	0.01	0.05	0.07	BDL	BDL	BDL	3.45	BDL	BDL
0.20	0.17	0.24	0.23	0.22	0.24	0.22	0.21	0.22	0.30	0.24	0.21	0.22	0.20	0.21	0.16	0.22	0.21
26.77	26.89	27.91	27.13	26.85	27.22	26.65	26.36	26.86	28.96	27.71	26.11	26.51	26.48	26.37	19.69	27.11	26.42
0.16	0.06	0.04	0.06	BDL	0.17	0.02	BDL	BDL	0.11	0.12	0.12	0.11	BDL	0.11	BDL	BDL	0.18
9.27	9.21	8.05	9.16	9.05	8.62	8.52	9.04	9.22	6.13	6.74	8.93	8.90	8.96	8.87	6.68	8.20	8.77
0.19	0.10	0.05	0.18	0.21	BDL	0.08	0.06	0.16	0.08	0.13	0.20	0.24	0.12	0.10	0.21	0.20	0.19
0.03	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.03	0.01	0.01	0.02	0.02	0.02	0.01	0.02
0.01	BDL	BDL	0.01	0.01	BDL	BDL	BDL	BDL	BDL	BDL	0.01	0.02	BDL	BDL	0.01	0.01	0.01
3.73	3.77	3.73	3.76	3.66	3.74	3.71	3.72	3.71	3.67	3.61	3.64	3.65	3.66	3.70	3.58	3.62	3.64
99.96	99.89	98.53	100.58	98.68	98.44	98.23	98.26	99.42	97.20	96.10	97.59	98.28	97.25	97.93	93.51	97.17	97.53
0.08	0.05	0.02	0.08	0.09	0.01	0.04	0.03	0.07	0.04	0.06	0.09	0.10	0.06	0.05	0.09	0.09	0.09
99.88	99.85	98.50	100.50	98.59	98.44	98.20	98.23	99.35	97.16	96.03	97.50	98.18	97.19	97.88	93.42	97.09	97.44
5.61	5.61	5.39	5.71	5.48	5.42	5.45	5.47	5.51	5.17	5.27	5.62	5.65	5.58	5.60	5.50	5.49	5.53
2.39	2.39	2.61	2.29	2.52	2.58	2.55	2.53	2.49	2.83	2.73	2.38	2.35	2.42	2.40	2.32	2.51	2.47
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.18	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
0.80	0.83	0.67	0.89	0.68	0.65	0.63	0.71	0.75	0.47	0.38	0.53	0.61	0.52	0.63	-	0.49	0.59
0.28	0.27	0.24	0.28	0.28	0.27	0.30	0.27	0.27	0.18	0.18	0.27	0.26	0.26	0.26	1.09	0.25	0.25
1.51	1.50	1.53	1.47	1.45	1.47	1.55	1.48	1.52	1.79	1.78	1.53	1.54	1.47	1.51	1.19	1.55	1.48
3.64	3.66	3.80	3.69	3.65	3.70	3.63	3.59	3.65	3.94	3.77	3.55	3.61	3.60	3.59	2.68	3.69	3.59
0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
-	-	-	-	-	-	0.01	-	-	-	-	0.01	-	-	-	0.60	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6.25	6.28	6.26	6.36	6.09	6.12	6.15	6.07	6.22	6.43	6.15	5.93	6.04	5.88	6.01	5.58	6	5.94
1.92	1.91	1.67	1.90	1.88	1.79	1.77	1.88	1.91	1.27	1.40	1.85	1.85	1.86	1.84	1.39	1.70	1.82
0.05	0.02	0.01	0.02	-	0.05	-	-	-	0.04	0.04	0.04	0.04	-	0.04	-	-	0.06
1.97	1.93	1.68	1.92	1.88	1.84	1.78	1.88	1.91	1.31	1.44	1.89	1.88	1.86	1.88	1.39	1.70	1.88
0.10	0.05	0.03	0.09	0.11	-	0.04	0.03	0.08	0.04	0.07	0.10	0.12	0.06	0.05	0.11	0.10	0.10
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.90	3.94	3.97	3.90	3.89	3.99	3.95	3.96	3.91	3.96	3.92	3.89	3.87	3.93	3.94	3.89	3.89	3.90
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
20.23	20.21	19.95	20.28	19.97	19.97	19.92	19.95	20.13	19.74	19.59	19.82	19.92	19.74	19.88	18.79	19.70	19.82

Appendix F-3b: Mica continued

72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr
34.02	34.08	34.28	34.17	34.64	34.32	34.24	34.33	34.26	34.31	34.27	34.09	34.22	31.68	31.71	31.71	31.74	31.91
2.07	2.13	2.15	2.07	2.14	2.12	2.08	2.07	2.13	2.17	2.08	2.08	2.25	1.49	1.52	1.54	1.52	1.51
15.83	15.59	15.49	15.49	15.29	15.64	15.42	15.46	15.51	15.39	15.84	15.56	15.66	13.08	13.49	13.51	13.42	13.53
6.25	6.39	6.17	6.26	6.42	6.34	6.21	6.24	6.47	6.33	6.23	6.22	6.28	2.41	2.34	2.27	2.26	2.28
BDL	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.07	BDL	BDL	BDL	BDL	BDL
0.20	0.25	0.22	0.22	0.20	0.18	0.19	0.23	0.20	0.20	0.24	0.21	0.22	0.28	0.32	0.28	0.25	0.31
26.82	26.54	26.48	26.64	26.35	26.27	26.59	26.70	26.86	26.53	26.85	26.60	26.15	32.36	32.03	31.77	32	31.55
BDL	BDL	0.14	0.16	0.16	0.19	0.17	0.22	0.08	0.15	BDL	BDL	0.13	0.10	BDL	BDL	0.08	0.12
8.79	8.51	8.76	8.74	8.73	8.98	8.97	8.86	8.99	8.97	9.07	8.93	9.19	8.21	8.17	8.28	8.24	8.34
0.08	0.17	0.09	0.11	0.26	0.31	0.17	0.23	0.13	0.11	0.05	0.15	0.14	0.19	0.10	0.02	BDL	0.05
0.02	0.02	0.02	0.02	0.02	BDL	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.04
BDL	0.01	BDL	BDL	0.02	0.03	0.01	0.02	BDL	BDL	BDL	BDL	BDL	0.01	BDL	BDL	BDL	BDL
3.69	3.64	3.68	3.67	3.63	3.61	3.65	3.63	3.68	3.68	3.72	3.65	3.67	3.33	3.38	3.40	3.41	3.40
97.77	97.35	97.48	97.54	97.85	97.99	97.72	98.02	98.33	97.87	98.38	97.52	98	93.18	93.07	92.82	92.95	93.03
0.04	0.08	0.04	0.05	0.11	0.13	0.08	0.10	0.06	0.05	0.03	0.07	0.06	0.09	0.05	0.02	0.01	0.03
97.73	97.27	97.44	97.49	97.74	97.86	97.64	97.92	98.27	97.82	98.35	97.46	97.93	93.09	93.02	92.80	92.94	93.01
5.53	5.54	5.58	5.56	5.63	5.58	5.57	5.58	5.57	5.58	5.57	5.55	5.57	5.15	5.16	5.16	5.16	5.19
2.47	2.46	2.42	2.44	2.37	2.42	2.43	2.42	2.43	2.42	2.43	2.45	2.43	2.51	2.59	2.59	2.57	2.59
-	-	-	-	-	-	-	-	-	-	-	-	-	0.34	0.26	0.25	0.27	0.22
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
0.57	0.53	0.55	0.53	0.57	0.58	0.53	0.55	0.55	0.53	0.61	0.53	0.57	-	-	-	-	-
0.25	0.26	0.26	0.25	0.26	0.26	0.25	0.25	0.26	0.27	0.25	0.26	0.28	0.18	0.19	0.19	0.19	0.18
1.51	1.55	1.50	1.52	1.56	1.54	1.50	1.51	1.57	1.53	1.51	1.51	1.52	0.59	0.57	0.55	0.55	0.55
3.65	3.61	3.60	3.62	3.58	3.57	3.62	3.63	3.65	3.61	3.65	3.62	3.56	4.40	4.36	4.32	4.35	4.29
0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.03	0.04
-	-	-	-	-	-	-	-	-	-	-	-	0.01	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6.01	5.99	5.94	5.95	6	5.98	5.93	5.98	6.05	5.97	6.06	5.94	5.96	5.21	5.15	5.10	5.12	5.07
1.82	1.77	1.82	1.81	1.81	1.86	1.86	1.84	1.87	1.86	1.88	1.85	1.91	1.70	1.70	1.72	1.71	1.73
-	-	0.04	0.05	0.05	0.06	0.05	0.07	0.03	0.05	-	-	0.04	0.03	-	-	0.03	0.04
1.82	1.77	1.86	1.86	1.86	1.92	1.92	1.91	1.89	1.91	1.88	1.85	1.95	1.73	1.70	1.72	1.74	1.77
0.04	0.09	0.05	0.06	0.13	0.16	0.09	0.12	0.07	0.06	0.03	0.08	0.07	0.10	0.05	0.01	-	0.02
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01
3.95	3.91	3.95	3.94	3.86	3.84	3.91	3.87	3.93	3.94	3.97	3.92	3.92	3.89	3.94	3.98	3.99	3.97
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
19.84	19.75	19.80	19.81	19.86	19.90	19.84	19.89	19.95	19.88	19.94	19.79	19.91	18.60	18.59	18.57	18.59	18.62

Appendix F-3b: Mica continued

90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107
Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr
33.61	33.39	33.50	33.70	33.16	33.53	33.53	33.50	33.02	32.99	33.06	32.41	32.91	33.12	32.70	31.97	31.71	32.61
1.78	1.79	1.75	1.75	1.74	1.79	1.77	1.72	4.09	1.29	1.66	6.07	1.76	1.76	4.72	1.37	1.48	1.51
14.63	14.66	14.67	14.70	14.65	14.69	14.75	14.84	13.53	14.04	14.43	12.50	14.39	14.37	13.20	14.49	13.79	14.33
2.35	2.31	2.36	2.34	2.28	2.37	2.38	2.44	2.10	2.90	2.42	1.88	2.31	2.27	2	2.77	2.48	2.65
BDL	BDL	BDL	BDL	BDL	0.03	0.01	0.15	1.34	0.08	BDL	2.76	BDL	BDL	1.85	BDL	0.01	BDL
0.31	0.32	0.31	0.31	0.32	0.32	0.30	0.33	0.26	0.33	0.30	0.30	0.34	0.35	0.28	0.40	0.36	0.36
31.85	31.40	31.94	31.40	31.71	31.76	31.56	31.48	29.16	32.64	31.44	25.62	31.43	31.44	27.45	33.52	31.46	32.74
0.15	0.10	0.13	0.18	0.13	0.08	0.14	0.19	0.13	0.05	0.04	0.08	0.11	0.05	0.11	0.14	2.78	BDL
8.64	8.68	8.56	8.73	8.48	8.18	8.42	8.34	7.66	6.37	8.42	6.73	8.62	8.69	7.37	7.30	7.75	7.95
0.14	0.18	0.19	0.18	0.10	0.13	0.11	0.24	0.12	0.14	0.12	0.51	0.17	0.07	0.24	0.11	0.15	0.21
0.03	0.03	0.03	0.03	0.02	0.04	0.03	0.02	0.02	0.02	0.04	0.02	0.03	0.03	0.02	0.03	0.88	0.03
BDL	0.01	0.01	0.01	BDL	BDL	BDL	0.02	BDL	BDL	BDL	0.06	0.01	BDL	0.02	BDL	BDL	0.01
3.54	3.50	3.51	3.52	3.52	3.53	3.54	3.50	3.50	3.46	3.48	3.30	3.46	3.51	3.42	3.47	3.26	3.45
97.03	96.37	96.97	96.84	96.11	96.44	96.55	96.76	94.92	94.32	95.43	92.24	95.54	95.67	93.37	95.56	96.10	95.85
0.06	0.08	0.09	0.08	0.05	0.06	0.05	0.11	0.06	0.07	0.06	0.22	0.08	0.04	0.11	0.06	0.26	0.09
96.96	96.28	96.88	96.76	96.07	96.37	96.50	96.66	94.86	94.25	95.37	92.02	95.46	95.63	93.27	95.51	95.84	95.76
5.47	5.43	5.45	5.48	5.39	5.45	5.45	5.45	5.37	5.37	5.38	5.27	5.35	5.39	5.32	5.20	5.16	5.30
2.53	2.57	2.55	2.52	2.61	2.55	2.55	2.55	2.59	2.63	2.62	2.40	2.65	2.61	2.53	2.78	2.64	2.70
-	-	-	-	-	-	-	-	0.04	-	-	0.33	-	-	0.15	0.02	0.20	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
0.27	0.24	0.26	0.30	0.20	0.27	0.28	0.29	-	0.06	0.14	-	0.11	0.14	-	-	-	0.05
0.22	0.22	0.21	0.21	0.21	0.22	0.22	0.21	0.50	0.16	0.20	0.74	0.22	0.22	0.58	0.17	0.18	0.18
0.57	0.56	0.57	0.57	0.55	0.57	0.58	0.59	0.51	0.70	0.59	0.46	0.56	0.55	0.49	0.67	0.60	0.64
4.33	4.27	4.34	4.27	4.31	4.32	4.29	4.28	3.97	4.44	4.28	3.49	4.27	4.28	3.73	4.56	4.28	4.45
0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.05	0.05	0.04	0.05	0.05	0.05
-	-	-	-	-	-	-	0.03	0.23	0.01	-	0.48	-	-	0.32	-	-	-
-	-	-	-	-	-	-	-	-	-	-	0.02	-	-	-	-	-	-
5.43	5.34	5.43	5.39	5.33	5.43	5.41	5.45	5.24	5.42	5.25	5.21	5.21	5.23	5.16	5.45	5.11	5.38
1.79	1.80	1.78	1.81	1.76	1.70	1.75	1.73	1.59	1.32	1.75	1.40	1.79	1.80	1.53	1.51	1.61	1.65
0.05	0.03	0.04	0.06	0.04	0.03	0.04	0.06	0.04	0.01	0.01	0.03	0.03	0.01	0.03	0.04	0.88	-
1.84	1.83	1.82	1.87	1.80	1.72	1.79	1.79	1.63	1.34	1.76	1.42	1.82	1.82	1.56	1.56	2.48	1.65
0.07	0.09	0.10	0.09	0.05	0.07	0.06	0.12	0.06	0.07	0.06	0.26	0.09	0.04	0.12	0.06	0.08	0.11
-	-	-	-	-	0.01	0.01	-	-	-	0.01	-	-	-	-	0.01	0.24	-
3.92	3.90	3.89	3.90	3.94	3.92	3.93	3.87	3.93	3.92	3.93	3.73	3.90	3.95	3.87	3.93	3.68	3.88
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
19.27	19.17	19.25	19.26	19.13	19.15	19.20	19.24	18.84	18.75	19.01	18.30	19.03	19.05	18.57	18.99	19.40	19.03

Appendix F-3b: Mica continued

108 Th Gr	109 Th Gr	110 Th Gr	111 Th Gr	112 Th Gr	113 Th Gr	114 Th Gr	115 Th Gr	116 Th Gr	117 Th Gr	118 Th Gr	119 Th Gr	120 Th Gr	121 Th Gr	122 Th Gr	123 Kg-Mn	124 Kg-Mn	125 Kg-Mn
32.64	31.20	42.65	32.53	33.93	32.01	32.66	33.35	31.98	33.47	33.89	31.50	31.81	32.99	33.57	45.47	45.46	40.91
1.52	1.28	1.68	2.05	1.88	2	2.01	1.71	1.52	1.81	1.82	1.44	1.50	1.69	1.65	0.13	0.04	0.03
14.31	14.21	13.22	15.64	15.59	15.49	15.58	14.92	14.93	14.92	14.84	14.22	14.33	14.25	14.30	30.27	27.38	24.64
2.57	3.06	2.02	2.41	2.29	2.38	2.36	2.47	2.71	2.37	2.29	2.86	2.73	2.41	2.32	2.01	1.69	2.56
BDL	BDL	BDL	BDL	0.03	BDL	BDL	BDL	BDL	BDL	0.02	0.01	0.03	0.02	0.04	BDL	0.11	0.08
0.41	0.42	0.25	0.29	0.24	0.29	0.27	0.32	0.31	0.32	0.29	0.34	0.33	0.34	0.28	0.13	0.16	0.16
32.90	34.01	28.25	30.99	30.07	32.01	31.33	32.93	34.65	32.83	32.56	35.19	34.14	32.78	31.91	7.76	12.92	17.10
0.09	0.11	0.12	0.13	0.23	0.19	0.07	0.11	0.02	0.11	BDL	0.08	0.12	0.26	0.24	0.03	0.16	0.06
8.18	6.46	7.37	9.02	8.17	8.57	8.86	8.32	7.04	8.75	8.69	6.46	6.88	8.19	8.04	10.82	9.40	8.43
0.20	0.06	0.09	0.19	0.01	0.04	0.12	BDL	0.09	0.09	0.12	0.22	0.08	0.04	0.10	0.39	0.28	0.09
0.03	0.03	0.01	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.01	0.02	0.02	0.02	BDL	0.02	0.06
0.01	BDL	BDL	0.01	BDL	BDL	BDL	BDL	BDL	BDL	BDL	0.01	BDL	BDL	BDL	0.04	0.02	BDL
3.46	3.44	3.86	3.51	3.60	3.54	3.54	3.61	3.52	3.59	3.58	3.42	3.47	3.54	3.52	4.22	4.21	4.02
96.31	94.27	99.52	96.79	96.06	96.54	96.84	97.77	96.81	98.27	98.13	95.76	95.45	96.51	96	101.27	101.84	98.13
0.09	0.03	0.04	0.08	0.01	0.02	0.05	0.01	0.04	0.04	0.05	0.09	0.04	0.02	0.05	0.17	0.12	0.05
96.22	94.24	99.48	96.70	96.05	96.52	96.78	97.76	96.76	98.23	98.08	95.67	95.41	96.49	95.96	101.10	101.72	98.08
5.31	5.08	6.94	5.29	5.52	5.21	5.31	5.42	5.20	5.44	5.51	5.12	5.17	5.37	5.46	6.81	6.81	6.13
2.69	2.72	1.06	2.71	2.48	2.79	2.69	2.58	2.80	2.56	2.49	2.73	2.75	2.63	2.54	1.19	1.19	1.87
-	0.20	-	-	-	-	-	-	-	-	-	0.15	0.08	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
0.05	-	1.47	0.29	0.51	0.18	0.30	0.29	0.06	0.30	0.36	-	-	0.10	0.20	4.16	3.65	2.48
0.19	0.16	0.21	0.25	0.23	0.24	0.25	0.21	0.19	0.22	0.22	0.18	0.18	0.21	0.20	0.01	-	-
0.62	0.74	0.49	0.59	0.55	0.58	0.57	0.60	0.66	0.57	0.56	0.69	0.66	0.59	0.56	0.45	0.38	0.57
4.48	4.63	3.84	4.22	4.09	4.35	4.26	4.48	4.71	4.47	4.43	4.79	4.64	4.46	4.34	0.97	1.62	2.14
0.06	0.06	0.03	0.04	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.04	0.02	0.02	0.02
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.02	0.01
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01	-	-
5.39	5.58	6.04	5.38	5.42	5.39	5.42	5.62	5.66	5.61	5.61	5.70	5.54	5.40	5.35	5.61	5.68	5.23
1.70	1.34	1.53	1.87	1.69	1.78	1.84	1.73	1.46	1.82	1.80	1.34	1.43	1.70	1.67	2.07	1.80	1.61
0.03	0.03	0.04	0.04	0.07	0.06	0.02	0.03	-	0.03	-	0.03	0.04	0.08	0.08	-	0.05	0.02
1.73	1.37	1.57	1.91	1.77	1.84	1.86	1.76	1.47	1.85	1.80	1.37	1.47	1.78	1.75	2.08	1.84	1.63
0.10	0.03	0.04	0.10	-	0.02	0.06	-	0.05	0.05	0.06	0.11	0.04	0.02	0.05	0.19	0.13	0.04
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.02
3.89	3.96	3.95	3.90	3.99	3.97	3.93	3.99	3.95	3.95	3.93	3.89	3.95	3.97	3.94	3.81	3.86	3.94
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
19.12	18.76	19.61	19.29	19.19	19.23	19.28	19.38	19.13	19.46	19.41	18.92	18.93	19.18	19.10	19.69	19.53	18.86

