

Metallogeny of the Boschhoek base metals occurrence and its geological context
with respect to the polymetallic mineralization of the Stavoren Fragment of the
Bushveld Complex, South Africa

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for the degree of Master of Science**

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DECLARATION

I declare that this thesis is my own unaided work, conducted under the supervision of Professor Paul, A.M. Nex. Any data sourced somewhere has been accordingly referenced and acknowledged. It is being submitted for the degree of Masters of Science in Geology at the University of the Witwatersrand, Johannesburg and has not been previously submitted for any degree or examination at any other university.

Signature of candidate:

A handwritten signature in black ink, appearing to read 'Rames Chauke', is written over a horizontal dotted line.

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ABSTRACT

The Boschhoek Prospect is an epigenetic mesothermal copper, lead, zinc and silver deposit within repeatedly fractured Nebo granite of the Lebowa Granite Suite. The Prospect is exposed as hilly gossanous bodies that grade vertically downwards into siderite-calcite-quartz veins system. Similar deposit occurred at Mutue Fides Tin deposit comprising predominantly of tin and fluorite within miarolitic Bobbejaankop granite. These deposits are associated with local scale structures and they are spatially separated by a regional sinistral strike-slip Wonderkop Fault. The study examines the spatial relationships and possible structural control the Wonderkop Fault bears on local scale structures. It investigates metallogeny of base metals and evaluates the petrological character of the Boschhoek Prospect in relation to the Mutue Fides deposits.

Extensive fieldwork characterising tectonic structures and structural analysis in the study areas suggest strong link between the Wonderkop Fault and the local scale structures. In syn- and post-BIC intrusion period, the northeast-southwest striking Wonderkop Fault underwent a compressional event directed at northwest-southeast that resulted in splay morphologies on the Transvaal inliers and the felsic plutonic bodies along the fault. Several warping events and rheological failures in response to this reactivation created small-scale faults and veins adjacent to the fault that are associated with polymetallic deposits. The local scale structures mimic morphologically and geodynamically the regional scale Wonderkop Fault.

Petrographic studies show pervasive sericitization of the Nebo granite is characteristic of mineralised zones. The varied nature of siderite-calcite-quartz-hematite veins suggest metalliferous fluids emanate from numerous sources including the LGS, the nearby inliers and the connate waters. Greisenization and albitization characterises the mineralised zones in the Bobbejaankop granite. The metals source emanate from magmatic-hydrothermal fluids concentrated in cupolas.

Geochemistry results suggest that the Nebo and Bobbejaankop granite are cogenetic and possibly share the same continental source as ascertain by normalised La/Yb ratios. The Bobbejaankop granite experienced higher fractionation degrees accompanied by intensive magmatic-hydrothermal alterations as ascertain by TEDI ($Ba \times (Sr/Rb)$), Zr/Hf versus Y/Ho, Yb/Nb ratios and normalised REE plots. Normalised

REE plots and petrographic studies suggest that Bobbejaankop granite melt assimilated the Stavoren granophyre and gave rise to the granophyric and the hydrothermally unaltered variety of the Klipkloof granite.

DEDICATIONS

To my son Ntlhari “Luther” Chauke

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Chapter 1: Research Overview

1.1. Introduction

The Bushveld Igneous Complex (BIC) is a Large Igneous Province (LIP) which comprises the early extrusive and bimodal Rooiberg Group (2057.3 ± 3.8 Ma; Harmer and Armstrong, 2000), the ultramafic and mafic Rustenburg Layered Suite (RLS) (2055.91 ± 0.26 Ma, CA-ID-TIMS age, Zeh et al., 2015), the Raseop Granophyre Suite (RGS) and the felsic Lebowa Granite Suite (Cawthorn et al., 2006; Figure 1.1). The ortho-magmatic to hydrothermal systems that accompanied the intrusion of the LGS led to formation of polymetallic mineralization hosted within the felsic components of the BIC and some of the inliers (McNaughton et al., 1993). The polymetallic suite consists of a Sn–Mo–W–Cu–Pb–Zn–As–Au–Ag–Fe–F–U–REE assemblage divisible into three ore-forming temperature ranges (Freeman, 1998; Robb et al., 2000). These polymetallic deposits often occur adjacent to regional scale faults that are geodynamically mirrored by local scale faults and veins that principally host the mineralization (Freeman, 1998). The intrusion of the 2054.2 ± 2.8 Ma (Harmer and Armstrong, 2000) Lebowa Granite Suite (LGS) of the Bushveld Igneous Complex (BIC) into the Transvaal Supergroup reactivated the Transvaal Basin lineaments and led into to the development of several country rock inliers (Hartzer, 1995). These inliers include the Crocodile River Dome and Rooiberg Fragment in the western limb and the Stavoren Fragment, Marble Hall Dome and Dennilton Dome preserved in the eastern limb of the BIC (Hartzer, 1995; 2000).

In the late 1920s and early 1980s, the LGS and the concomitant roof rocks were a main target for tin (Sn) and fluorite (F) exploration and exploitation and to a lesser extent base metals (Crocker et al., 2001; Bailie and Robb, 2004). Extensive studies on mineralization of these deposits have been conducted (cf. Wagner, 1921; Ollila, 1981; Pollard et al., 1991; McNaughton et al., 1993). Numerous prominent tin and fluorite deposits such as the Zaaipiaats tin (Pollard et al., 1989, 1991; McNaughton et al., 1993), Vergenoeg fluorite (Crocker, 1985) and Rooiberg tin (Stear, 1977; Ollila, 1981) had been discovered and then later extensively studied. Prominent discoveries of base metals included Spoedwel Copper (Scoggings, 1991), the Houtenbek molybdenum deposit and Albert Silver Mine (Robb et al., 1994). Notable polymetallic studies included fluid inclusion studies by Freeman (1998), and comprehensive

studies by Ollila (1981) and Bailie and Robb (2004) classification of the known polymetallic deposits. This thesis contribute into extensive work conducted on polymetallic deposits (eg. Stear, 1976; Rozendaal et al., 1995; Crocker et al., 2001) and further provide geochemical genetic evaluation of the granite as host rocks (cf. Kleemann and Twist, 1989; Hill et al., 1996) and field evidence of regional structural control in fracture-hosted deposits (cf. Freeman, 1998).

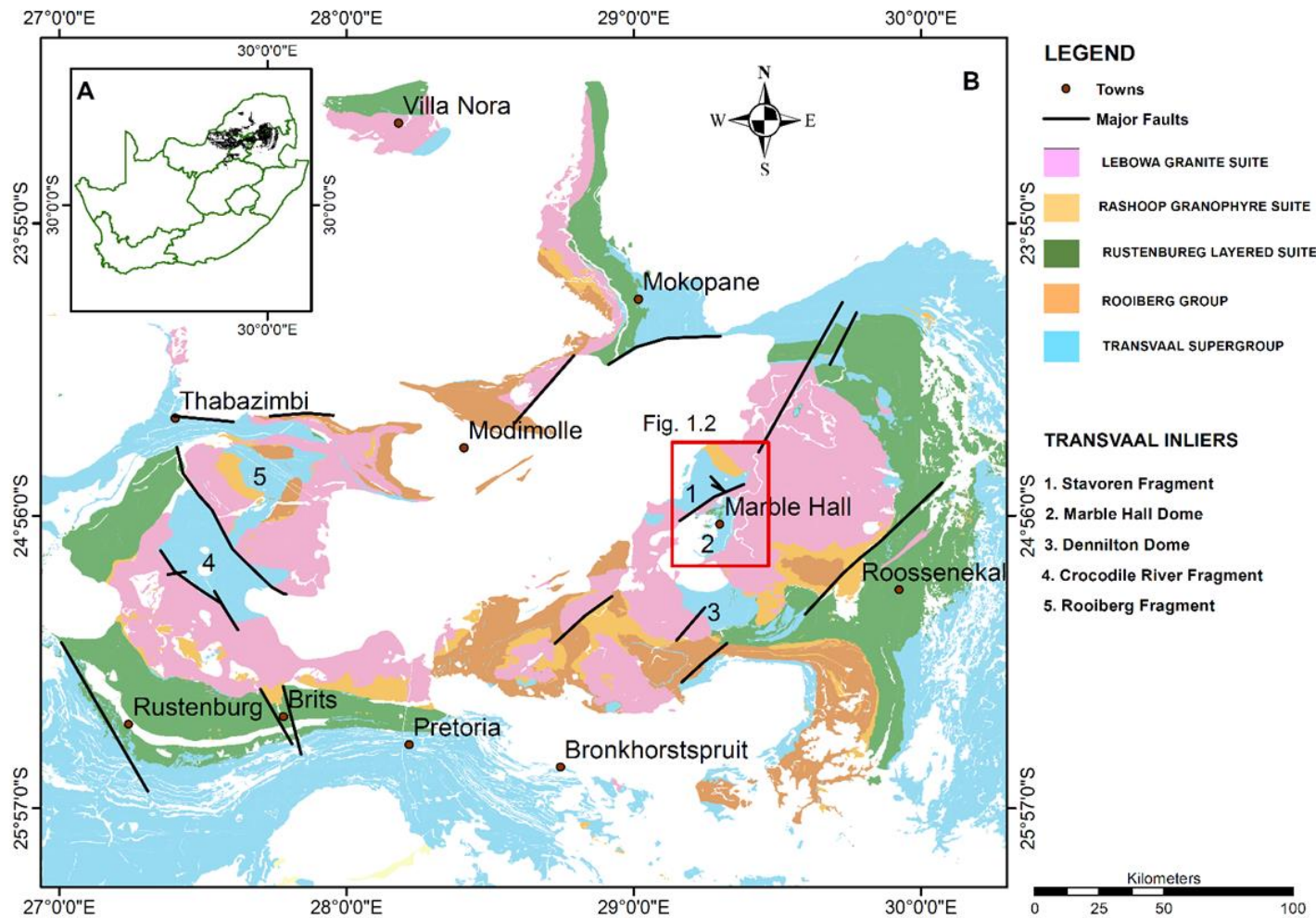


Figure 1.1: Geological map of the Bushveld Igneous Complex within the Transvaal Supergroup and its inliers. Inliers 1 and 2 denote the Stavoren Fragment and Marble Hall Dome respectively, and occur adjacent to the study area enclosed within the red polygon enlarged in Figure 1.2. The rest of the Transvaal inliers are numbered 3-5 (Reproduced using Council for Geoscience 1:250 000 geological map).

In the 1970s, the Mission Exploration Company re-evaluated the Boschhoek base metal Prospect in the eastern limb of the BIC 15 km northeast of Marble Hall, Limpopo Province (Smits 1980; Figure 1.2). The Boschhoek Prospect is an epigenetic mesothermal Cu-Zn-Pb-Ag deposit hosted within fractured Nebo granite of the LGS (Smits, 1980; Freeman, 1998; Robb et al., 2000; Evans, 2015). This Prospect is exposed as a gossanous body situated 2 km east of the Marble Hall Dome and is characterised by a steeply dipping vein system that strikes northeast to southwest (Smits, 1980). Similar mineralization was exploited in the Mutue Fides (Grass Valley Mine) near the Stavoren Fragment on the eastern limb in the early 1900s (Figure 1.2). The Mutue Fides mineralization however constituted a Sn-Cu-Pb-Zn-As-F assemblage in pegmatitic veins within Bobbejaankop Granite (Wagner, 1921). Boschhoek and Mutue Fides are separated by the Wonderkop Fault; a regional dextral-strike slip fault that shaped the surrounding structural character (Hartzer, 1995; Uken, 1998). The existence of these polymetallic deposits within the LGS and near Transvaal inliers warrants a study of the genetic relationship between them.

This project aims to study the metallogeny of the Cu-Pb-Zn-Ag mineralization at Boschhoek and compare it to the mineralization of the polymetallic deposits in the Stavoren Fragment, particularly at Mutue-Fides (Figure 1.2). The research will define the nature of the geochemical signature of the Prospect, its geology and geological structures with respect to mineralization. This will be achieved by studying the litho-geochemistry of the host rocks and reviewing the petrographic character of the host rocks and the ores. The study will employ the use of field structural mapping in addition to the electromagnetic and radiometric geophysical analysis together with remote sensing interpretations to map fractures and decipher structural relationships.

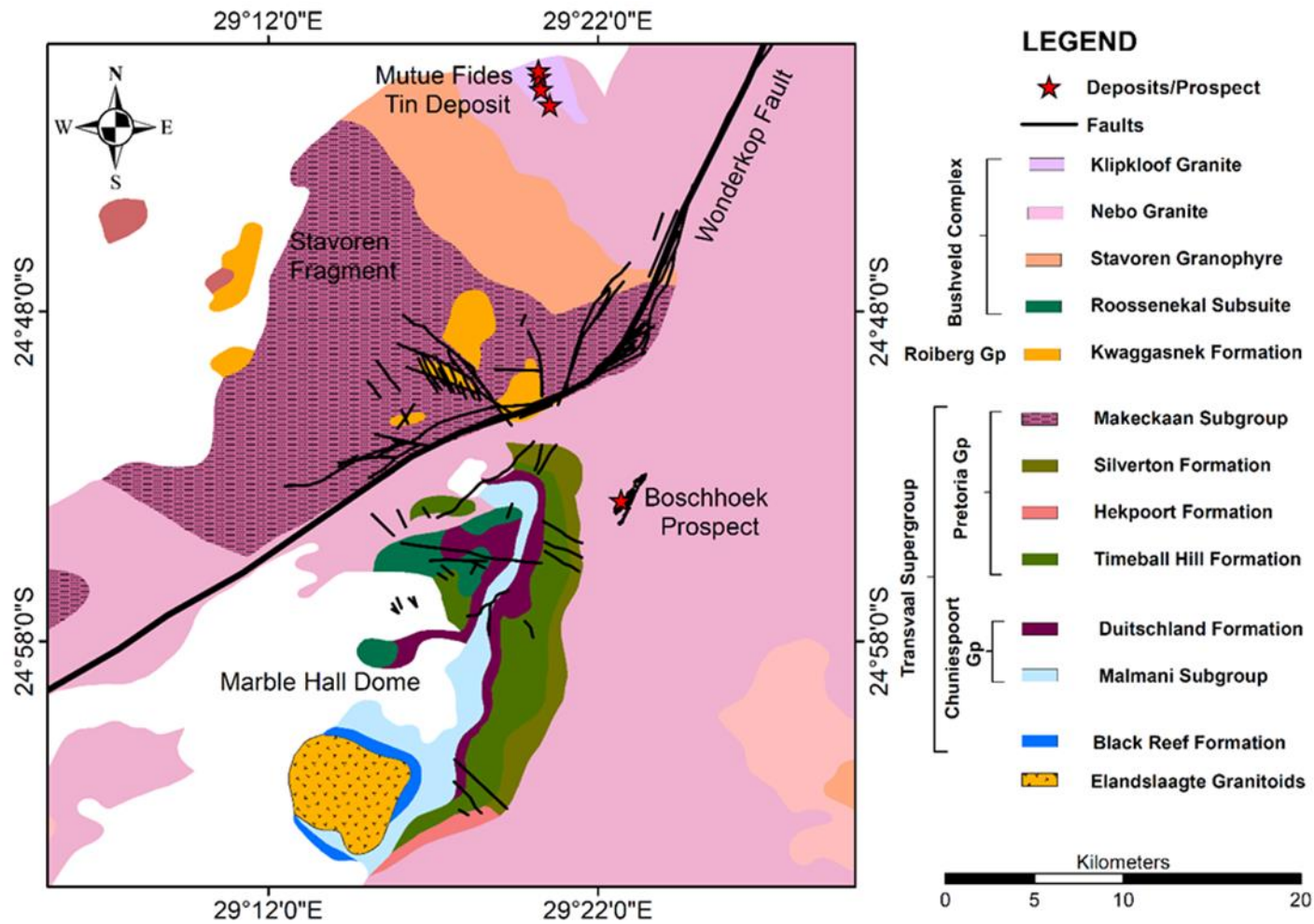


Figure 1.2: Geological map of the Marble Hall Dome and Stavoren Fragment with LGS related polymetallic mineral occurrences (study areas and mineral occurrences indicated by red stars) (Reproduced from the Council for Geoscience 1:250 000 geological map).

1.2. Aims and objectives

The goal of this research is to document the metallogenesis of the Boschhoek Prospect, compare it with the mineralization in the Stavoren Fragment and suggest genetic relationships if possible. Further aims of this research are to document the petrology and petrography of the rocks, the base metal mineralogy and geochemical variations of different lithologies and minerals within the study area. The research will also examine the regional and local structures that facilitated mineralization.

In order to achieve the objectives above, the research will address the following questions;

- (1) What are the structural controls on mineralization and what are the expressions of fluids moving along these pathways in Boschhoek Prospect?
- (2) What are the characteristics of the alteration associated with mineralization?
- (3) What is the effect of the host rock lithology on mineralization and is the Mutue Fides (Bobbejaankop granite-hosted) mineralization similar to that found in the Boschhoek Prospect (Nebo granite-hosted)?

1.3. Previous Work

This subsection covers the discovery, the historical exploration activities and the literature relating to polymetallic mineralization of the Boschhoek Prospect and the Mutue Fides-Stavoren Tin Field. Notable previous workers in the Boschhoek Prospect include Smits (1977; 1980; 1986) and Evans (2015). Freeman (1998) compared the geological setting and mineralogical descriptions of the Prospect conducted by Smits (1977) to the nearby similar deposits such as the Albert Silver Mine and the Spoedwel Mine. Wagner (1921) conducted extensive documentation of the geology and mineralogy of the Mutue Fides – Stavoren and subsequently proposed a mineralising system that later polymetallic deposits studies relied upon in the LGS (eg. Crocker, 1979; Crocker et al., 2001).

1.3.1. Boschhoek Prospect

Anglo Rand Mining first investigated the mineralization on the Farms Boschhoek 752 KS and Rooibokkop 744 KS in 1948 (Crocker et al., 2001). Mission Exploration Company later revaluated the Prospect in 1977 and drilled seven boreholes. African

Selection Trust also reassessed the Prospect in 1988 (Crocker et al., 2001). In 2010 Lerama Resources revisited the Prospect and drilled a further eight boreholes in two phases of exploration to evaluate the Prospect. Smits (1977) and Smits (1986) conducted a mineralogical investigation using the data from the seven boreholes core drilled by Mission Exploration Company and documented paragenesis of mineral assemblages comprising stage one minerals such as siderite, pyrite and pyrrhotite; main phase minerals that include chalcopyrite, galena and sphalerite and last stage minerals including hematite, bornite and chalcocite. Mineral assemblages of stage one emanated from magmatic hydrothermal solutions introduced into pre-existing fractures (Smits, 1980). Recurring fracturing of the Boschhoek structure system permitted Nebo granite (host-rock) and magmatic-fluid interaction which took place in mesothermal conditions (Smits, 1977; 1980). The consequent wall-rock alteration was characterised by sericite alteration followed by main phase mineral assemblages and lastly meteoric water mixing with the magmatic fluids resulting in chlorite alteration characterised the last stage (Smits, 1977; 1980).

Evans (2015) investigated the nature, structural style and origin of the Boschhoek deposit using borehole core from Lerama Resources and field mapping. He described the Boschhoek Fracture System as a sigmoidal-shaped sinistral shear-zone having conducted local-scale field mapping of the study area. Evans (2015) attributed the formation of the shear-zone as a response to a regional tectonic event triggered by emplacement of the Bushveld Complex and inferred that this resembles an Iron Oxide Copper Gold (IOCG) system, analogous to the Olympic Dam deposit of Australia.

1.3.2. Mutue Fides and Stavoren

Wagner (1921) described the geology, structure and tin mineralization in the Mutue Fides-Stavoren Tin Field. The tin mineralization and subordinate base metals were described as tabular and regular replacement veins; impregnations (irregular replacements); pipe-like bodies; “ore boulders”, “pockets” and “eyes” and pegmatite-related (Wagner, 1921; Crocker et al., 2001). Mineralised Bobbejaankop and associated aplitic granites in the Mutue Fides are characterised by pervasive seritization and greisenization and the structures of the Mutue Fides - Stavoren Tin Field were described as steeply dipping fissure systems striking NE-SW, NNE-SSW and WNW-ESE (Wagner, 1921). Freeman (1998) conducted fluid inclusion studies of

the mineralised fluids on samples from the Mutue Fides (Grass Valley tin mine) and concluded that Sn-Mo-W precipitated from a magmatic dominated system at above 400°C.

1.4. Mining history of the Mutue Fides-Stavoren area

The Mutue Fides-Stavoren area has history of tin mining including the Mutue Fides Tin Mine, Stavoren Tin Mine, Gaasterland, Vlakfontein Mine, Rodewaal (operated under Union Tin Mine) and Tambootieboom (Union Tin Mine) (Crocker et al., 2001; Figure 1.3). Mutue Fides Tin Mine operated on the farm Mutue Fides 648 KS hosted by red Bobbejaankop Granite (Wagner, 1921). Between the years 1913 and 1938, 2,969 ton of tin was recovered from the 205,560 ton of ore (Crocker et al., 2001 and references therein; Figure 1.3). The average grade was 1.45 % tin with recorded 2.8 % Sn and 0.8 % Sn highest and lowest grades respectively. Several ore bodies were exploited in various workings on Stavoren ore (Crocker et al., 2001 and references therein). The Camp Line Workings contained 8% Sn ore per tonne recoveries within 12 m depth and 350 m extent on surface. The B Line Workings were the most prominent with approximately 20 separate pipes; the B4 pipe for instance recorded a yield of 7% WO₃ and 6% Cu. Wagner (1921) described 50 known small deposits on the farm. Exploitation of tin took place on two pipes termed A1 and A2 beneath the contact between granophyric granite and granophyre (Wagner, 1921; Crocker et al., 2001). The A1 pipe yielded 10% Sn. A grade of 10% scheelite (CaWO₄) was exploited from A2 pipe. Both pipes were limited to 13-18 m depth (Crocker et al., 2001). Prominent exploitation of tin within granophyric granites in contact with granophyre occurred on the farms Roodewal 678 KS and Tambootieboom 686 KS (Figure 1.3). There were three main workings on Roodewal 678 KS; Battery Section, Northern workings and Western workings exploiting cassiterite, wolframite and copper ores. In 1919 and 1920, Union Tin produced 10 tons of tin. Operations ceased in 1920 (Crocker et al., 2001). Wagner (1921) described 16 known Prospects on farm Tambootieboom 686 KS.

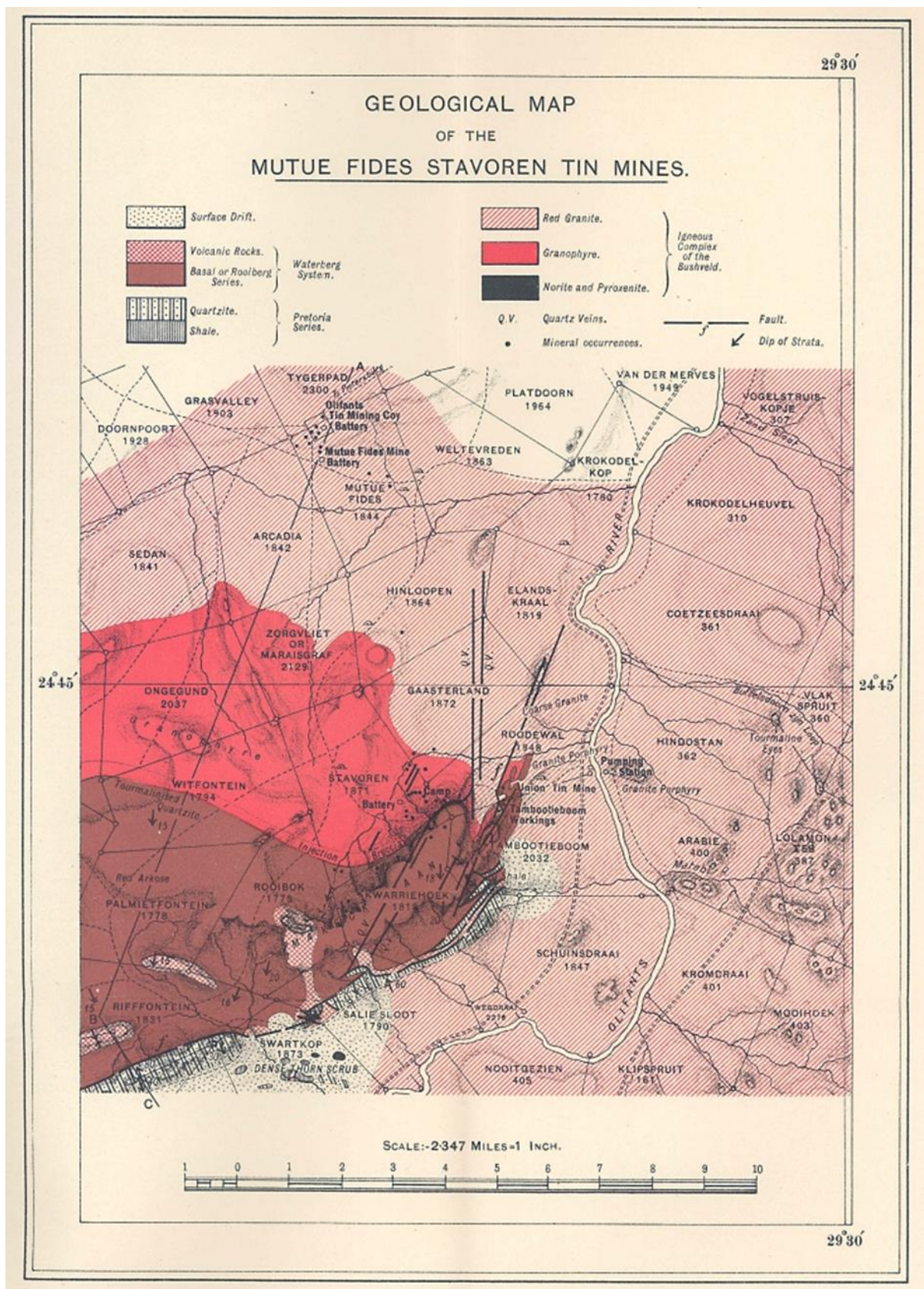


Figure 1.3: Geological map with farms of the workings in the Mutue Fides- Stavoren area (Wagner, 1921).