Appendix F-3b: Mica continued

126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143
Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn
34.36	33.56	33.42	33.44	34.24	34.50	33.02	32.37	34.25	32.33	34.31	31.67	32.97	33.56	36.98	43.47	43.46	38.91
1.90	1.84	1.67	1.81	1.93	1.82	1.56	1.37	1.91	1.36	1.88	1.36	1.24	1.53	2.11	0.13	0.04	0.03
16.96	17.41	17.22	16.85	17.01	16.84	16.78	16.78	17.13	17.07	17.09	17.51	17.03	17.50	16.34	30.27	27.38	24.64
6.22	6.50	6.61	6.34	5.94	6.92	6.89	7.14	5.97	6.69	6.24	6.80	6.66	6.99	6.80	2.01	1.69	2.56
BDL	0.02	0.01	0.06	0.03	0.04	0.07	0.08	0.06	0.05	0.04	0.05	0.13	0.03	0.33	BDL	0.11	0.08
0.17	0.19	0.17	0.19	0.13	0.16	0.20	0.18	0.16	0.18	0.16	0.20	0.17	0.18	0.15	0.13	0.16	0.16
29.61	30.41	30.42	30.14	30.21	28.62	30.77	31.42	29.64	31.56	29.19	32.01	32.19	31.10	26.79	7.76	12.92	17.10
0.03	0.04	0.02	0.03	BDL	BDL	0.05	0.05	BDL	0.05	0.02	0.02	0.06	0.05	BDL	0.03	0.16	0.06
9.10	8.62	7.87	8.53	8.95	8.74	7.46	6.71	8.96	6.73	8.83	6.25	5.56	6.42	7.20	10.82	9.40	8.43
0.83	0.67	0.73	0.62	0.34	0.69	0.73	0.39	0.67	0.45	0.68	0.53	0.26	0.61	0.65	0.39	0.28	0.09
0.07	0.10	0.08	0.10	0.10	0.06	0.08	0.08	0.09	0.09	0.09	0.08	0.06	0.08	0.06	BDL	0.02	0.06
0.13	0.09	0.11	0.08	0.03	0.10	0.11	0.04	0.09	0.05	0.09	0.06	0.02	0.08	0.09	0.04	0.02	BDL
3.54	3.59	3.54	3.56	3.71	3.59	3.51	3.60	3.58	3.58	3.58	3.54	3.67	3.60	3.66	4.12	4.11	3.91
102.92	103.03	101.87	101.75	102.61	102.08	101.22	100.20	102.50	100.19	102.21	100.10	100.02	101.74	101.16	99.17	99.73	96.03
0.36	0.30	0.33	0.28	0.16	0.30	0.33	0.18	0.30	0.21	0.31	0.24	0.12	0.28	0.29	0.17	0.12	0.05
102.55	102.73	101.54	101.46	102.45	101.77	100.89	100.02	102.20	99.98	101.90	99.85	99.90	101.46	100.87	99	99.61	95.97
5.15	5.03	5.01	5.01	5.13	5.17	4.95	4.85	5.13	4.84	5.14	4.75	4.94	5.03	5.54	6.51	6.51	5.83
2.85	2.97	2.99	2.98	2.87	2.83	2.96	2.96	2.87	3.01	2.86	3.09	3.01	2.97	2.46	1.49	1.49	2.17
-	-	-	0.01	-	-	0.09	0.19	-	0.14	-	0.16	0.05	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
0.14	0.10	0.05	-	0.13	0.14	-	-	0.16	-	0.16	-	-	0.12	0.43	3.86	3.35	2.18
0.21	0.21	0.19	0.20	0.22	0.21	0.18	0.15	0.21	0.15	0.21	0.15	0.14	0.17	0.24	0.01	-	-
1.39	1.45	1.48	1.42	1.33	1.55	1.54	1.59	1.33	1.50	1.39	1.52	1.49	1.56	1.52	0.45	0.38	0.57
3.71	3.81	3.81	3.78	3.79	3.59	3.86	3.94	3.71	3.96	3.66	4.01	4.03	3.90	3.36	0.97	1.62	2.14
0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
-	-	-	0.01	-	-	0.01	0.01	0.01	-	-	-	0.02	-	0.05	-	0.02	0.01
0.04	0.03	0.03	0.02	-	0.03	0.03	0.01	0.03	0.01	0.03	0.02	-	0.02	0.03	0.01	-	-
5.48	5.60	5.55	5.43	5.49	5.51	5.61	5.72	5.45	5.63	5.45	5.72	5.70	5.78	5.61	5.31	5.38	4.93
1.74	1.65	1.50	1.63	1.71	1.67	1.43	1.28	1.71	1.29	1.69	1.19	1.06	1.23	1.38	2.07	1.80	1.61
-	0.01	-	-	-	-	0.01	0.01	-	0.01	-	-	0.02	0.01	-	-	0.05	0.02
1.75	1.66	1.51	1.64	1.71	1.67	1.44	1.30	1.71	1.30	1.69	1.20	1.08	1.24	1.38	2.08	1.84	1.63
0.39	0.32	0.35	0.29	0.16	0.33	0.35	0.19	0.32	0.21	0.32	0.25	0.12	0.29	0.31	0.19	0.13	0.04
0.02	0.03	0.02	0.02	0.03	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	-	-	0.02
3.59	3.66	3.63	3.68	3.81	3.66	3.63	3.79	3.66	3.77	3.66	3.73	3.86	3.69	3.68	3.81	3.86	3.94
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
19.23	19.26	19.06	19.06	19.20	19.18	18.96	18.83	19.16	18.80	19.14	18.76	18.73	19.02	18.99	19.39	19.23	18.56

Appendix F-3b: Mica continued

144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161
Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn	Kg-Mn
32.36	31.56	31.42	31.44	32.24	32.50	31.02	30.37	33.52	32.25	30.33	32.31	29.67	30.97	34.15	35.52	35.32	33.19
1.90	1.84	1.67	1.81	1.93	1.82	1.56	1.37	1.98	1.91	1.36	1.88	1.36	1.24	2.06	1.63	1.77	2.09
16.96	17.41	17.22	16.85	17.01	16.84	16.78	16.78	17.05	17.13	17.07	17.09	17.51	17.03	16.69	17.27	17.51	16.95
6.22	6.50	6.61	6.34	5.94	6.92	6.89	7.14	6.37	5.97	6.69	6.24	6.80	6.66	6.22	6.02	5.82	5.66
BDL	0.02	0.01	0.06	0.03	0.04	0.07	0.08	BDL	0.06	0.05	0.04	0.05	0.13	0.03	0.15	0.11	0.02
0.17	0.19	0.17	0.19	0.13	0.16	0.20	0.18	0.17	0.16	0.18	0.16	0.20	0.17	0.20	0.20	0.20	0.16
29.61	30.41	30.42	30.14	30.21	28.62	30.77	31.42	28.54	29.64	31.56	29.19	32.01	32.19	28.81	27.75	28.01	29.54
0.03	0.04	0.02	0.03	BDL	BDL	0.05	0.05	BDL	BDL	0.05	0.02	0.02	0.06	BDL	0.07	0.06	BDL
9.10	8.62	7.87	8.53	8.95	8.74	7.46	6.71	9.62	8.96	6.73	8.83	6.25	5.56	9.12	8.34	8.30	9.48
0.83	0.67	0.73	0.62	0.34	0.69	0.73	0.39	0.70	0.67	0.45	0.68	0.53	0.26	0.77	0.61	0.60	0.71
0.07	0.10	0.08	0.10	0.10	0.06	0.08	0.08	0.08	0.09	0.09	0.09	0.08	0.06	0.07	0.05	0.07	0.13
0.13	0.09	0.11	0.08	0.03	0.10	0.11	0.04	0.10	0.09	0.05	0.09	0.06	0.02	0.12	0.08	0.08	0.10
3.44	3.49	3.44	3.46	3.61	3.49	3.41	3.50	3.54	3.48	3.48	3.48	3.44	3.57	3.52	3.63	3.63	3.50
100.82	100.93	99.77	99.65	100.51	99.98	99.12	98.10	101.66	100.40	98.08	100.11	97.99	97.92	101.77	101.31	101.47	101.53
0.36	0.30	0.33	0.28	0.16	0.30	0.33	0.18	0.31	0.30	0.21	0.31	0.24	0.12	0.34	0.27	0.27	0.33
100.46	100.63	99.45	99.36	100.34	99.67	98.80	97.91	101.35	100.10	97.88	99.80	97.75	97.79	101.43	101.05	101.20	101.21
4.85	4.73	4.71	4.71	4.83	4.87	4.65	4.55	5.02	4.83	4.54	4.84	4.45	4.64	5.12	5.32	5.29	4.97
3	3.07	3.04	2.98	3	2.97	2.96	2.96	2.98	3.02	3.01	3.02	3.09	3.01	2.88	2.68	2.71	2.99
0.16	0.20	0.25	0.31	0.17	0.15	0.39	0.49	-	0.14	0.44	0.14	0.46	0.35	-	-	-	0.03
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
-	-	-	-	-	-	-	-	0.03	-	-	-	-	-	0.07	0.37	0.39	-
0.21	0.21	0.19	0.20	0.22	0.21	0.18	0.15	0.22	0.21	0.15	0.21	0.15	0.14	0.23	0.18	0.20	0.24
1.39	1.45	1.48	1.42	1.33	1.55	1.54	1.59	1.42	1.33	1.50	1.39	1.52	1.49	1.39	1.34	1.30	1.27
3.71	3.81	3.81	3.78	3.79	3.59	3.86	3.94	3.58	3.71	3.96	3.66	4.01	4.03	3.61	3.48	3.51	3.70
0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
-	-	-	0.01	-	-	0.01	0.01	-	0.01	-	-	-	0.02	-	0.02	0.02	-
0.04	0.03	0.03	0.02	-	0.03	0.03	0.01	0.03	0.03	0.01	0.03	0.02	-	0.04	0.02	0.02	0.03
5.34	5.50	5.50	5.43	5.35	5.36	5.61	5.72	5.28	5.29	5.63	5.29	5.72	5.70	5.33	5.43	5.44	5.23
1.74	1.65	1.50	1.63	1.71	1.67	1.43	1.28	1.84	1.71	1.29	1.69	1.19	1.06	1.74	1.59	1.59	1.81
-	0.01	-	-	-	-	0.01	0.01	-	-	0.01	-	-	0.02	-	0.02	0.02	-
1.75	1.66	1.51	1.64	1.71	1.67	1.44	1.30	1.84	1.71	1.30	1.69	1.20	1.08	1.74	1.61	1.60	1.81
0.39	0.32	0.35	0.29	0.16	0.33	0.35	0.19	0.33	0.32	0.21	0.32	0.25	0.12	0.37	0.29	0.28	0.34
0.02	0.03	0.02	0.02	0.03	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.03
3.59	3.66	3.63	3.68	3.81	3.66	3.63	3.79	3.65	3.66	3.77	3.66	3.73	3.86	3.61	3.70	3.70	3.63
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
18.93	18.96	18.76	18.76	18.90	18.88	18.66	18.53	19.12	18.86	18.50	18.84	18.46	18.43	19.07	19.04	19.04	19.01

Appendix F-3b: Mica continued

162 Kg-Mn	163 Kg-Mn	164 Kg-Mn	165 Kg-Mn	166 Kg-Mg	167 Kg-Mg	168 Kg-Mg	169 Kg-Mg	170 Kg-Mg	171 Kg-Mg	172 Kg-Mg
31.56	32.33	34.98	36.11	32.79	39.09	41.46	39.86	37.60	44.04	36.64
1.53	2	2.11	1.50	0.61	0.16	0.24	0.29	0.12	0.66	0.17
17.50	17.25	16.34	17.13	22.05	16.79	26.69	23.88	23.52	30.36	15.56
6.99	6.15	6.80	7.07	3.41	1.10	1.86	2.97	3.91	1.23	4.73
0.03	0.04	0.33	0.03	BDL	0.09	0.05	0.05	0.02	0.23	0.10
0.18	0.19	0.15	0.16	0.16	0.07	0.07	0.08	0.18	BDL	0.12
31.10	30.08	26.79	28.75	18.07	18.33	6.40	10.84	14.63	5.91	22.70
0.05	BDL	BDL	0.07	0.07	0.25	0.20	0.11	0.11	BDL	BDL
6.42	8	7.20	6.97	9.05	10.25	10.78	9.20	7.95	11.24	5.98
0.61	0.66	0.65	0.63	0.15	0.14	0.24	0.38	0.38	0.59	0.17
0.08	0.09	0.06	0.03	0.05	BDL	BDL	BDL	BDL	BDL	0.04
0.08	0.09	0.09	0.08	0.03	0.03	0.06	0.11	0.11	0.20	0.04
3.50	3.50	3.56	3.68	3.52	3.54	3.87	3.71	3.67	4	3.50
99.64	100.39	99.06	102.19	89.97	89.84	91.92	91.50	92.19	98.48	89.75
0.28	0.30	0.29	0.27	0.07	0.06	0.10	0.16	0.16	0.25	0.08
99.36	100.09	98.77	101.92	89.89	89.78	91.82	91.34	92.03	98.23	89.67
4.73	4.85	5.24	5.41	5.45	6.50	6.90	6.63	6.25	7.33	6.09
3.09	3.05	2.76	2.59	2.55	1.50	1.10	1.37	1.75	0.67	1.91
0.18	0.11	-	-	-	-	-	-	-	-	-
8	8	8	8	8	8	8	8	8	8	8
-	-	0.13	0.44	1.78	1.79	4.13	3.31	2.86	5.28	1.14
0.17	0.23	0.24	0.17	0.08	0.02	0.03	0.04	0.02	0.08	0.02
1.56	1.37	1.52	1.58	0.85	0.27	0.46	0.74	0.97	0.31	1.17
3.90	3.77	3.36	3.60	2.51	2.55	0.89	1.51	2.04	0.82	3.16
0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.02	-	0.02
-	-	0.05	-	-	0.02	-	0.01	-	0.04	0.02
0.02	0.03	0.03	0.02	0.01	0.01	0.02	0.04	0.04	0.07	0.01
5.66	5.40	5.31	5.81	5.24	4.66	5.53	5.61	5.91	6.53	5.53
1.23	1.53	1.38	1.33	1.92	2.17	2.29	1.95	1.69	2.39	1.27
0.01	-	-	0.02	0.02	0.08	0.06	0.04	0.04	-	-
1.24	1.53	1.38	1.35	1.94	2.25	2.35	1.99	1.72	2.39	1.27
0.29	0.31	0.31	0.30	0.08	0.07	0.13	0.20	0.20	0.31	0.09
0.02	0.02	0.01	-	0.01	-	-	-	-	-	0.01
3.69	3.66	3.68	3.70	3.91	3.92	3.87	3.80	3.80	3.69	3.90
4	4	4	4	4	4	4	4	4	4	4
18.72	18.82	18.69	19.16	19.19	18.92	19.88	19.60	19.63	20.91	18.80

**Stoichiometrically calculated; **Calculated according to Tischendorf et al. (1997).*

Abbreviations: Thamaga Granite (Th Gr); Kgale Granite – Main Phase (Kg-Mn); Kgale Granite – Marginal Phase (Kg-Mg); and Below Detection Limit (BDL).

Appendix F-4a: Chlorite EPMA compositions from the Lebowa Granite Suite.

# Granite	1 NG	2 NG	3 NG	4 NG	5 NG	6 NG	7 NG	8 NG	9 NG	10 NG	11 NG	12 NG	13 NG	14 NG	15 NG	16 NG	17 NG	18 NG	19 NG
SiO ₂	30.16	30.36	29.90	31.23	32	29.27	31.44	30.74	29.19	30.03	34.29	31.48	31.91	31.96	33.06	34.06	32.28	30.15	29.72
TiO ₂	0.65	1.08	0.69	1.25	1.30	0.08	0.09	0.40	0.75	1.54	0.19	2.31	0.15	0.19	0.18	0.23	0.73	0.90	0.40
Al ₂ O ₃	15.14	13.61	14.42	13.30	13.12	13.35	12.87	13.46	14.10	14.05	12.34	12.95	13.35	13.33	12.99	12.32	12.83	13.20	14.04
MgO	2.48	1.43	1.87	1.64	1.80	1.85	2.11	2.40	2.87	2.09	3.40	3.64	3.92	3.93	3.63	3.53	1.89	2.43	2.81
CaO	0.18	0.05	0.07	0.03	0.06	0.08	0.07	0.09	0.09	0.05	0.18	1.79	0.12	0.11	0.13	0.22	0.05	0.15	0.07
MnO	0.37	0.57	0.38	0.52	0.50	0.57	0.55	0.68	0.57	0.48	0.61	0.62	0.57	0.62	0.60	0.53	0.57	0.45	0.61
FeO	33.94	35.69	33.87	34.17	33.92	37.49	35.91	35.29	35.18	35.10	33.23	33.21	34.35	34.54	34.37	33.03	34.55	34.25	35.81
Na ₂ O	0.13	BDL	0.13	0.11	0.23	0.18	0.09	0.14	0.10	0.11	0.15	BDL	BDL	0.17	0.01	0.01	0.07	0.10	0.22
K ₂ O	2.27	2.44	3.46	4	3.95	2.02	3.06	0.95	1.69	3.08	1.10	1.29	1.21	1.12	1.37	1.19	3.20	3.75	1.05
F	0.06	BDL	0.07	BDL	0.02	BDL	0.09	BDL	0.02	BDL	BDL	BDL	0.16	0.11	0.06	BDL	0.05	BDL	BDL
Cl	0.42	0.43	0.82	0.85	0.73	0.59	0.66	0.08	0.30	0.48	0.09	0.17	0.10	0.11	0.14	0.10	0.74	0.89	0.23
H ₂ O*	10.21	10.11	9.83	10.04	10.20	9.85	10	10.27	10.10	10.23	10.67	10.69	10.38	10.47	10.59	10.62	10.10	9.87	10.21
Total	96.01	95.77	95.49	97.15	97.83	95.31	96.94	94.51	94.96	97.25	96.25	98.15	96.22	96.64	97.12	95.84	97.05	96.14	95.16
O=F,Cl	0.12	0.10	0.21	0.19	0.17	0.13	0.19	0.02	0.08	0.11	0.02	0.04	0.09	0.07	0.06	0.02	0.19	0.20	0.05
Total	95.89	95.68	95.27	96.96	97.66	95.17	96.75	94.49	94.88	97.14	96.23	98.11	96.13	96.57	97.07	95.82	96.86	95.94	95.11
Cations Proportions Based on 28 Oxygens (apfu)																			
Tetrahedral Site																			
Si	6.86	6.90	6.80	7.10	7.28	6.66	7.15	6.99	6.64	6.83	7.80	7.16	7.26	7.27	7.52	7.75	7.34	6.86	6.76
AlIV	1.14	1.10	1.20	0.90	0.72	1.34	0.85	1.01	1.36	1.17	0.20	0.84	0.74	0.73	0.48	0.25	0.66	1.14	1.24
Z Sum	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Octahedral Site																			
AlVI	2.92	2.55	2.66	2.67	2.79	2.23	2.60	2.60	2.42	2.60	3.11	2.63	2.83	2.84	3	3.05	2.78	2.39	2.52
Ti	0.11	0.18	0.12	0.21	0.22	0.01	0.01	0.07	0.13	0.26	0.03	0.40	0.03	0.03	0.03	0.04	0.12	0.15	0.07
Mg	0.84	0.49	0.63	0.56	0.61	0.63	0.71	0.81	0.97	0.71	1.15	1.24	1.33	1.33	1.23	1.20	0.64	0.82	0.95
Fe ^{tot}	6.45	6.79	6.44	6.50	6.45	7.13	6.83	6.71	6.69	6.67	6.32	6.32	6.53	6.57	6.54	6.28	6.57	6.51	6.81
Mn	0.07	0.11	0.07	0.10	0.10	0.11	0.10	0.13	0.11	0.09	0.12	0.12	0.11	0.12	0.11	0.10	0.11	0.09	0.12
Ca	0.04	0.01	0.02	-	0.01	0.02	0.02	0.02	0.02	0.01	0.04	0.44	0.03	0.03	0.03	0.05	0.01	0.04	0.02
□*	1.56	1.87	2.06	1.95	1.81	1.87	1.72	1.65	1.66	1.65	1.23	0.87	1.14	1.08	1.06	1.28	1.76	1.99	1.51
Y Sum	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Interlayer																			
K	0.66	0.71	1	1.16	1.15	0.59	0.89	0.27	0.49	0.89	0.32	0.37	0.35	0.32	0.40	0.34	0.93	1.09	0.30
Na	0.06	-	0.06	0.05	0.10	0.08	0.04	0.06	0.04	0.05	0.07	-	-	0.07	-	-	0.03	0.04	0.10
X Sum	0.72	0.71	1.06	1.21	1.25	0.66	0.93	0.34	0.54	0.94	0.38	0.37	0.35	0.40	0.40	0.35	0.96	1.13	0.40
Anion Site																			
F	0.04	-	0.05	-	0.01	-	0.07	-	0.02	-	-	-	0.12	0.08	0.04	-	0.04	-	-
Cl	0.16	0.16	0.31	0.33	0.28	0.23	0.25	0.03	0.12	0.19	0.03	0.06	0.04	0.04	0.05	0.04	0.28	0.34	0.09
OH*	15.80	15.84	15.64	15.67	15.70	15.77	15.68	15.97	15.87	15.81	15.97	15.94	15.84	15.88	15.90	15.96	15.68	15.66	15.91
A Sum	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Sum	36.72	36.71	37.06	37.21	37.25	36.66	36.93	36.34	36.54	36.94	36.38	36.37	36.35	36.40	36.40	36.35	36.96	37.13	36.40

*Stoichiometrically calculated. Abbreviations: Nebo Granite (NG); Bobbejaankop Granite (BG); Lease Granite (LG); and Below Detection Limit (BDL).

Appendix F-4a: Chlorite continued

20 NG	21 NG	22 NG	23 NG	24 NG	25 NG	26 NG	27 NG	28 NG	29 NG	30 NG	31 NG	32 NG	33 NG	34 NG	35 NG	36 NG	37 NG	38 NG	39 NG	40 NG
31.27	31.45	31.66	32.37	31.27	31.49	31.11	35.45	33.23	32.10	32.04	32.72	29.28	31.07	30.91	30.51	29.95	31.43	31.72	30.43	31.02
1.02	1.02	2.59	2.18	1.72	1.57	0.60	0.46	0.71	0.33	0.14	0.09	0.08	0.23	1.29	0.06	0.07	0.07	0.10	0.66	0.49
13.31	13.15	13.13	14.12	13.72	13.23	13.52	10.85	11.72	12.50	12.11	12.05	13.09	12.63	12.92	13.39	12.95	12.35	12.59	13	12.25
1.78	2	2.13	3.04	1.97	3.72	3.65	2.47	2.46	1.29	1.14	1.62	1.09	1.44	1.48	2.43	1.77	1.52	1.48	1.91	2.25
0.09	0.08	0.90	0.09	0.09	1.05	0.13	0.21	0.18	0.14	0.13	0.15	0.17	0.11	0.09	0.18	0.11	0.12	0.18	0.08	0.12
0.52	0.46	0.47	0.38	0.51	0.53	0.53	0.48	0.38	0.56	0.57	0.70	0.62	0.68	0.37	0.56	0.63	0.64	0.59	0.55	0.65
35.40	33.71	33.70	32.53	33.60	33	33.86	31.23	31.95	34	34.77	34.83	37.38	35.89	34.68	34.58	35.81	34.69	34.21	34.67	34.17
0.17	0.32	0.17	0.23	0.09	0.09	0.11	0.09	0.12	0.20	0.21	0.19	0.12	0.32	0.19	0.10	0.06	0.34	0.38	0.05	0.31
3.58	4.63	4.71	5.11	3.73	1.25	1.94	3.47	4.34	4.40	4.63	2.10	1.91	2	5.11	2.58	2.61	3.17	3.57	3.64	2.54
BDL	0.09	0.05	0.19	BDL	0.04	0.08	0.04	BDL	0.04	BDL	0.09	0.02	0.03	BDL	BDL	0.03	0.03	0.04	BDL	BDL
0.81	1.06	0.87	1.05	0.75	0.21	0.37	0.18	0.69	1.41	1.69	0.67	0.86	0.69	1.64	0.88	0.95	1.07	1.12	1.17	0.75
10.13	9.90	10.35	10.34	10.21	10.51	10.26	10.46	10.12	9.63	9.49	9.93	9.56	9.86	9.64	9.83	9.61	9.66	9.70	9.67	9.82
98.07	97.87	100.73	101.63	97.67	96.70	96.16	95.39	95.89	96.60	96.91	95.12	94.19	94.96	98.32	95.09	94.55	95.07	95.69	95.83	94.36
0.18	0.28	0.22	0.32	0.17	0.06	0.12	0.06	0.16	0.34	0.38	0.19	0.20	0.17	0.37	0.20	0.22	0.25	0.27	0.27	0.17
97.88	97.59	100.51	101.31	97.50	96.64	96.04	95.33	95.74	96.27	96.53	94.93	93.99	94.79	97.95	94.89	94.33	94.82	95.42	95.56	94.19
7.11	7.15	7.20	7.36	7.11	7.16	7.08	8.06	7.56	7.30	7.29	7.44	6.66	7.07	7.03	6.94	6.81	7.15	7.21	6.92	7.05
0.89	0.85	0.80	0.64	0.89	0.84	0.92	-	0.44	0.70	0.71	0.56	1.34	0.93	0.97	1.06	1.19	0.85	0.79	1.08	0.95
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.68	2.68	2.72	3.15	2.79	2.71	2.70	2.97	2.70	2.65	2.53	2.67	2.17	2.45	2.49	2.53	2.28	2.46	2.59	2.40	2.34
0.17	0.17	0.44	0.37	0.29	0.27	0.10	0.08	0.12	0.06	0.02	0.02	0.01	0.04	0.22	0.01	0.01	0.01	0.02	0.11	0.08
0.60	0.68	0.72	1.03	0.67	1.26	1.24	0.84	0.83	0.44	0.39	0.55	0.37	0.49	0.50	0.82	0.60	0.52	0.50	0.65	0.76
6.73	6.41	6.41	6.19	6.39	6.28	6.44	5.94	6.08	6.47	6.61	6.62	7.11	6.83	6.60	6.58	6.81	6.60	6.51	6.59	6.50
0.10	0.09	0.09	0.07	0.10	0.10	0.10	0.09	0.07	0.11	0.11	0.13	0.12	0.13	0.07	0.11	0.12	0.12	0.11	0.11	0.13
0.02	0.02	0.22	0.02	0.02	0.26	0.03	0.05	0.04	0.03	0.03	0.04	0.04	0.03	0.02	0.04	0.03	0.03	0.04	0.02	0.03
1.69	1.95	1.40	1.17	1.74	1.13	1.39	2.03	2.15	2.25	2.30	1.97	2.18	2.04	2.09	1.91	2.15	2.27	2.23	2.12	2.16
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
1.04	1.34	1.37	1.48	1.08	0.36	0.56	1.01	1.26	1.28	1.34	0.61	0.55	0.58	1.48	0.75	0.76	0.92	1.04	1.05	0.74
0.07	0.14	0.07	0.10	0.04	0.04	0.05	0.04	0.05	0.09	0.09	0.08	0.05	0.14	0.08	0.05	0.03	0.15	0.17	0.02	0.14
1.11	1.48	1.44	1.58	1.12	0.40	0.61	1.04	1.31	1.36	1.44	0.69	0.61	0.72	1.57	0.80	0.79	1.07	1.20	1.08	0.87
-	0.07	0.04	0.14	-	0.03	0.06	0.03	-	0.03	-	0.07	0.01	0.02	-	-	0.02	0.02	0.03	-	-
0.31	0.41	0.33	0.41	0.29	0.08	0.14	0.07	0.27	0.54	0.65	0.26	0.33	0.27	0.63	0.34	0.37	0.41	0.43	0.45	0.29
15.69	15.52	15.63	15.46	15.71	15.89	15.80	15.90	15.73	15.43	15.35	15.68	15.65	15.72	15.37	15.66	15.62	15.57	15.54	15.55	15.71
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
37.11	37.48	37.44	37.58	37.12	36.40	36.61	37.04	37.31	37.36	37.44	36.69	36.61	36.72	37.57	36.80	36.79	37.07	37.20	37.08	36.87

Appendix F-4a: Chlorite continued

41 NG	42 NG	43 NG	44 NG	45 NG	46 NG	47 NG	48 NG	49 NG	50 NG	51 NG	52 NG	53 NG	54 NG	55 NG	56 NG	57 NG	58 NG	59 NG	60 NG	61 NG
32.27	30.63	30.50	32.12	31.05	30.90	29.57	33.72	31.55	32.36	32.22	30.10	30.86	32.21	31.26	31.56	31.54	32.09	30.60	29.52	28.28
0.81	0.07	0.03	0.21	0.03	0.08	0.58	0.06	0.03	0.03	0.40	0.28	0.36	0.40	0.29	0.39	0.35	0.46	0.28	0.29	0.26
12.70	13.07	12.52	12.38	12.76	12.42	13.18	12.21	13.09	12.58	12.37	13.50	12.64	12.26	12.58	12.42	12.43	12.11	12.52	12.97	13.97
2.12	2.74	2.39	3.54	2.01	2.16	2.30	0.76	0.77	0.63	0.90	1.78	1.08	0.94	2.17	1.90	1.35	1.08	1.14	1.15	2.86
0.11	0.08	0.15	0.20	0.11	0.14	0.10	0.09	0.06	0.07	0.06	0.06	0.07	0.05	0.11	0.11	0.19	0.14	0.20	0.10	0.08
0.70	0.60	0.66	0.66	0.64	0.66	0.57	0.55	0.64	0.58	0.58	0.67	0.63	0.57	0.62	0.55	0.50	0.57	0.65	0.63	0.61
34.94	34.71	33.93	34.45	35.08	35.26	34.80	34.20	36.42	34.63	34.10	35.21	35.42	34.44	33.94	33.70	34.62	33.54	35.50	36.65	36.73
0.19	0.08	0.12	0.14	0.46	0.51	0.24	0.18	0.18	0.23	BDL	0.19	0.19	0.28	0.19	0.17	0.55	0.11	0.23	0.15	0.12
3.24	2.73	3.13	1.57	2.47	2.29	2.29	4.12	3.64	5.13	5.37	2.88	3.92	4.88	3.20	3.71	4.34	5.18	3.17	2.27	1.16
0.06	BDL	0.13	0.03	BDL	BDL	BDL	0.09	0.13	0.09	0.09	0.05	BDL	BDL	BDL	BDL	BDL	0.13	0.10	0.08	0.06
0.95	1.01	1.13	0.38	0.82	0.75	0.73	1.38	1.28	1.85	1.84	0.94	1.21	1.58	0.97	1.23	1.37	1.65	1.07	0.72	0.38
10.07	9.79	9.44	10.27	9.86	9.85	9.76	9.73	9.63	9.41	9.39	9.71	9.62	9.59	9.78	9.66	9.66	9.38	9.52	9.60	9.87
98.15	95.53	94.12	95.95	95.30	95.03	94.11	97.09	97.42	97.59	97.34	95.37	95.98	97.21	95.12	95.41	96.89	96.41	94.96	94.12	94.40
0.24	0.23	0.31	0.10	0.18	0.17	0.16	0.35	0.34	0.45	0.45	0.23	0.27	0.36	0.22	0.28	0.31	0.43	0.28	0.20	0.11
97.91	95.30	93.81	95.85	95.12	94.86	93.94	96.75	97.08	97.14	96.89	95.14	95.71	96.85	94.90	95.13	96.58	95.99	94.68	93.92	94.28
7.34	6.97	6.94	7.30	7.06	7.03	6.73	7.67	7.18	7.36	7.33	6.84	7.02	7.32	7.11	7.18	7.17	7.30	6.96	6.71	6.43
0.66	1.03	1.06	0.70	0.94	0.97	1.27	0.33	0.82	0.64	0.67	1.16	0.98	0.68	0.89	0.82	0.83	0.70	1.04	1.29	1.57
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.74	2.47	2.29	2.62	2.48	2.36	2.26	2.94	2.68	2.73	2.64	2.46	2.41	2.61	2.48	2.51	2.50	2.54	2.32	2.19	2.18
0.14	0.01	-	0.04	-	0.01	0.10	0.01	-	-	0.07	0.05	0.06	0.07	0.05	0.07	0.06	0.08	0.05	0.05	0.05
0.72	0.93	0.81	1.20	0.68	0.73	0.78	0.26	0.26	0.21	0.31	0.60	0.37	0.32	0.74	0.64	0.46	0.37	0.39	0.39	0.97
6.65	6.60	6.45	6.55	6.67	6.71	6.62	6.50	6.93	6.59	6.49	6.70	6.74	6.55	6.45	6.41	6.58	6.38	6.75	6.97	6.99
0.13	0.12	0.13	0.13	0.12	0.13	0.11	0.11	0.12	0.11	0.11	0.13	0.12	0.11	0.12	0.11	0.10	0.11	0.13	0.12	0.12
0.03	0.02	0.04	0.05	0.03	0.03	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.03	0.03	0.05	0.03	0.05	0.03	0.02
1.59	1.85	2.28	1.41	2.01	2.03	2.11	2.16	1.99	2.33	2.37	2.04	2.29	2.33	2.13	2.24	2.26	2.49	2.33	2.26	1.69
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
0.94	0.79	0.91	0.46	0.72	0.67	0.66	1.20	1.06	1.49	1.56	0.84	1.14	1.41	0.93	1.08	1.26	1.50	0.92	0.66	0.34
0.08	0.04	0.05	0.06	0.20	0.22	0.10	0.08	0.08	0.10	-	0.09	0.08	0.12	0.09	0.07	0.24	0.05	0.10	0.07	0.05
1.03	0.83	0.96	0.52	0.92	0.89	0.77	1.28	1.14	1.59	1.56	0.92	1.22	1.54	1.01	1.15	1.50	1.55	1.02	0.73	0.39
0.04	-	0.10	0.02	-	-	-	0.06	0.09	0.06	0.06	0.03	-	-	-	-	-	0.09	0.07	0.06	0.04
0.37	0.39	0.43	0.15	0.31	0.29	0.28	0.53	0.49	0.71	0.71	0.36	0.47	0.61	0.37	0.47	0.53	0.64	0.41	0.28	0.15
15.59	15.61	15.47	15.83	15.69	15.71	15.72	15.41	15.42	15.22	15.23	15.60	15.53	15.39	15.63	15.52	15.47	15.27	15.52	15.66	15.81
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
37.03	36.83	36.96	36.52	36.92	36.89	36.77	37.28	37.14	37.59	37.56	36.92	37.22	37.54	37.01	37.15	37.50	37.55	37.02	36.73	36.39

Appendix F-4a: Chlorite continued

62 NG	63 NG	64 NG	65 NG	66 NG	67 NG	68 NG	69 NG	70 NG	71 NG	72 NG	73 NG	74 NG	75 NG	76 NG	77 NG	78 NG	79 NG	80 BG	81 BG	82 BG
30.70	30.67	32.19	31.36	30.49	29.39	27.95	30.65	30.74	30.52	32.40	29.18	26.74	31.38	30.86	32.11	29.06	31.57	23.59	25.68	24.25
0.16	0.27	0.26	0.30	0.25	2.09	1.52	1.15	0.70	0.90	1.15	0.83	0.72	1.91	1.46	1.44	0.19	1.09	0.15	0.02	BDL
12.46	12.79	12.28	12.69	13.58	13.22	13.98	12.54	13.10	13.18	12.66	14.31	15.62	13.43	13.64	13.06	13.97	13.27	20.21	19.62	20.61
1.85	1.26	1.05	1.08	2.81	2.51	2.81	1.67	2.64	2.33	2.14	3.07	2.96	2.14	1.96	1.54	2.57	1.90	1.70	2.16	2.02
0.09	0.10	0.09	0.06	0.07	1.20	0.22	0.03	0.12	0.32	0.03	0.11	0.07	0.19	0.05	0.04	0.06	0.03	0.02	0.04	0.01
0.65	0.67	0.68	0.57	0.62	0.60	0.49	0.41	0.57	0.69	0.72	0.54	0.57	0.48	0.51	0.58	0.55	0.69	0.41	0.39	0.38
35.13	35.66	34.60	34.82	34.18	34.29	34.32	34.61	33.53	34.94	34.85	34.52	36.54	34.64	34.33	33.87	37.11	34.17	43.07	39.85	41.18
0.41	0.22	0.08	0.25	0.33	0.10	0.08	BDL	BDL	0.15	0.12	BDL	BDL	0.17	0.06	BDL	0.07	0.05	0.06	0.09	0.23
2.70	2.58	3.86	4.36	1.70	1.41	2.38	5.45	2.98	1.26	2.69	1.60	1.02	4.21	3.27	3.94	1.28	2.53	0.06	0.59	0.50
BDL	0.09	0.04	BDL	0.07	0.12	0.06	BDL	0.06	0.08	0.12	0.11	BDL	0.06	0.08	BDL	0.07	0.05	0.03	BDL	0.08
0.87	0.81	1.26	1.49	0.51	0.26	0.67	1.26	0.67	0.13	0.37	0.28	0.17	0.72	0.56	0.74	0.36	0.40	0.02	0.02	0.02
9.73	9.68	9.65	9.56	9.98	10.09	9.73	9.71	9.92	10.16	10.31	10.03	10.05	10.30	10.13	10.19	9.98	10.21	10.06	9.88	10.13
94.75	94.80	96.05	96.54	94.58	95.28	94.21	97.48	95.03	94.66	97.55	94.58	94.46	99.64	96.91	97.51	95.26	95.94	99.38	98.34	99.41
0.20	0.22	0.30	0.34	0.14	0.11	0.18	0.28	0.18	0.06	0.14	0.11	0.04	0.19	0.16	0.17	0.11	0.11	0.02	-	0.04
94.56	94.57	95.75	96.20	94.44	95.18	94.04	97.20	94.85	94.60	97.42	94.47	94.42	99.45	96.75	97.34	95.15	95.83	99.36	98.34	99.37
6.98	6.97	7.32	7.13	6.93	6.68	6.36	6.97	6.99	6.94	7.37	6.64	6.08	7.14	7.02	7.30	6.61	7.18	5.40	5.88	5.55
1.02	1.03	0.68	0.87	1.07	1.32	1.64	1.03	1.01	1.06	0.63	1.36	1.92	0.86	0.98	0.70	1.39	0.82	2.60	2.12	2.45
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.32	2.40	2.61	2.53	2.57	2.23	2.10	2.33	2.50	2.47	2.76	2.47	2.27	2.74	2.67	2.80	2.35	2.74	2.85	3.17	3.12
0.03	0.05	0.05	0.05	0.04	0.36	0.26	0.20	0.12	0.15	0.20	0.14	0.12	0.33	0.25	0.25	0.03	0.19	0.03	-	-
0.63	0.43	0.36	0.36	0.95	0.85	0.95	0.57	0.90	0.79	0.73	1.04	1	0.72	0.67	0.52	0.87	0.65	0.58	0.74	0.69
6.68	6.78	6.58	6.62	6.50	6.52	6.53	6.58	6.38	6.64	6.63	6.57	6.95	6.59	6.53	6.44	7.06	6.50	8.25	7.63	7.89
0.13	0.13	0.13	0.11	0.12	0.12	0.10	0.08	0.11	0.13	0.14	0.10	0.11	0.09	0.10	0.11	0.11	0.13	0.08	0.07	0.07
0.02	0.02	0.02	0.02	0.02	0.29	0.05	-	0.03	0.08	-	0.03	0.02	0.05	0.01	0.01	0.01	-	-	0.01	-
2.20	2.19	2.25	2.30	1.79	1.63	2.01	2.24	1.97	1.73	1.54	1.65	1.53	1.48	1.77	1.87	1.57	1.79	0.21	0.37	0.23
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
0.78	0.75	1.12	1.27	0.49	0.41	0.69	1.58	0.86	0.37	0.78	0.46	0.30	1.22	0.95	1.14	0.37	0.73	0.02	0.17	0.14
0.18	0.10	0.04	0.11	0.15	0.05	0.04	-	-	0.07	0.05	-	-	0.08	0.02	-	0.03	0.02	0.03	0.04	0.10
0.96	0.84	1.16	1.38	0.64	0.46	0.73	1.58	0.86	0.43	0.83	0.46	0.30	1.30	0.97	1.14	0.40	0.75	0.04	0.21	0.25
-	0.07	0.03	-	0.05	0.08	0.04	-	0.04	0.06	0.09	0.08	-	0.04	0.06	-	0.05	0.03	0.02	-	0.06
0.34	0.31	0.49	0.57	0.20	0.10	0.26	0.49	0.26	0.05	0.14	0.11	0.07	0.28	0.21	0.28	0.14	0.15	-	-	-
15.66	15.62	15.49	15.43	15.76	15.82	15.70	15.51	15.70	15.89	15.77	15.81	15.93	15.68	15.73	15.72	15.81	15.81	15.97	15.99	15.93
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
36.96	36.84	37.16	37.38	36.64	36.46	36.73	37.58	36.86	36.43	36.83	36.46	36.30	37.30	36.97	37.14	36.40	36.75	36.04	36.21	36.25