1.5. Review of the Polymetallic Mineralization Model

The polymetallic suite in the LGS consists of a variable Sn–Mo–W–Cu–Pb–Zn–As–Au–Ag–Fe–F–U–REE assemblage (Robb et al., 1994; Freeman, 1998; Bailie and Robb, 2004). Freeman (1998) and Robb et al. (2000) divided this polymetallic assemblage into three stages based on the crystallization of indicative dominant minerals and ore-forming temperature ranges. These stages are; Sn-(Mo-W) mineralization occurring at high temperature ($>400^{\circ}\text{C}$) (eg. the Zaaiplaats and Mutue Fides - Stavoren Tin Fields deposits; Figure 1.4), the base metals; Cu-Pb-Zn and precious metals Au-Ag together with As forming ores at intermediate temperatures between 400 and 200°C (eg. the Boschhoek Prospect, Albert Silver and Spoedwel deposits; Figure 1.4). Hydrothermal low temperature deposits of Fe-F-U-REEs ores forming below 200°C (eg. the Ruigtepoort–Blokspuit, Buffalo, Vergenoeg and Zwartkloof deposits; Figure 1.4). Alternatively, polymetallic deposits can be divided into four types based on associative minerals, predominant metals and host rock; (1) a tourmaline– cassiterite – sulphide association, (2) a fluorite – molybdenite – REE – sulphide association, (3) a sulphide – carbonate base and precious metal rich association and (4) a late-stage oxidized hematite – pitchblende –fluorite association superimposed on the preceding assemblages (Bailie and Robb, 2004). The development of these associations takes place in both granites (endogranitic) and associated country rocks (exogranitic). The hydrothermal system that prevailed in the high radiothermal heat producing high-heat producing Bushveld granites long after their emplacement is one key principal factor that driven polymetallic mineralization (Pollard et al., 1991; McNaughton et al., 1993; Robb et al., 2000; Gleason et al., 2011). Fluid inclusion studies by Pollard et al. (1991) and Freeman (1998) suggested the polymetallic ore fluids to have emanated from at least three sources that include Bushveld Complex magmatic melt, connate water and Transvaal Supergroup basinal derived brine.

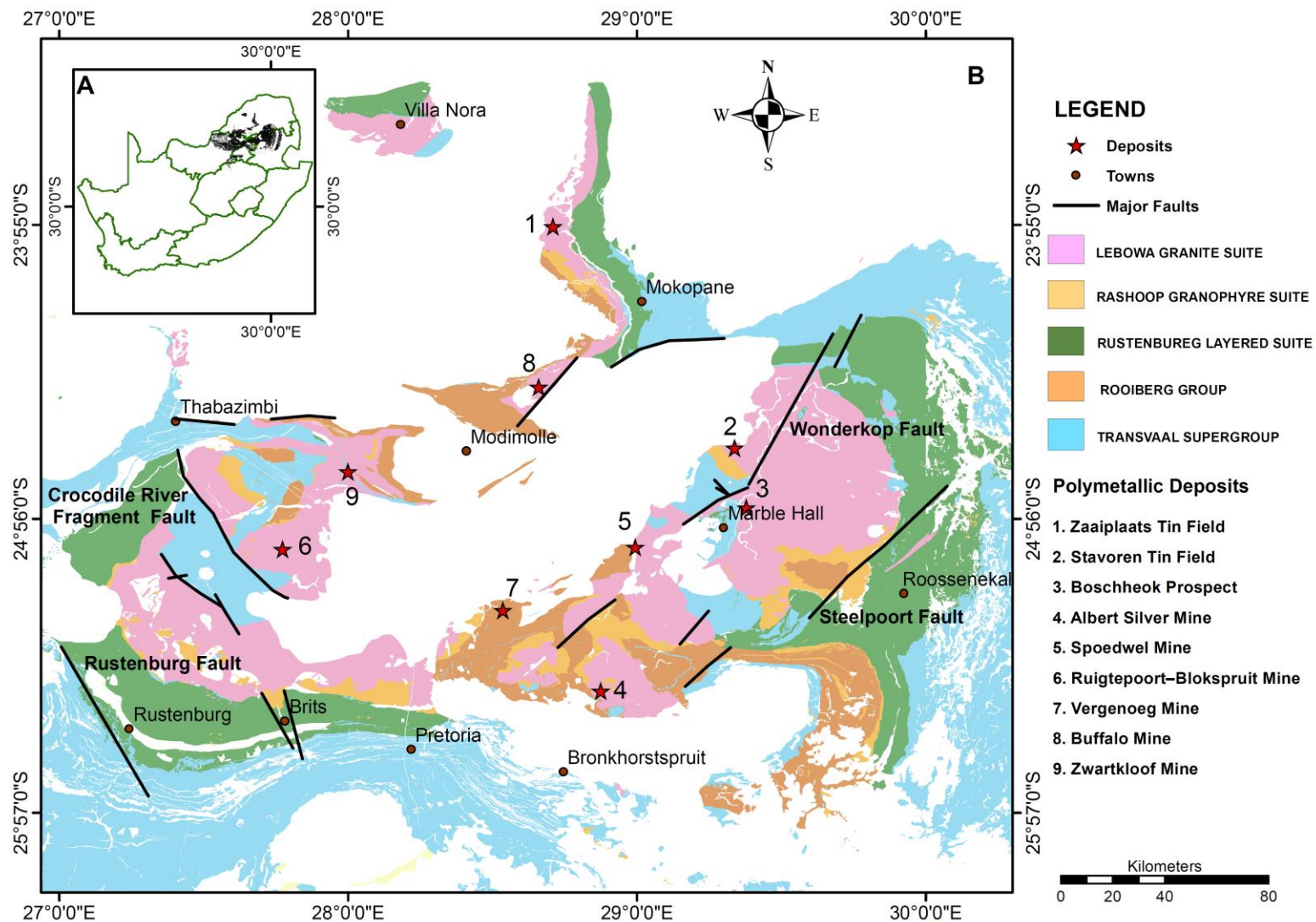


Figure 1.4: Geological map of the Bushveld Igneous Complex with notable polymetallic deposits locations denoted by red stars. The majority of these polymetallic deposit fields (denoted by 1-9) occur adjacent to structural lineaments (Robb et al., 2000; Crocker et al., 2001; Mutele et al., 2017).

Sn-(Mo-W) and possibly As mineralization often occurs in highly fractionated and/or altered varieties of the Bushveld granites as disseminated ores formed by fractional crystallisation related processes (Crocker, 1986; Robb et al. 1994;). Commonly, these assemblages are found in pockets or 'eyes' characterised by pegmatites or complex pipe-like bodies in miarolitic granites (Wagner, 1921; Pollard et al. 1989). Wagner (1921) and also Bailie and Robb (2004) noted greisen and propylitic alteration accompanying these assemblages. Apart from the Zaaiplaats Tin Field in the northern limb characterised by both disseminated and pipe-like bodies, the assemblages are largely fracture-related and most of these deposits are located near or on the flank of a regional fault (Freeman, 1998). Freeman (1998) asserted that the fracture systems can act as a conduit and facilitate mixing for mineralising fluids. Sericite alteration and moderate to low pH and moderate salinity often pronounce the intermediate temperatures episode. The low-temperature assemblage may also take place in the same fracture system and form because of alteration of the sulphide assemblage to form secondary minerals (Crocker, 1976). Phyllic alteration, acidic pH and low saline conditions often accompany these assemblages (Freeman, 1998).

1.6. Methodology

The study areas (Farm Boschhoek and Farm Mutue Fides) fall on the 2429CD Marble Hall mapsheet, mapped by Hartzler (1994) and later remapped by Hartzler (2000). The 1:100 000 mapsheet was partly remapped for this study with attention focussed on known polymetallic mineralization (Farms Mutue Fides, Stavoren and Boschhoek), localized geological structures, and regional Wonderkop Fault geodynamics. Fieldwork was conducted with the aid of a Global Positioning System (GPS), a compass-clinometer to record outcropping beds and structural information and Google Maps to infer some contacts. Geological data collected include primary bedding strike, dip and dip directions. Geological data collected along the fault zone included lineations, veins, foliations and slickensides. Although rarely present, ripple-marks and cross-bedding directions were recorded from the sedimentary rocks.

Airborne electromagnetic geophysical data acquired from the Council for Geoscience (CGS) was quantitatively analysed to delineate linear surface and subsurface geological features. The Geophysics and Remote Sensing Unit of the CGS conducted qualitative analysis of the geophysical data including Reduction to Pole (RTP)

transformation, Vertical Derivatives and Edge Detection Filtering. The details of the aircraft, equipment and survey specifications are specified in table 3.1 and table 3.2 respectively. Landsat 7 and SENTINEL 2 remote sensing data from the United States Geological Survey website were downloaded and utilized to assist in the definition of the types and limits of alteration associated with geology, geological structures and/or polymetallic mineralization.

This research study utilised a 5 cm diameter borehole core (BHDD-003) from the Farm Boschhoek drilled in 2010. Another borehole core (7-cm diameter) was examined from the farm Mutue Fides northeast of the Stavoren Fragment drilled in the early 1970s. The borehole cores from these farms were logged geologically and structurally with specific attention paid to the relationships between lithology, alteration and mineralization. Samples were taken for petrological and geochemical investigations. The whole rock major and minor elements were determined using WD X-Ray Fluorescence (XRF-Panalytical) and the trace elements by Inductively Coupled Plasma Mass Spectrometry (ICP-MS Perkin Elmer Elan DRC-e quadrupole) both at the Earth Lab, University of the Witwatersrand.

Chapter 2: Geological Setting

2.1. Regional geology and lithostratigraphy

The study areas; Boschhoek Prospect and Mutue Fides are located towards the western periphery of the LGS in the eastern limb of the BIC (Figure 1.1; Figure 1.2). The study areas are adjacent to the highly deformed inliers of the Transvaal Supergroup that are separated by the regional northeast trending Wonderkop Fault (Figure 1.4). The RGS rocks, the RLS subsuite and Karoo Supergroup rocks occur in close proximity to the Stavoren Fragment and the Marble Hall Dome respectively. For the sake of brevity; only the lithostratigraphic successions that are in close proximity to the study areas and have influence and/or a possible relationship with the polymetallic mineralization are described in detail.

2.1.1. Transvaal Supergroup

The Neoproterozoic to Paleoproterozoic (circa. 2660 Ma - 2050 Ma) sedimentary and volcanic package of the Transvaal Supergroup, occurs in three structural basins namely the Transvaal, the Griqualand West and the Kanye (Botswana) basins (Eriksson and Reckzo, 1995; Eriksson et al., 2006). On average, the stratigraphic package that developed on the Kaapvaal Craton attains 15 km in thickness. The BIC intruded the Transvaal Supergroup rocks of the Transvaal Basin and the latter formed roof and floor rocks to the intrusion (Figure 1.1). In the vicinity of the study areas, the Marble Hall Dome and the Stavoren Fragment formed roof rocks to the BIC intrusion and are spatially related to the Wonderkop Fault (Figure 1.2).

The Transvaal Supergroup of the Transvaal basin comprises protobasinal Bloempoot Formation successions, basal Black Reef Formation, Chuniespoort Group and Pretoria Group. The protobasinal successions are characterised by mafic lavas, pyroclastic rocks, poorly sorted alluvial-fluvial and fine-grained basinal rocks (Hartzer, 1994; Eriksson and Reckzo, 1995). The Black Reef Formation unconformably overlies protobasinal rocks and it comprises chiefly mature quartz arenites, minor conglomerates and mudrocks (Eriksson et al., 2006). Henry et al. (1990) noted an upward fining from the intermittent basal conglomerate overlain by thicker sandstones and thin mudrocks. The 2550 Ma Chuniespoort Group (Walraven, 1995) is subdivided into three successions comprising basal Malmani Subgroup, Penge Formation and Duitschland Formation. The Malmani Subgroup comprises five

Formations (Oaktree, Monte Christo, Lyttelton, Eccles and Frisco Formations) based on chert content, morphology of stromatolites, intercalation of shales and erosional fronts (Walraven, 1995).

These Formations are characterised by carbonaceous shales, dolomites (stromatolitic and oolitic), limestones, chert, breccias and quartzites (Eriksson et al., 2006). The Penge Formation is the only stratigraphic unit in the Transvaal Basin characterised by Banded Iron Formations (BIF). The BIF comprises cycles of stilpnomelane lutite and chert followed by sideritic and haematitic chert (Eriksson et al., 2006). Further up in the cycles the chert bands become magnetite rich (Beukes, 1980). The Deutschland Formation unconformably overlies the Penge Formation. It comprises predominantly dolomitic mudrocks, minor dolomites with quartzites and chert breccias (Eriksson and Reekzo, 1995).

Table 2.1: Lithostratigraphy of the proto-basinal and basal successions and the Chunniespoort Group of the Transvaal Supergroup (Hartzer, 1994; Eriksson and Reckzo, 1995; Eriksson et al, 2006).

Stratigraphy		Lithologies
Chunniespoort Group	Duitschland Formation	Mudrocks, dolomites, quartzite and chert breccias
	Penge Formation	Banded Iron Formation
	Malmani Subgroup	Frisco, Eccles, Lyttelton, Monte Christo and Oaktree Formations (from top downwards)
Black Reef Formation		Quartz arenites, conglomerates and mudrocks
Bloempoot Formation		Mafic lavas, pyroclastic rocks, poorly sorted alluvial-fluvial and fine-grained basinal rocks

The Pretoria Group is characterised by at least 6000 m of sedimentary rocks deposited after a 80 Ma hiatus accompanied by uplift and karst weathering (Eriksson and Reckzo, 1995; Eriksson et al., 2006). The Pretoria Group successions comprised predominantly mudrocks and sandstones with interbedded basaltic to andesitic lavas and lesser conglomerates, diamictites and carbonates (Table 2.2). The low-grade metamorphism recrystallized sandstones and mudrocks of the Timeball Hill, Strubenkop, Silverton, Vermont, Nederhorst and Houtenburg Formations to quartzites and slates respectively (Eriksson et al., 2006).

Table 2.2: Summary of Pretoria Group successions and their respective lithologies. The successions in bold are correlated to the Mackekaan Subgroup outcropping in the Stavoren Fragment (SACS, 1980; Hartzer, 2000).

Group	Formation	Lithology
Pretoria	Houtenberg	Hornfels, quartzite lenses
	Steenskaampsberg	Quartzite, shale
	Nederhorst	Shale, hornfels, carbonate rocks
	Rayton	Shale
	Lakenlei	Quartzite
	Vermont	Shale; siltstone
	Magaliesberg	Sandstone
	Silverton	Shale, lava
	Daspoort	Sandstone
	Strubenkop	Shale
	Dwaal Heuwel	Sandstone
	Hekpoort	Andesite
	Boshoek	Conglomerate, sandstone
	Timeball Hill	Shale, sandstone, lava
	Rooihoogte	Conglomerate, sandstone

2.1.2. The Marble Hall Dome

The Marble Hall Dome is characterised as a north-northwest striking anticline of extremely deformed and metamorphosed Transvaal Supergroup successions (Hartzer, 1995; Figure 2.1). The pear-shaped Marble Hall Dome is bound to the east and northeast by Bushveld granites while Karoo Supergroup rocks terminate the Dome towards the west (Figure 2.1). The oldest rocks in the Marble Hall Dome are

correlated with the protobasinal Bloempoot Formation (Hartzer, 1994). The circa. 2733 Ma succession (Eriksson and Reckzo, 1995), comprising mafic lavas, pyroclastic rocks, poorly sorted alluvial-fluvial and fine-grained basinal rocks overlies a granitoid-gneiss domal structure called the Elandslaagte Dome situated on the southern end of the Marble Hall Dome (Hartzer, 1995; Hartzer, 2000).

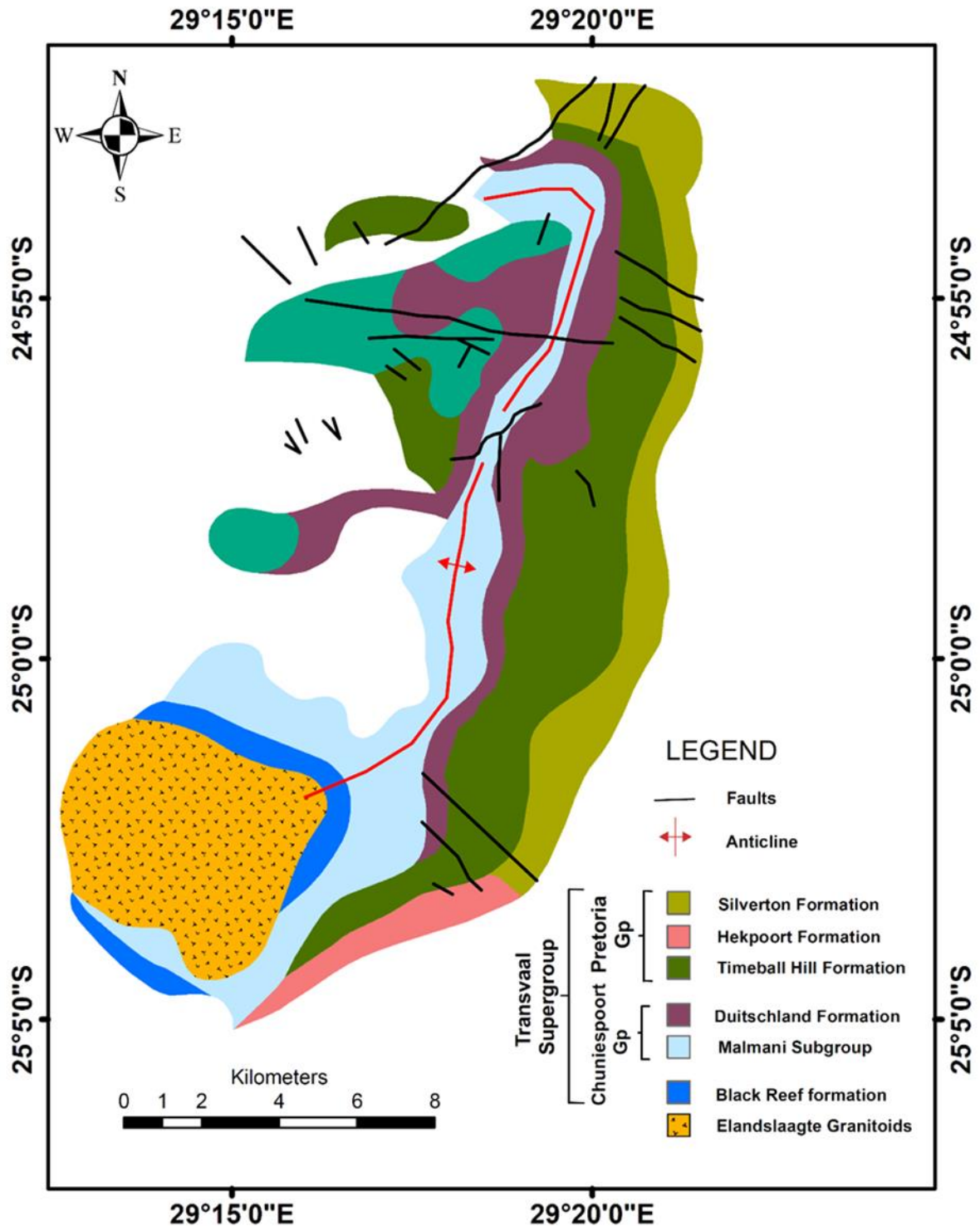


Figure 2.1: Simplified geological map of Marble Hall Dome. Relatively younger successions are masked out in white (modified after Hartzer, 1995).

The quartzite rocks of the basal Black Reef Formation (circa. 2642 Ma; Eriksson and Reckzo, 1995) unconformably overlies the Bloempoot Formation (Hartzer, 1994; De Waal and Armstrong, 2000). Thin lenses of iron-formation correlated with the Penge

Formation unconformable overlies the Bloempoot Formation (Hartzer, 1994). The Malmani Subgroup of the Chunniespoort Group and Duitschland Formation rests unconformable on the relatively iron-poor Penge Formation (Hartzer, 2000). The dolomite, chert, transgressive shale and ferruginous characterise the Malmani Subgroup. The mudstones, carbonaceous mudrocks, limestone and dolomite with subordinate conglomerates, diamictites and lavas of the Duitschland Formation 'sandwich' the older Chunniespoort Group rocks (Hartzer, 2000).

The Pretoria Group rocks define the periphery of the Marble Hall Dome to the west (Figure 1.2). The mudrocks, quartzites and minor diamictites and the intercalated Klapperkop Quartzite Member of the Timeball Hill Formation rest unconformable on the Duitschland Formation marking the onset of the Pretoria Group succession in the Marble Hall Dome. (Hartzer, 1994. Eriksson et al., 2006). The Timeball Hill Formation is unconformable overlain by the Hekpoort Formation characterised by andesite lavas, minor pyroclastic rocks, quartzites, and shale conglomerates (Eriksson et al., 2006). The youngest rocks of the Pretoria Group in the Marble Hall Dome comprise shales correlated with the Machadodorp Member of the Silverton Formation (De Waal and Armstrong, 2000). Hornfels of the metamorphosed Lydenburg Shale, another Silverton Formation Member, are infrequently located at the contact with the Bushveld Granite (Hartzer, 1994).

The western portion of the Marble Hall dome is characterised by the irregular intrusive Marble Hall diorite (De Waal and Armstrong, 2000; Figure 2.1). The 2055.6 ± 3.1 Ma (De Waal and Armstrong, 2000) mesocratic to leucocratic diorite sills are inferred to be contemporaneous with the Bushveld Complex and possibly related to the Uitkomst Complex satellite intrusion (De Waal and Armstrong, 2000). The LGS also intruded the Marble Hall Dome (Hartzer, 1994). The geodynamic adjustments of the Marble Hall Dome as a response to the Wonderkop Fault reactivation and Bushveld Complex intrusion led to complex deformation on the northern portion (Hartzer, 1994). The Dome is preserved as series of folds and truncated by sinistral faults striking northeast (Hartzer, 1994; Figure 2.1). Aeromagnetic studies conducted by Babayeju (1999) noted numerous basic dykes cutting the Transvaal sequence. Eales et al. (1984) attributed the dykes to the circa. 180 Ma Karoo magmatic event.

2.1.3. The Stavoren Fragment

The Stavoren Fragment is a high-lying tract of land characterised by the Mackekaan Subgroup of the upper Pretoria Group succession (circa. 2080 Ma) and lower Rooiberg Group (circa. 2061 Ma) (Wagner, 1921; Hartzer, 1995; Figure 2.2). Younger BIC and Karoo rocks surround the inlier; it is bound by Bushveld granites to the south and east. The Stavoren granophyre (a localized Rashoop granophyre equivalent) forms the boundary to the inlier in the north and northeast and it is bound by the Eccu Group to the west and north (Figure 2.2). The Wonderkop Fault separates the Stavoren Fragment from the Marble Hall Dome. The fragment has been interpreted as a roof pendant intruded by a BIC intrusion that subsequently underwent low-grade metamorphism (Hartzer, 1995).