Appendix F-4a: Chlorite continued

83 BG	84 BG	85 BG	86 BG	87 BG	88 BG	89 BG	90 BG	91 BG	92 BG	93 BG	94 BG	95 BG	96 BG	97 BG	98 BG	99 BG	100 BG	101 BG	102 BG	103 BG
21.39	23.88	23.28	24.13	22.62	30.82	26.72	27.32	27.09	25.47	26.63	27.24	23.85	26.86	24.12	25.88	25.14	27.27	26.64	26.63	25.43
0.04	0.07	0.07	0.06	0.07	0.13	0.26	0.04	0.03	0.89	0.71	0.87	1.82	2.44	0.99	1.90	2	0.34	1.12	0.15	0.16
20.05	20.40	20.32	19.56	20.49	21.80	18.58	19.39	19.74	17.54	18.18	17.75	18.30	16.83	17.82	17.13	17.71	20.15	17.67	19.27	20.05
2.09	2.46	2	2.14	1.74	2.93	3	3.57	3.36	1.92	1.87	1.59	1.34	1.36	1.54	1.74	1.74	1.11	1.32	1.69	1.58
0.01	BDL	0.02	0.03	0.01	0.16	0.17	0.16	0.11	0.07	0.07	0.07	0.05	0.04	0.05	0.05	0.06	0.08	0.03	0.06	0.05
0.38	0.40	0.43	0.37	0.43	0.40	0.55	0.52	0.48	0.43	0.43	0.39	0.43	0.48	0.42	0.46	0.37	0.40	0.43	0.43	0.39
43.52	42.05	42.46	43.50	42.13	28.85	38.59	36.86	38.21	41.71	40.83	41.55	40.65	40.33	41.86	40.79	41.32	38.26	42.28	39.92	37.62
BDL	BDL	0.16	0.05	0.01	0.02	0.34	0.09	BDL	0.08	BDL	0.13	BDL	BDL	0.03	0.11	BDL	0.04	BDL	0.10	0.09
0.01	0.02	0.27	0.01	0.35	2.73	0.11	0.06	0.12	0.09	0.10	0.19	0.51	0.16	0.37	0.24	0.20	1.27	0.16	0.21	1.34
0.10	0.04	0.06	BDL	BDL	0.11	BDL	BDL	0.03	BDL	0.09	0.09	0.08	0.10	0.08	BDL	0.06	0.05	0.05	0.05	0.05
0.03	0.02	BDL	0.03	0.03	0.04	0.04	0.03	0.02	0.31	0.24	0.31	0.19	0.33	0.24	0.34	0.28	0.08	0.34	0.12	0.11
10.01	10.16	10.20	10	10.27	11.11	9.95	10.08	10.13	9.92	9.73	9.78	10.07	9.64	10.02	9.96	9.93	10.33	9.89	9.84	10.33
97.65	99.51	99.29	99.87	98.16	99.09	98.32	98.13	99.32	98.43	98.89	99.96	97.28	98.56	97.53	98.62	98.82	99.38	99.96	98.47	97.20
0.05	0.02	0.03	0.01	0.01	0.06	0.01	0.01	0.02	0.07	0.09	0.11	0.08	0.11	0.09	0.08	0.09	0.04	0.10	0.05	0.04
97.60	99.49	99.26	99.86	98.15	99.03	98.31	98.12	99.30	98.36	98.80	99.85	97.21	98.45	97.44	98.54	98.73	99.34	99.86	98.42	97.16
4.90	5.47	5.33	5.52	5.18	7.06	6.12	6.26	6.20	5.83	6.10	6.24	5.46	6.15	5.52	5.93	5.76	6.24	6.10	6.10	5.82
3.10	2.53	2.67	2.48	2.82	0.94	1.88	1.74	1.80	2.17	1.90	1.76	2.54	1.85	2.48	2.07	2.24	1.76	1.90	1.90	2.18
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.31	2.97	2.82	2.80	2.71	4.94	3.13	3.49	3.53	2.57	3	3.03	2.40	2.69	2.33	2.55	2.54	3.68	2.87	3.30	3.23
-	0.01	0.01	0.01	0.01	0.02	0.04	-	-	0.15	0.12	0.15	0.31	0.42	0.17	0.33	0.34	0.06	0.19	0.03	0.03
0.71	0.84	0.68	0.73	0.59	1	1.03	1.22	1.15	0.66	0.64	0.54	0.46	0.47	0.53	0.59	0.59	0.38	0.45	0.58	0.54
8.33	8.05	8.13	8.33	8.07	5.52	7.39	7.06	7.32	7.99	7.82	7.96	7.78	7.72	8.01	7.81	7.91	7.33	8.10	7.64	7.20
0.07	0.08	0.08	0.07	0.08	0.08	0.11	0.10	0.09	0.08	0.08	0.08	0.08	0.09	0.08	0.09	0.07	0.08	0.08	0.08	0.08
-	-	-	-	-	0.04	0.04	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	-	0.01	0.01
0.56	0.04	0.27	0.05	0.53	0.40	0.26	0.09	-	0.54	0.32	0.23	0.95	0.60	0.86	0.62	0.53	0.46	0.30	0.36	0.91
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
-	-	0.08	-	0.10	0.80	0.03	0.02	0.04	0.03	0.03	0.06	0.15	0.05	0.11	0.07	0.06	0.37	0.05	0.06	0.39
-	-	0.07	0.02	-	0.01	0.15	0.04	-	0.04	-	0.06	-	-	0.01	0.05	-	0.02	-	0.04	0.04
-	-	0.15	0.02	0.11	0.81	0.18	0.06	0.04	0.06	0.03	0.11	0.15	0.05	0.12	0.12	0.06	0.39	0.05	0.11	0.43
0.07	0.03	0.04	-	-	0.08	-	-	0.02	-	0.06	0.06	0.06	0.07	0.06	-	0.05	0.04	0.04	0.04	0.03
0.01	-	-	0.01	0.01	0.02	0.02	0.01	-	0.12	0.09	0.12	0.07	0.13	0.09	0.13	0.11	0.03	0.13	0.05	0.04
15.92	15.97	15.95	15.99	15.99	15.90	15.98	15.99	15.97	15.88	15.84	15.82	15.87	15.80	15.85	15.86	15.84	15.93	15.83	15.92	15.92
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
36	36.01	36.15	36.02	36.11	36.81	36.18	36.06	36.04	36.06	36.03	36.11	36.15	36.05	36.12	36.12	36.06	36.39	36.05	36.11	36.43

Appendix F-4a: Chlorite continued

104 BG	105 BG	106 BG	107 BG	108 BG	109 BG	110 BG	111 LG	112 LG	113 LG	114 LG	115 LG	116 LG	117 LG	118 LG	119 LG	120 LG	121 LG	122 LG	123 LG
31.14	27.74	27.55	26.38	24.94	26.54	25.52	29.20	32.61	32.25	26.07	31.26	30.95	27.93	27.50	31.26	30.60	29.10	30.07	29.16
0.17	0.17	0.62	0.52	0.46	0.94	0.84	0.07	0.05	0.07	0.09	0.05	0.06	0.10	0.05	0.04	0.05	0.05	0.11	0.08
21.77	19.39	18.54	19.39	19.75	18.14	18.31	15.66	17.98	18.66	16.18	16.80	17.91	16.17	16.61	16.97	15.99	16.11	17.85	16.64
1.41	1.66	1.86	1.37	2.12	1.86	1.50	6.60	6.38	6.06	3.74	3.75	4.23	4.04	7.23	6.91	4.49	4.82	5.55	5.42
0.04	0.12	0.06	0.06	0.06	0.07	0.06	0.18	0.11	0.10	0.38	0.37	0.31	0.35	0.19	0.14	0.28	0.22	0.20	0.13
0.27	0.41	0.47	0.37	0.40	0.44	0.41	0.34	0.34	0.31	1.20	0.22	0.25	0.33	0.35	0.34	0.20	0.23	0.77	0.32
30.07	37.58	40.53	38.70	40.27	40.52	40.42	27.18	25.74	25.62	32.63	27.17	27.22	33.05	27.95	24.23	28.72	29.53	27.02	26.53
0.14	0.11	0.15	0.23	BDL	0.31	0.21	0.16	BDL	BDL	0.06	BDL	0.14	0.13	0.12	BDL	0.12	BDL	BDL	BDL
2.85	0.59	0.23	1.14	0.21	0.56	0.53	4.34	5.23	4.79	3.66	3.77	3.77	4.34	3.79	5.35	5	5.43	4.38	4.84
0.16	0.07	BDL	0.13	BDL	BDL	0.02	0.37	0.12	0.26	0.07	0.14	0.39	0.23	0.34	0.37	0.41	0.07	0.12	0.35
0.04	0.10	0.21	0.11	0.03	0.31	0.20	0.05	0.04	0.10	0.08	0.05	0.07	0.13	0.02	0.02	0.06	BDL	0.07	0.03
11.02	9.90	10.02	10.24	10.17	10.15	10.13	10.10	11.17	10.98	9.96	10.43	10.39	10.16	10.10	10.53	10.22	10.43	10.69	10.09
99.07	97.82	100.24	98.62	98.44	99.86	98.15	94.25	99.76	99.20	94.11	94.01	95.69	96.95	94.23	96.16	96.15	96	96.82	93.58
0.07	0.05	0.05	0.08	0.01	0.07	0.05	0.17	0.06	0.13	0.05	0.07	0.18	0.13	0.15	0.16	0.19	0.03	0.06	0.15
98.99	97.77	100.19	98.54	98.43	99.79	98.10	94.09	99.70	99.07	94.06	93.94	95.51	96.83	94.09	96	95.96	95.97	96.75	93.43
7.13	6.35	6.31	6.04	5.71	6.08	5.84	6.62	7.40	7.32	5.91	7.09	7.02	6.34	6.24	7.09	6.94	6.60	6.82	6.61
0.87	1.65	1.69	1.96	2.29	1.92	2.16	1.38	0.60	0.68	2.09	0.91	0.98	1.66	1.76	0.91	1.06	1.40	1.18	1.39
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
5	3.58	3.31	3.27	3.04	2.97	2.78	2.81	4.20	4.31	2.24	3.58	3.81	2.66	2.68	3.63	3.22	2.91	3.59	3.06
0.03	0.03	0.11	0.09	0.08	0.16	0.14	0.01	-	0.01	0.01	-	0.01	0.02	-	-	0.01	-	0.02	0.01
0.48	0.57	0.64	0.47	0.72	0.63	0.51	2.23	2.16	2.05	1.26	1.27	1.43	1.37	2.45	2.34	1.52	1.63	1.88	1.83
5.76	7.20	7.76	7.41	7.71	7.76	7.74	5.16	4.88	4.86	6.19	5.15	5.16	6.27	5.30	4.60	5.45	5.60	5.13	5.03
0.05	0.08	0.09	0.07	0.08	0.09	0.08	0.07	0.07	0.06	0.23	0.04	0.05	0.06	0.07	0.07	0.04	0.04	0.15	0.06
0.01	0.03	0.02	0.01	0.02	0.02	0.01	0.04	0.03	0.02	0.09	0.09	0.07	0.08	0.05	0.03	0.07	0.05	0.05	0.03
0.66	0.52	0.08	0.68	0.35	0.37	0.73	1.68	0.65	0.69	1.97	1.85	1.46	1.54	1.45	1.33	1.70	1.75	1.19	1.96
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
0.83	0.17	0.07	0.33	0.06	0.16	0.16	1.26	1.51	1.39	1.06	1.09	1.09	1.26	1.10	1.55	1.45	1.57	1.27	1.40
0.06	0.05	0.07	0.10	-	0.14	0.09	0.07	-	-	0.02	-	0.06	0.06	0.05	-	0.05	-	-	-
0.89	0.22	0.13	0.43	0.07	0.30	0.25	1.33	1.51	1.39	1.08	1.09	1.15	1.31	1.15	1.55	1.50	1.57	1.27	1.40
0.11	0.05	-	0.09	-	-	0.02	0.27	0.08	0.19	0.05	0.10	0.28	0.16	0.24	0.27	0.30	0.05	0.08	0.25
0.01	0.04	0.08	0.04	0.01	0.12	0.08	0.02	0.02	0.04	0.03	0.02	0.03	0.05	-	-	0.02	-	0.03	0.01
15.87	15.91	15.92	15.87	15.99	15.88	15.91	15.72	15.90	15.77	15.92	15.88	15.69	15.79	15.75	15.72	15.68	15.95	15.89	15.74
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
36.89	36.22	36.13	36.43	36.07	36.30	36.25	37.33	37.51	37.39	37.08	37.09	37.15	37.31	37.15	37.55	37.50	37.57	37.27	37.40

Appendix F-4b: Chlorite EPMA compositions from the Gaborone Granite Suite.

#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Granite	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr	Th Gr
SiO ₂	26.58	28.89	29.60	28.11	28.22	29.21	29.36	30.06	29.34	29.07	29.58	28.53	27.44	29.94	27.31	27.53	30.29
TiO ₂	0.47	0.72	0.87	0.67	0.58	0.75	0.65	0.86	0.92	0.82	1.01	0.41	0.55	0.84	0.30	0.50	0.76
Al ₂ O ₃	15.77	15.63	16	15.67	15.63	15.94	15.66	15.67	15.19	15.40	15.13	15.68	15.07	16.01	15.27	16.13	15.49
MgO	5.36	5.05	4.64	5.14	5.20	4.75	5.08	4.58	4.35	4.49	4.41	4.30	5.17	4.87	5.89	5.19	4.91
CaO	0.05	0.04	0.03	0.03	0.03	0.02	0.03	0.02	0.03	0.05	BDL	1.14	0.03	BDL	0.04	0.03	0.03
MnO	0.36	0.36	0.29	0.40	0.39	0.36	0.37	0.33	0.29	0.26	0.32	0.33	0.35	0.36	0.42	0.41	0.30
FeO	37.77	35.52	34.55	36.07	36.25	35.44	35.79	34.16	35.77	36.19	36.20	35.38	37.85	35.44	37.35	37.01	34.43
Na ₂ O	0.06	0.20	0.16	0.11	BDL	BDL	BDL	BDL	0.08	0.28	0.06	0.07	0.15	0.29	0.02	BDL	0.32
K ₂ O	1.87	3.53	4.73	3.35	2.54	4.17	3.48	4.92	4.14	3.79	4.38	1.53	1.87	4.39	0.98	2.29	4.63
F	0.09	BDL	0.14	0.09	0.14	BDL	0.10	0.03	0.05	BDL	BDL	BDL	BDL	0.01	BDL	BDL	BDL
Cl	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.02	BDL	0.02	0.04
H ₂ O*	10.51	10.84	10.93	10.72	10.68	10.92	10.89	10.95	10.81	10.84	10.91	10.62	10.57	11.11	10.55	10.69	11.03
Total	98.91	100.79	101.95	100.37	99.68	101.57	101.43	101.60	100.98	101.21	102.02	98	99.07	103.28	98.14	99.80	102.23
O≡F,Cl	0.04	-	0.06	0.04	0.06	-	0.05	0.02	0.03	-	-	-	0.01	0.01	-	0.01	0.01
Total	98.87	100.79	101.88	100.33	99.61	101.57	101.38	101.58	100.95	101.20	102.02	98	99.06	103.27	98.14	99.79	102.22
Cations Proportions Based on 28 Oxygens (apfu)																	
Tetrahedral Site																	
Si	6.04	6.56	6.73	6.39	6.41	6.64	6.67	6.83	6.67	6.61	6.72	6.48	6.23	6.80	6.21	6.26	6.88
Al ^{IV}	1.96	1.44	1.27	1.61	1.59	1.36	1.33	1.17	1.33	1.39	1.28	1.52	1.77	1.20	1.79	1.74	1.12
Z Sum	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Octahedral Site																	
Al ^{VI}	2.26	2.75	3.01	2.58	2.60	2.91	2.86	3.03	2.73	2.73	2.77	2.68	2.27	3.09	2.30	2.57	3.03
Ti	0.08	0.12	0.15	0.11	0.10	0.13	0.11	0.15	0.16	0.14	0.17	0.07	0.09	0.14	0.05	0.09	0.13
Mg	1.82	1.71	1.57	1.74	1.76	1.61	1.72	1.55	1.47	1.52	1.49	1.46	1.75	1.65	2	1.76	1.66
Fe ^{tot}	7.18	6.75	6.57	6.85	6.89	6.73	6.80	6.49	6.80	6.88	6.88	6.72	7.19	6.73	7.10	7.03	6.54
Mn	0.07	0.07	0.06	0.08	0.07	0.07	0.07	0.06	0.06	0.05	0.06	0.06	0.07	0.07	0.08	0.08	0.06
Ca	0.01	-	-	-	-	-	-	-	-	0.01	-	0.28	-	-	0.01	-	-
□*	0.58	0.59	0.64	0.62	0.57	0.55	0.43	0.72	0.78	0.67	0.62	0.73	0.62	0.31	0.47	0.47	0.57
Y Sum	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
Interlayer																	
K	0.54	1.02	1.37	0.97	0.74	1.21	1.01	1.43	1.20	1.10	1.27	0.44	0.54	1.27	0.28	0.66	1.34
Na	0.03	0.09	0.07	0.05	-	-	-	-	0.03	0.12	0.03	0.03	0.07	0.13	0.01	-	0.14
X Sum	0.57	1.11	1.44	1.02	0.74	1.21	1.01	1.43	1.23	1.22	1.29	0.48	0.61	1.40	0.30	0.66	1.48
Anion Site																	
F	0.06	-	0.10	0.07	0.10	-	0.07	0.02	0.04	-	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.02
OH*	15.93	16	15.89	15.93	15.89	15.99	15.92	15.97	15.95	15.99	15.99	15.99	15.99	15.99	16	15.99	15.98
A Sum	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Sum	36.57	37.11	37.44	37.02	36.74	37.21	37.01	37.43	37.23	37.22	37.29	36.48	36.61	37.40	36.30	36.66	37.48

*Stoichiometrically calculated. Abbreviations: Thamaga Granite (Th Gr); Kgale Granite – Main Phase (Kg-Mn); Kgale Granite – Marginal Phase (Kg-Mg); and Below Detection Limit (BDL).