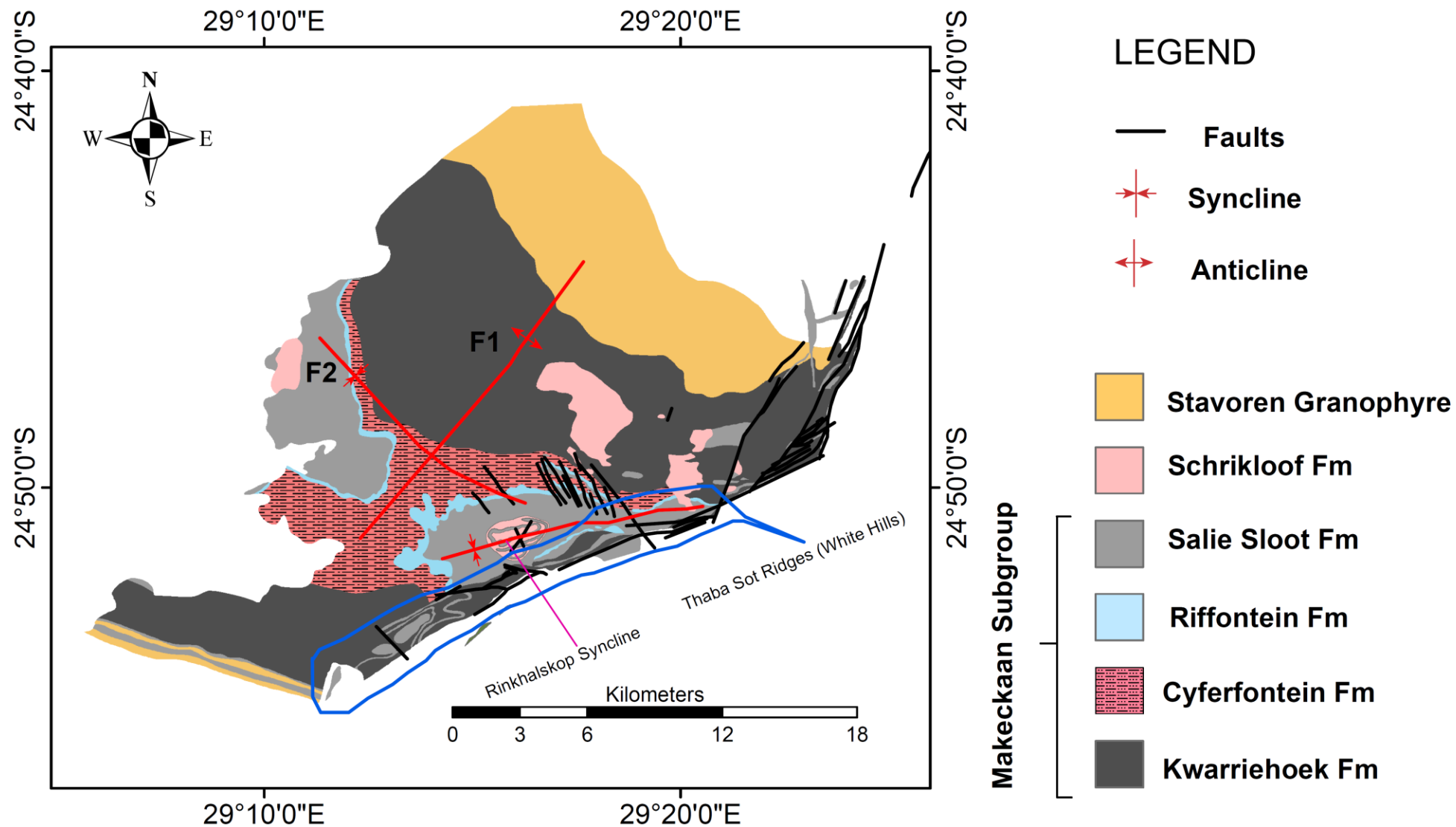


Figure 2.2: Simplified geological map of the Stavoren Fragment (modified after Hartzer, 1995).

Hartzer (1995) subdivided the Stavoren Fragment physiographically into a plateau and a range of ridges that demarcate the Wonderkop Fault to the south east of the Fragment. The Makeckaan Subgroup characterises the plateau and comprises the Kwarriehoek Formation, Cyferfontein Formation, Riffontein Formation and the uppermost Salie Sloot Formation (Hartzer, 1995; Table 2.3). The Kwarriehoek Formation is characterised by downward fining and sorting of sedimentary rocks comprising feldspathic quartzite, conglomerate, arkosic sandstone, greywacke and shale (Hartzer, 1995). It delineates a synformal structure formed by the interference of northeast-southwest striking folds (F1) and the northwest- southeast striking folds (F2) (Hartzer, 1995; Figure 2.2). The unconformable overlying shale unit of the Cyferfontein Formation is almost restricted to within the Kwarriehoek Formation synformal structure (Figure 2.2). The orthoquartzite and shale units of the Riffontein Formation and Salie Sloot Formation respectively completes the stratigraphy of the Makeckaan Subgroup (Table 2.2).

Table 2.3: Subdivisions of Makeckaan Subgroup (Hartzer, 1994).

Formation (not recognised by SACS)	Lithologies	Correlating succession in Pretoria Group
Kwarriehoek Formation	Feldspathic quartzite, conglomerate, greywacke and shale	Nederhorst Formation
Cyferfontein Formation	Shale	Nederhorst Formation
Riffontein Formation	orthoquartzite	Steenskaampsberg Formation
Salie Sloot Formation	Shale	Houtenbek Formation

The Rooiberg Group lavas unconformable overlie the Makeckaan Subgroup in the Rinkhalskop syncline along the Wonderkop Fault (Hartzer, 1995; Figure 2.2). Apart from the Rooiberg Felsites found in the Rinkhalskop syncline, several other sheets of felsites, forming ridges occur within the Fragment (Hartzer, 1995; Figure 2.2). The

series of ridges along the Wonderkop Fault are termed the Thaba Sot Ridge (Figure 2.2). The Thaba Sot ridges are often crossed by two faults trending to the northwest and to the north east (Figure 2.2).

2.2. Bushveld Igneous Complex

The BIC is situated north of Pretoria and occupies over 350 000 km³ extending for 66 000km² (Cawthorn and Walraven, 1998; Buick et al., 2001; Figure 1.1). The intrusion occurs in four limbs; western, eastern, northern and Bethal and a fifth limb (Groot Marico) exits in further west. The intrusion has thickness varying between 7 and 9 km. It is generally accepted that the BIC intruded and cooled within 1 million years (Cawthorn and Walraven, 1998; Zeh et al., 2015). The layers of the Bushveld Complex were proposed to be almost horizontal during formation however; they now dip towards the centre of the intrusion (Gough and van Niekerk, 1959; Cawthorn and Walraven, 1998).

2.2.1. Rooiberg Group

The bimodal Rooiberg Group represents the first episode of the magmatic activity related to the Bushveld Igneous Complex (Twist and French, 1983; Eriksson et al., 1995). The mainly basaltic and rhyolitic rocks of the Rooiberg Group have an estimated volume of up to 300 000 km³ upon eruption with a thickness of at least 5 km (Twist and French, 1983). The Rooiberg Group is considered one of the largest acidic volcanic provinces in the world (Twist and French, 1983; Harmer and Armstrong, 2000; Lenhardt et al., 2017).

The Rooiberg Group comprises four formations based on field-textures and geochemistry, and are in ascending order Dullstroom, Damwal, Kwaggasnek and Schrikkloof Formations (Schweitzer, 1987; Schweitzer et al., 1995; Table 2.4). In the southeastern portion of the BIC, the RLS occurs above the lower portions of Dullstroom Formation and the rest of the Rooiberg Group successions extruded above RLS (Jolayemi et al., 2020).

The basal Dullstroom Formation is characterised by thick basaltic and dacitic lavas with minor sedimentary intercalated beds and pyroclastic layers (French and Twist, 1983; Harmer and Von Gruenewaldt, 1991). The lava types distinguishing the Dullstroom Formation include low-Ti basaltic andesite, basal rhyolite, high-Ti basalt, high-Mg felsites, high-Fe-Ti-P andesite and low felsites (Schweitzer et al., 1995;

Jolayemi et al., 2020). The Damwal Formation comprises dacites and rhyolite lavas interbedded with quartzites and sandstones (Schweitzer et al., 1995). The low-Mg and high Fe-Ti-P felsites characterises these lava types (Schweitzer et al., 1995). The Kwaggasnek Formation is predominantly composed of rhyolites with minor quartzites, shales and agglomerates from low-Mg lava types (Schweitzer et al., 1995). The Schrikkloof Formation comprises low-Mg rhyolites with minor quartzites (Schweitzer et al., 1995).

Table 2.4: Formations of the Rooiberg Group and their respective main lithologies, estimated thicknesses and inferred magma types (Schweitzer et al., 1995, Buchanan et al., 2006).

Formation	Lithologies	Thickness (m)	Magma Type	
Schrikkloof	Rhyolite	200-3000	Schrikkloof felsite	Low-Mg
Kwaggasnek	Rhyolite, shale	500-2500	Kwaggasnek felsite	Low-Mg
Damwal	Dacite, rhyolite	1000-2500	Bothasberg felsite, High Fe-Ti-P felsite	Low-Mg
Dullstroom	Basalt to rhyolite	Up to 2000	High Mg felsite, Low Ti basalt, High Ti basalt Basal rhyolite	

2.2.2. Rashoop Granophyre Suite

Rashoop Granophyre Suite (RGS; 2061 ± 5.5 Ma; Harmer and Armstrong, 2000) comprises three units subdivided based on textural differences namely; the Stavoren Granophyre, the Rooikop Granophyre Porphyry (Diepkloof Granophyre) and the Zwartbank Pseudo granophyre (Von Gruenewaldt, 1968; SACS, 1980; Walraven, 1987). The Stavoren Granophyre represents the magmatic granophyre type of Walraven (1987) and both the Rooibok Granophyre Porphyry and the Zwartbank Pseudogranophyre are classed as metamorphic granophyre types (Walraven, 1987;

Hatton and Schweitzer, 1995). Walraven (1987) which was later corroborated by Hatton and Schweitzer (1995) suggested that the RGS represented small volumes of shallow magma intrusion of partially re-melted Rooiberg volcanics. In contrast Walraven (1987) suggested that other granophyres (those younger or coeval to RLS) formed possibly from melting and recrystallisation of Rooiberg volcanic rocks or by metasomatism of sedimentary rocks because of hot intrusive magmas of the RLS. The Stavoren Granophyre is the most widespread and prominent granophyre type in the Bushveld Complex (Walraven, 1987).

2.2.3. Rustenburg Layered Suite

The emplacement of the Rustenburg Layered Suite (RLS) took place at relatively shallow crustal levels beneath the Rooiberg Group and the RGS (Cawthorn and Walraven, 1998). The RLS comprises five stratigraphic zones namely the Marginal, Lower, Critical, Main and Upper zones which are characterised by ultramafic to mafic cumulate rocks (Hall, 1932; Eales and Cawthorn, 1996; Table 2.5).

Table 2.5: Lithostratigraphy of the Rustenburg Layered Suite (Hall, 1932).

Suite	Zone	Subzone (characteristic lithologies)
Rustenburg Layered Suite	Upper	Subzone C (olivine=, apatite-dioritic)
		Subzone B (olivine-gabbonoritic)
		Subzone A (magnetite-gabbonoritic)
	Main	Upper subzone (gabbonorite)
		Lower subzone (gabbonoritic, noritic)
	Critical	upper subzone (norite, anorthosite, pyroxenite)
		lower subzone (pyroxenitic)
	Lower	Upper subzone (pyroxenitic)
		Middle subzone (harzburgitic)
		Lower subzone (pyroxenitic)
	Marginal	(norite)

2.2.3. Lebowa Granite Suite

The intrusion of the LGS marked the last major magmatic event of the BIC and developed as a compositionally zoned sheeted body of A-type granites (Kleemann and Twist, 1989; Hill et al., 1996). The Bushveld granites developed a large sheeted pluton with estimated thickness between 2.5 to 3.5 km covering an aerial of extent of 30 000 km² (Molyneux and Klinker, 1978; Kleemann and Twist, 1989). SACS (1980) recognised seven facies of the Bushveld granites. These varieties include Nebo, Klipkloof, Lease, Bobbejaankop, Sekhukhune, Verena, Balmoral and Makhutso granites (MacCaskie, 1983; Ferré et al., 1999; Wilson et al., 2000). The Nebo granite is the most common type and is often cross-cut and/or grades into other facies; aplitic Klipkloof granite and Bobbejaankop are distinguished by colour and texture and they are also widespread (Kleemann and Twist, 1989). Other facies are restricted to certain locations and consequently named after those areas. Their respective appearance and contact relations with the surrounding rocks as described in MacCaskie (1983) Kleemann and Twist (1989) and shown in table 2.6.

Table 2.6: Summary of LGS facies in the eastern Limb of BIC and their respective characteristics (MacCaskie 1983; Kleemann and Twist, 1989).

Granite Facies (subtypes)	Characteristics
Lease granite	Grey to pink, aplitic microgranite, transitional contacts with Bobbejaankop and Klipkloof granites
Klipkloof granite	Pink, medium to fine grained, sharp contacts with Nebo granite.
Bobbejaankop granite	Pink to brick red, coarse to medium, sharp contacts with granophyre and transitional with Nebo granite
Nebo granite (Sekhukhune, Verena, Makhutso)	Grey to pale pink, coarse to very coarse grained, sharp contacts with rhyolite and transitional with granophyre

2.3. Local Geology

The study areas; the Boschhoek Prospect and the Mutue Fides-Stavoren Tin Field are situated roughly 20 km northeast and 30 km north of Marble Hall Town respectively in Limpopo Province (Figure 1.2). Both the Boschhoek Prospect and the Mutue Fides -

Stavoren area occur within the LGS of the BIC and are adjacent to Transvaal Supergroup inliers separated by the Wonderkop Fault. The Boschhoek Prospect is underlain by the Nebo granite that is cross-cut by veins structures (MacCaskie, 1983; Smits, 1980, Evans, 2015). The Mutue Fides-Stavoren field comprises the Kwarriehoek Formation of the Makeckaan Subgroup, the Stavoren Granophyre of the RGS in addition to the Nebo and Klipkloof granites of the LGS (Crocker and Callaghan, 1979).

2.3.1. Boschhoek Prospect

In the Boschhoek Prospect the Nebo granite forms east-west low undulating domal hills cross-cut perpendicularly by a vein array (MacCaskie, 1983, Figure 2.3). In some areas within the vicinity of the Prospect, these Nebo granite domal outcrops are often rounded, exfoliated and jointed (MacCaskie, 1983). The Nebo granite in the Boschhoek Prospect is typically pale pink, coarse-grained, equi-angular and chiefly consists of quartz, perthite and hornblende (Kleemann and Twist, 1989; Evans, 2015). The greyish-brown coarse Nebo granite variety often outcrops in the surrounding of the Boschhoek Prospect veins system as described by MacCaskie (1983) to east of the Boschhoek Prospect. The colour difference is attributed to a change from hornblende-rich to biotite-rich granite with stratigraphic height (MacCaskie, 1983).

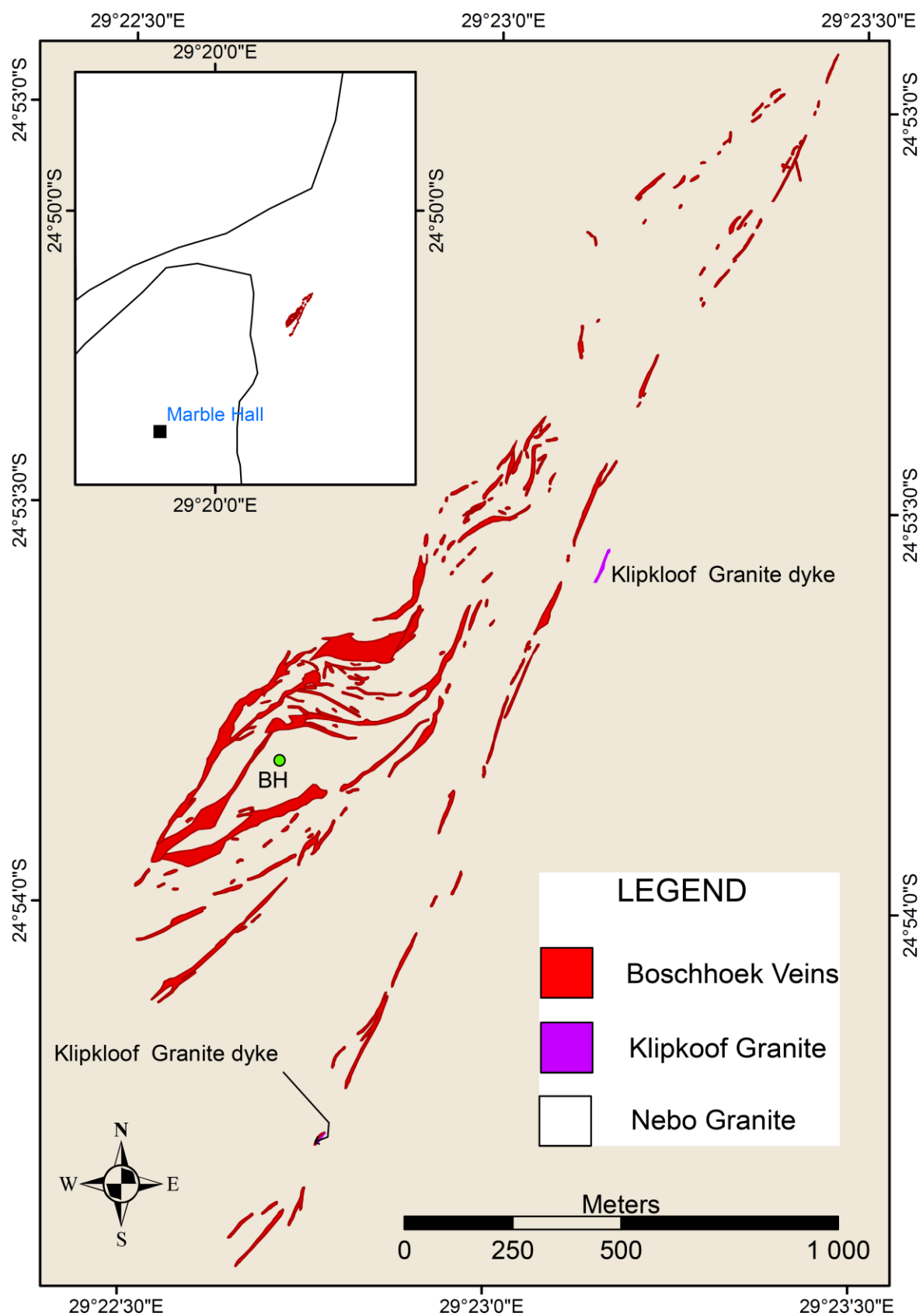


Figure 2.3: Map showing the Boschhoek Prospect local geology depicting the vein structure (adapted from Evans, 2015). BH denotes the location of the borehole BHDD 003.

Gossanous ridges striking northeast to southwest cap the array of veins at the Boschhoek Prospect (Smits, 1979, Evans, 2015; Figure 2.3). The veins comprising siderite, pyrite, calcite and quartz exhibit a sigmoidal dextral wrench structure, referred to as Boschhoek structure by Evans (2015) (Figure 2.3). The steeply dipping veins range from few centimetres to 10 m wide (Evans, 2015).

The contacts between capping gossanous veins and the altered Nebo granite on the surface are often not well exposed and prompt ambiguous vein width measurements to reach 25 m in some areas (Evans, 2015). These 25 m wide macroscale veins often contain brecciated veins characterised by granitic fragments and first generation siderite and quartz veins cemented together by secondary siderite and/or quartz (Evans, 2015). These various sized veins form sub-parallel to the main vein structure. Further, away from the centre of the Boschhoek structure, the veins becomes patchy and converge (Figure 2.3). The eastern periphery of the Boschhoek structure is characterised by somewhat evenly spaced un-coalesced (at least on the surface) veins parallel to the main vein system. This end of the vein system did not take the sinuous form of the main Boschhoek Structure prompting inference that it may have formed at a later stage (Evans, 2015).

A Klipkloof granite dyke intruded the Nebo granite in the eastern periphery of the Boschhoek Structure parallel to the Boschhoek Prospect vein system. The Klipkloof granite exhibits several textural varieties including aplitic, albitized fine to medium grained and porphyritic types (Kleemann and Twist, 1989). The dyke at Boschhoek Prospect takes the form of red fine-grained aplitic Klipkloof granite (Evans, 2015). The Klipkloof granite represents the most fractionated variety of the LGS (Kleemann and Twist, 1989).

2.3.2. Mutue Fides-Stavoren

The rocks attributed to the Mackekaan Subgroup, the Stavoren granophyre and the Nebo granite and its fractionated hydrothermally-altered varieties characterise the Mutue Fides-Stavoren Tin Field. The area underlain by the Makeckaan Subgroup and the Rooiberg Group felsites is characterised by hills that resulted from the faulting and folding of the strata (Crocker et al., 2001). The Wonderkop Fault truncates the folded Mackekaan rocks to the northeast of the Fragment (Crocker et al., 2001; Figure 1.2).

Down-fining folded and faulted Kwarriehoek Formation comprising feldspathic quartzite, conglomerate, arkosic sandstone, greywacke and shale were observed at the edge of the Fragment (Crocker et al., 2001).

Quaternary successions concealed the granites and granophyres in the area to the north of the Kwarriehoek Formation, exposure of these felsic rocks are limited to relatively flat outcrops of up to 10s of metres and as such, contact relationships and continuity of veins amongst these felsic rocks are not apparent. Previous workers (eg. Wagner, 1921; Crocker et al., 2001) relied on drill holes and exhumed materials from mining activities to study contact relationships of granite facies and the nature of veins (Crocker et al., 2001). The farm Mutue Fides is comprised of predominantly aplitic-Lease granite that is occasionally porphyritic and the fine- to medium-grained microgranitic Klipkloof granite (Crocker et al., 2001). Brick-red medium-grained Bobbejaankop granite referred to as Red granite by Wagner (1921) frequently outcrops on the farm Mutue Fides (Wagner, 1921; Crocker et al., 2001). The historical Grass Valley mine at Mutue Fides mine was situated on this type of granite and quite often these Bobbejaankop granite outcrops are altered (Crocker et al., 2001). Granophyric granite, resembling the Klipkloof granite seldom outcrops on the farm Mutue Fides but prominent outcrops are found on the farm Stavoren and on adjacent farms such as farm Arcadia (Wagner, 1921). Underground mining reports and field observations from the mined-out material show that all these granite facies possess pegmatitic veins comprising k-feldspar and quartz in addition and are mineralised in some cases (Crocker et al., 2001).

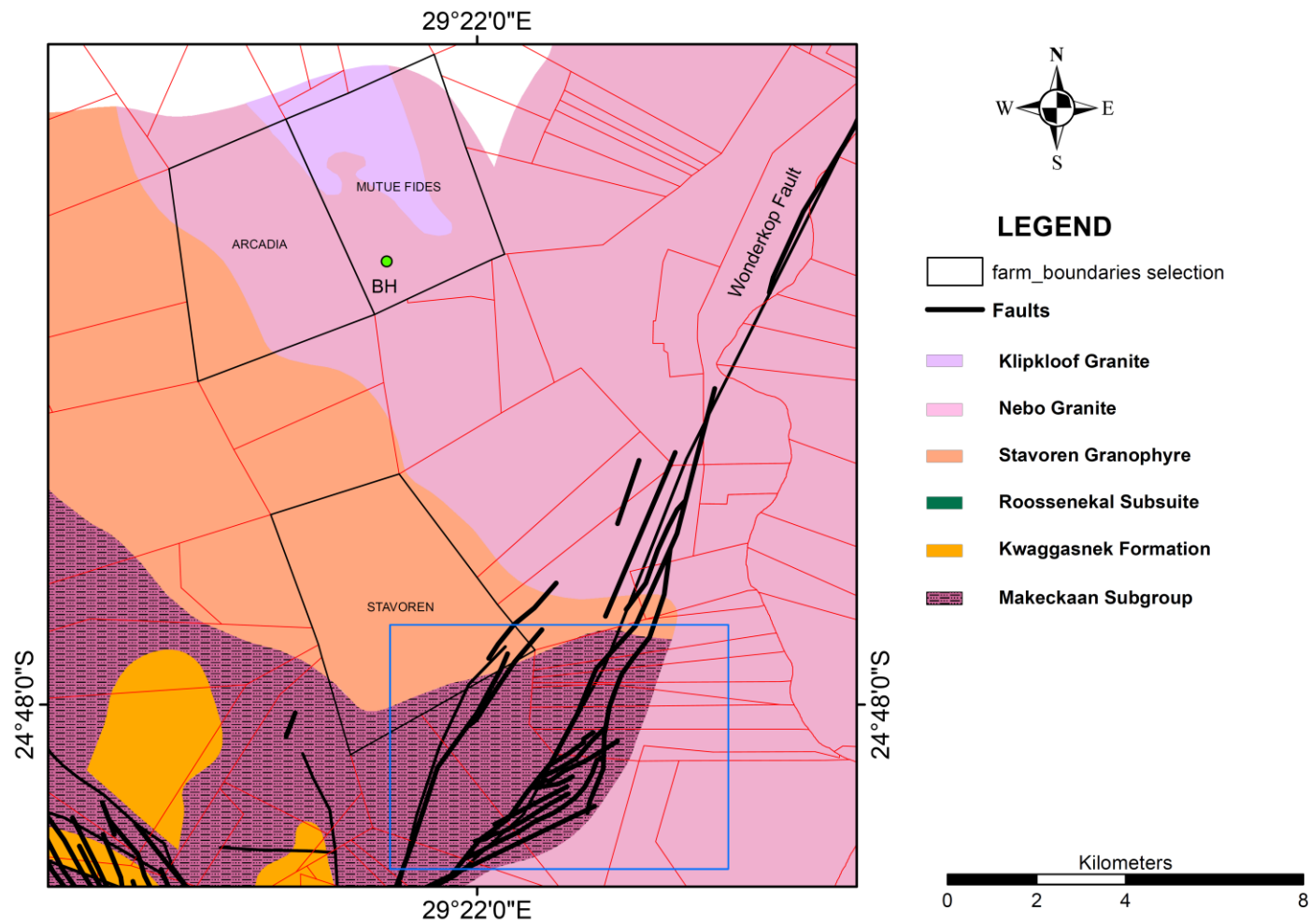


Figure 2.4: Geological map of the Mutue Fides Stavoren Tin field with various farm boundaries of interest. The blue rectangle denotes the area characterised by the Kwarriehoek Formation of the Makeckaan Subgroup that is folded and truncated by Wonderkop Fault. BH denotes the location of borehole 648 KS/1. (Map reproduced from Council for Geoscience 1:250 000 geological map).