Appendix F-4b: Chlorite continued

20 NG	21 NG	22 NG	23 NG	24 NG	25 NG	26 NG	27 NG	28 NG	29 NG	30 NG	31 NG	32 NG	33 NG	34 NG	35 NG	36 NG	37 NG	38 NG	39 NG	40 NG
31.27	31.45	31.66	32.37	31.27	31.49	31.11	35.45	33.23	32.10	32.04	32.72	29.28	31.07	30.91	30.51	29.95	31.43	31.72	30.43	31.02
1.02	1.02	2.59	2.18	1.72	1.57	0.60	0.46	0.71	0.33	0.14	0.09	0.08	0.23	1.29	0.06	0.07	0.07	0.10	0.66	0.49
13.31	13.15	13.13	14.12	13.72	13.23	13.52	10.85	11.72	12.50	12.11	12.05	13.09	12.63	12.92	13.39	12.95	12.35	12.59	13	12.25
1.78	2	2.13	3.04	1.97	3.72	3.65	2.47	2.46	1.29	1.14	1.62	1.09	1.44	1.48	2.43	1.77	1.52	1.48	1.91	2.25
0.09	0.08	0.90	0.09	0.09	1.05	0.13	0.21	0.18	0.14	0.13	0.15	0.17	0.11	0.09	0.18	0.11	0.12	0.18	0.08	0.12
0.52	0.46	0.47	0.38	0.51	0.53	0.53	0.48	0.38	0.56	0.57	0.70	0.62	0.68	0.37	0.56	0.63	0.64	0.59	0.55	0.65
35.40	33.71	33.70	32.53	33.60	33	33.86	31.23	31.95	34	34.77	34.83	37.38	35.89	34.68	34.58	35.81	34.69	34.21	34.67	34.17
0.17	0.32	0.17	0.23	0.09	0.09	0.11	0.09	0.12	0.20	0.21	0.19	0.12	0.32	0.19	0.10	0.06	0.34	0.38	0.05	0.31
3.58	4.63	4.71	5.11	3.73	1.25	1.94	3.47	4.34	4.40	4.63	2.10	1.91	2	5.11	2.58	2.61	3.17	3.57	3.64	2.54
BDL	0.09	0.05	0.19	BDL	0.04	0.08	0.04	BDL	0.04	BDL	0.09	0.02	0.03	BDL	BDL	0.03	0.03	0.04	BDL	BDL
0.81	1.06	0.87	1.05	0.75	0.21	0.37	0.18	0.69	1.41	1.69	0.67	0.86	0.69	1.64	0.88	0.95	1.07	1.12	1.17	0.75
10.13	9.90	10.35	10.34	10.21	10.51	10.26	10.46	10.12	9.63	9.49	9.93	9.56	9.86	9.64	9.83	9.61	9.66	9.70	9.67	9.82
98.07	97.87	100.73	101.63	97.67	96.70	96.16	95.39	95.89	96.60	96.91	95.12	94.19	94.96	98.32	95.09	94.55	95.07	95.69	95.83	94.36
0.18	0.28	0.22	0.32	0.17	0.06	0.12	0.06	0.16	0.34	0.38	0.19	0.20	0.17	0.37	0.20	0.22	0.25	0.27	0.27	0.17
97.88	97.59	100.51	101.31	97.50	96.64	96.04	95.33	95.74	96.27	96.53	94.93	93.99	94.79	97.95	94.89	94.33	94.82	95.42	95.56	94.19
7.11	7.15	7.20	7.36	7.11	7.16	7.08	8.06	7.56	7.30	7.29	7.44	6.66	7.07	7.03	6.94	6.81	7.15	7.21	6.92	7.05
0.89	0.85	0.80	0.64	0.89	0.84	0.92	-	0.44	0.70	0.71	0.56	1.34	0.93	0.97	1.06	1.19	0.85	0.79	1.08	0.95
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.68	2.68	2.72	3.15	2.79	2.71	2.70	2.97	2.70	2.65	2.53	2.67	2.17	2.45	2.49	2.53	2.28	2.46	2.59	2.40	2.34
0.17	0.17	0.44	0.37	0.29	0.27	0.10	0.08	0.12	0.06	0.02	0.02	0.01	0.04	0.22	0.01	0.01	0.01	0.02	0.11	0.08
0.60	0.68	0.72	1.03	0.67	1.26	1.24	0.84	0.83	0.44	0.39	0.55	0.37	0.49	0.50	0.82	0.60	0.52	0.50	0.65	0.76
6.73	6.41	6.41	6.19	6.39	6.28	6.44	5.94	6.08	6.47	6.61	6.62	7.11	6.83	6.60	6.58	6.81	6.60	6.51	6.59	6.50
0.10	0.09	0.09	0.07	0.10	0.10	0.10	0.09	0.07	0.11	0.11	0.13	0.12	0.13	0.07	0.11	0.12	0.12	0.11	0.11	0.13
0.02	0.02	0.22	0.02	0.02	0.26	0.03	0.05	0.04	0.03	0.03	0.04	0.04	0.03	0.02	0.04	0.03	0.03	0.04	0.02	0.03
1.69	1.95	1.40	1.17	1.74	1.13	1.39	2.03	2.15	2.25	2.30	1.97	2.18	2.04	2.09	1.91	2.15	2.27	2.23	2.12	2.16
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
1.04	1.34	1.37	1.48	1.08	0.36	0.56	1.01	1.26	1.28	1.34	0.61	0.55	0.58	1.48	0.75	0.76	0.92	1.04	1.05	0.74
0.07	0.14	0.07	0.10	0.04	0.04	0.05	0.04	0.05	0.09	0.09	0.08	0.05	0.14	0.08	0.05	0.03	0.15	0.17	0.02	0.14
1.11	1.48	1.44	1.58	1.12	0.40	0.61	1.04	1.31	1.36	1.44	0.69	0.61	0.72	1.57	0.80	0.79	1.07	1.20	1.08	0.87
-	0.07	0.04	0.14	-	0.03	0.06	0.03	-	0.03	-	0.07	0.01	0.02	-	-	0.02	0.02	0.03	-	-
0.31	0.41	0.33	0.41	0.29	0.08	0.14	0.07	0.27	0.54	0.65	0.26	0.33	0.27	0.63	0.34	0.37	0.41	0.43	0.45	0.29
15.69	15.52	15.63	15.46	15.71	15.89	15.80	15.90	15.73	15.43	15.35	15.68	15.65	15.72	15.37	15.66	15.62	15.57	15.54	15.55	15.71
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
37.11	37.48	37.44	37.58	37.12	36.40	36.61	37.04	37.31	37.36	37.44	36.69	36.61	36.72	37.57	36.80	36.79	37.07	37.20	37.08	36.87

Appendix F-4b: Chlorite continued

41 NG	42 NG	43 NG	44 NG	45 NG	46 NG	47 NG	48 NG	49 NG	50 NG	51 NG	52 NG	53 NG	54 NG	55 NG	56 NG	57 NG	58 NG	59 NG	60 NG	61 NG
32.27	30.63	30.50	32.12	31.05	30.90	29.57	33.72	31.55	32.36	32.22	30.10	30.86	32.21	31.26	31.56	31.54	32.09	30.60	29.52	28.28
0.81	0.07	0.03	0.21	0.03	0.08	0.58	0.06	0.03	0.03	0.40	0.28	0.36	0.40	0.29	0.39	0.35	0.46	0.28	0.29	0.26
12.70	13.07	12.52	12.38	12.76	12.42	13.18	12.21	13.09	12.58	12.37	13.50	12.64	12.26	12.58	12.42	12.43	12.11	12.52	12.97	13.97
2.12	2.74	2.39	3.54	2.01	2.16	2.30	0.76	0.77	0.63	0.90	1.78	1.08	0.94	2.17	1.90	1.35	1.08	1.14	1.15	2.86
0.11	0.08	0.15	0.20	0.11	0.14	0.10	0.09	0.06	0.07	0.06	0.06	0.07	0.05	0.11	0.11	0.19	0.14	0.20	0.10	0.08
0.70	0.60	0.66	0.66	0.64	0.66	0.57	0.55	0.64	0.58	0.58	0.67	0.63	0.57	0.62	0.55	0.50	0.57	0.65	0.63	0.61
34.94	34.71	33.93	34.45	35.08	35.26	34.80	34.20	36.42	34.63	34.10	35.21	35.42	34.44	33.94	33.70	34.62	33.54	35.50	36.65	36.73
0.19	0.08	0.12	0.14	0.46	0.51	0.24	0.18	0.18	0.23	BDL	0.19	0.19	0.28	0.19	0.17	0.55	0.11	0.23	0.15	0.12
3.24	2.73	3.13	1.57	2.47	2.29	2.29	4.12	3.64	5.13	5.37	2.88	3.92	4.88	3.20	3.71	4.34	5.18	3.17	2.27	1.16
0.06	BDL	0.13	0.03	BDL	BDL	BDL	0.09	0.13	0.09	0.09	0.05	BDL	BDL	BDL	BDL	BDL	0.13	0.10	0.08	0.06
0.95	1.01	1.13	0.38	0.82	0.75	0.73	1.38	1.28	1.85	1.84	0.94	1.21	1.58	0.97	1.23	1.37	1.65	1.07	0.72	0.38
10.07	9.79	9.44	10.27	9.86	9.85	9.76	9.73	9.63	9.41	9.39	9.71	9.62	9.59	9.78	9.66	9.66	9.38	9.52	9.60	9.87
98.15	95.53	94.12	95.95	95.30	95.03	94.11	97.09	97.42	97.59	97.34	95.37	95.98	97.21	95.12	95.41	96.89	96.41	94.96	94.12	94.40
0.24	0.23	0.31	0.10	0.18	0.17	0.16	0.35	0.34	0.45	0.45	0.23	0.27	0.36	0.22	0.28	0.31	0.43	0.28	0.20	0.11
97.91	95.30	93.81	95.85	95.12	94.86	93.94	96.75	97.08	97.14	96.89	95.14	95.71	96.85	94.90	95.13	96.58	95.99	94.68	93.92	94.28
7.34	6.97	6.94	7.30	7.06	7.03	6.73	7.67	7.18	7.36	7.33	6.84	7.02	7.32	7.11	7.18	7.17	7.30	6.96	6.71	6.43
0.66	1.03	1.06	0.70	0.94	0.97	1.27	0.33	0.82	0.64	0.67	1.16	0.98	0.68	0.89	0.82	0.83	0.70	1.04	1.29	1.57
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.74	2.47	2.29	2.62	2.48	2.36	2.26	2.94	2.68	2.73	2.64	2.46	2.41	2.61	2.48	2.51	2.50	2.54	2.32	2.19	2.18
0.14	0.01	-	0.04	-	0.01	0.10	0.01	-	-	0.07	0.05	0.06	0.07	0.05	0.07	0.06	0.08	0.05	0.05	0.05
0.72	0.93	0.81	1.20	0.68	0.73	0.78	0.26	0.26	0.21	0.31	0.60	0.37	0.32	0.74	0.64	0.46	0.37	0.39	0.39	0.97
6.65	6.60	6.45	6.55	6.67	6.71	6.62	6.50	6.93	6.59	6.49	6.70	6.74	6.55	6.45	6.41	6.58	6.38	6.75	6.97	6.99
0.13	0.12	0.13	0.13	0.12	0.13	0.11	0.11	0.12	0.11	0.11	0.13	0.12	0.11	0.12	0.11	0.10	0.11	0.13	0.12	0.12
0.03	0.02	0.04	0.05	0.03	0.03	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.03	0.03	0.05	0.03	0.05	0.03	0.02
1.59	1.85	2.28	1.41	2.01	2.03	2.11	2.16	1.99	2.33	2.37	2.04	2.29	2.33	2.13	2.24	2.26	2.49	2.33	2.26	1.69
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
0.94	0.79	0.91	0.46	0.72	0.67	0.66	1.20	1.06	1.49	1.56	0.84	1.14	1.41	0.93	1.08	1.26	1.50	0.92	0.66	0.34
0.08	0.04	0.05	0.06	0.20	0.22	0.10	0.08	0.08	0.10	-	0.09	0.08	0.12	0.09	0.07	0.24	0.05	0.10	0.07	0.05
1.03	0.83	0.96	0.52	0.92	0.89	0.77	1.28	1.14	1.59	1.56	0.92	1.22	1.54	1.01	1.15	1.50	1.55	1.02	0.73	0.39
0.04	-	0.10	0.02	-	-	-	0.06	0.09	0.06	0.06	0.03	-	-	-	-	-	0.09	0.07	0.06	0.04
0.37	0.39	0.43	0.15	0.31	0.29	0.28	0.53	0.49	0.71	0.71	0.36	0.47	0.61	0.37	0.47	0.53	0.64	0.41	0.28	0.15
15.59	15.61	15.47	15.83	15.69	15.71	15.72	15.41	15.42	15.22	15.23	15.60	15.53	15.39	15.63	15.52	15.47	15.27	15.52	15.66	15.81
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
37.03	36.83	36.96	36.52	36.92	36.89	36.77	37.28	37.14	37.59	37.56	36.92	37.22	37.54	37.01	37.15	37.50	37.55	37.02	36.73	36.39

Appendix F-4b: Chlorite continued

62 NG	63 NG	64 NG	65 NG	66 NG	67 NG	68 NG	69 NG	70 NG	71 NG	72 NG	73 NG	74 NG	75 NG	76 NG	77 NG	78 NG	79 NG	80 BG	81 BG	82 BG
30.70	30.67	32.19	31.36	30.49	29.39	27.95	30.65	30.74	30.52	32.40	29.18	26.74	31.38	30.86	32.11	29.06	31.57	23.59	25.68	24.25
0.16	0.27	0.26	0.30	0.25	2.09	1.52	1.15	0.70	0.90	1.15	0.83	0.72	1.91	1.46	1.44	0.19	1.09	0.15	0.02	BDL
12.46	12.79	12.28	12.69	13.58	13.22	13.98	12.54	13.10	13.18	12.66	14.31	15.62	13.43	13.64	13.06	13.97	13.27	20.21	19.62	20.61
1.85	1.26	1.05	1.08	2.81	2.51	2.81	1.67	2.64	2.33	2.14	3.07	2.96	2.14	1.96	1.54	2.57	1.90	1.70	2.16	2.02
0.09	0.10	0.09	0.06	0.07	1.20	0.22	0.03	0.12	0.32	0.03	0.11	0.07	0.19	0.05	0.04	0.06	0.03	0.02	0.04	0.01
0.65	0.67	0.68	0.57	0.62	0.60	0.49	0.41	0.57	0.69	0.72	0.54	0.57	0.48	0.51	0.58	0.55	0.69	0.41	0.39	0.38
35.13	35.66	34.60	34.82	34.18	34.29	34.32	34.61	33.53	34.94	34.85	34.52	36.54	34.64	34.33	33.87	37.11	34.17	43.07	39.85	41.18
0.41	0.22	0.08	0.25	0.33	0.10	0.08	BDL	BDL	0.15	0.12	BDL	BDL	0.17	0.06	BDL	0.07	0.05	0.06	0.09	0.23
2.70	2.58	3.86	4.36	1.70	1.41	2.38	5.45	2.98	1.26	2.69	1.60	1.02	4.21	3.27	3.94	1.28	2.53	0.06	0.59	0.50
BDL	0.09	0.04	BDL	0.07	0.12	0.06	BDL	0.06	0.08	0.12	0.11	BDL	0.06	0.08	BDL	0.07	0.05	0.03	BDL	0.08
0.87	0.81	1.26	1.49	0.51	0.26	0.67	1.26	0.67	0.13	0.37	0.28	0.17	0.72	0.56	0.74	0.36	0.40	0.02	0.02	0.02
9.73	9.68	9.65	9.56	9.98	10.09	9.73	9.71	9.92	10.16	10.31	10.03	10.05	10.30	10.13	10.19	9.98	10.21	10.06	9.88	10.13
94.75	94.80	96.05	96.54	94.58	95.28	94.21	97.48	95.03	94.66	97.55	94.58	94.46	99.64	96.91	97.51	95.26	95.94	99.38	98.34	99.41
0.20	0.22	0.30	0.34	0.14	0.11	0.18	0.28	0.18	0.06	0.14	0.11	0.04	0.19	0.16	0.17	0.11	0.11	0.02	-	0.04
94.56	94.57	95.75	96.20	94.44	95.18	94.04	97.20	94.85	94.60	97.42	94.47	94.42	99.45	96.75	97.34	95.15	95.83	99.36	98.34	99.37
6.98	6.97	7.32	7.13	6.93	6.68	6.36	6.97	6.99	6.94	7.37	6.64	6.08	7.14	7.02	7.30	6.61	7.18	5.40	5.88	5.55
1.02	1.03	0.68	0.87	1.07	1.32	1.64	1.03	1.01	1.06	0.63	1.36	1.92	0.86	0.98	0.70	1.39	0.82	2.60	2.12	2.45
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.32	2.40	2.61	2.53	2.57	2.23	2.10	2.33	2.50	2.47	2.76	2.47	2.27	2.74	2.67	2.80	2.35	2.74	2.85	3.17	3.12
0.03	0.05	0.05	0.05	0.04	0.36	0.26	0.20	0.12	0.15	0.20	0.14	0.12	0.33	0.25	0.25	0.03	0.19	0.03	-	-
0.63	0.43	0.36	0.36	0.95	0.85	0.95	0.57	0.90	0.79	0.73	1.04	1	0.72	0.67	0.52	0.87	0.65	0.58	0.74	0.69
6.68	6.78	6.58	6.62	6.50	6.52	6.53	6.58	6.38	6.64	6.63	6.57	6.95	6.59	6.53	6.44	7.06	6.50	8.25	7.63	7.89
0.13	0.13	0.13	0.11	0.12	0.12	0.10	0.08	0.11	0.13	0.14	0.10	0.11	0.09	0.10	0.11	0.11	0.13	0.08	0.07	0.07
0.02	0.02	0.02	0.02	0.02	0.29	0.05	-	0.03	0.08	-	0.03	0.02	0.05	0.01	0.01	0.01	-	-	0.01	-
2.20	2.19	2.25	2.30	1.79	1.63	2.01	2.24	1.97	1.73	1.54	1.65	1.53	1.48	1.77	1.87	1.57	1.79	0.21	0.37	0.23
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
0.78	0.75	1.12	1.27	0.49	0.41	0.69	1.58	0.86	0.37	0.78	0.46	0.30	1.22	0.95	1.14	0.37	0.73	0.02	0.17	0.14
0.18	0.10	0.04	0.11	0.15	0.05	0.04	-	-	0.07	0.05	-	-	0.08	0.02	-	0.03	0.02	0.03	0.04	0.10
0.96	0.84	1.16	1.38	0.64	0.46	0.73	1.58	0.86	0.43	0.83	0.46	0.30	1.30	0.97	1.14	0.40	0.75	0.04	0.21	0.25
-	0.07	0.03	-	0.05	0.08	0.04	-	0.04	0.06	0.09	0.08	-	0.04	0.06	-	0.05	0.03	0.02	-	0.06
0.34	0.31	0.49	0.57	0.20	0.10	0.26	0.49	0.26	0.05	0.14	0.11	0.07	0.28	0.21	0.28	0.14	0.15	-	-	-
15.66	15.62	15.49	15.43	15.76	15.82	15.70	15.51	15.70	15.89	15.77	15.81	15.93	15.68	15.73	15.72	15.81	15.81	15.97	15.99	15.93
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
36.96	36.84	37.16	37.38	36.64	36.46	36.73	37.58	36.86	36.43	36.83	36.46	36.30	37.30	36.97	37.14	36.40	36.75	36.04	36.21	36.25