2.4. Tectonic setting and structural geology

The Transvaal Supergroup Basin, within whose successions the BIC intruded, was deposited on the Kaapvaal Craton (Eriksson et al., 2006). The Kaapvaal Craton is regarded as an Archean Eon continent that formed by means of amalgamation and accretion of tonalitic gneisses (circa. 3.7 – 3.6 Ga) and younger Archean granite greenstone terranes (circa. 3.5 – 3.0 Ga) (Armstrong et al., 1990; Robb et al., 1994; Lowe and Byerly, 2007; Figure 2.4). Extensive terrane accretion took place along the two east northeast-west southwest trending lineaments Thabazimbi-Murchison lineament (TML) and Barberton lineament (BL) (Poujol et al., 2003). The sporadic extension and rifting of these prominent sutures together with the north northeast - south southwest trending Colesburg lineament (CL) defined the outer limits of the neo-Archean to paleo-Proterozoic basins and inherently dictated the sediment sources areas (Good and De Wit, 1997; Eglington and Armstrong, 2004).

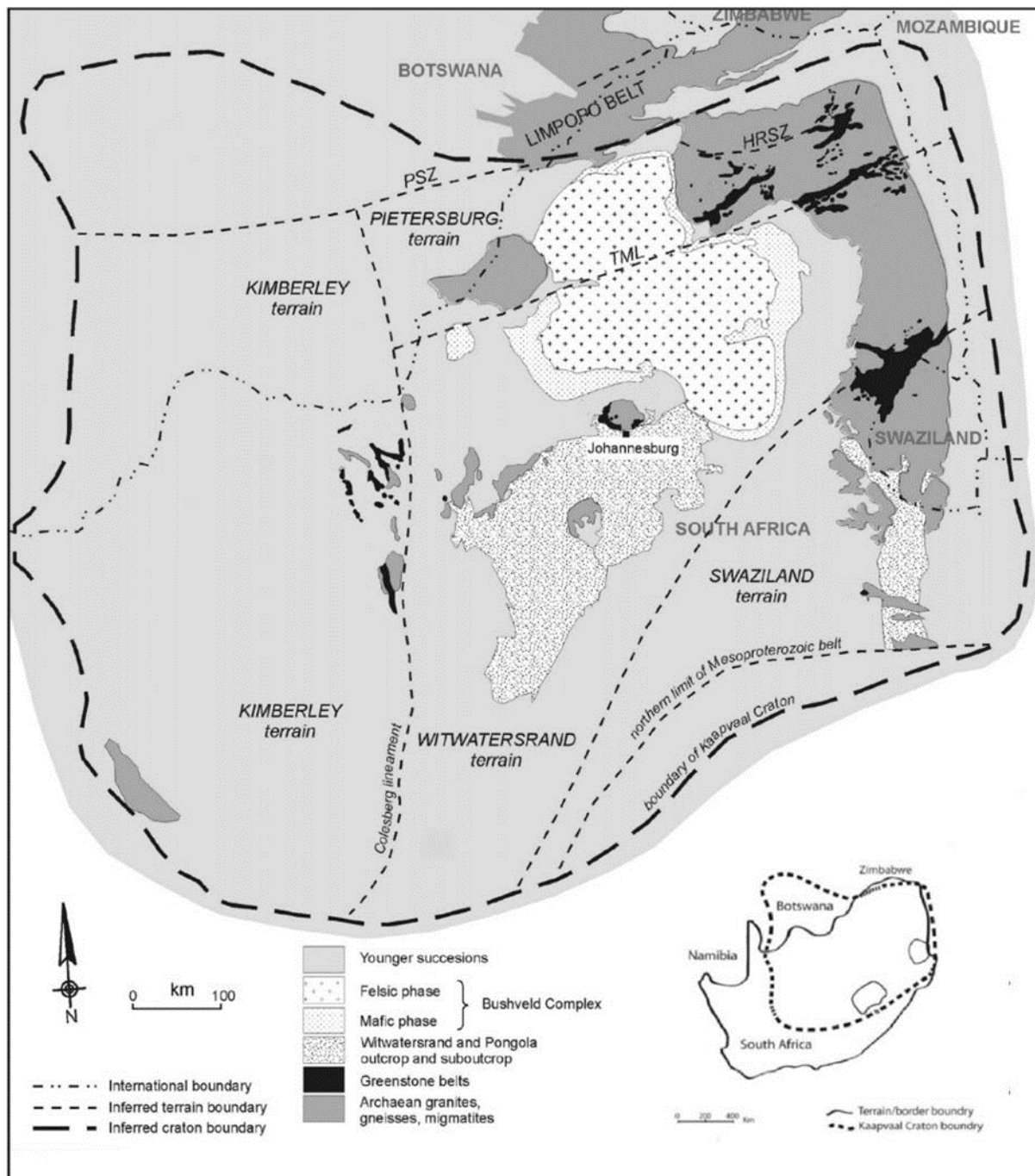


Figure 2.4: The inferred boundaries of the Kaapvaal Craton in relation to South Africa (bottom right). Inferred terrain boundaries of the Kaapvaal Craton and the subsequent collisional Green Stone Belts. Hout River Shear Zone =HRSZ; the Palala shear zone =PSZ (adapted from Eglington and Armstrong, 2004).

The reactivation of the TML in response to a far field stress linked to the Limpopo Orogeny created weakness zones in the Transvaal Basin that facilitated the intrusion of the Bushveld Igneous Complex and subsequently the basin acted as outer limits of the intrusion (Good and de Wit, 1997). The Bushveld Complex is traversed by several regional structures that exhibit the architectural signature and preceding structural

geodynamics of the Kaapvaal Craton influenced by Transvaal basin developments (Du Plessis and Walraven, 1990). These regional structures include the Wonderkop Fault and the Steelpoort Fault in the eastern limb and the Rustenburg Fault and Crocodile River Fragment Fault in the western limb (Figure 1.4). Du Plessis and Walraven (1990) and Bumby et al. (1998) have suggested that movement on the TML, BL and other major deep-seated cratonic sutures created far-field stresses from which these regional structures emanate. Uken (1998) attributed the regional scale structures to be a result of plume-related underplating and gravitational loading in addition to the combinations of lateral extension on a craton scale.

In the eastern Limb of the BIC, the Wonderkop Fault and the Steelpoort Fault trend northeast-southwest which is thought to be as a consequence of 2.20 Ga sinistral wrenching along the TML (Du Plessis and Walraven, 1990). Although these regional structures became prominent during and after Transvaal Supergroup basin infill, their development dates back to the 2.95-2.57 Ga events such as collision of terranes along northern and western margins of Kaapvaal Craton and Limpopo orogeny (Silver et al., 2004).

2.4.1. The Wonderkop Fault

The Wonderkop Fault is a regional left-lateral strike-slip fault striking northeast-southwest situated northeast of Boschhoek Prospect (Visser, 1989). The Fault extends for 120 km from the north of Pretoria to the northeastern portion of Transvaal Basin southeast of Polokwane (Hartzer, 1994; Figure 2.3). The Wonderkop Fault predates both the Transvaal Supergroup and BIC, however, the Wonderkop Fault transects both sequences due to several reactivations postdating the emplacement and crystallisation of the BIC (Hartzer, 1994).

Bailie (1997) described the Wonderkop Fault as a crustal lineament parallel to the Steelpoort Fault (another crustal lineament in the Eastern limb of the BIC; Figure 1.1). A large mass of Nebo granite lies in a shallow graben between the Wonderkop Fault and Steelpoort Fault (Molyneux and Klinkert, 1978). The subsidence of the Nebo granite body mass was due to the inwards downwards throw movements of both the Steelpoort and Wonderkop Faults in response to isostatic adjustment after LGS intrusion (Molyneux and Klinkert, 1978). Bailie (1997) suggested that major crustal warping occurred parallel to major lineaments. Along the Wonderkop Fault, the

resultant warping directly influenced the shape and outcrop patterns of Marble Hall Dome and Stavoren Fragment, Moloto Dome and other minor domes (Molyneux and Klinkert, 1978; Hartzer, 1994). The resultant doming produced tensional fracturing within which fluids can percolate, interact and alter country rocks geochemistry and/or form mineralization (Hartzer, 1994).

The Wonderkop Fault zone separates Marble Hall Dome and Stavoren Fragment in an area characterised by a series of northeast striking faults and sub-parallel series of folds (Hartzer, 1994). Northwest of the Wonderkop Fault zone is the Thaba Sot ridge which is the most prominent feature in the Stavoren Fragment directly related to the Wonderkop Fault Zone (Hartzer, 1994). It is recognised by a 20 - 50 m thick breccia unit that dips to the southeast (Wagner, 1927; Hartzer, 1994).

Chapter 3: Geophysics and Remote Sensing

The Boschhoek Prospect and Mutue Fides tin deposits are spatially associated with local and sub-regional structures and possess various alteration types such as propylitic and phyllic alterations (Smits, 1980). This chapter encompasses an interpretation of geophysical and remote sensing datasets with the aim of delineating structural features and sub-surface alteration proximal to possible mineralization. The succeeding structural geology chapter employs field observations to validate the visible lineaments and presents data from local scale structures related to the lineaments. Airborne magnetic data and Landsat 7 are employed to delineate the lineaments. The latter technique together with gamma-ray spectrometric data are used to discriminate alteration types associated with the polymetallic deposits.

3.1. Geophysics

The airborne electromagnetic geophysical and gamma-ray spectrometric data used in this project was acquired from Council for Geoscience (CGS), Geophysics and Remote Sensing unit. The details of the aircraft, the equipment used and the geophysical survey specifications are specified in table 3.1 and table 3.2 respectively.

Table 3.1: Data collection survey specifications (Cole, 2012).

Item	Value
Contractor	CGS
Survey Date	February-March 2009
Aircraft	Cessna 210 (ZS-KRB)
Flight line direction	North-South
Tie line direction	East-West
Flight line spacing	200 m
Tie line spacing	2000 m
Terrain clearance	80 m

Aircraft speed	250 km/h
Data recorded	Total magnetic field intensity and radiometrics

Table 3.2: Specifications of the magnetometer equipment utilised for the survey (Cole, 2012).

Item	Value
Magnetometer	Geometrics G823A caesium vapour
Sampling rate	10 Hz
Instrument resolution	0.01 nT
Noise envelope	<0.1 nT
Spectrometer	Radiation Solutions
Sampling rate	1 Hz
Litres of crystal	32 litres downward, 4 litres upward
Positioning	SATLOC real-time differential GPS
Accuracy	<2 m in x and y <3 m in z
Altimeter	Riegl laser altimeter
Resolution	10 Hz
Accuracy	<2 m

3.1.1. Electromagnetic data

An electromagnetic survey entails measuring the magnetic field of the Earth's crust which is dependent on the distribution of the magnetic minerals. These minerals include magnetite, titanohematite, titanomagnetite, pyrrhotite, maghemite and pure iron (Grant, 1984). Magnetic surveys record magnetic fields generated by these minerals in response to the geomagnetic field induced by the instrument. The measured magnetisation may include the remanent magnetisation in addition to the induced field. The remanent magnetisation is relatively uniform in similar mineral

and/or rock types however, the uniformity is dependent on grain sizes (Clark, 1997). Larger grain sizes of a particular mineral/or rock may exhibit numerous magnetic domains with higher magnetic susceptibilities but poor remanent magnetisation retention (Clark, 1997). This phenomenon creates differences in geomagnetic field over time and consequently, the International Geomagnetic Reference Field (IGRF) created a model to calculate intensity, declination and inclination for specific locations over a five year period.

The study area had the following magnetic field properties at the time of the survey in June to December 2009;

Magnetic intensity = 28648 nT

Declination = -17.3191°

Inclination = -62.62174°.

The Geophysics and Remote Sensing Unit of the CGS conducted several qualitative analysis of the geophysical data provided by the survey including Reduction to Pole (RTP) transformation, Analytical Signal calculation and Vertical Derivatives. The RTP transformation adjusts the magnetic data recorded on inclined magnetic earth's field to provide a symmetrical anomaly of a vertically dipping body directly above the source. It also enables induced magnetization to create an anomaly of a non-remanent body directly above the anomaly source. Analytical Signal (AS) computes 'the square root of the sum of the squares of the vertical and the two horizontal derivatives of the total magnetic field' (Roest et al., 1992). The calculation enables tracing of maximum amplitudes of the magnetic body without using the magnetization/density ratios of the magnetic data. The Vertical Derivative provides vertical spatial separation of high frequency data with respect to low frequency data and subsequently emphasizes anomalies resulting from shallow sources. The derivative also improves distinction of anomalies resulting from different sources (Milligan and Gunn, 1997). The Edge Detection Filtering technique such as Horizontal Gradient Magnitude (HGM) enhances the edges of a discontinuity body (Blakely, 1996).

The Total Magnetic Intensity (TMI) image after removal of IGRF and RTP transformation is shown in figure 3.1. The RTP transformation on the TMI image was informed by similarities in the synthetic models and TMI data comparisons as outlined by Cole (2012). The similarities suggests that anomalies in the survey area emanate

from induced magnetisation implying that the induced magnetisation flow is in the same direction as the present day magnetic field and thus permits RTP transformation (Gunn et al., 1997; Cole, 2012). It would be impossible however, to apply RTP transformation in the TMI data if the anomalies emanated from the remanent magnetisation as there would be differences between the remanent magnetization original magnetic field and the current magnetic field directions.

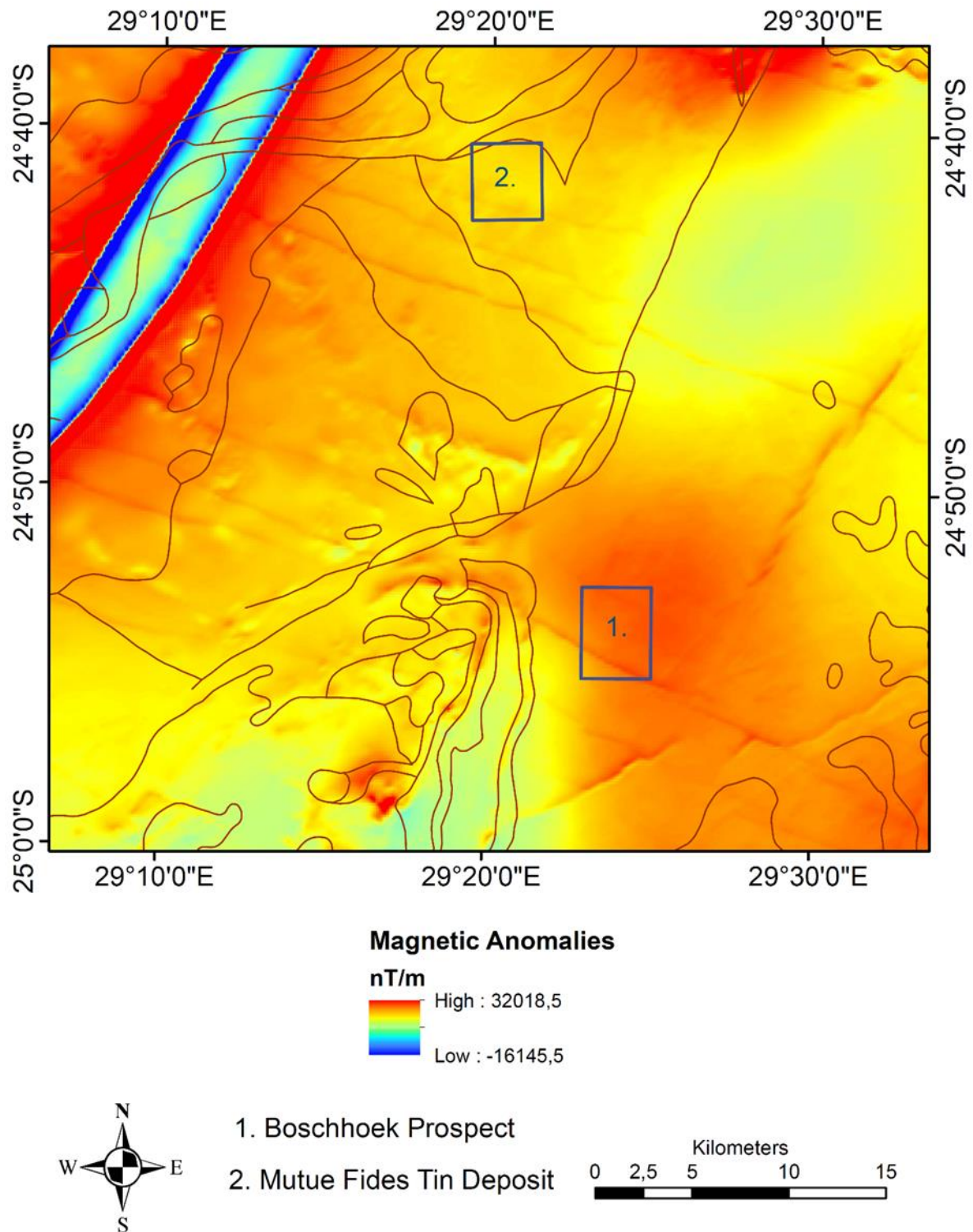


Figure 3.1: Total Magnetic Intensity data after removal of IGRF and RTP transformation. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.

The Analytical Signal (AS) was calculated to validate the absence of the remanence magnetism in the anomalies (Figure 3.2). The maximum amplitudes of the calculated AS are traced to recreate their magnetic causative bodies. Since the AS function is independent of the magnetic declination and inclination, the strike and dip of body and

the remanent magnetism, similar anomalies of the RTP transformed TMI to AS implies absence of the remanent magnetism. (Babayaju, 1999 and references therein; Cole, 2012).

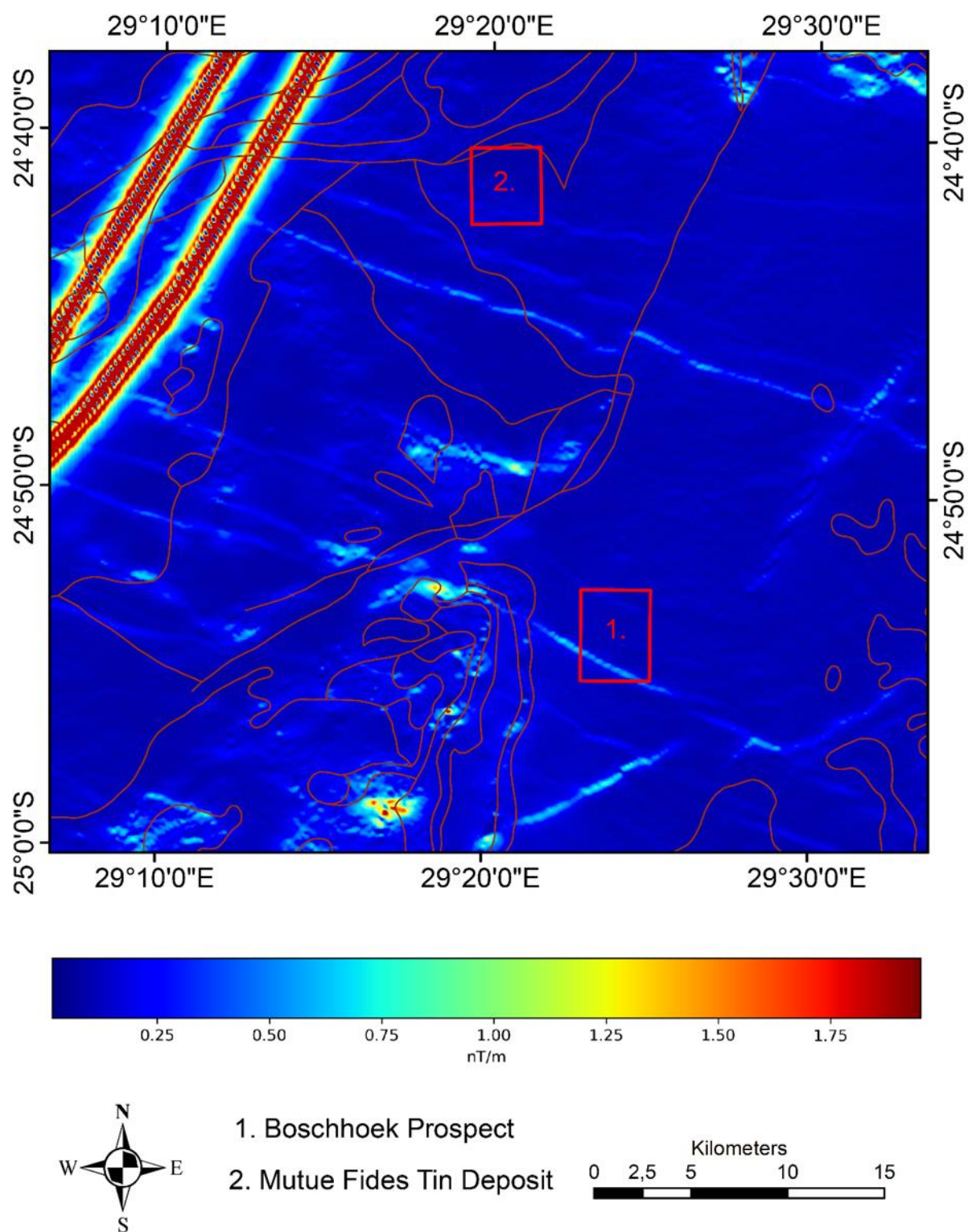


Figure 3.2: Map showing Analytical Signal data of the study areas depicting lineaments bodies, similar to the TMI. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.

The First Vertical Derivative was calculated using the RTP transformed TMI data (Figure 3.3). It emphasizes causative bodies from relatively shallow sources and distinguish the anomalies sources as outlined above.

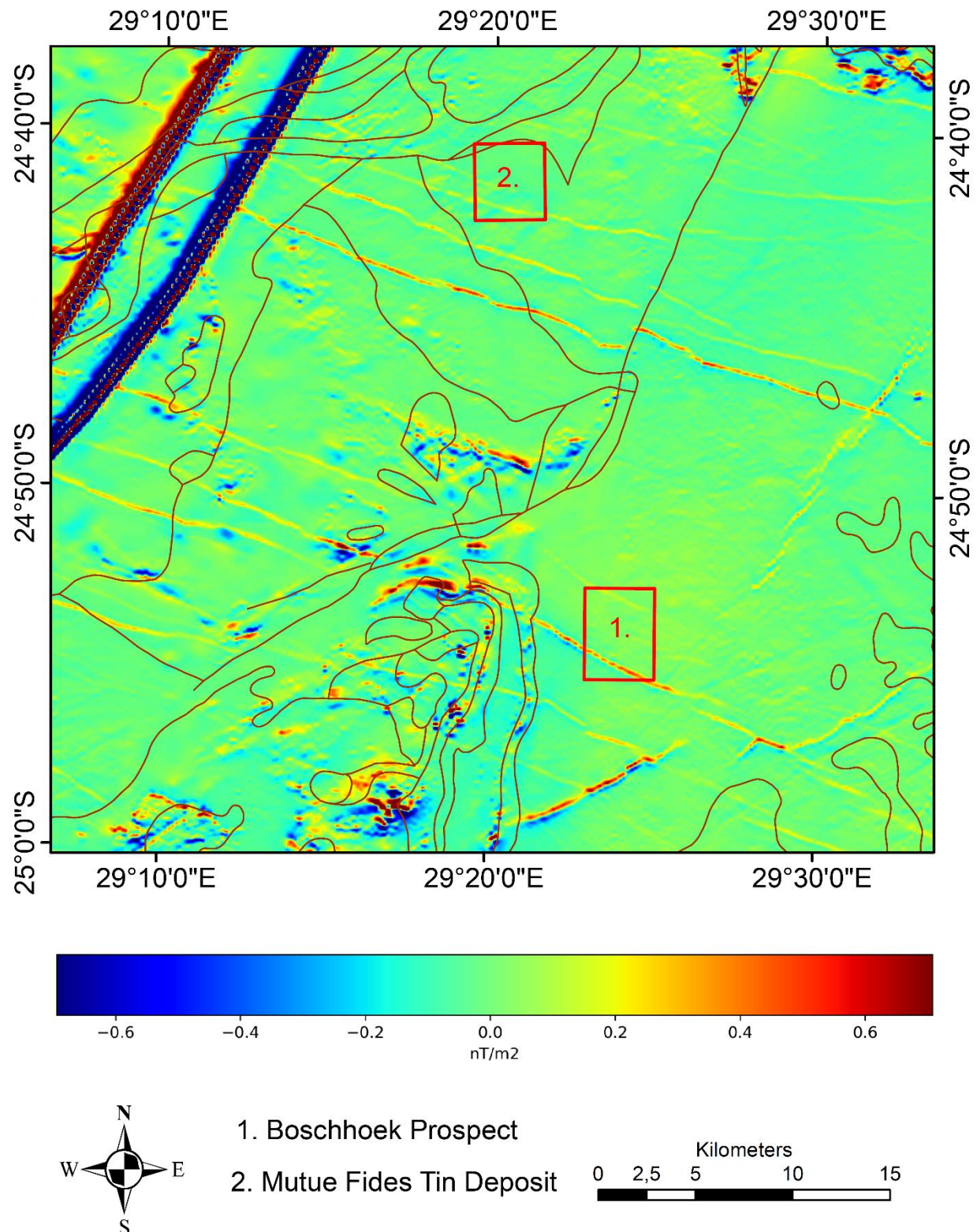


Figure 3.3: Map showing Vertical Derivative calculated from the RTP transformed TMI data. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.

3.1.1.1. Synthesis of Magnetic data

The total magnetic intensity data and various filtered images are synthesized in this section to unravel the magnetic character of the survey area and the surrounding environment. Towards the north-west of the images (Figure 3.1-3.3), there are communication or power lines running northeast possessing large anomalies that obscure the magnetic character of the underlying geology being probed.

Generally, the survey area depicts two magnetic signatures distinguishing the underlying geology and the structural fabrics. The geology of the survey area comprising the felsic rocks of the BIC and the siliciclastic rocks of the Transvaal Supergroup show moderate magnetic intensity anomalies (Figure 3.1). The area to the southwest of Boschhoek Prospect (Area 1) has a relatively higher magnetic intensity anomaly that is surrounded by a cold anomaly. There are 'blobs' of relatively negative anomalies associated with the Rooiberg Group felsites. These anomalies do not lie directly above the felsites. This lower magnetic intensity may be indicative of remanent magnetisation in the felsites and due to that, the anomalies do not occur directly above the diorites implying that the RTP transformation did not bring about any change on the TMI data. Similarly, the Analytical Signal depicts the high magnetic intensity in the area southwest of Marble Hall and the negative anomalies associated with the felsites. (Figure 3.2). The Vertical Derivative on the other hand shows the above-described anomalies as contradicting magnetic signatures (Figure 3.3). In some cases, the negative anomalies occur as mirror images of the positive anomalies located adjacent to one another.

The airborne magnetic data (Figures 3.1, 3.2 and 3.3) suggests the presence of west-northwest and east-northeast trending lineaments crossing the Nebo Granite and the Transvaal Supergroup inliers. There are northeast southwest trending structures on the Nebo Granite towards the east of each of the figures. The Vertical Derivative (Figure 3.2) is better at illustrating both these sets of structures. The airborne data did not map the known northeast-southwest Wonderkop Fault however; the Vertical Derivative data shows off-sets of several northwest and east-northeast southwest faults truncated by the Wonderkop Fault. These faults also truncate the Karoo Series to the west of the Stavoren Fragment suggesting that the last episode of the Wonderkop Fault took place after deposition of Karoo Supergroup.

The Boschhoek Prospect (Area 1) show a relatively higher magnetic intensity anomaly with respect to the Mutue Fides Tin (Area 2) (Figure 3.1). Both areas are cross-cut by west-northwest and east-northeast trending structures. The relatively local scale Boschhoek structures were not shown by the airborne magnetic data.

3.1.2. Gamma-ray Radiometric data

Gamma-ray Spectrometry entails measuring emitted gamma-rays during the decay of radiogenic-isotopes of naturally occurring potassium (K), uranium (eU) and thorium (eTh) elements in the weathered rocks and soils (Minty, 1997). However, these elements are not the only radiogenic elements but they are the only naturally occurring elements that can produce enough gamma rays measurable at survey heights (Minty, 1997). K is measured directly from gamma-ray emission when ^{40}K decays to argon (Grant, 1998). Daughter nucleides of parental Th and U are measured using distinct peaks of ^{208}Tl and ^{214}Bi , respectively and subsequently these peaks are used to calculate the parental concentrations (Grant, 1998). These concentrations are expressed as equivalent parts per million (reported as eU and eTh).

These elements occur in various rock forming minerals and as such their presence or absence in measured in-situ rocks and soil may give an indication of the bedrock geology and the alteration processes that may have occurred (Dickson and Scott, 1997; Shives et al., 2000). Potassium is the most abundant of the three elements with a crystal abundance of 2.3% and occurs in rock minerals such as K-feldspars, micas and illite clays (Emsley, 2001). Th and U have crustal abundance of 12 ppm and 3 ppm respectively (Emsley, 2001). The latter occur in radioactive granites, pegmatites, syenite and some black shales. Th occurs in accessory minerals such as zircon, apatite, sphene, epidote and monazite.

The Gama-Ray spectrometric data is employed in this subsection to map and possibly delineate alteration signatures in the survey area. A total count image overlain by geological contacts is shown in figure 3.4. K, eTh and eU channel gamma-ray spectrometric concentration data channels are shown in figure 3.5, 3.6 and 3.7 respectively. A ternary composite imagery of reclassified K, eU and eTh channels is shown in figure 3.8.

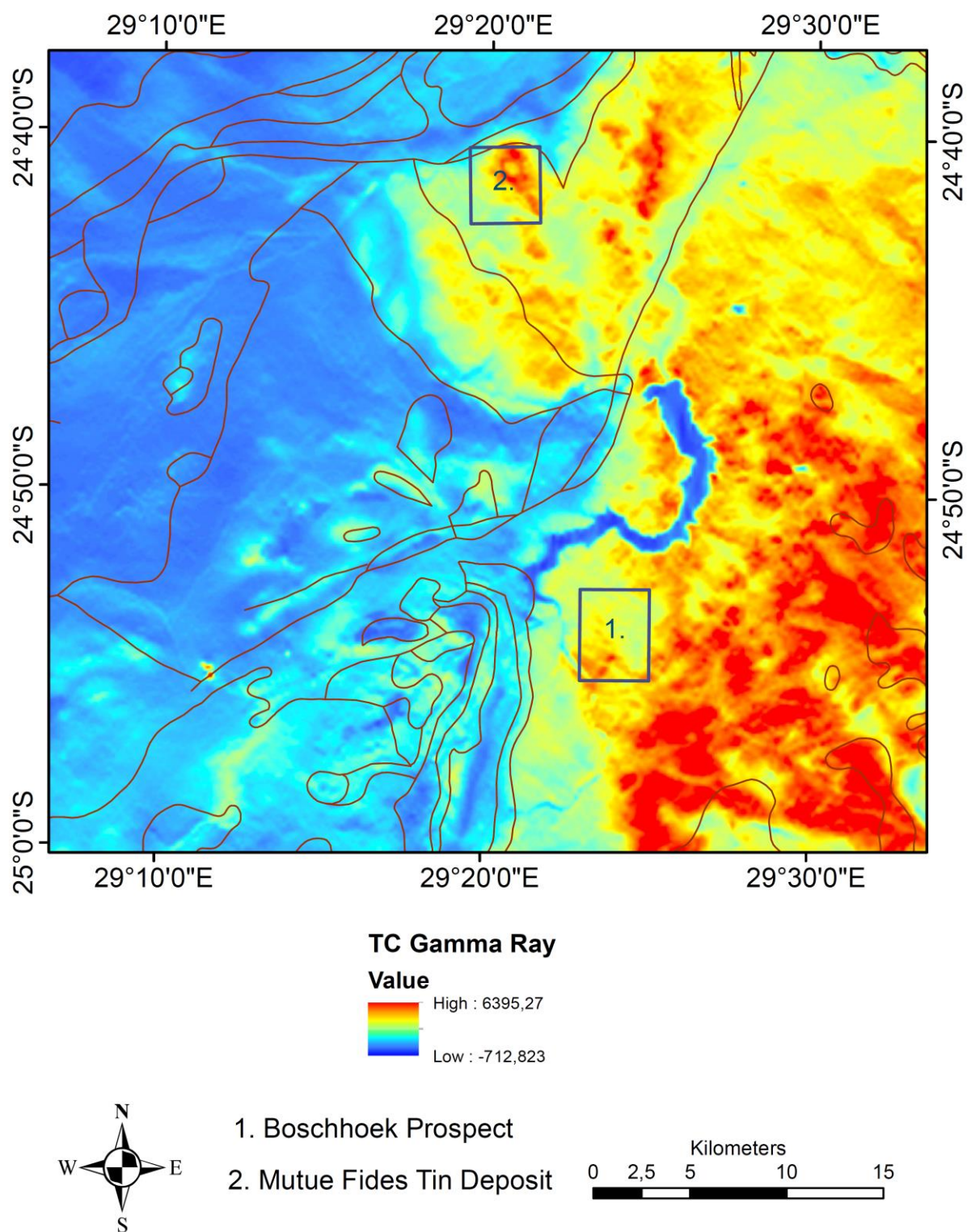


Figure 3.4: Total counts gamma-ray imagery of the area of interest overlain by geological contacts of the survey area. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.

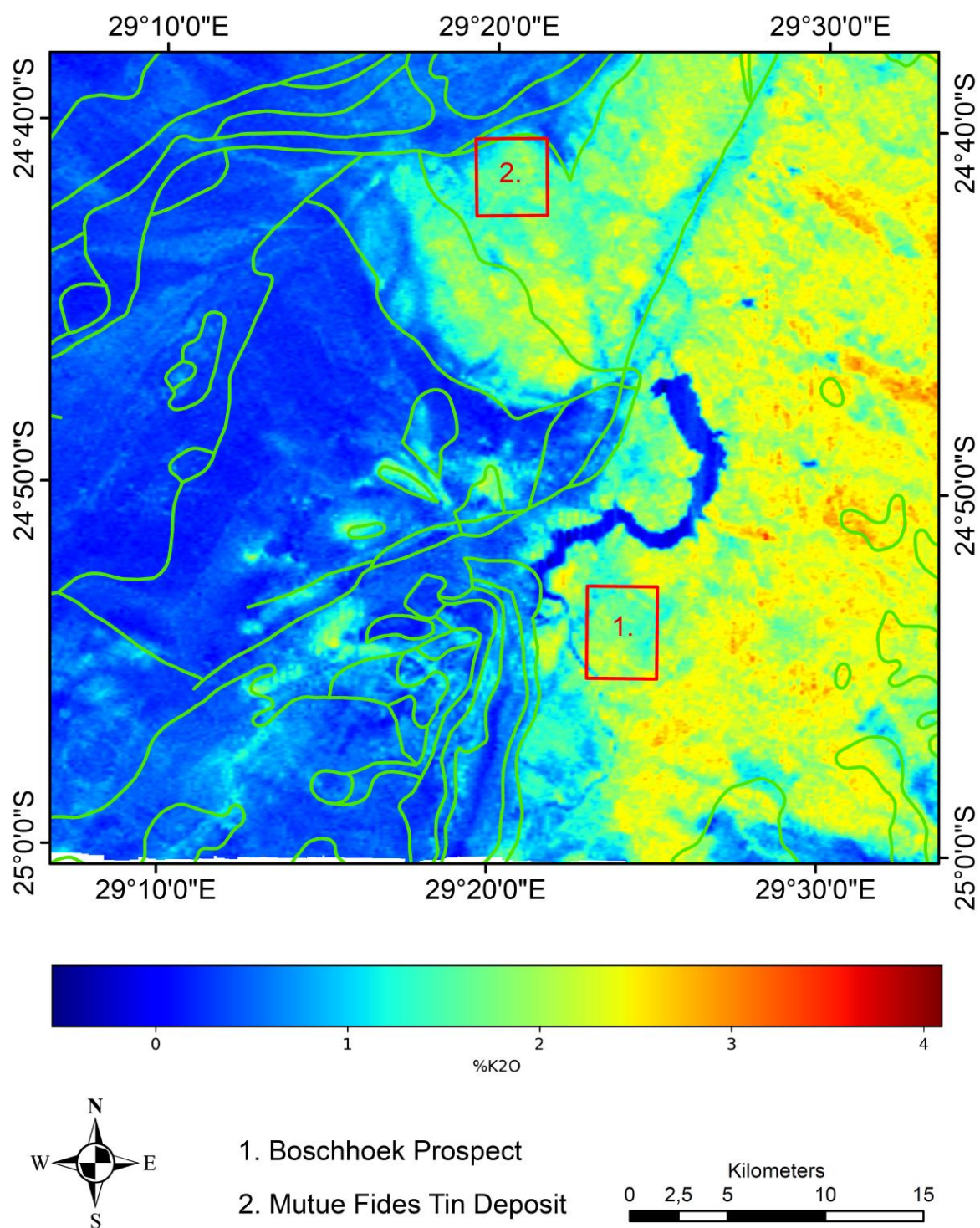


Figure 3.5: Imagery of potassium channel gamma-ray spectrometric concentration data in the survey area overlain by geological contacts. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.

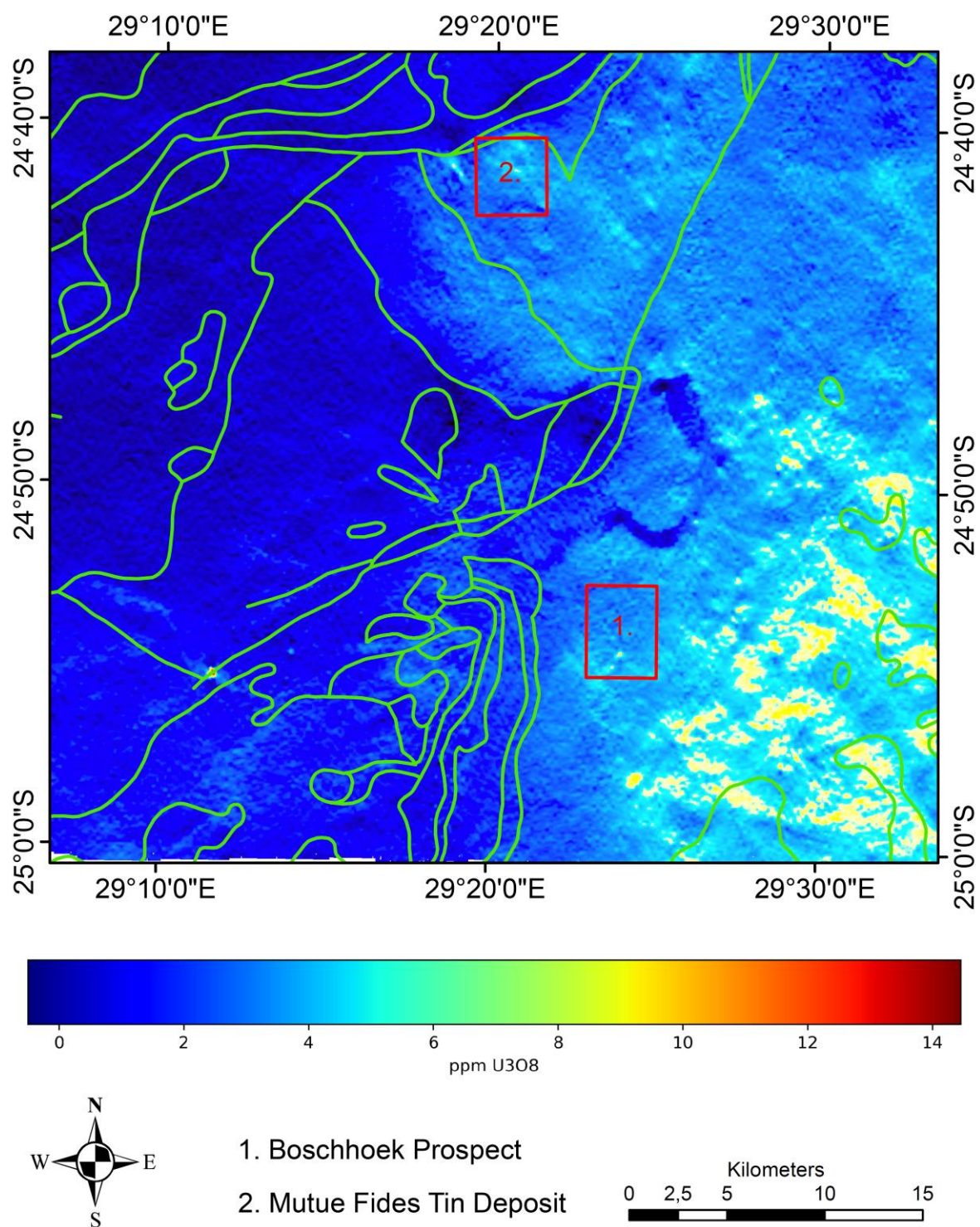


Figure 3.6: Imagery of eU channel gamma-ray spectrometric concentrations data. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.

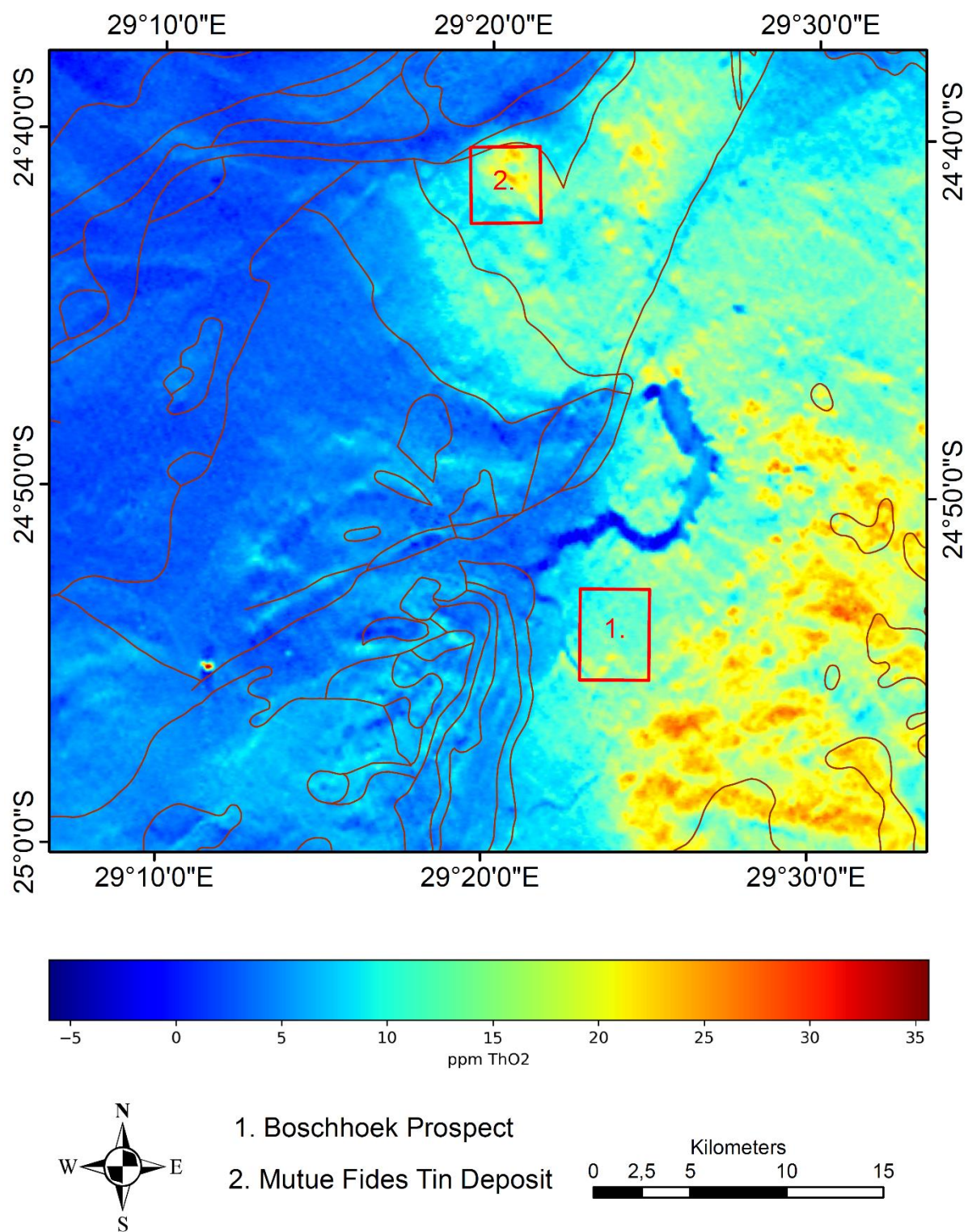


Figure 3.7: Imagery of eTh channel gamma-ray spectrometric concentrations data overlain by geological contacts of the survey area. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.

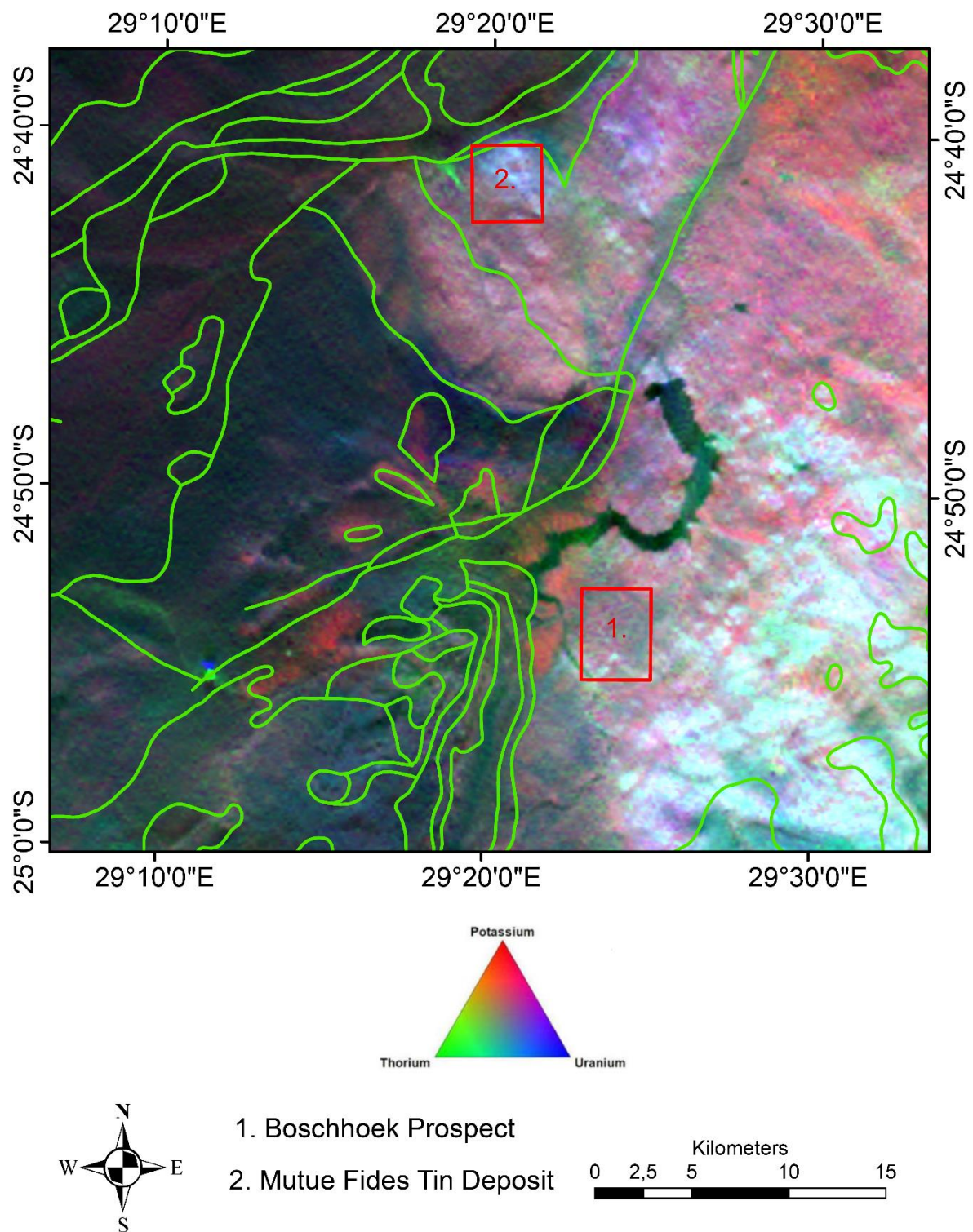


Figure 3.8: Ternary composite imagery of reclassified K, eU and eTh in ArcGIS. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.

3.1.2.1. Synthesis of Radiometric data

Generally, felsic rocks of igneous origin are relatively enriched in all three radioelements (Galbraith and Saunders, 1983). Accordingly, the Nebo granite of the LGS and the Stavoren granophyre of the RGS in the survey area show higher concentrations in radioelements relatively to the inliers (Figure 3.5; Figure 3.6; Figure 3.7). The concentration of radioelements is even higher within areas underlain by more fractionated portions of the igneous rocks. Thorium shows an exponential increase with increasing Si content in igneous rocks and as such, the eTh/eU may be used to distinguish degree of fractionation within igneous suites (Dickson and Scott, 1997).