Appendix F-4b: Chlorite continued

83 BG	84 BG	85 BG	86 BG	87 BG	88 BG	89 BG	90 BG	91 BG	92 BG	93 BG	94 BG	95 BG	96 BG	97 BG	98 BG	99 BG	100 BG	101 BG	102 BG	103 BG
21.39	23.88	23.28	24.13	22.62	30.82	26.72	27.32	27.09	25.47	26.63	27.24	23.85	26.86	24.12	25.88	25.14	27.27	26.64	26.63	25.43
0.04	0.07	0.07	0.06	0.07	0.13	0.26	0.04	0.03	0.89	0.71	0.87	1.82	2.44	0.99	1.90	2	0.34	1.12	0.15	0.16
20.05	20.40	20.32	19.56	20.49	21.80	18.58	19.39	19.74	17.54	18.18	17.75	18.30	16.83	17.82	17.13	17.71	20.15	17.67	19.27	20.05
2.09	2.46	2	2.14	1.74	2.93	3	3.57	3.36	1.92	1.87	1.59	1.34	1.36	1.54	1.74	1.74	1.11	1.32	1.69	1.58
0.01	BDL	0.02	0.03	0.01	0.16	0.17	0.16	0.11	0.07	0.07	0.07	0.05	0.04	0.05	0.05	0.06	0.08	0.03	0.06	0.05
0.38	0.40	0.43	0.37	0.43	0.40	0.55	0.52	0.48	0.43	0.43	0.39	0.43	0.48	0.42	0.46	0.37	0.40	0.43	0.43	0.39
43.52	42.05	42.46	43.50	42.13	28.85	38.59	36.86	38.21	41.71	40.83	41.55	40.65	40.33	41.86	40.79	41.32	38.26	42.28	39.92	37.62
BDL	BDL	0.16	0.05	0.01	0.02	0.34	0.09	BDL	0.08	BDL	0.13	BDL	BDL	0.03	0.11	BDL	0.04	BDL	0.10	0.09
0.01	0.02	0.27	0.01	0.35	2.73	0.11	0.06	0.12	0.09	0.10	0.19	0.51	0.16	0.37	0.24	0.20	1.27	0.16	0.21	1.34
0.10	0.04	0.06	BDL	BDL	0.11	BDL	BDL	0.03	BDL	0.09	0.09	0.08	0.10	0.08	BDL	0.06	0.05	0.05	0.05	0.05
0.03	0.02	BDL	0.03	0.03	0.04	0.04	0.03	0.02	0.31	0.24	0.31	0.19	0.33	0.24	0.34	0.28	0.08	0.34	0.12	0.11
10.01	10.16	10.20	10	10.27	11.11	9.95	10.08	10.13	9.92	9.73	9.78	10.07	9.64	10.02	9.96	9.93	10.33	9.89	9.84	10.33
97.65	99.51	99.29	99.87	98.16	99.09	98.32	98.13	99.32	98.43	98.89	99.96	97.28	98.56	97.53	98.62	98.82	99.38	99.96	98.47	97.20
0.05	0.02	0.03	0.01	0.01	0.06	0.01	0.01	0.02	0.07	0.09	0.11	0.08	0.11	0.09	0.08	0.09	0.04	0.10	0.05	0.04
97.60	99.49	99.26	99.86	98.15	99.03	98.31	98.12	99.30	98.36	98.80	99.85	97.21	98.45	97.44	98.54	98.73	99.34	99.86	98.42	97.16
4.90	5.47	5.33	5.52	5.18	7.06	6.12	6.26	6.20	5.83	6.10	6.24	5.46	6.15	5.52	5.93	5.76	6.24	6.10	6.10	5.82
3.10	2.53	2.67	2.48	2.82	0.94	1.88	1.74	1.80	2.17	1.90	1.76	2.54	1.85	2.48	2.07	2.24	1.76	1.90	1.90	2.18
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
2.31	2.97	2.82	2.80	2.71	4.94	3.13	3.49	3.53	2.57	3	3.03	2.40	2.69	2.33	2.55	2.54	3.68	2.87	3.30	3.23
-	0.01	0.01	0.01	0.01	0.02	0.04	-	-	0.15	0.12	0.15	0.31	0.42	0.17	0.33	0.34	0.06	0.19	0.03	0.03
0.71	0.84	0.68	0.73	0.59	1	1.03	1.22	1.15	0.66	0.64	0.54	0.46	0.47	0.53	0.59	0.59	0.38	0.45	0.58	0.54
8.33	8.05	8.13	8.33	8.07	5.52	7.39	7.06	7.32	7.99	7.82	7.96	7.78	7.72	8.01	7.81	7.91	7.33	8.10	7.64	7.20
0.07	0.08	0.08	0.07	0.08	0.08	0.11	0.10	0.09	0.08	0.08	0.08	0.08	0.09	0.08	0.09	0.07	0.08	0.08	0.08	0.08
-	-	-	-	-	0.04	0.04	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	-	0.01	0.01
0.56	0.04	0.27	0.05	0.53	0.40	0.26	0.09	-	0.54	0.32	0.23	0.95	0.60	0.86	0.62	0.53	0.46	0.30	0.36	0.91
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
-	-	0.08	-	0.10	0.80	0.03	0.02	0.04	0.03	0.03	0.06	0.15	0.05	0.11	0.07	0.06	0.37	0.05	0.06	0.39
-	-	0.07	0.02	-	0.01	0.15	0.04	-	0.04	-	0.06	-	-	0.01	0.05	-	0.02	-	0.04	0.04
-	-	0.15	0.02	0.11	0.81	0.18	0.06	0.04	0.06	0.03	0.11	0.15	0.05	0.12	0.12	0.06	0.39	0.05	0.11	0.43
0.07	0.03	0.04	-	-	0.08	-	-	0.02	-	0.06	0.06	0.06	0.07	0.06	-	0.05	0.04	0.04	0.04	0.03
0.01	-	-	0.01	0.01	0.02	0.02	0.01	-	0.12	0.09	0.12	0.07	0.13	0.09	0.13	0.11	0.03	0.13	0.05	0.04
15.92	15.97	15.95	15.99	15.99	15.90	15.98	15.99	15.97	15.88	15.84	15.82	15.87	15.80	15.85	15.86	15.84	15.93	15.83	15.92	15.92
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
36	36.01	36.15	36.02	36.11	36.81	36.18	36.06	36.04	36.06	36.03	36.11	36.15	36.05	36.12	36.12	36.06	36.39	36.05	36.11	36.43

Appendix F-4b: Chlorite continued

104 BG	105 BG	106 BG	107 BG	108 BG	109 BG	110 BG	111 LG	112 LG	113 LG	114 LG	115 LG	116 LG	117 LG	118 LG	119 LG	120 LG	121 LG	122 LG	123 LG
31.14	27.74	27.55	26.38	24.94	26.54	25.52	29.20	32.61	32.25	26.07	31.26	30.95	27.93	27.50	31.26	30.60	29.10	30.07	29.16
0.17	0.17	0.62	0.52	0.46	0.94	0.84	0.07	0.05	0.07	0.09	0.05	0.06	0.10	0.05	0.04	0.05	0.05	0.11	0.08
21.77	19.39	18.54	19.39	19.75	18.14	18.31	15.66	17.98	18.66	16.18	16.80	17.91	16.17	16.61	16.97	15.99	16.11	17.85	16.64
1.41	1.66	1.86	1.37	2.12	1.86	1.50	6.60	6.38	6.06	3.74	3.75	4.23	4.04	7.23	6.91	4.49	4.82	5.55	5.42
0.04	0.12	0.06	0.06	0.06	0.07	0.06	0.18	0.11	0.10	0.38	0.37	0.31	0.35	0.19	0.14	0.28	0.22	0.20	0.13
0.27	0.41	0.47	0.37	0.40	0.44	0.41	0.34	0.34	0.31	1.20	0.22	0.25	0.33	0.35	0.34	0.20	0.23	0.77	0.32
30.07	37.58	40.53	38.70	40.27	40.52	40.42	27.18	25.74	25.62	32.63	27.17	27.22	33.05	27.95	24.23	28.72	29.53	27.02	26.53
0.14	0.11	0.15	0.23	BDL	0.31	0.21	0.16	BDL	BDL	0.06	BDL	0.14	0.13	0.12	BDL	0.12	BDL	BDL	BDL
2.85	0.59	0.23	1.14	0.21	0.56	0.53	4.34	5.23	4.79	3.66	3.77	3.77	4.34	3.79	5.35	5	5.43	4.38	4.84
0.16	0.07	BDL	0.13	BDL	BDL	0.02	0.37	0.12	0.26	0.07	0.14	0.39	0.23	0.34	0.37	0.41	0.07	0.12	0.35
0.04	0.10	0.21	0.11	0.03	0.31	0.20	0.05	0.04	0.10	0.08	0.05	0.07	0.13	0.02	0.02	0.06	BDL	0.07	0.03
11.02	9.90	10.02	10.24	10.17	10.15	10.13	10.10	11.17	10.98	9.96	10.43	10.39	10.16	10.10	10.53	10.22	10.43	10.69	10.09
99.07	97.82	100.24	98.62	98.44	99.86	98.15	94.25	99.76	99.20	94.11	94.01	95.69	96.95	94.23	96.16	96.15	96	96.82	93.58
0.07	0.05	0.05	0.08	0.01	0.07	0.05	0.17	0.06	0.13	0.05	0.07	0.18	0.13	0.15	0.16	0.19	0.03	0.06	0.15
98.99	97.77	100.19	98.54	98.43	99.79	98.10	94.09	99.70	99.07	94.06	93.94	95.51	96.83	94.09	96	95.96	95.97	96.75	93.43
7.13	6.35	6.31	6.04	5.71	6.08	5.84	6.62	7.40	7.32	5.91	7.09	7.02	6.34	6.24	7.09	6.94	6.60	6.82	6.61
0.87	1.65	1.69	1.96	2.29	1.92	2.16	1.38	0.60	0.68	2.09	0.91	0.98	1.66	1.76	0.91	1.06	1.40	1.18	1.39
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
5	3.58	3.31	3.27	3.04	2.97	2.78	2.81	4.20	4.31	2.24	3.58	3.81	2.66	2.68	3.63	3.22	2.91	3.59	3.06
0.03	0.03	0.11	0.09	0.08	0.16	0.14	0.01	-	0.01	0.01	-	0.01	0.02	-	-	0.01	-	0.02	0.01
0.48	0.57	0.64	0.47	0.72	0.63	0.51	2.23	2.16	2.05	1.26	1.27	1.43	1.37	2.45	2.34	1.52	1.63	1.88	1.83
5.76	7.20	7.76	7.41	7.71	7.76	7.74	5.16	4.88	4.86	6.19	5.15	5.16	6.27	5.30	4.60	5.45	5.60	5.13	5.03
0.05	0.08	0.09	0.07	0.08	0.09	0.08	0.07	0.07	0.06	0.23	0.04	0.05	0.06	0.07	0.07	0.04	0.04	0.15	0.06
0.01	0.03	0.02	0.01	0.02	0.02	0.01	0.04	0.03	0.02	0.09	0.09	0.07	0.08	0.05	0.03	0.07	0.05	0.05	0.03
0.66	0.52	0.08	0.68	0.35	0.37	0.73	1.68	0.65	0.69	1.97	1.85	1.46	1.54	1.45	1.33	1.70	1.75	1.19	1.96
12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12
0.83	0.17	0.07	0.33	0.06	0.16	0.16	1.26	1.51	1.39	1.06	1.09	1.09	1.26	1.10	1.55	1.45	1.57	1.27	1.40
0.06	0.05	0.07	0.10	-	0.14	0.09	0.07	-	-	0.02	-	0.06	0.06	0.05	-	0.05	-	-	-
0.89	0.22	0.13	0.43	0.07	0.30	0.25	1.33	1.51	1.39	1.08	1.09	1.15	1.31	1.15	1.55	1.50	1.57	1.27	1.40
0.11	0.05	-	0.09	-	-	0.02	0.27	0.08	0.19	0.05	0.10	0.28	0.16	0.24	0.27	0.30	0.05	0.08	0.25
0.01	0.04	0.08	0.04	0.01	0.12	0.08	0.02	0.02	0.04	0.03	0.02	0.03	0.05	-	-	0.02	-	0.03	0.01
15.87	15.91	15.92	15.87	15.99	15.88	15.91	15.72	15.90	15.77	15.92	15.88	15.69	15.79	15.75	15.72	15.68	15.95	15.89	15.74
16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
36.89	36.22	36.13	36.43	36.07	36.30	36.25	37.33	37.51	37.39	37.08	37.09	37.15	37.31	37.15	37.55	37.50	37.57	37.27	37.40

Appendix F-5: Average Electron Probe Micro-Analyser (EPMA) detection Limits (DL) of the elements measured in the analyses of cassiterite, tourmaline, mica and chlorite at Rhodes University and the University of the Witwatersrand (Wits).

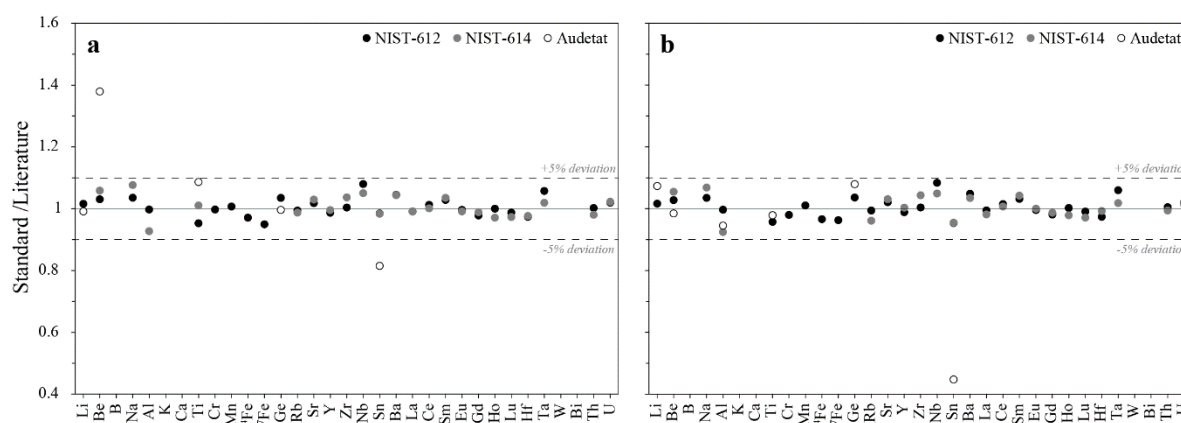
Rhodes University				Wits	
JEOL JXA-8230 EPMA				CAMECA SX5-FE EPMA	
Cassiterite		Tourmaline		Mica & Chlorite	
Element	DL (ppm)	Element	DL (ppm)	Element	DL (ppm)
Sn	610	Si	292	Si	199
Fe	288	Al	274	Al	200
W	1155	Fe	426	Fe	637
Ti	374	Ti	393	Ti	152
Nb	467	Mg	182	Mg	214
Ta	994	Mn	373	Mn	441
Mn	305	Ca	170	Ca	134
		K	122	K	306
		Na	202	Na	314
				Cl	159
				F	2561

Appendix G: Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) standards and data.

Appendix Ga: Quartz LA-ICP-MS trace elemental detection limits and comparison with standard material.

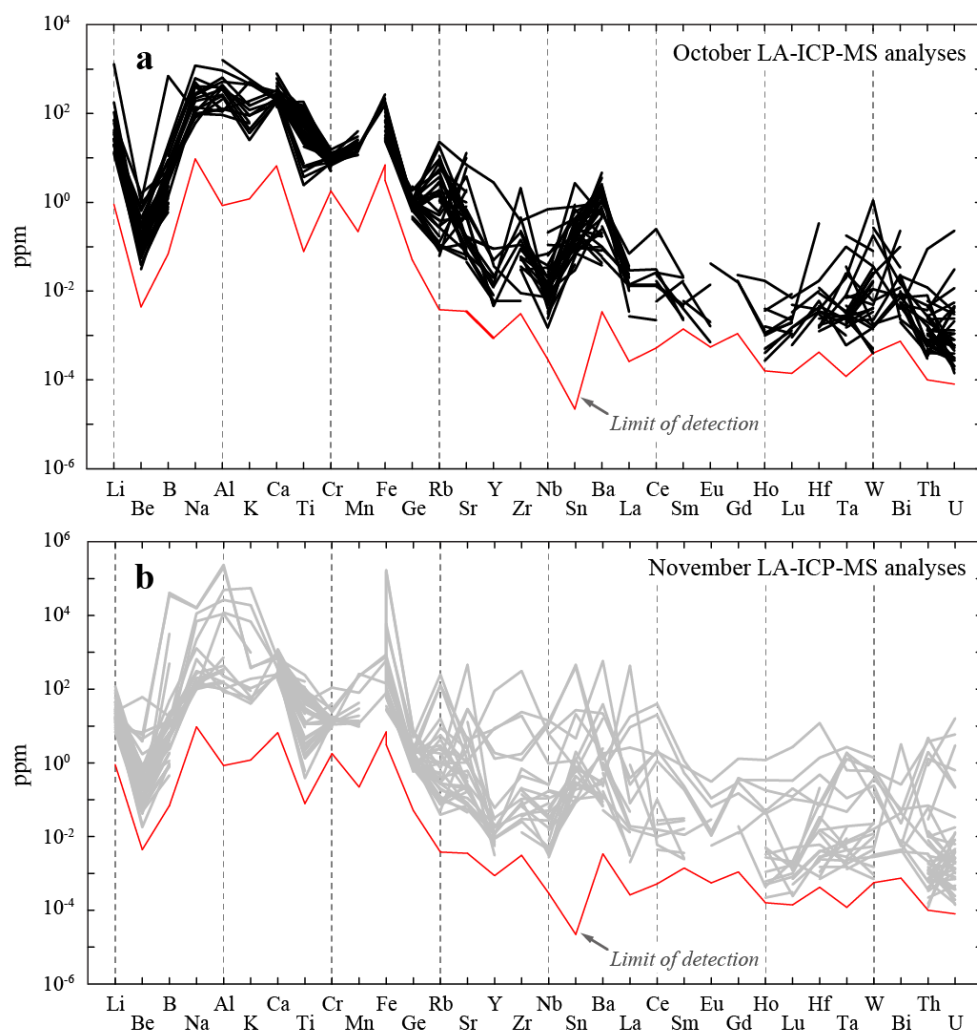
The trace elemental analyses acquired, during October and November 2020, using the Australian Scientific Instruments (ASI) Resolution 193 nm ArF excimer system coupled to a Thermo Scientific Fisher sector-field ICPMS (Element XR), returned accurate and precise values, within 5% deviation of the published concentrations of elements from the primary standard NIST 612 (Appendix Ga-1) (Jochum et al., 2011). The secondary standard NIST 614 (Gao et al., 2002) was also consistently within 5% deviation of published concentrations, however Sn from the secondary standard, Audétat-Qz (Audétat et al., 2015) is slightly more variable.

According to Audétat et al. (2015), the published Sn content of the Audétat-Qz standard is variable and inconsistent, due to erroneous signal caused by polyatomic interference of $^{38}\text{Ar}^{40}\text{Ar}^{40}\text{Ar}$ with ^{118}Sn . However, as the secondary standard NIST 614 consistently returned accurate measurements of ^{118}Sn , the use of Sn in the interpretation of quartz compositions is reliable yet limited as to avoid unrealistic interpretations, and the Audétat-Qz discrepancy is inconsequential.



Appendix Ga-1: Graphs illustrating the accuracy and precision of the LA-ICP-MS analyses, by comparing the average compositions of the primary (NIST 612) and secondary (NIST 614 and Audétat-Qz) standards to published values (Gao et al., 2002; Jochum et al., 2011; Audétat et al., 2015). (a) Ablation set run in October. (b) Ablation set run in November. Dashed lines indicate 5% deviation from the standard composition.

The concentrations for elements, when measured within the quartz, using the ASI Thermo Scientific Fisher sector-field ICPMS were above their respective limits of detection. This is illustrated for both the October and November ablation sets in Appendix Ga-2.



Appendix Ga-2: Graphs illustrating the limit of detection for each element compared to the measured concentration within the analysed quartz samples. **(a)** Ablation set run in October. **(b)** Ablation set run in November. Red line indicated limit of detection.

Appendix Gb: Quartz LA-ICP-MS trace elemental compositions from the Zaaipplaats tin field granites and hydrothermal pipe.

Point#	1-1	1-2	1-3	2-1	2-2	3-1	4-1	4-2	4-3	5-1	5-2	6-1	6-2	7-1	7-2	8-1
Sample	3119a	3119a	3119a	3119a	3119a	3119a	3119a	3119a	3119a	3119a	3119a	3119a	3119a	3119a	3119a	3119a
Lith.	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG	NG
⁷ Li	-	25.9000	19.6000	320	-	20.3000	22	-	-	28.4500	450	-	43	38	27.5000	-
⁹ Be	-	-	0.0390	-	0.0600	0.0750	-	-	-	-	-	-	0.0820	0.1550	-	-
¹¹ B	0.6900	-	1	3.5000	1.3400	0.7100	0.6500	0.8900	0.7980	0.4500	3.7000	1.9000	2.7700	3.2300	0.6800	0.8400
²³ Na	-	-	-	410	-	-	-	-	-	-	-	-	-	100	-	-
²⁷ Al	93	117	85.6000	120	113	82.8000	90	90	-	109	156	82	149	122.1000	99	82.9000
³⁹ K	-	-	-	-	-	-	-	-	-	-	-	-	-	190	-	-
⁴⁴ Ca	160	-	240	-	-	180	-	490	-	210	230	-	220	330	392	360
⁴⁹ Ti	144	170	98	180	139	108	132	121	114	152	50	118	56.6000	67	151	106
⁵² Cr	8.1000	-	-	10.4000	15.4000	9.4000	9.6000	9.2000	-	-	12.6000	13.1000	-	-	5.4000	10
⁵⁵ Mn	-	-	-	20	30.5000	-	-	-	-	-	21.9000	19	-	14	-	22
⁵⁴ Fe	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
⁵⁷ Fe	-	-	-	90	190	-	-	-	-	-	25	-	-	33	-	-
⁷² Ge	-	0.5600	0.7900	-	-	0.7600	0.4800	1.1200	-	-	-	-	0.9700	1.1800	0.6000	0.6200
⁸⁵ Rb	-	-	-	1.1000	0.2950	-	0.1100	-	1.9000	-	0.6300	-	0.2700	5.6000	-	2.9000
⁸⁸ Sr	0.0730	0.5700	0.2800	0.4600	0.8100	-	0.0650	-	-	-	10	-	0.0770	1.7000	0.9000	0.4600
⁸⁹ Y	0.0060	-	-	-	-	-	-	-	-	-	-	-	0.0080	-	0.0134	0.0047
⁹⁰ Zr	0.0060	0.0850	0.0130	-	0.0900	-	0.4600	0.0350	-	0.0360	-	-	-	0.0800	0.1600	-
⁹³ Nb	-	-	-	0.0079	0.0210	-	0.0040	-	0.0054	-	-	0.0047	-	-	0.0280	-
¹¹⁸ Sn	0.0790	0.0870	0.0700	0.3800	0.7000	0.0960	-	-	0.1150	-	0.2000	0.1850	-	0.3000	0.0470	0.1300
¹³⁷ Ba	0.2100	0.8200	0.2500	0.5900	0.5000	-	0.0900	-	-	-	3.6000	0.7300	0.6600	2.6000	0.0900	4.7000
¹³⁹ La	-	-	-	0.0290	-	-	0.0240	-	0.0170	-	-	-	-	-	0.0080	-
¹⁴⁰ Ce	-	-	0.0170	0.0310	0.0200	-	-	0.0260	-	-	0.0700	-	-	-	0.0410	-
¹⁴⁷ Sm	0.0010	0.0032	0.0024	0.0022	-	-	-	0.0200	-	-	-	0.0020	0.0030	0.0001	-	-
¹⁵³ Eu	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0140
¹⁵⁷ Gd	-	-	-	-	-	0.0170	-	-	-	-	-	-	-	-	-	-
¹⁶⁵ Ho	-	-	-	-	-	0.0013	-	-	0.0016	-	-	-	0.0005	0.0003	-	0.0010
¹⁷⁵ Lu	-	-	-	0.0011	-	-	-	-	-	0.0002	-	-	0.0013	-	-	0.0020
¹⁷⁸ Hf	-	-	-	-	0.0029	-	-	-	-	-	0.0046	-	-	0.0058	0.0040	-
¹⁸¹ Ta	-	-	-	-	-	-	-	0.0031	-	-	0.0023	-	-	-	0.0012	0.0047
¹⁸² W	0.0700	-	0.0021	0.2700	-	0.0240	0.0015	0.0014	-	-	0.0170	-	-	-	0.0001	0.0016
²⁰⁹ Bi	-	-	-	0.0340	-	-	-	-	-	-	-	0.0073	-	0.0190	-	0.0090
²³² Th	0.0008	-	0.0025	-	-	-	0.0001	-	-	0.0011	-	0.0016	0.0004	0.0006	0.0001	0.0047
²³⁸ U	0.0008	-	0.0005	-	0.0091	0.0011	-	-	-	0.0006	0.0150	-	-	-	-	-

Abbreviations and symbols: Below detection limit (-); Nebo Granite (NG); Bobbejaankop Granite (BG); Lease Granite (LG); and Hydrothermal Pipe (HP).