Ternary composite images of reclassified K, eTh and eU depicts these fractionated locations of igneous rocks with white background i.e. all three radioelements concentrations are higher in those locations (Figure 3.8). Areas characterised by low counts of the three radioelement appear dark, alternatively in areas where one channel dominates the assigned colour to that particular channel stands out (Figure 3.8).

Relatively fractionated Bobbejaankop and Lease granites underlie the Mutue Fides tin area and it appears white, implying higher concentrations of all three channels (Figure 3.8). The Boschhoek Prospect is characterised by a combination of red and green colours (Figure 3.8).

Phyllic and potassic alterations in igneous suites may be indicative of mineralization (Huston et al., 1998). In phyllic alteration zones, K bearing minerals such as k-feldspar and biotite are replaced by weathering susceptible mineral assemblage comprising sericite, pyrite and lessor quartz (Shives et al., 2000). Consequently, these zones will have low K concentration resulting in higher ratios of both eTh and U against K. In potassic alteration zones, the formation of K bearing minerals such as k-feldspar, biotite and some amphiboles will elevate the K concentration. Consequently, both eTh and eU ratios against K will be relatively lower (Huston et al., 1998).

K and eTh concentrations from the study area were rationed to produce variations of the eTh/K ratios in order to map possible alterations (Figure 3.9). The eTh/K ratios were calculated from classified eTh and K in ArcGIS since the eTh is in ppm and K is in wt. %. The areas depicted by red patches in Figure 3.9 depict possible areas of phyllic alteration. These phyllic alteration zones were envisaged to occur in the study areas however, the eTh/K ratios did not delineate alteration

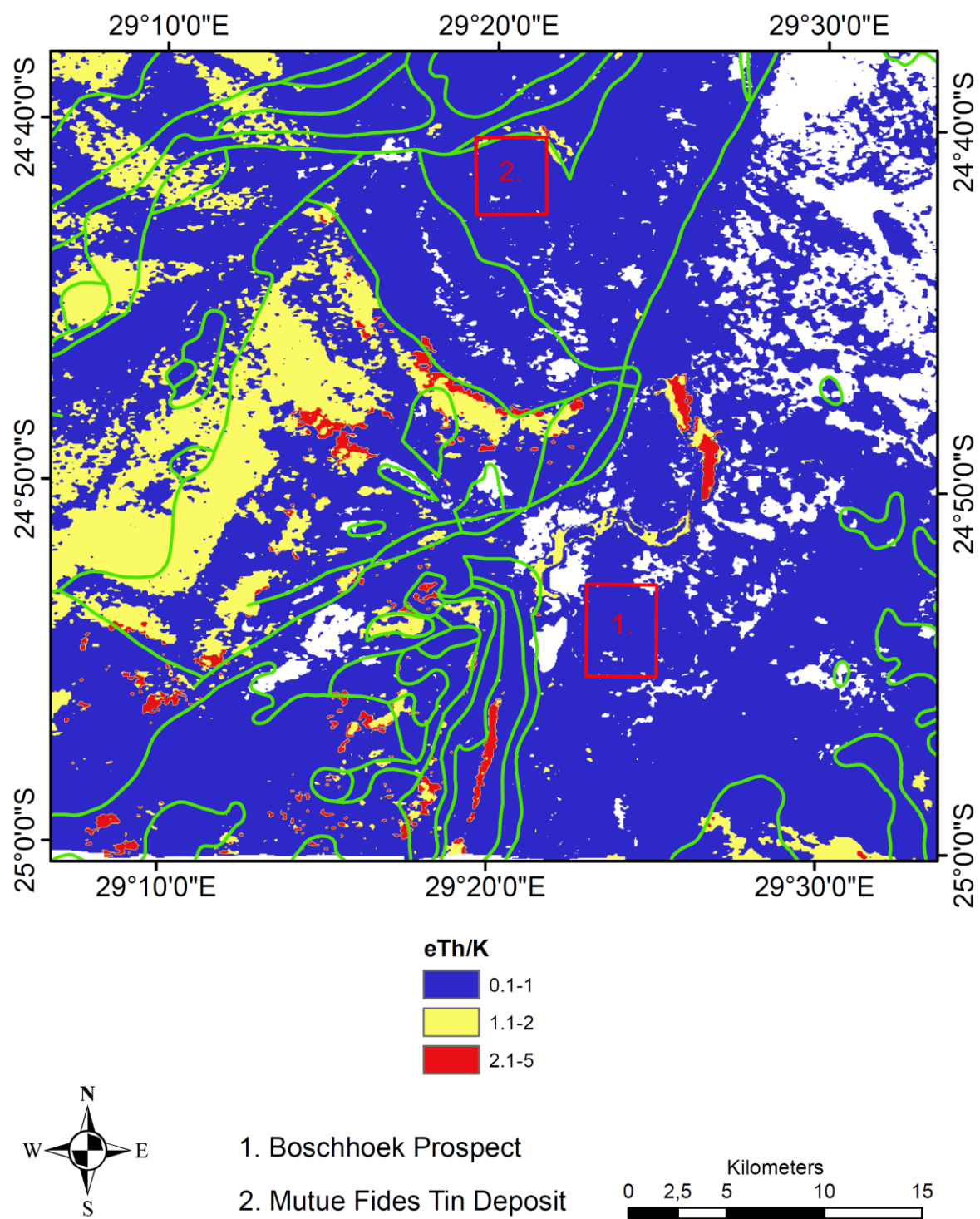


Figure 3.9: Imagery of reclassified channels of eTh/K ratios overlain by geological contacts of the survey area. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.

3.2. Remote Sensing

Landsat 7 Enhanced Thematic Mapper (ETM+) and Sentinel 2 remote sensing data obtained from the United State Geological Survey (2019) website were utilized to discriminate bedrock geology and other cover features; i.e. land classification types. These remote sensing layers were also employed to delineate various kinds of alteration associated with the background geology and geological structures.

3.2.1. Landsat 7

The Landsat 7 scene used for the study; path 170 row 77 was photographed on 10/05/2006. Thurmond et al. (2006) noted that the Landsat 7 provides imagery of the Earth's surface in seven bands (Figure 3.10). Detection is at 30 m ground resolution for six bands; four of those in the visible to near-infrared (VNIR) wavelengths and two bands available in the shortwave infrared (SWIR) wavelengths. One band is available at ground resolution of 60 m at thermal infrared (TIR) wavelengths. One additional panchromatic band at ground resolution of 60 m is also available.

Landsat ETM+ Bands

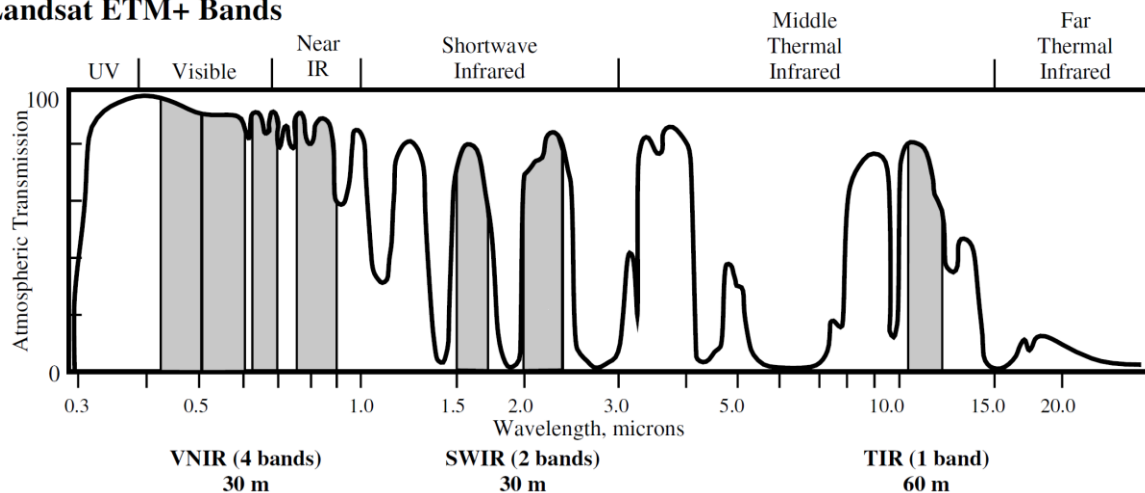
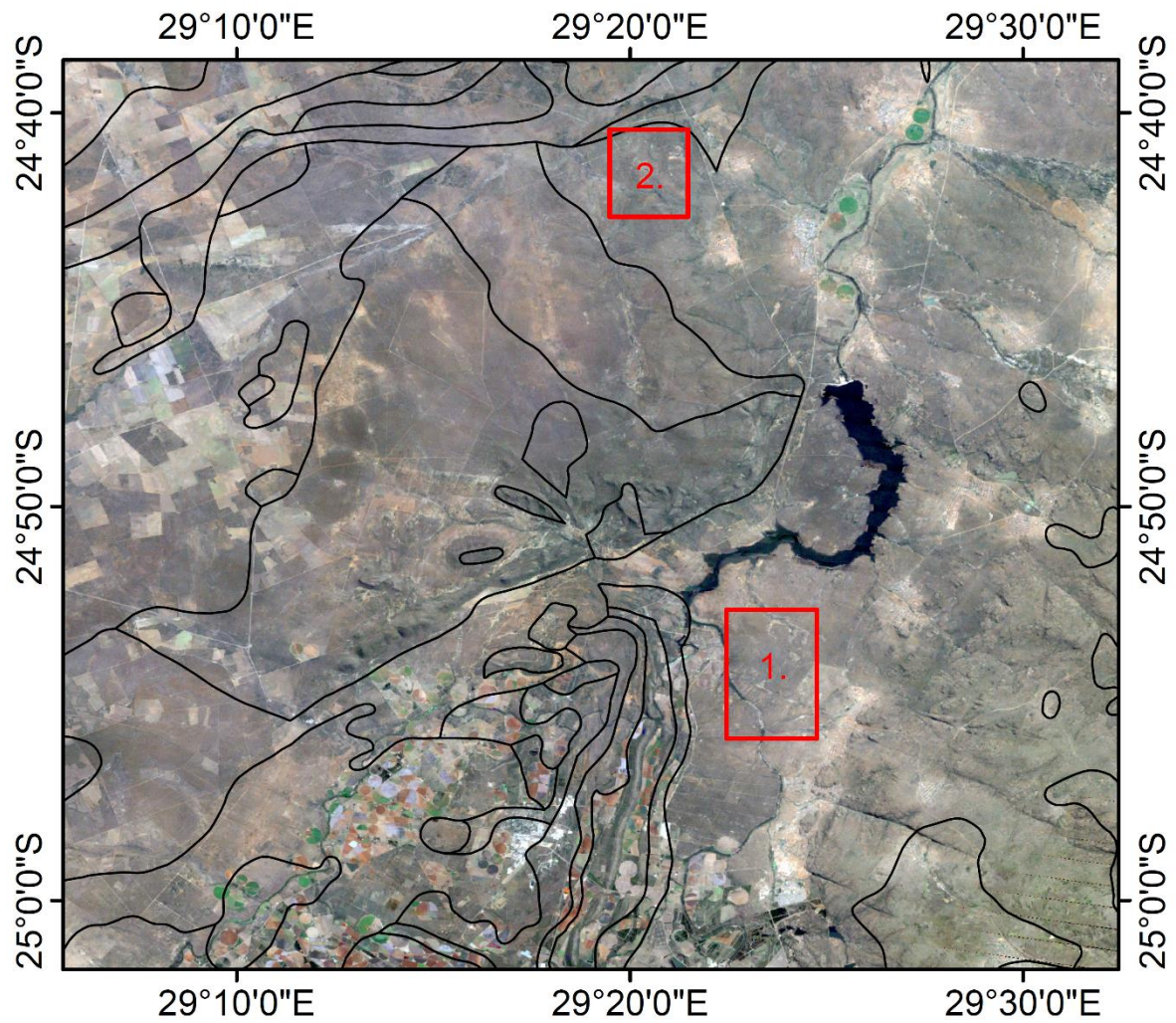


Figure 3.10: Electromagnetic spectrum with respective Landsat 7 ETM+ bands and their corresponding wavelengths (Thurmond et al., 2006).

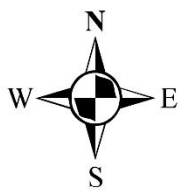
Various ground surfaces possess different spectral signatures, i.e. they reflect or absorb electromagnetic radiation at various wavelengths (Thurmond et al., 2006). It is possible however, for different ground surfaces to have similar absorption features at the same or similar wavelengths. There are several ways to mitigate this ambiguity but the most common method is applying the Landsat 7 ETM in conjunction with other remote sensing imagery types generated from ASTER or SENTINEL 2 and using Google Earth as a reference.

Landsat 7 ETM interpretations rely on creating ternary colour images by assigning electromagnetic bands to red, green and blue colour bands (RGB Image). Composite images from Landsat 7 ETM data are created using the composite bands function in the Raster manipulation tool from ArcGIS.

A 3-2-1 combination from the resultant composite image resembles a human eye/brain comprehension. i.e. a Landsat 7 band combination of 3-2-1 (RGB) ternary image will recreate what an area will look like to the human eye (Peña and Abdelsalam, 2006; Figure 3.11). Band combination 7-4-2 preserves better morphological features and consequently maps various lithological units (Peña and Abdelsalam, 2006) (Figure 3.12). The ridges of the Thaba Sot (White Hills) are notable along the Wonderkop Fault Zone together with the Olifants River and the Flag Boshielo Dam (Figure 3.12).



Band Combination 3 2 1 (Natural Colours)



1. Boschhoek Prospect

2. Mutue Fides Tin Deposit

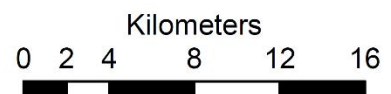
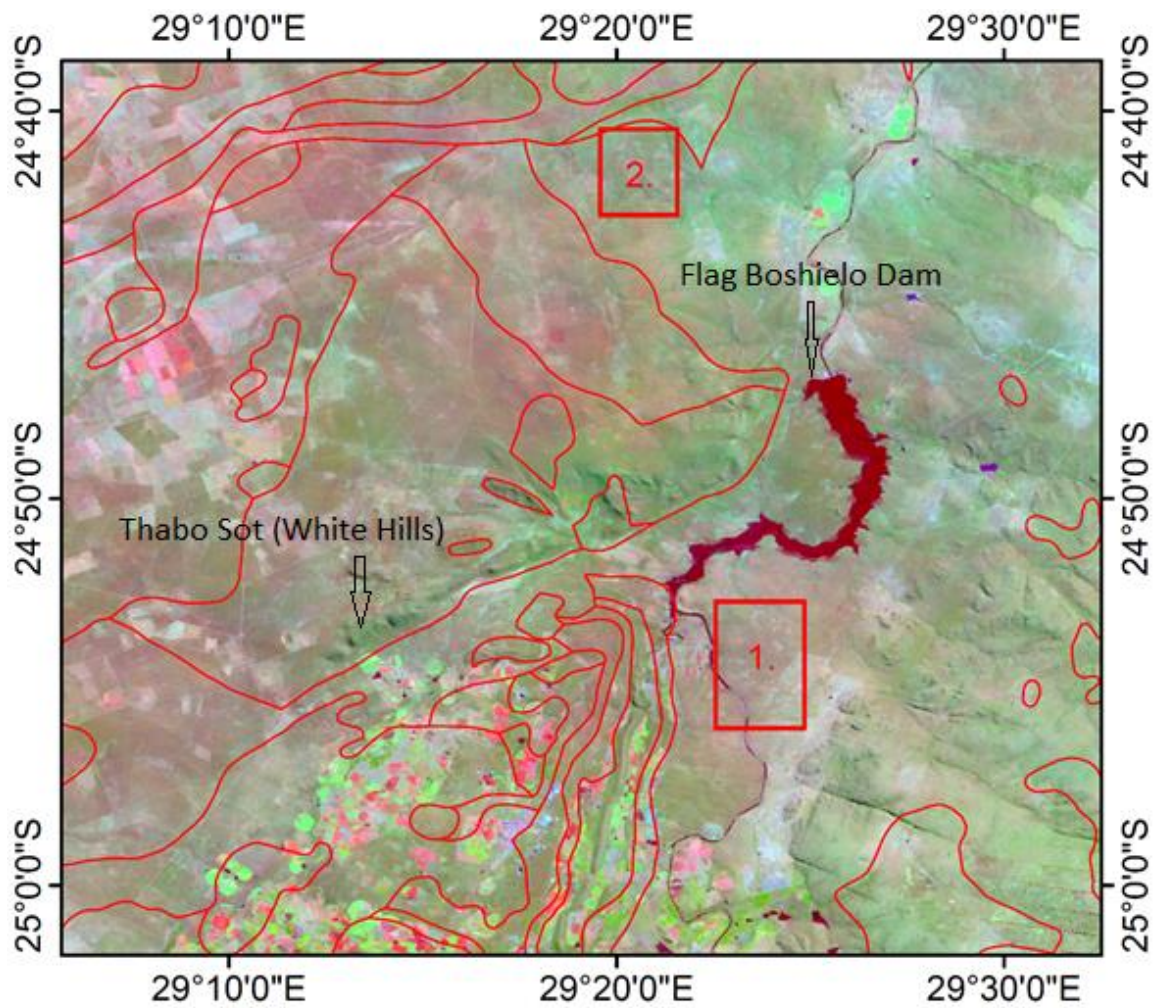


Figure 3.11: A Landsat 7 composite image from 3-2-1 bands of the study areas and the surrounding area of interest overlain by geological contacts. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.



Band Combination 7 4 2



1. Boschhoek Prospect

2. Mutue Fides Tin Deposit

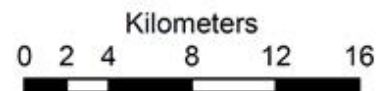


Figure 3.12: A Landsat 7 composite image from 7-4-2 bands depicting morphological features of the study areas. Boschhoek Prospect and Mutue Fides tin deposit are denoted by numbers 1 and 2 respectively.

Band ratios are widely used to emphasize various aspects of the Landsat data (Ott et al., 2006). The ratio 3/1 is used to delineate areas characterized by iron-bearing minerals as band 3 reflects iron-bearing minerals but these minerals are strongly absorbed in band 1. Band 5 strongly reflects clay minerals and band 7 absorbs them,

making 5/7 band ratio a clay-ratio (Ott et al., 2006). Peña and Abdelsalam (2006) noted hydroxyl and silicate-rich minerals are emphasized by 4/5 band ratio and band ratio 4/3 strongly depicts vegetation. Clay and iron ratios may be indicative of hydrothermal alteration loci and possible mineralization. A ternary composite image of the three band ratios 5/7, 4/3 and 3/1 delineates clay rich (red), iron-oxide rich (blue) and vegetated areas (green). On inspection of the composite image, it does not map the envisaged signatures as achieved by Cole (2012).

3.2.2. Sentinel 2

The Sentinel 2 Multi Spectral Imager instrument possesses similar bands to the Landsat Thematic Mapper family of instruments (Flood, 2017; Figure 3.13). These instruments, in principle give comparable measurements, as they possess virtually the same spectral windows however, the Sentinel 2 instrument produces visible and near-infrared bands at a spatial resolution of 10 meters and the red and near-infrared bands and two shortwave infrared bands at a 20-meter spatial resolution as opposed to Land 7 ETM mapper with 30 m resolution (Flood, 2017). Sentinel 2 imagery recorded on 06/07/2019 of path T074619 was available for the study areas. This Sentinel 2 imagery was chosen for lithological classification and possible alteration patterns as the Landsat 7 scene could not clearly delineate the alteration patterns. Furthermore, Sentinel 2 possesses better resolution and presents the more recent imagery scene.

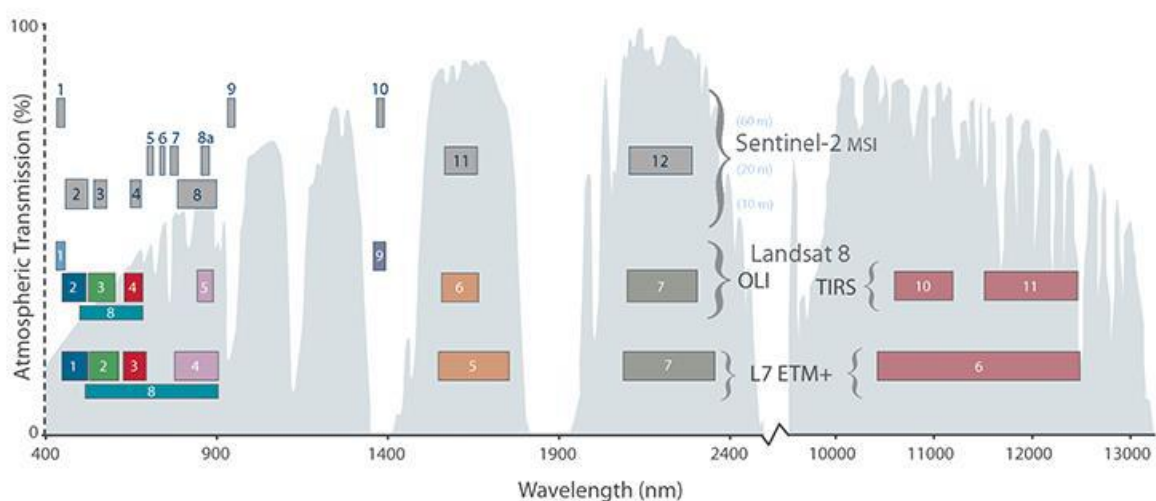


Figure 3.13: Comparison of Sentinel 2 with Landsat 7 and 8 (USGS, 2019).

Band combination 4-3-2 in Sentinel 2 creates a natural image similar to the Landsat 7. Band ratios in Sentinel 2 can be also manipulated to emphasize certain features as previously described following the Ott et al. (2006) classifications. Clay minerals are absorbed in band 12 but possesses high reflectance in band 11 and calculating the 12/11 band ratio will highlight clay-rich mineral locations. The band 4/2 ratio highlights the iron-bearing minerals as band 4 reflects iron-bearing minerals but they are absorbed in band 2. The 8/11 band ratio highlights hydroxyl and silicate rich minerals over iron rich minerals and highlights vegetation. Similarly to Landsat 7, Sentinel 2 did not map any envisaged alteration haloes.

Ternary images of clay-vegetation-iron oxide do not effectively map the alteration haloes expected in the study areas. This may be due to several factors including vegetation cover that may have masked out areas with alteration and thick unconsolidated quaternary sand associated with the study areas. Field observations suggest that alteration patterns in polymetallic mineralization in the study areas are usually localized within few centimeters and to a couple of meters on the surface and as such remote sensing images cannot map or decipher these alterations. Furthermore, artisanal and historical mining and exploration in the Mutue Fides-Stavoren area, resulted in large holes which may have destroyed any surface alteration signature.

Chapter 4: Structural features of the study areas

Tectonic structures along the Wonderkop Fault particularly the faults, veins, micro-veinlets and pegmatites situated between the Marble Hall Dome and the Stavoren Fragment were examined to help unravel the kinematic history of the Wonderkop Fault. Relatively small-scale veins, pegmatites and faults from the Boschhoek Prospect and those to the northeast of the Stavoren Fragment were documented (Figure 4.1). The structural data presented are grouped according to location for better understanding of the kinematic history in each location. The structural data from the Mutue Fides-Stavoren Fragment is presented in section 4.1, the data from the Boschhoek Prospect and the surrounding area is presented in 4.2 and that for the Wonderkop Fault is presented in section 4.3.

On inspection of the collected structural data and examination of geophysical data presented in Chapter 3, the joint datasets trending in an east - west direction from all the data collection locations were omitted from the structural analysis in this chapter as these data are part of later events. However, the data are presented for each location.

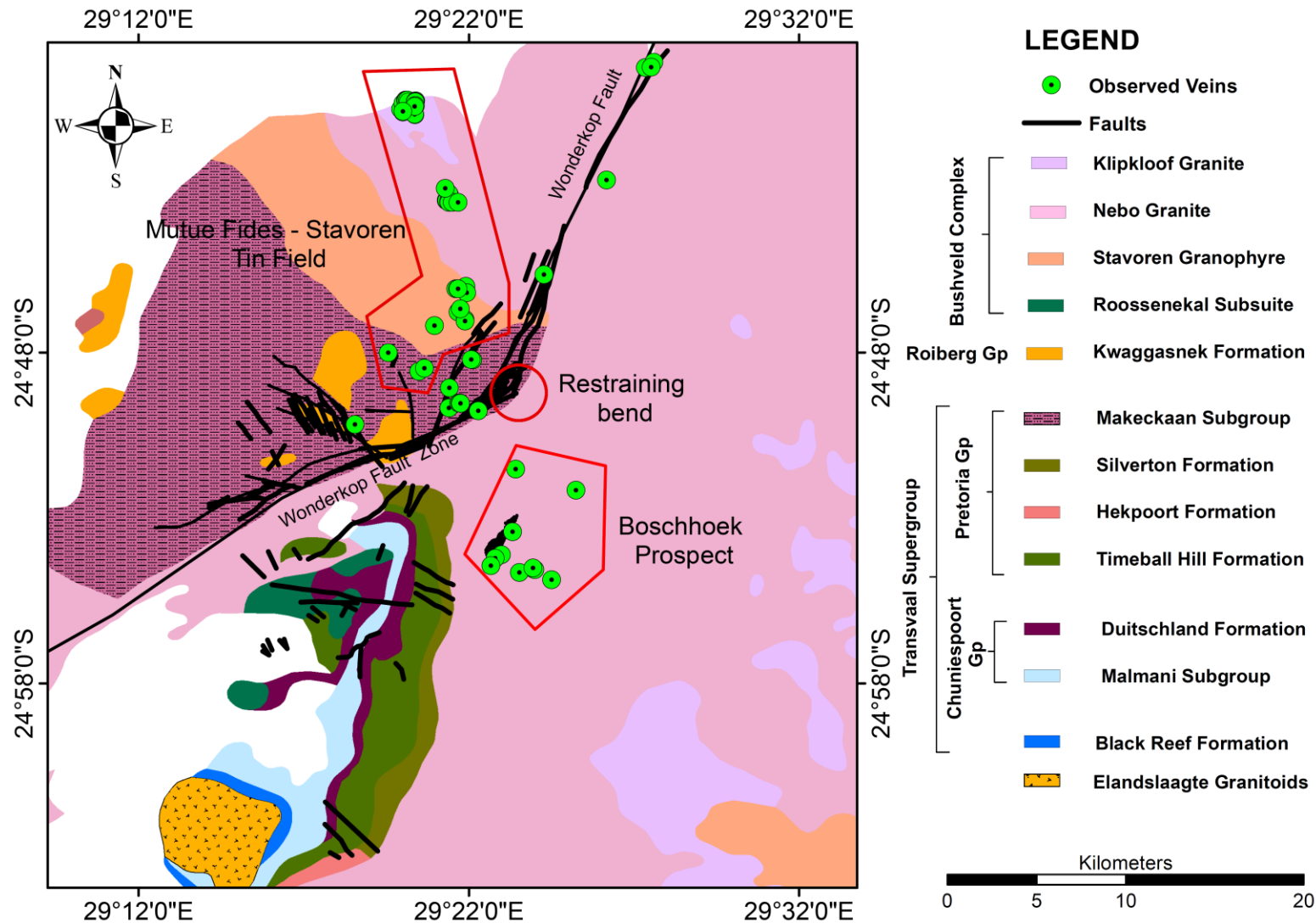


Figure 4.1: Geological map of the study areas showing the locations of veins (green circles) described during fieldwork. Red polygons delineate vein observations as a group per area of study (Reproduced from the Council for Geoscience 1:250 000 geological map).

4.1. Structures described in the Mutue Fides - Stavoren area

The Mutue Fides - Stavoren area contains a wide range of vein sizes, pegmatites and joints, with the former exhibiting three different orientations and various mineralogies (Figure 4.2). The mineralogy of the veins comprises predominantly quartz and seldom quartz-feldspar pegmatite bodies. The quartz veins occur in all lithologies in the Stavoren Fragment including Kwarriehoek Formation, Stavoren granophyre and Nebo granite and its facies as described in Chapter 2. The quartz-feldspar pegmatites are common in the Stavoren granophyre and the Nebo granite including its fractionated facies. In some cases, the quartz-feldspar pegmatites occur as pipe-like or vein-like bodies that are zoned with black mica on the margins of these bodies. Wagner (1921) noted zonation in the vein-like bodies comprising raven mica (black mica) as the rim, followed by the quartz-feldspar pegmatite bordered inwards by scheelite and/or cassiterite. The 'core' often comprised fluorite and/or calcite (Wagner, 1921). These minerals were observed in some old diggings as remnants in the Stavoren Fragment area but the zonations were destroyed during mining and processing.

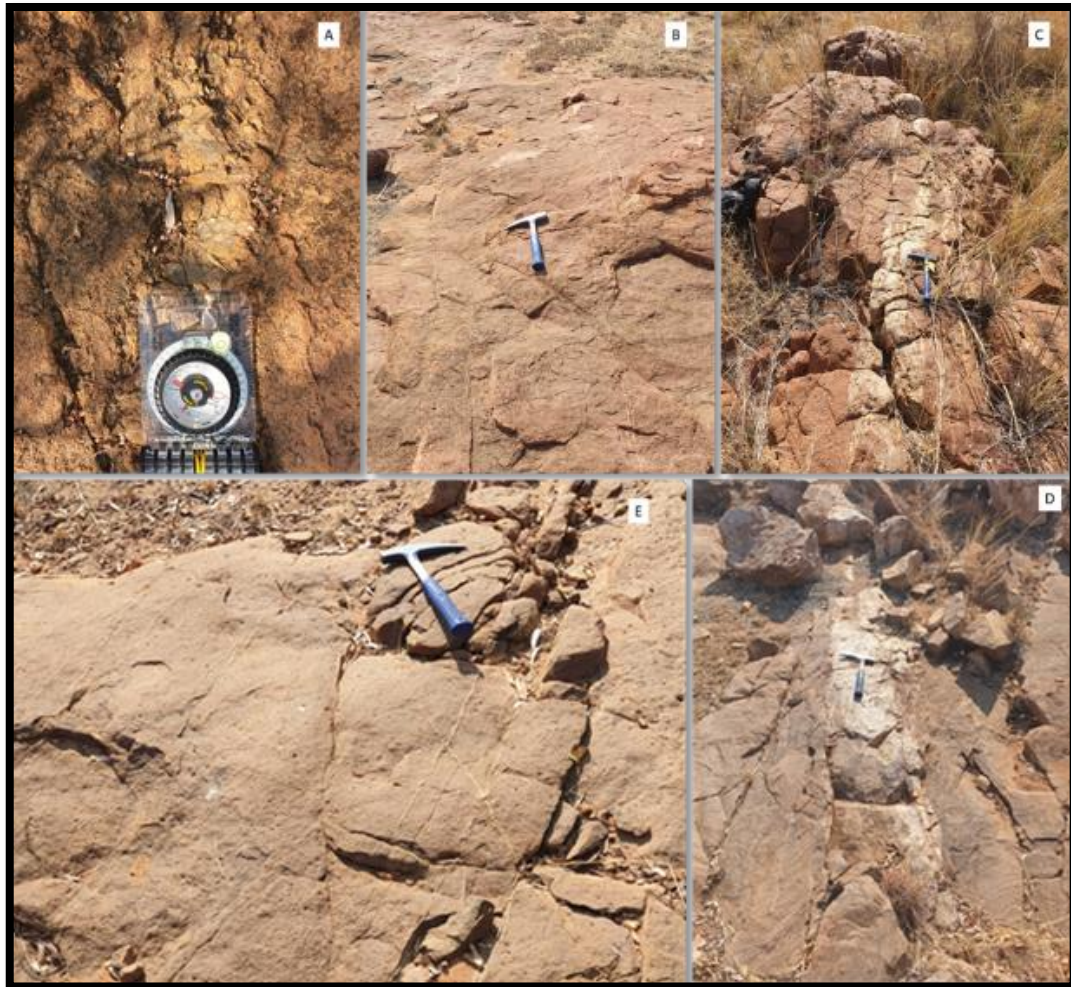


Figure 4.2: Field photographs showing various vein types and sizes in the study areas. A: pegmatite vein-like body in granite. B: parallel quartz in granite veins. C and D: quartz veins in sedimentary rocks. E: Conjugate quartz veins (Photos taken facing northeast).

The veins in the Mutue Fides – Stavoren area range from micro-veinlets (<10 mm wide) to minor veins (10-50 cm thickness). The quartz veins occur as both micro veinlets and minor veins; however, they are particularly common as micro veinlets. The quartz-feldspar veins on the other hand, occur only as minor veins (Figure 4.2A). Both vein sizes strike in two dominant directions; northeast and east-northeast. The least dominant trend directions of the veins are east southeast and north. (Figure 4.3). These veins are sub-vertical, dipping between 70°- 90° to the northwest (Figure 4.3).

Table 4.1: Vein orientatiaton, sizes, and their dominant mineralogy from the mutue Fides-Stavoren area.

Vein/Joint Type	Size (Width)	Dominant Orientation	Mineralogy
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Micro veinlets	<10 mm	NE, ENE	Quartz
Minor veins	10 – 50 cm	NE, ENE	Quartz, Quartz- Feldspar, Calcite, Fluorite
Joints	<10 mm fracture	ESE	X

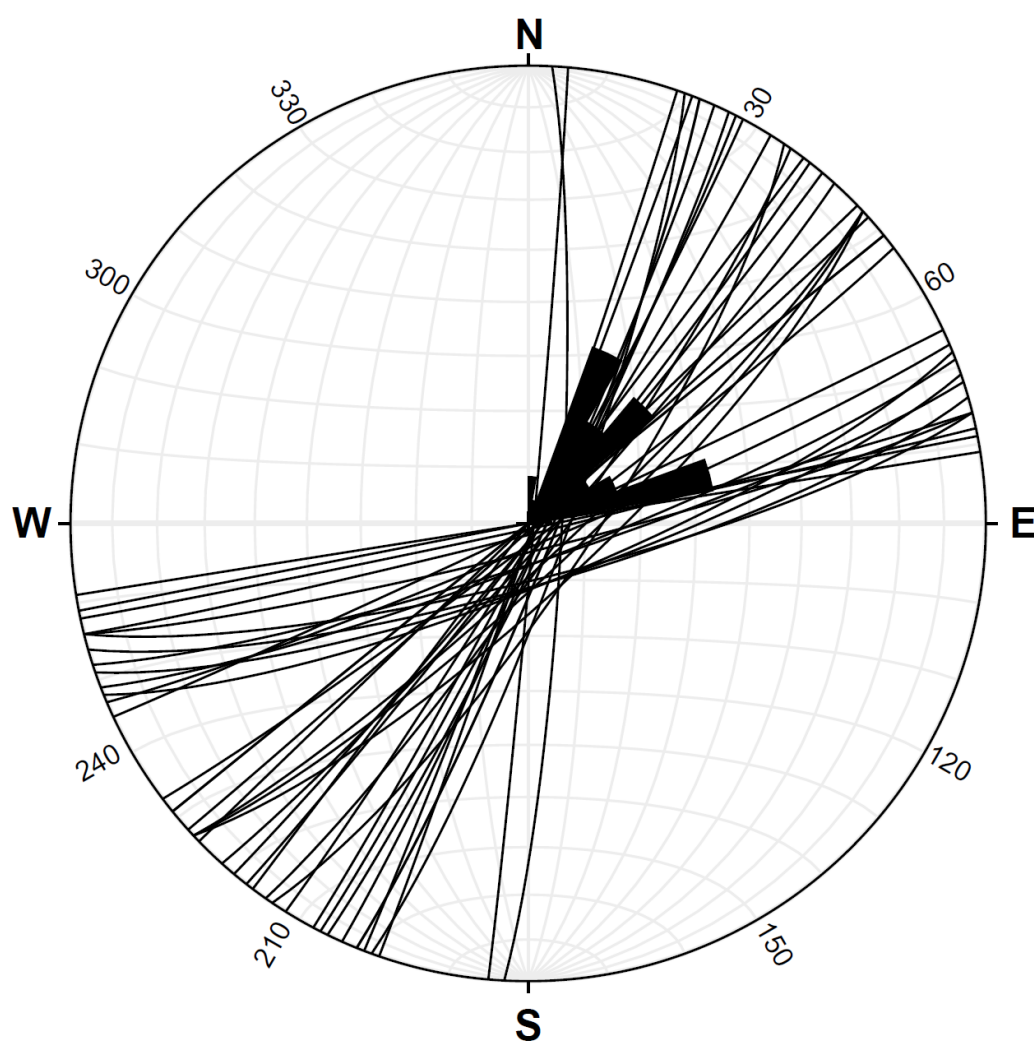


Figure 4.3: Stereonet diagram depicting planes (black lines) of veins from Mutue Fides – Stavoren are and the corresponding rose diagram (black petals). N=39. Plotted using the Stereonet 11 software (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013).

The northeast trending quartz veins seldom occur in isolation, they often occur in pairs or a set of three veins that are sub-parallel or parallel (Figure 4.4). In cases where all three sets of sub-parallel veins occur altogether, they form splay structures (Figure

4.5). This phenomenon is most common in micro veinlets and seldom occurs in minor veins. In some cases the northeast veins obstruct the vertical east-west joints and quartz veins ranging from micro-veinlets (<10 mm) to veinlets (circa. 1 cm width). These east-west joints, micro-veinlets and veinlets terminate at the main-veins range suggesting that they represent a later event(s) (Figure 4.6).

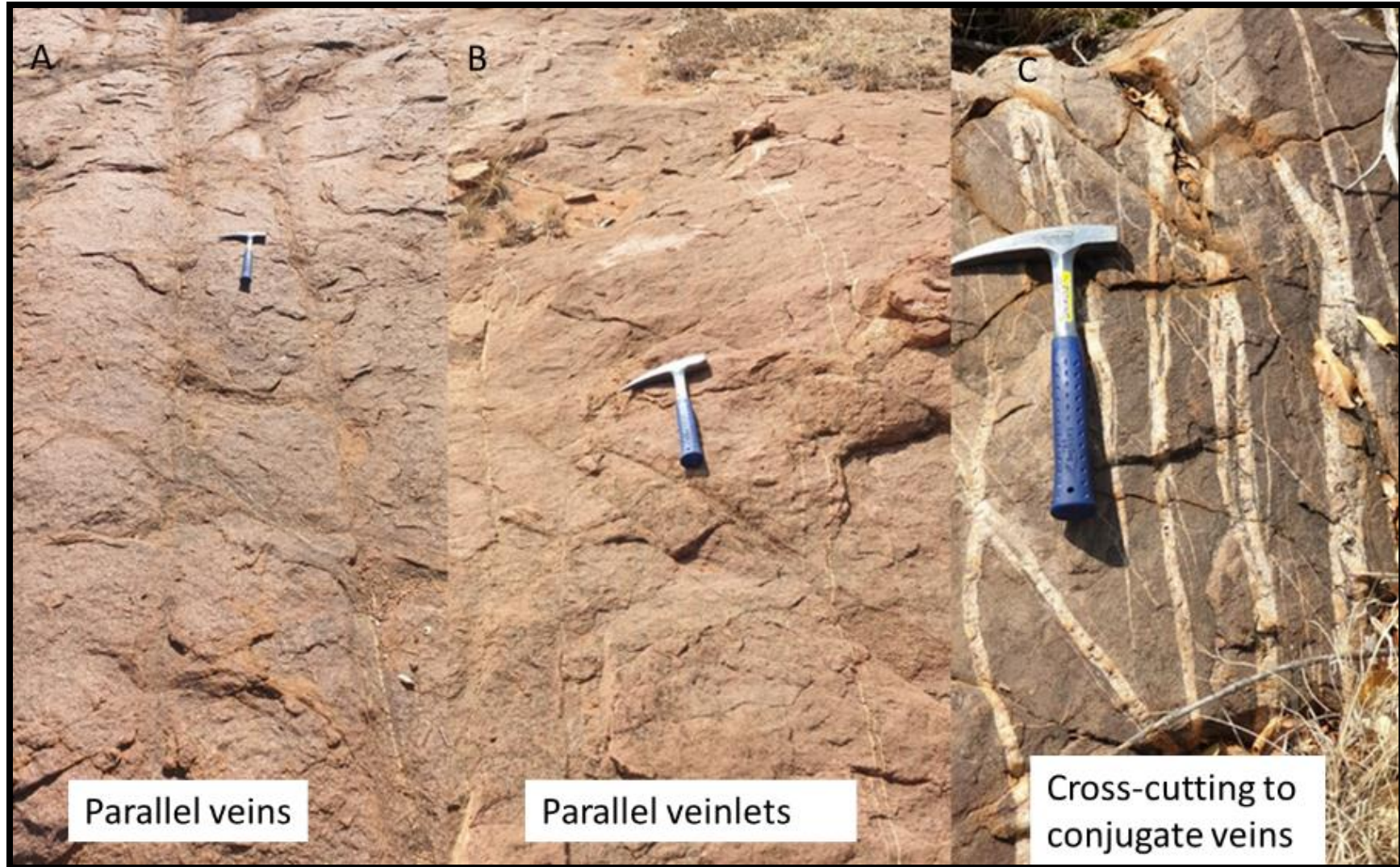


Figure 4.4: Photographs showing parallel and sub-parallel quartz veins in the Stavoren area (Photos taken facing northeast).



Veinlets showing splay morphologies

Figure 4.5: Photograph showing the splay morphology of quartz veins in the Stavoren area (Photos taken facing northeast).



Figure 4.6: Photographs showing joints and quartz veins in granite. A: East-west trending vertical joints. B: East west joints and vein terminating at northeast trending vein (weathered on the surface) at Stavoren (Photos taken facing west).

4.2. Boschhoek Prospect

The Boschhoek Prospect contains primarily gossan and quartz veins truncating the weathered Nebo granite which occur as an array of sigmoidal veins termed the Boschhoek Structure by Evans (2015) (Figure 2.3). The gossan veins comprise hematite, goethite and minor limonite (Evans, 2015). These form ridges that range between 10 and 25 m in thickness (Figure 4.7). The ridges are traceable for over 1000 m and notably become patchy away from the centre of the Boschhoek structure (Figure 2.3). At the centre of the Boschhoek structure where veins exhibit sigmoidal shapes (referred to as the main vein), the gossans, veins and Nebo granite are brecciated and cemented by siderite or quartz. Away from the centre of the main vein, the gossan veins form a sub-parallel array of veins that converge at some 2000 m northeast from the centre of Boschhoek structure (Figure 2.3). The sub-parallel veins range between 2 and 10 m thickness. The eastern periphery of the Boschhoek structure shows a distinct northeast-trending linear gossan vein parallel to the main. The eastern periphery vein ranges between 1 and 2 m in thicknesses. This distinct vein also terminates at the same point as the other veins characterising the main vein.

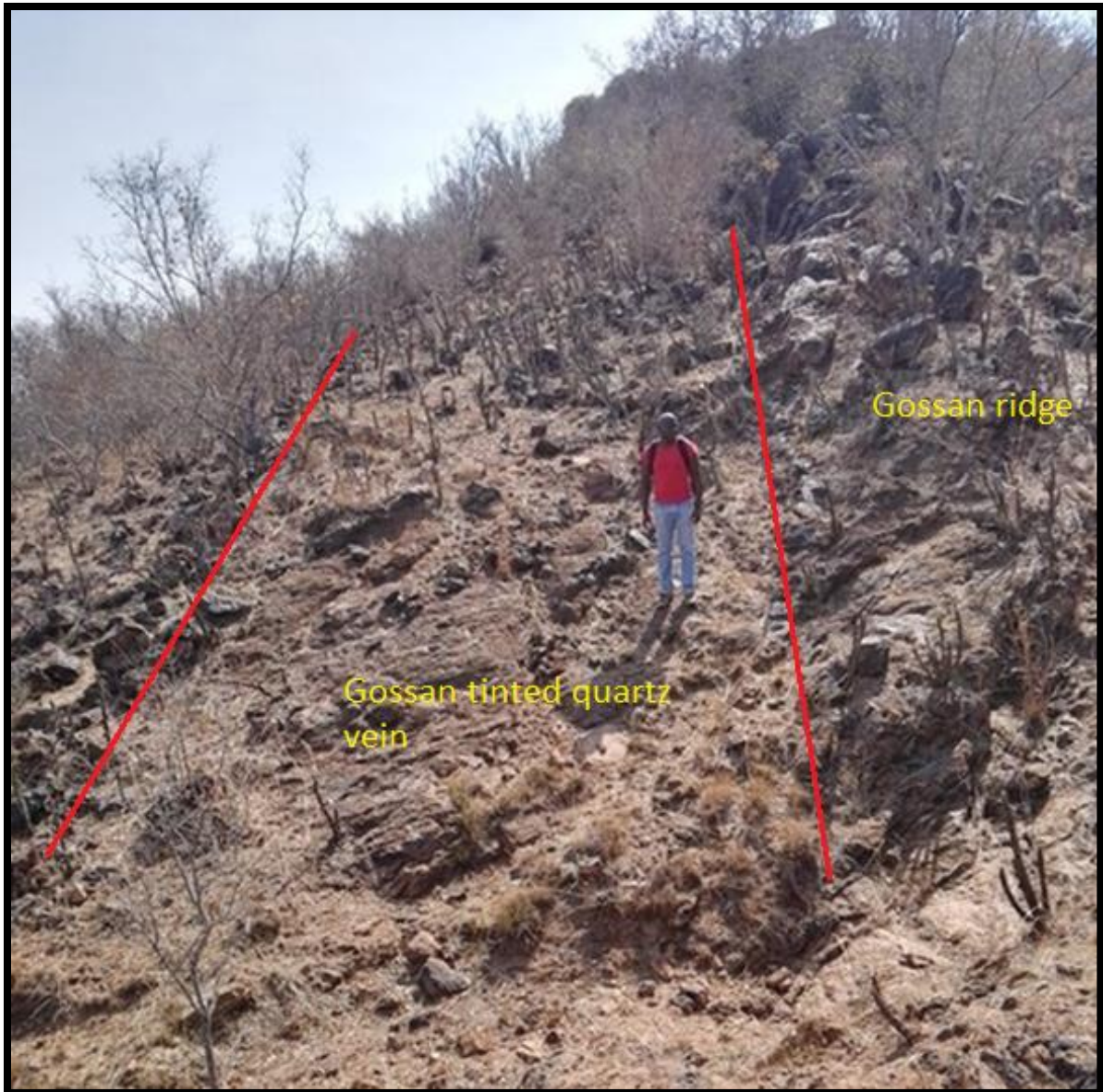


Figure 4.7: Field photograph showing a gossanous vein on the Boschhoek Prospect (Photo taken facing northeast).

The quartz veins on the surface of Boschhoek Structure show two generations. The first generation occurs on the edges of the main gossan veins and appear to be “sandwiching” the gossan ridges (Figure 4.7). These veins are often tinted with a dusky red colour and have thicknesses of between 10 and 50 cm. The second generation of quartz veins truncate the gossan veins forming an intricate sub-parallel network of veins (Figure 4.8). This generation of veins have thicknesses between 1 and 10 cm. The quartz veins truncating the Nebo granite are often accompanied by joints. These quartz veins have thicknesses less than 1 mm. A summary of vein types and their respective thicknesses are presented in table 4.2.

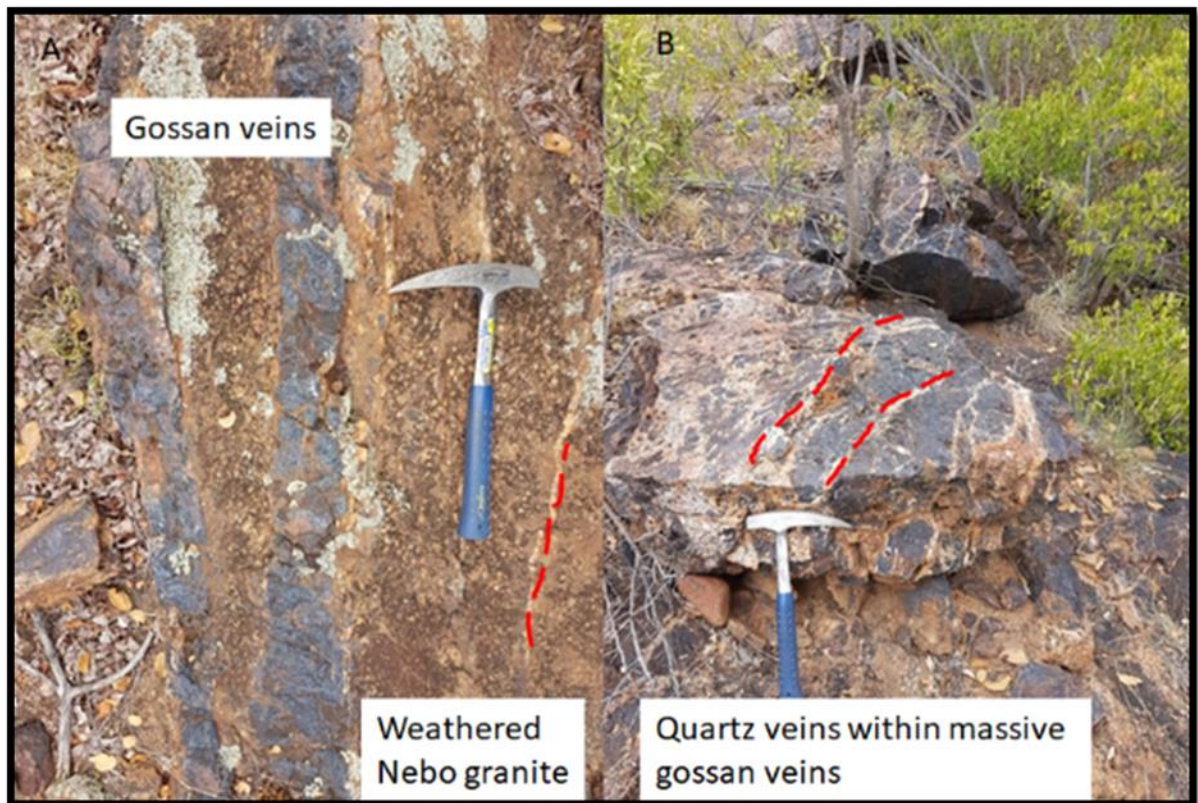


Figure 4.8: Various size of veining in Boschhoek Prospect. A: Semi-parallel gossan veins in weathered Nebo granite. B: Irregular quartz veins with massive gossan vein. (Photos taken facing northeast).