Appendix Gb: Quartz continued.

9-1 3119a NG	9-2 3119a NG	10-1 3119a NG	10-2 3119a NG	11-1 3119a NG	12-1 3119a NG	12-2 3119a NG	1-1 47-8b BG	1-2 47-8b BG	2-1 47-8b BG	2-2 47-8b BG	2-3 47-8b BG	3-1 47-8b BG	3-2 47-8b BG	4-1 47-8b BG	4-2 47-8b BG	4-3 47-8b BG
35	-	20	17.3000	21.3000	22.7000	-	-	-	-	-	-	-	-	-	-	-
-	-	0.0810	-	-	-	-	-	-	-	-	0.0900	-	-	0.2560	-	0.0310
2.5600	0.7800	0.6000	4.1000	0.5900	0.6630	0.7600	0.8200	0.6800	11	6.4000	0.9400	1.7800	0.5700	15.9000	3.7000	2.2000
-	-	-	120	-	-	-	-	-	500	260	-	-	-	-	-	-
133	92	85.2000	250	180	90	87	112	103.8000	110	520	106.1000	117.1000	115	121	132	101
-	-	-	-	-	-	-	-	-	510	450	-	-	-	-	-	-
-	225	-	190	330	240	-	-	240	230	310	330	271	170	228	190	155
122	98	153	82.7000	128.7000	135	155	60.7000	75.3000	60.1000	60	68.3000	71.6000	72.2000	54.5000	74	84
8.1000	6.6000	9.6000	7.2000	-	-	12.7000	9.9000	6.6000	-	-	6.5000	6.8000	8	6.4000	7.9000	-
-	-	-	-	16.5000	-	16	11.6000	-	50	41.5000	-	13.8000	-	-	-	-
-	-	-	-	-	-	210	-	-	-	-	-	-	-	-	-	-
-	-	-	-	171	-	-	-	-	41	240	-	24	-	185	50	-
0.4300	0.6600	0.5300	-	0.7900	0.9900	1.1000	0.7800	0.5600	1	-	0.8700	0.9000	-	0.9100	-	0.9900
0.0890	0.1260	-	1.1000	-	-	0.1040	-	-	18	11.3000	-	0.4000	-	0.1100	-	0.0900
0.5100	1.9000	-	0.1700	0.1700	2.2000	0.0520	-	-	0.5500	0.1490	-	-	0.0750	-	-	0.1200
0.0046	-	-	-	0.0900	-	-	-	-	-	0.0150	0.0030	-	-	0.0370	-	-
0.0900	0.0310	0.0550	0.0600	0.1100	0.0300	-	-	-	-	-	-	-	0.0200	0.0090	0.0300	0.0350
0.0150	0.0015	-	0.0051	0.0102	0.0340	0.2100	-	0.2100	-	0.2100	-	0.0110	-	0.0072	-	-
-	0.0580	0.0800	-	0.1300	0.1040	-	0.0690	-	0.1600	0.4300	0.0730	0.0970	0.0900	0.8900	0.1400	0.1500
0.4800	1.8000	-	1.8000	0.4400	0.1950	0.0800	-	-	1.8000	2.4000	0.0380	0.0820	-	-	-	-
-	0.0034	-	-	-	-	-	-	0.0027	0.0310	0.0139	-	-	-	-	-	-
-	-	-	0.0600	0.0240	-	-	-	0.0022	-	0.0260	-	-	-	0.0009	-	-
-	-	-	-	0.0040	-	-	-	-	-	-	0.0040	0.0037	0	0	0.0080	0.0060
0.0035	-	-	0.0042	0.0007	-	-	-	-	-	-	-	-	-	-	-	0.0020
-	0.0089	-	-	-	0.0120	-	-	-	0.0310	-	-	-	-	-	-	-
-	-	0.0004	-	0.0036	-	-	-	-	-	-	-	-	-	-	-	0.0004
-	-	0.0015	0.0015	0.0086	-	-	-	-	0.0022	-	0.0008	-	-	0.0049	-	-
-	0.0015	0.0035	0.0043	-	-	0.0044	-	-	-	-	-	-	0.0021	0.0038	-	-
0.0020	0.0250	0.0024	-	-	0.0016	-	0.0032	-	-	0.0081	-	-	-	0.0200	-	0.0021
0.0023	0.0060	0.0250	-	0.0051	-	-	0.0004	0.0070	-	0.1800	-	-	-	1.1000	-	0.0110
-	0.0120	-	0.0100	-	-	0.0045	-	-	-	0.0150	-	-	0.0020	0.0023	-	-
0.0003	-	0.0010	0.0003	0.0044	0.0014	0.0007	0	0.0011	-	0.0027	0.0005	-	0.0004	0.0008	0.0002	0.0060
-	0.0022	0.0045	0.0046	0.0116	0.0002	0.0006	0.0016	0.0002	0.0019	0.0055	0.0003	0.0004	0.0004	0.0006	-	0.0030

Appendix Gb: Quartz continued.

5-1	5-2	5-3	6-1	6-2	7-1	7-2	8-1	8-2	8-3	8-4	9-1	9-2	9-3	10-1	10-2	11-1
47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b	47-8b
BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG
-	-	280	20.6000	-	-	-	-	900	-	-	-	23.9000	-	-	-	-
-	-	-	-	0.1000	0.0670	-	0.1250	-	-	-	-	0.6500	0.9500	-	0.1700	-
0.6200	1.3600	-	1.4800	4.9100	0.9500	0.9500	1.2300	0.3400	0.7100	-	1.3000	8.1000	4.5000	0.8000	6	0.6700
-	140	-	-	-	-	-	-	-	-	-	-	220	60	-	80	-
112.4000	111	97	242	290	110.9000	125.8000	94	109.4000	81	114.9000	95	350	390	152	208	102.7000
-	-	-	-	-	-	-	-	-	-	-	-	44	120	-	-	-
-	-	310	-	180	170	270	-	178	220	-	-	220	190	800	-	-
67.6000	64.7000	74	33.4000	2.4400	77	59.3000	151	183	113	57.9000	68	36.1000	31.1000	73	4.9000	63.4000
-	11.3000	-	9.7000	7.8000	8.6000	9	9.5000	-	-	8.4000	10.2000	8.1000	9.8000	9.1000	10.9000	7
-	-	-	-	-	-	-	-	-	-	-	17.9000	19	24.5000	-	40	-
-	-	-	-	-	-	-	-	-	-	-	220	-	-	-	-	-
-	52	-	-	-	-	-	-	-	-	-	-	90	110	-	-	-
-	1.3600	-	1.2200	1.1000	-	-	-	-	1.0200	1.0500	1.1300	1.1500	1.1800	1.2000	1.8900	0.5400
-	0.2700	0.0620	-	-	-	-	0.2500	-	0.1700	-	0.3900	1.4000	3.7000	-	4.8000	-
-	13	6	-	-	0.2100	-	-	-	-	0.0380	0.4500	0.4200	0.1600	-	0.1200	0.6300
-	-	-	0.0140	-	-	-	-	-	-	-	-	-	0.0900	-	0.0120	-
29	-	0.0500	2.1000	-	-	0.2100	0.2400	0.0540	-	-	0.0320	-	-	0.0830	-	-
-	-	0.0700	0.0070	-	0.0111	0.0060	-	0.0110	0.0370	0.0166	-	-	0.0270	0.0380	-	0.0120
0.0900	-	0.1800	0.0710	0.0500	-	-	-	-	-	0.1670	-	-	0.1000	0.6000	0.2500	0.0660
0.1000	0.0700	0.0430	-	-	-	-	-	-	-	-	-	0.2500	0.7100	1.4000	0.1700	1.2000
-	-	-	-	-	-	-	-	-	-	-	-	-	0.0140	0.0200	-	-
-	-	-	-	-	-	-	0.0079	-	-	-	-	-	0.0140	-	-	-
-	-	0.0050	0.0010	-	0.0100	0.0076	-	0.0270	-	-	-	0.0025	0.0049	-	-	-
-	0.0140	0.0140	-	-	-	-	0.0120	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	0.0170	-	-	-
-	-	-	-	-	-	-	-	0.0016	-	-	-	0.0005	0.0011	-	-	-
0.0001	0.0009	-	-	-	-	0.0014	-	0.0011	0.0033	-	-	-	0.0027	-	-	-
-	0.0060	0.0006	0.0026	-	-	-	0.0009	-	0.0100	-	0.0017	0.0015	-	0.0140	-	-
0.0015	0.0006	-	-	0.0030	0.0027	-	-	-	-	0.0034	0.0026	0.0080	0.0020	-	-	0.0017
0.0034	0.0015	-	-	-	0.0260	-	0.0015	-	-	0.0340	0.0040	0.0049	-	-	-	-
-	-	0.0220	-	-	-	0.0056	-	-	-	-	-	0.2300	0.0150	-	-	-
0.0010	0.0010	0.0120	-	0.0002	0.0010	0.0006	0.0120	0.0007	0.0013	0.0045	0.0007	-	-	0.0004	0.0004	0.0015
-	-	0.0034	0.0006	-	0.0006	-	-	0.0011	-	-	0.0003	0.0043	-	0.0021	0.0003	0.0003

Appendix Gb: Quartz continued.

1-1	2-1	3-1	3-2	4-1	4-2	5-1	5-2	6-1	6-2	7-1	8-1	8-2	9-1	10-1	10-2	11-2
47-7	47-7	47-7	47-7	47-7	47-7	47-7	47-7	47-7	47-7	47-7	47-7	47-7	47-7	47-7	47-7	47-7
BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG
-	-	-	-	-	-	-	-	-	-	-	-	-	33.8000	-	-	-
-	-	-	-	-	0.0400	0.1100	-	-	-	-	-	-	-	0.3050	-	-
0.6400	4.4000	0.8900	0.6000	0.8900	0.8100	2.8000	0.8500	0.6300	6.9000	110	0.8850	-	1.8200	0.9500	0.5200	-
-	90	-	-	-	-	99	-	-	-	-	-	-	-	-	-	-
114.2000	130	123.9000	118.3000	111	112.4000	93.4000	93	100.3000	147	112	126.1000	124	315	244	120	-
-	-	-	-	-	-	60	-	-	-	-	90	-	-	25.2000	-	-
166	210	320	330	-	280	-	170	180	150	140	220	620	-	185	-	195
80.5000	86	56.6000	58.3000	102	80.6000	93.6000	96	71.4000	80	89	67.3000	50.6000	42	65	65.3000	59.6000
5	8.4000	7.1000	-	10.2000	10.3000	9.5000	8.1000	7.6000	7.2000	-	5.9000	-	9.2000	5.1200	7	6.7000
-	19.1000	-	-	-	-	17.7000	14.4000	-	-	51	-	-	-	-	-	-
-	-	-	-	-	-	159	-	-	-	-	-	-	-	-	111	-
-	26	-	-	-	-	-	120	-	170	160	-	-	-	66	-	29
0.7900	0.6400	-	-	1.1900	0.8200	-	-	0.8300	0.8100	1.1100	0.7000	0.6680	1.1300	1.0300	1.1000	1.1500
0.0800	1.6000	0.1800	-	-	-	2.7300	1.4000	-	-	1.4000	-	1.9000	-	0.5100	-	-
-	0.1700	-	0.0700	0.1500	-	0.0590	0.0840	0.7000	0.0460	-	-	-	0.0420	3.8000	0.0310	0.0900
0.0071	0.0230	0.0070	0.0200	-	-	-	-	-	0.0059	-	0.0140	-	-	0.0390	-	-
-	-	-	0.3800	0.0530	0.0570	-	-	-	-	-	-	-	-	-	-	-
0.0024	-	-	-	-	-	-	0.0150	-	-	-	-	-	0.0031	0.0313	-	0.1100
0.2300	0.3300	0.8000	0.8000	0.2600	-	-	-	0.2500	0.5500	0.0780	0.0960	0.1298	0.0400	0.0810	-	0.1000
0.0600	-	-	-	0.1700	0.1400	0.1700	0.1500	-	-	-	-	2.4000	-	1.1800	-	-
-	-	-	-	-	-	-	-	-	-	0.0070	-	-	-	-	-	-
-	0.0140	0.0045	-	0.0240	-	-	-	-	-	-	-	-	-	0.0022	-	0.0460
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.0028	0.0072	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	0.0013	0.0007	-	-	-	0.0016	-	0.0003	0.0012	-	-	-	-	0.0012	-	-
-	-	-	-	-	0.0022	-	0.0006	0.0011	-	-	0.0020	0.0027	0.0026	0.0019	-	-
0.0012	-	-	-	-	0.3400	0.0030	0.0034	-	-	-	-	-	-	-	-	-
0.0025	-	-	-	-	-	0.0010	0.0017	-	-	-	-	-	-	0.0360	0.0024	0.0024
-	-	0.0120	-	0.0044	-	-	0.0160	-	-	-	-	-	0.0022	0.0018	0.0005	-
-	0.0071	-	-	-	0.0057	0.0077	-	-	-	0.0430	-	-	0.0230	0.0028	-	-
0.0013	-	0.0006	0.0016	0.0003	0.0003	-	0.0048	-	-	-	-	-	0.0006	-	-	-
0.0013	0.0028	-	-	-	-	-	0.0005	0.0080	0.0020	-	-	-	0.0003	0.0034	-	0.0004

Appendix Gb: Quartz continued.

1-1	1-2	2-1	2-2	3-1	4-1	4-2	5-1	6-1	6-2	6-3	6-4	7-1	7-2	8-1	9-1	9-2
15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4
BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG	BG
14.3000	10.5000	13.9000	8.8000	38	18.6800	9.9000	23.3000	-	13.3000	16.7000	22.7000	13	44.4000	19.1000	13.5700	13.3000
-	0.1800	-	0.0360	0.2180	-	-	0.0930	-	-	0.0180	0.1080	-	0.2870	-	-	-
-	4.7000	1.0300	11	2.7700	34	3.3000	9.1000	-	1.0800	0.9700	4.4300	-	2.9000	1.4100	0.7900	-
-	-	-	510	-	-	-	160	-	-	-	-	-	-	-	-	-
-	117	109.3000	157	231	152.2000	117.6000	155.9000	-	105.8000	110	145.6000	107	291	-	103.2000	105
-	-	-	280	-	-	-	600	-	-	-	-	-	-	-	-	-
-	320	289	320	245	790	430	460	-	412	400	360	170	360	-	290	250
87	80	85	75.3000	30.7000	81.2000	50.9000	27.8000	78.9000	76.6000	58.6000	1.3200	74	30.5000	54.5000	162	104
12.1000	14.5000	-	12.6000	11	11.8000	12.3000	12.5000	-	10.2000	9.2000	9.6000	11.6000	-	12.6000	-	13.7000
-	-	-	23	-	-	-	88	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
100	73	60	-	-	250	61	100	-	-	-	-	-	-	-	-	-
0.9600	0.7500	0.7000	-	1.4300	0.9700	0.8900	0.7800	0.7700	1.3000	0.8000	1.0600	-	1.8630	1.2000	0.4300	0.9600
-	0.5400	0.0830	3.6000	-	-	-	18	-	-	-	-	-	0.1800	0.0390	-	-
0.4800	-	0.2500	0.3500	-	-	1.8000	1.5000	-	0.0840	-	0.1260	0.0340	0.1100	0.0700	0.0417	-
-	-	0.0061	-	-	-	-	-	-	-	0.0092	-	-	0.0210	-	-	-
0.0730	-	-	0.0490	0.0130	0.0660	-	0.0230	0.3200	0.0350	0.0300	0.0940	-	-	-	0.0635	-
-	0.0450	-	0.0054	0.0044	0.0170	0.0044	0.0058	-	0.0800	0.0270	0.0031	-	0.1800	-	-	-
0.0570	0.1900	0.2700	0.0970	-	1.2800	0.2900	0.0410	-	-	0.4400	-	0.1500	0.1160	0.1040	0.0810	0.0690
-	0.2700	0.1050	1.7000	-	-	0.1300	3.4000	0.1400	0.0700	-	0.1200	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	0.0180	-	-	-	-	-	-
-	-	-	0.0130	-	-	-	-	0.0110	-	-	1.4000	0.0600	-	-	-	-
-	-	-	-	-	-	0.0110	-	-	-	-	-	-	-	-	0.0033	-
-	-	0.0029	-	-	-	0.0290	-	0.0060	-	-	0.0046	-	-	0.0070	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	0.0005	0.0001	0.0004	-	-	0.0022	-	0.0042	-	-	0.0016	0.0004	-	-	-
-	0.0015	0.0008	0.0016	-	-	0.0005	0.0026	-	-	0.0009	-	-	0.0021	-	-	-
0.0380	-	0.0041	-	0.0015	0.0150	0.0022	0.0003	-	0.0027	-	-	-	0.0008	-	-	-
-	-	0.0028	-	0.0015	0.0044	-	-	0.0230	-	0.0045	-	-	0.0180	-	-	0.0015
0.0046	0.4400	0.0240	-	0.0007	0.0009	-	2.7000	-	0.0120	-	-	0.0021	-	0.0080	0.0016	-
-	-	-	-	-	-	-	0.0090	-	-	-	-	-	-	-	-	-
-	0.0012	0.0030	0.0004	0.0011	0.0002	0.0006	0.0007	-	0.0012	-	0.0002	0.0018	0.0010	-	0.0006	0.0001
-	0.0008	0.0021	0.0005	0.0004	0.0005	0.0007	0.0012	0.0017	0.0120	0.0022	0.0038	0.0014	0.0025	-	-	0.0130

Appendix Gb: Quartz continued.

9-3	10-1	10-2	11-1	11-2	12-1	12-2	13-1	13-2	1-1	1-2	2-1	2-2	3-1	3-2	4-1	4-2
15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	15-4	47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2
BG	BG	BG	BG	BG	BG	BG	BG	BG	LG	LG	LG	LG	LG	LG	LG	LG
11.2000	12	9.6800	18	15.7000	16.8000	28	7.7000	11.9400	-	14.5000	-	-	8.8600	17.3000	-	-
-	-	-	0.0660	0.0480	-	1.7300	-	-	-	-	-	0.5500	6.7000	0.5380	-	0.0700
1.0500	5.3000	2.3000	3200	0.4600	-	5	2.5000	1.6440	3.1000	-	1.1500	23	13.8000	18.9000	-	0.8500
-	650	159	-	-	-	7000	130	-	-	-	-	120	11300	-	-	-
240	84	95	110	112.1000	-	11100	101.6000	118	-	108	131.8000	164	26400	196.6000	-	116
-	58	40.6000	-	-	-	980	190	-	-	-	-	-	19000	-	-	-
900	250	290	185	220	-	-	250	-	-	290	700	280	346	280	-	600
70	113	86	103	81.9000	50	26.4000	89.8000	66.6000	44	54.2000	60	4.3000	24.2000	4.8200	59.5000	73.4000
-	-	-	13.1000	12.8000	13.7000	14.5000	13.8000	13.5000	110	13.7000	-	14	11	13.4000	14.4000	16.7000
-	-	-	19	-	-	-	13	-	80	7.4000	-	11	12	-	-	9.6000
-	-	-	-	-	-	-	-	-	600	71	-	-	79	-	-	-
-	-	66	150	-	-	350	-	24	-	-	-	35	830	-	-	-
1.0800	0.8500	0.5800	-	-	0.8900	1.5400	0.6300	-	2.9000	0.9700	1.1500	1.3600	1.5600	1.6300	0.9300	1.0600
0.2800	2.6000	4.4000	0.0500	-	-	16	9	0.6100	-	-	0.2000	0.4700	130	-	-	0.0970
0.1900	1.1200	0.2200	4.9000	-	-	0.2600	2.4000	0.0710	-	-	0.0700	-	1.1500	0.0710	-	0.0550
-	0.0174	-	-	-	-	0.0320	0.0031	0.0060	-	-	0.0110	-	8.8000	-	-	0.0080
0.1800	0.2100	-	-	-	0.0330	0.1050	-	-	0.8000	-	0.7000	-	19	-	-	-
0.0370	-	0.0900	-	0.0700	-	0.1090	0.0150	-	-	0.0031	0.2500	-	0.9600	0.0027	-	0.0190
-	-	-	-	-	0.0810	0.2300	0.0950	0.2000	-	11	-	0.0840	1.1700	0.2300	0.3400	-
0.5400	1.0400	0.1400	0.2200	-	-	1.8000	2.5000	-	-	-	-	-	39	-	-	-
0.0030	-	-	-	-	-	2.6000	-	-	-	-	-	-	0.2570	-	-	0.0020
-	0.0075	-	0.0600	0.0044	-	1.6100	0.0068	-	-	-	0.0370	0.0360	2.1900	0.1800	-	0.1000
-	-	-	-	0.0036	-	-	-	-	0.0700	0.0080	-	-	0.2300	-	0.0110	0.0025
-	0.0050	-	-	-	-	0.0095	-	-	-	0.0017	-	0.0025	0.0136	0.0057	-	-
-	-	-	0.0120	0.0120	-	-	-	0.0140	-	-	-	-	0.3900	0.0130	-	0.0190
0.0033	-	0.0050	0.0470	-	-	0.0011	-	-	-	-	0.0041	-	0.1800	-	0.0049	0.0004
0.0050	-	0.0014	0.0012	0.0007	-	0.0017	-	-	0.0052	-	-	-	0.1210	-	-	-
0.0060	-	-	0.2100	0.0039	-	0.0150	-	-	-	-	-	0.0006	0.4800	0.0024	0.0036	-
0.0019	0.0067	-	-	0.0075	-	0.0190	0.0013	-	-	-	-	-	0.1100	0.0022	-	0.0026
-	0.0120	0.1600	-	0.0160	-	0.0220	0.0032	0.0008	-	-	0.0014	0.0049	0.2400	-	-	0.0015
-	-	0.0064	-	0.0440	-	-	0.0044	-	-	-	-	3.2000	0.0055	-	-	-
0.0140	-	0.0006	0.0008	0.0060	-	0.0098	0.0004	0.0080	0.0060	-	0.0010	0.0100	1.2800	0.0010	-	0.0016
0.0019	-	0.0002	0.0004	0.0013	-	0.0177	0.0041	0.0010	-	0.0001	0.0046	0.0062	0.6300	0.0004	0.0012	-

Appendix Gb: Quartz continued.

5-1	5-2	6-1	6-2	6-3	7-1	7-2	8-1	8-2	8-3	8-4	9-1	9-2	10-1	11-1	13-1	13-2
47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2	47-2
LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG
16.8000	26	12.7000	7.6000	29.2000	-	9.1000	8.4000	-	10.9000	28.9000	-	-	-	12.5000	-	7.1000
0.1370	0.8200	0.0210	-	-	-	-	0.0610	0.0900	0.4500	0.2460	-	-	0.7400	0.6200	-	0.0415
3.3900	9.8000	-	0.9500	1.2700	16	1.1200	0.8700	2.1000	16.7000	4.9800	-	-	49	13.3600	3	500
-	270	-	-	-	160	-	-	-	310	-	-	-	1280	-	-	-
198.9000	430	147	123.1000	286	350	163.6000	111	135	153	282	128	123	220	205	114	118
-	62	-	-	-	-	-	-	-	-	-	-	-	106	-	-	-
260	-	-	200	-	298	-	530	1300	270	280	-	280	220	257	250	451
21.2000	2.5300	62	52.7000	39.6000	43.0600	42.7000	77	64	11.3000	12.2000	75	50.9000	29.4000	9.2000	46.9700	65.1000
-	18	-	10.8000	16.2000	-	15.7000	10.9000	-	11.7000	40	14.4000	-	-	-	-	-
-	10.7000	-	-	-	-	43	-	-	30	-	-	-	24.4000	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
29	230	-	-	-	-	-	-	-	170	-	-	-	530	-	-	-
1.8400	2.1100	1.0200	0.8400	1.4400	0.6600	1.2200	0.6600	0.7930	2.4100	1.4100	0.9100	1.0900	1.6900	1.8300	0.6700	0.6200
2.4000	2.9800	-	0.1020	-	0.9700	0.1200	-	-	1.8000	0.0950	-	-	5.6000	-	-	0.4100
0.3900	0.3100	5	0.2200	-	1.0300	-	-	0.0540	0.1600	-	-	13	0.9700	0.1400	-	0.6100
-	-	0.0290	0.0055	-	-	0.0090	-	0.0100	-	-	0.0087	0.0070	0.0600	-	-	0.0180
-	-	-	-	-	-	-	-	-	0.0260	-	0.0250	-	0.4400	-	-	0.0401
-	0.0088	0.0031	0.0024	0.0250	6	0.0025	-	0.0050	0.0050	0.0150	-	0.0060	0.2600	-	0.0075	0.0509
-	-	0.4400	-	-	0.7000	-	-	0.1200	0.0850	0.3000	-	-	21	0.8000	2	0.7000
0.1700	0.4200	0.0870	0.1700	0.2300	0.2900	-	-	-	0.3800	-	-	-	1.8000	0.2800	0.1151	0.0650
-	-	-	0.0038	430	-	-	0.0027	-	-	-	-	-	0.0190	-	-	-
-	-	-	-	0.0060	0.0160	-	-	-	-	-	-	-	0.0154	-	0.0064	0.0270
-	-	-	0.0800	0.0024	-	-	0.0015	-	0.0250	0.0015	-	-	0.0111	-	-	0.0312
-	-	-	-	-	-	-	-	-	-	-	-	0.0180	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	0.0003	-	0.0023	0.0006	-	-	0.0013	0.0015	-	-	0.0006	0.0027	0.0050	-	-
-	-	-	-	-	0.0010	-	-	-	-	0.0020	-	-	0.0021	0.0003	0.0002	-
0.0021	-	0.0036	-	0.0027	0.0237	-	0.0015	0.0030	0.0002	-	-	-	0.0800	-	0.0029	0.0011
-	0.0029	-	0.0024	0.0043	1.9000	-	-	-	-	-	-	-	0.0470	-	-	0.0089
-	-	-	0.0028	0.0054	0.1040	-	0.0017	0.0004	-	0.0004	0.0009	0.0039	0.3700	0.0063	0.0090	-
-	-	-	0.0039	-	-	-	-	0.0077	-	-	-	-	0.0550	-	-	-
0.0013	0.0004	0.0003	0.0034	0.0015	0.0290	0.0120	0.0004	0.0005	0.0019	0.0012	-	0.0007	0.0690	0.0014	-	0.0061
-	0.0020	0.0011	0.0001	0.0002	2.9800	0.0020	-	0.0003	0.0007	0.0002	0.0002	0.0082	0.0330	0.0004	0.0004	0.0019

Appendix Gb: Quartz continued.

1-1 47-6 LG	2-1 47-6 LG	2-2 47-6 LG	3-1 47-6 LG	4-1 47-6 LG	4-2 47-6 LG	5-1 47-6 LG	5-2 47-6 LG	6-1 47-6 LG	6-2 47-6 LG	7-1 47-6 LG	7-2 47-6 LG	8-1 47-6 LG	8-2 47-6 LG	9-1 47-6 LG	9-2 47-6 LG	10-1 47-6 LG
61	27.7000	-	-	-	18.6000	71	-	12.7000	13.8000	20	27	108	1300	180	34.3000	26.5000
0.2800	0.3300	-	-	0.6400	0.2230	1.5700	0.1700	0.0550	0.2050	0.1500	0.3200	0.0800	1.0100	0.1400	0.4300	0.1180
2.4200	3.8300	1.2000	2.2900	15.7000	2.8000	5.1900	6.1000	1.5600	4.7500	4.4000	2.9200	2.2900	700	2.3500	9.1000	1.7500
-	-	-	-	620	-	-	190	-	-	410	-	-	110	-	-	-
401	228	41	253	340	308	571	266	193.8000	185	390	321	830	439	283	1600	213
-	-	-	-	160	-	-	36	-	-	63	-	-	90	-	600	-
-	280	410	220	-	900	-	180	230	310	-	190	180	170	420	230	290
26	7.4000	-	20.8000	6.5000	18	18	6.1000	27	3.7000	31.6000	23.2000	72.5000	29.2000	26.7000	41.2000	25
8.2000	-	-	9.5000	10.2000	10.1000	10.4000	8	7	7.3000	9.6000	9.2000	9.4000	8.5000	-	7.9000	6.8600
-	-	-	-	26	-	-	18.8000	-	-	18.1000	-	-	17.5000	-	11.9000	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	71	-	-	130	-	-	-	-	170	-	-	150	-
1.8000	1.0600	1.9000	1.1300	0.8000	0.8900	2.3000	0.7700	1.3400	1.4000	-	-	-	1.1200	1.1300	1.1200	1
-	-	-	-	8.1000	0.3800	0.5900	2.7000	-	-	1.8000	-	0.1540	1.8000	-	23	-
-	-	-	0.3300	0.5900	0.0910	-	0.6900	-	-	0.0940	-	-	1	-	7	0.0900
-	-	-	-	0.0490	-	-	0.0500	0.0140	0.0140	-	-	0.0125	-	-	2.8000	-
0.1000	-	-	0.2300	-	-	-	0.2100	-	-	0.0360	0.1100	0.1430	0.0600	-	0.3800	-
-	-	-	0.0120	0.0630	-	-	0.0200	-	-	0.0100	-	0.0084	0.0210	0.0034	0.7000	-
1.5000	0.0710	-	-	0.4100	0.0860	-	0.1700	-	0.4000	0.0290	-	0.3000	-	0.1400	0.8000	-
-	-	-	0.2900	1.4000	0.2400	-	2.3300	-	-	0.4800	0.3000	0.1000	0.0570	-	1	-
-	-	-	0.0120	0.0360	-	-	0.0100	-	0.0044	-	-	0.0200	0.0130	-	0.0700	-
0.0058	-	0.0077	-	-	0.0700	-	-	-	-	-	0.0440	-	0.0130	-	0.2500	-
0.0170	-	-	-	0.0120	-	0.0037	0.0150	0.0032	-	-	-	-	0.0045	-	0.0210	0.0015
-	-	-	-	-	-	-	0.0016	-	-	-	0.0420	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	0.0160	0.0140	-	-	0.0230	0.0070
-	-	0.0022	0.0014	0.0040	-	-	-	-	0.0001	-	-	-	-	0.0001	0.0170	-
-	-	-	-	0.0022	-	0.0007	-	-	-	-	-	-	-	-	0.0070	0.0001
0.0119	-	-	-	-	0.0001	-	-	-	-	0.0066	0.0025	0.0090	-	-	0.0170	0.0004
0.0032	-	0.0033	-	0.1800	-	-	0.0070	0.0019	0.0015	-	-	0.0035	0.0028	-	0.1000	-
-	-	-	0.0015	0.0800	-	-	0.0110	0.0042	-	-	0.0009	0.0004	-	-	0.0360	-
-	-	-	0.0071	-	0.0050	0.0049	0.0077	-	-	-	-	-	-	-	0.0040	0.0050
0.0013	-	0.0049	0.0080	0.0029	-	0.0020	-	-	-	0.0005	-	0.0017	0.0019	0.0004	0.0890	0.0037
0.0011	0.0008	-	0.0001	0.0005	0.0009	0.0008	-	-	0.0020	-	0.0002	0.0002	-	0.0042	0.2300	0.0310

Appendix Gb: Quartz continued.

10-2	11-1	11-2	1-1	3-1	3-2	4-1	4-2	4-3	5-1	6-1	6-2	8-1	9-1	9-2	10-2
47-6	47-6	47-6	3991	3991	3991	3991	3991	3991	3991	3991	3991	3991	3991	3991	3991
LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG	LG
27	22.7000	73	19.1000	14.1000	18.3000	46.1000	-	29.2000	22.8000	29.5000	32.2000	-	15.5000	26.1000	20.6000
0.7600	0.1120	0.3000	0.0710	0.0770	0.1000	0.8000	2.7300	0.7100	0.0550	0.8730	0.7600	-	0.0430	0.3400	0.5020
7.9000	5.8100	20	0.8000	0.8200	1.8900	4.1000	3.2800	4.9400	0.8930	6.4000	5.2500	-	4.7000	1.1400	4.4500
281	260	1200	-	-	-	-	-	-	-	140	-	-	100	-	-
640	250	930	157	148.6200	230	317	92	196	149	321	280	-	151	221	220
150	57	470	-	-	90	-	-	-	-	-	-	-	49	-	-
280	2700	200	-	-	-	1100	230	400	300	-	257	-	1200	1200	190
24	21.4000	50	57.6000	45	25.3000	11.5000	44.4000	2.4300	56.2000	3.8000	2.6000	53	54.8000	38.5000	3.3000
9.6000	8.1000	-	14.7000	12.3000	15	14.7000	22.3000	14.5000	11.5000	-	16.7000	16.1000	13.3000	-	12
14.3000	13	-	-	-	-	-	-	-	-	-	-	-	14	-	-
270	160	-	-	-	-	-	280	-	-	-	-	-	-	-	-
-	230	28	-	-	-	-	6500	-	-	-	-	-	110	-	-
-	1.7700	1.8300	0.9600	0.9400	1.1300	1.6400	1.0700	1.4800	1.0700	2.2200	1.2000	1.2800	1.0900	0.9000	1.4300
6.9000	3.8000	9.4000	-	-	-	-	0.1880	-	-	0.9900	-	1.0100	1.0400	0.0730	0.1200
0.4300	0.2500	0.5200	0.2200	-	0.0800	-	0.1210	0.0350	-	0.4500	-	-	460	0.1660	0.0450
-	-	-	-	-	0.0130	0.0124	7.8000	-	-	-	-	-	0.0103	0.0120	-
-	-	0.0910	-	0.1400	0.0720	-	59	0.0280	-	-	0.9000	-	-	0.0840	-
0.0132	0.0044	0.0155	0.0052	0.0310	0.1700	0.1100	57.1000	-	0.0032	-	-	-	0.0150	-	-
0.2800	0.4500	0.7000	0.1030	0.4300	0.0850	-	1040000	-	1.2500	-	0.2600	-	-	-	0.5000
0.9900	0.2100	0.1720	0.1280	-	-	-	1.2600	-	0.0700	-	-	-	0.0840	0.9500	-
-	-	-	0.0160	-	-	-	1.7100	-	-	-	-	0.9000	-	0.0170	-
-	0.0150	-	0.0100	-	-	-	6.6200	-	-	-	0.0210	0.0090	0.0520	-	-
-	-	0.0090	0.0163	-	-	-	1.9700	-	-	-	0.0270	-	-	-	-
0.0090	-	-	-	-	-	0.0070	0.1390	-	-	-	-	-	0.0060	-	0.0094
-	-	-	-	-	-	-	2.0900	-	-	-	-	-	-	-	-
0.0140	0.0004	-	-	-	0.0002	-	0.6600	-	-	-	-	-	-	-	-
-	-	-	-	-	0.0003	-	0.2090	0.0033	-	-	-	-	0.0012	-	-
0.0024	0.0001	0.0060	0.0017	0.0120	-	-	5.3000	-	-	0.0055	0.0027	-	0.0340	-	0.0019
0.0028	0.0028	-	-	0.0015	-	-	5.3900	0.0022	-	-	0.0064	-	0.0049	0.0042	-
0.0240	0.0080	-	0.0150	-	-	-	52	0.0100	-	-	-	-	-	-	0.0100
0.1000	0.0037	-	-	-	0.0044	-	0.0164	-	-	-	-	-	0.0080	0.0039	-
-	0.0007	0.0023	0.0007	-	-	-	6.6000	0.0011	0.0020	0.0005	-	-	0.0021	0.0600	-
0.0010	0.0014	0.0024	-	0.0024	-	-	23.2000	-	-	-	-	0.0100	0.0027	0.0025	-

Appendix Gb: Quartz continued.

10-3 3991 LG	11-1 3991 LG	12-1 3991 LG	12-2 3991 LG	2-1 3979 HP	4-1 3979 HP	6-1 3979 HP	6-4 3979 HP	6-5 3979 HP	6-6 3979 HP	7-2 3979 HP	7-3 3979 HP	8-1 3979 HP	8-2 3979 HP
23	9.4000	60	-	95	47	142	120	81	48.9000	44	17	45.8000	13.4000
0.6600	0.2600	0.2610	-	0.3500	-	-	0.5100	0.1950	-	-	-	0.0900	0.0660
4.1300	2.5200	2.8900	-	6.7000	-	-	11	6.6770	3.9900	-	2.5000	4.5200	1.8400
-	-	-	-	-	-	-	100	-	-	-	-	200	-
187.5000	112	322	80	580	-	-	730	530	490	-	128.9300	288	145
-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	220	275	-	420	-	-	350	1100	290	-	254	180	184
2.1800	1.5400	13.7000	-	-	-	-	1.4000	1.7400	0.3900	7	0.6000	1.7000	-
16.2000	14.3000	-	-	-	-	18.7000	-	-	13.1000	-	-	11.2000	7.4600
-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	27	-
1.2700	1.1300	1.7100	1.7100	2.4000	1.6000	1.8800	3.3000	1.5900	1.5000	1.3560	1.1780	1.8990	1
-	-	-	-	-	0.2900	-	0.2700	-	-	-	-	-	0.2710
-	-	0.0890	80	-	2.2000	-	0.2300	-	0.2300	-	-	-	0.0810
-	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	0.0200	-	0.2800	-	-	0.2000	-	3.7000	-	-	-
-	0.0045	0.0050	-	-	-	-	0.0620	0.1200	-	-	-	-	0.0042
-	-	-	2.3000	-	-	-	0.5900	-	-	-	-	-	-
-	-	0.0520	-	-	0.1400	0.0972	16	0.0560	0.5400	-	0.1206	-	1.0200
-	-	0.0130	0.0150	-	-	-	-	-	-	0.0060	-	-	0.0470
-	-	-	-	-	-	-	-	0.0360	-	-	0.0080	-	-
0.0039	-	-	0.0210	0.0120	-	0.0350	-	-	-	-	-	0.0210	-
-	-	0.0069	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	0.0128	-	-	-	-	-
-	-	0.0011	0.0013	-	-	-	0.0018	-	-	-	-	0.0011	-
-	-	-	-	-	-	-	-	-	-	-	-	-	-
0.0011	0.0051	-	-	-	0.0065	-	0.0095	-	-	-	-	0.0007	0.0150
-	-	-	-	-	-	-	-	-	-	-	-	0.0018	-
-	-	0.0080	-	-	0.0091	-	-	-	0.0008	-	-	0.0045	-
0.0029	-	-	-	-	-	-	-	-	-	-	-	-	-
-	-	0.0001	-	-	-	-	-	-	0.0007	-	-	-	-
0.0048	0.0050	-	0.0015	-	-	-	0.0009	0.0003	0.0013	-	-	-	0.0001