Table 4.2: Vein orientatiati on, sizes, and their dominant mineralogy from the Boschhoek Prospect.

Vein/Joint Type	Size (Width)	Dominant Orientation	Mineralogy
Veinlets	1-10 cm	NE	Quartz
Minor veins	10 - 50 cm	NE	Quartz
Veins	1 - 5 m	NE, ENE	Quartz,
Medium veins	2 - 10 m	NE	Quartz
Main Veins	10 - 25 m	NE	Gossan, Quartz, Goethite Limonite,
Joints	<10 mm fracture	ESE	X

The gossan and quartz veins show various orientations. The dominant trend directions are north, northeast and east southeast (Figure 4.9). These veins are steeply dipping to vertical (70°- 90°). The average mean vector of the Boschhoek structure is calculated at $041^{\circ} \pm 28^{\circ}$. The large error margin is attributed to sigmoidal-shaped veins in the main vein and the east-west veins often accompanied by joints. The sub-parallel veins and the distinct vein show a general trend of northeast.

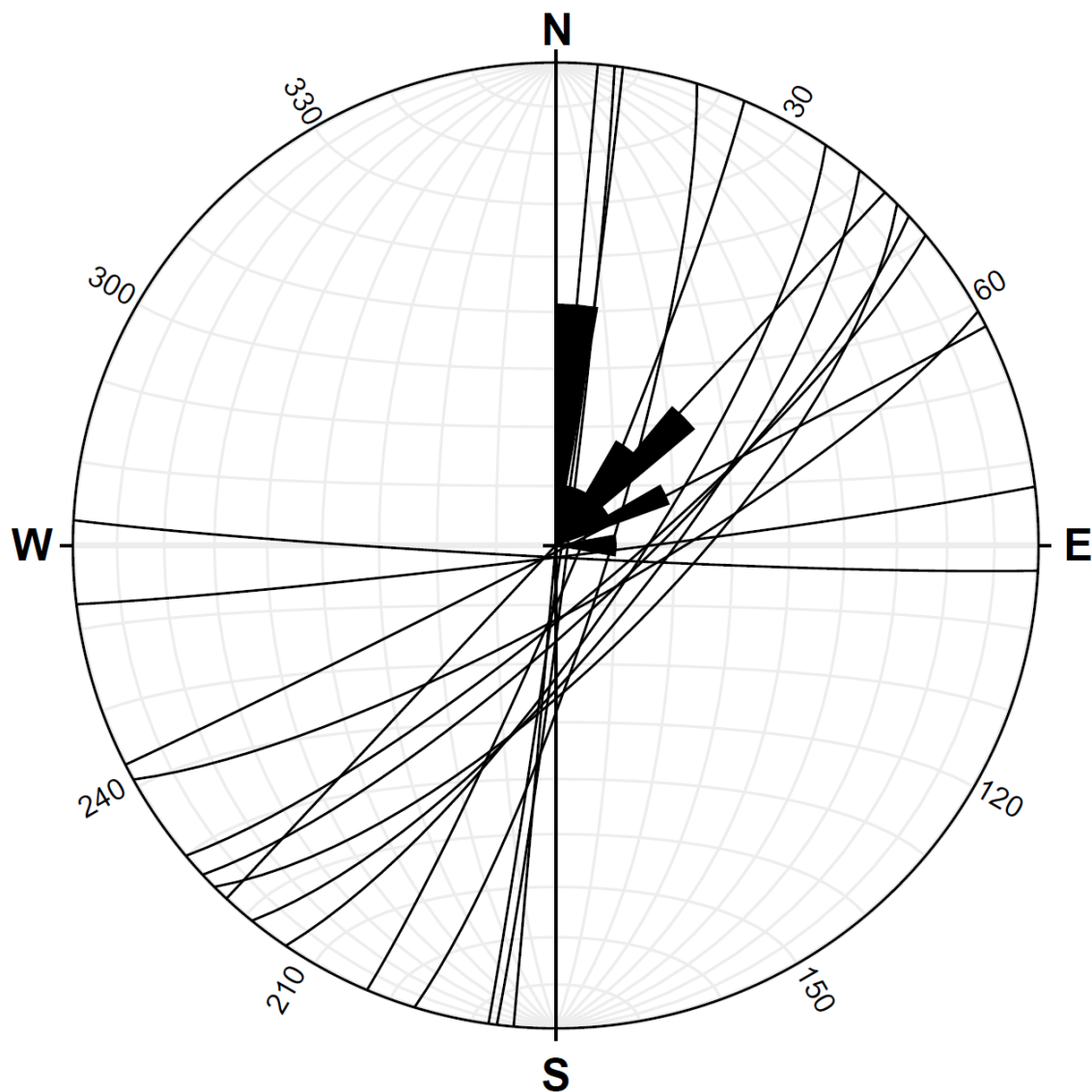


Figure 4.9: Stereonet diagram depicting planes (black lines) of veins from Boschhoek Prospect and the corresponding rose diagram (black petals). N=16. Plotted using the Stereonet 11 software (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013).

4.3. Faulting and veining along the Wonderkop Fault Zone

Fieldwork recording of structural data along the Wonderkop Fault covered the Wonderkop Fault Zone and the area to the north-northeast of the fault zone (along the Wonderkop Fault) after a restraining bend, to the north of Boschhoek Prospect (Figure 4.1). The Wonderkop Fault Zone occupies an area between the Marble Hall Dome and the Stavoren Fragment (Hartzer, 1995). The Wonderkop Fault east of the restraining bend transects mainly the Nebo granite and the Stavoren Granophyre (Figure 4.1).

In the Wonderkop Fault Zone, the veins contains numerous vein orientations with various thicknesses and mineralogies. The Wonderkop Fault main vein comprises quartz and gossans, with the former exhibiting distinct textures representing various generations. The quartz veins show zonation; a haematite-tinted quartz occupies the margins of the veins (Figure 4.10A). This quartz transitions into coarse-grained quartz crystals towards the centre of the vein (Figure 4.10B). These inner quartz crystals are coarse and exhibit syntaxial growth. In some instances, the quartz crystals in the veins are well-developed with euhedral quartz crystals. The crystal growth of these syntaxial quartz crystals is perpendicular to the general northeast-southwest trend direction of the Wonderkop Fault in the Fault Zone. In some instances, the centre of the main veins exhibits brecciated quartz grains cemented together by an iron-rich gossanous matrix (Figure 4.10C). The gossan matrix appears to be goethite with a reddish-yellow colour. The main veins range between 1 to 40 m in thickness and are traceable for over 2000 m along strike.

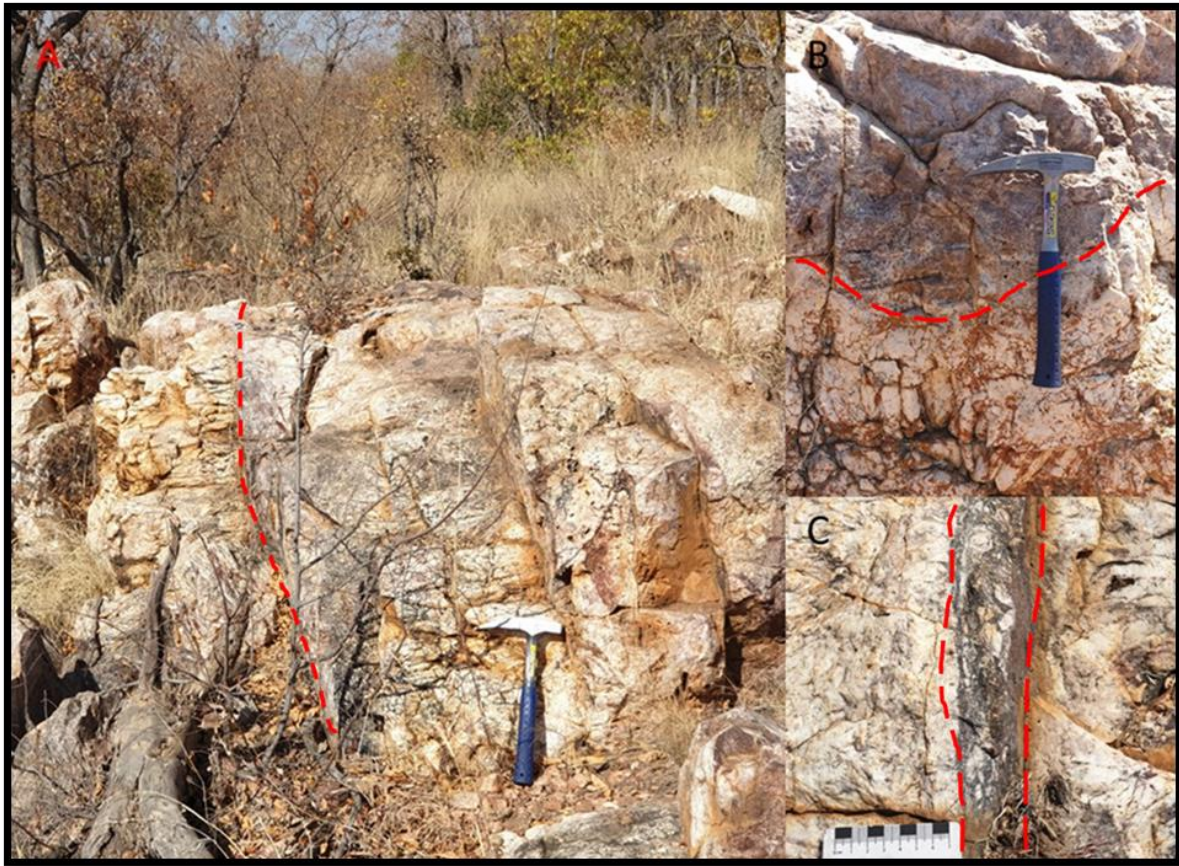


Figure 4.10: Field photographs showing quartz veins along the Wonderkop Fault. A and B: Typical veins in the fault zone showing a vein-zonation comprising tinted quartz in the outer limits grading into coarse-grained quartz crystals. C: Brecciated coarse quartz crystals cemented by gossanous matrix within the coarse-grained quartz vein (Photos taken facing southeast).

The veins flanking the main veins comprise quartz on the margins with relatively coarse euhedral quartz crystals towards the centre. The centres of the flanking veins are often brecciated and cemented together by iron-rich gossanous matrix (Figure 4.11). The gossan matrix comprise reddish yellow-goethite. The brecciation in the flanking veins is similar to the brecciated centres of the main veins. The flanking veins range between 5 to 15 cm in width and are traceable for up to 100 m.

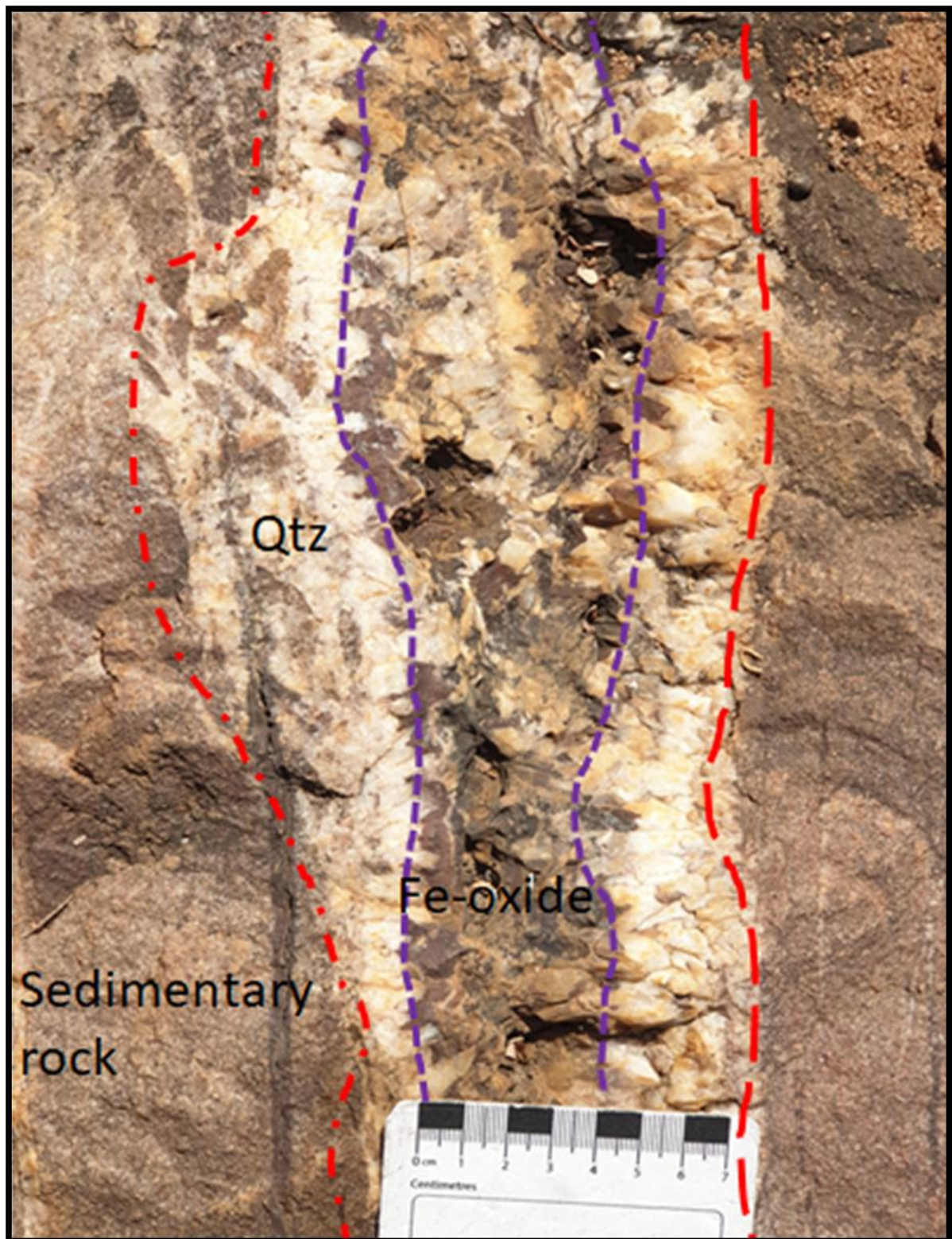


Figure 4.11: Field photograph showing vein zonation with margins exhibiting coarse-grained quartz crystals with inner brecciated quartz crystals cemented by gossanous matrix (Photo taken of planar horizontal surface).

The main veins along the Wonderkop Fault north of the restraining bend, and the Boschhoek Prospect contains quartz and gossan (Figure 4.12). The gossans are

made up of hematite and goethite. They appear to have tinted the quartz veins. These tinted quartz veins are cross-cut by white quartz veins representing a second generation, similar to the main veins in the Boschhoek structure. The transition from gossan-tinted margins into coarse-grained quartz crystals towards the centre of the veins and brecciation as observed in the Wonderkop Fault Zone is absent. The main veins range between 1 to 10 m in thickness and are traceable up to 50 m along strike. Flanking veins do occur and comprise quartz veins and often occur in pairs (Figure 4.13). These veins are faulted in some cases suggesting a sinistral strike-slip offset of the regional Wonderkop Fault (Figure 4.14). These flanking veins range between 1 to 10 cm in thickness and are traceable for at least 5 m (Figure 4.15).



Figure 4.12: Photographs of the Wonderkop Fault main vein to the north of the restraining bend. A: Gossan tinted quartz vein. B: main vein with secondary quartz veins. (Photos taken facing north northeast).



Figure 4.13: Field photograph of flanking quartz veins to the main vein of the Wonderkop Fault to north of the restraining bend showing various vein widths (Photo taken facing north east).

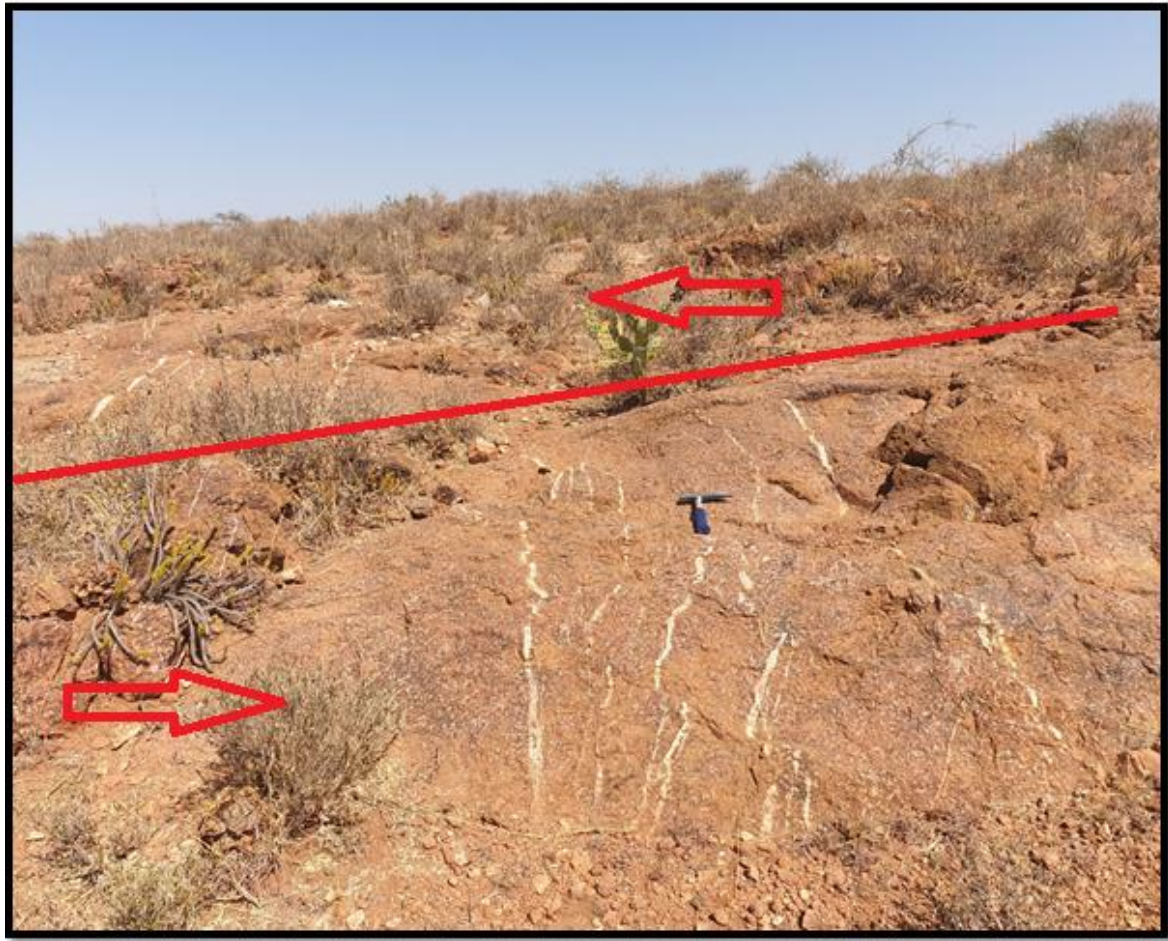


Figure 4.14: Field photograph showing an array of quartz veins suggesting post-vein sinistral faulting (Photo taken facing north-northwest).

The main veins and the flanking veins in the Wonderkop Fault Zone trend to the northeast (circa 45°) and are sub-vertical (Figure 4.15). The main vein along the Wonderkop Fault north of the restraining bend and its respective flanking veins trend north-northeast (circa less than 30°) and are vertical (Figure 4.15). Both the Wonderkop Fault Zone and the area north of the restraining bend exhibit splay morphologies (Figure 4.1; Figure 4.15). The characteristics of the veins encountered in the Wonderkop Fault are summarized in table 4.3.

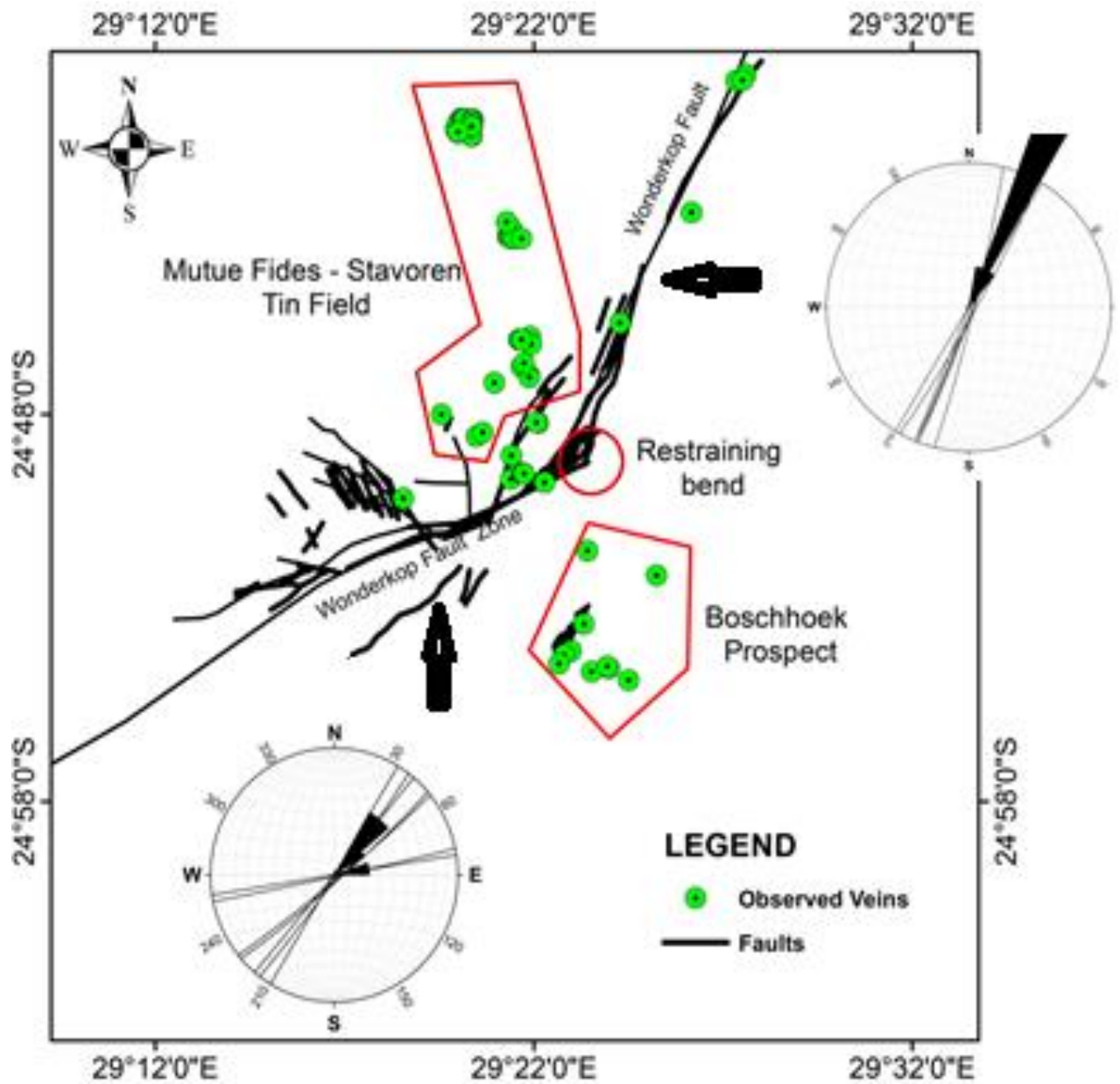


Figure 4.15: Structural map of the study areas showing the splay morphology of the Wonderkop Fault. The stereonet diagrams represent the structural character of the Wonderkop Fault in the fault zone and northeast of the restraining bend to the north of Boschhoek Prospect. (Stereonet software used by Allmendinger et al., (2012) and Cardozo and Allmendinger, (2013)).

Table 4.3: Characteristics of veins along the Wonderkop Fault.

	Wonderkop Fault Zone		Wonderkop Fault after restraining bend	
	Main vein	Flanking vein	Main vein	Flanking vein
Vein size (width)	1-40 m	5 – 15 cm	1-10 m	1-10 cm
Traceable distance	2000 m	10 m	50 m	5 m
Mineralogy	Tinted quartz, Coarse quartz, crystals, Brecciated quartz with gossan matrix	Coarse quartz, crystals, Brecciated quartz with gossan matrix	Tinted quartz, Coarse quartz crystals	quartz
Orientation	NE	NE	NNE	NNE

4.4. Structural analysis

In general, the veins in the Stavoren Fragment, the Boschoek Prospect and the area along the Wonderkop Fault show a dominant northeast orientation (Figure 4.17). However, in each location there are numerous clusters of veins with trend directions distinguished as subsidiary to the dominant northeast trend. Contrasting vein mineralogy is considered to represent distinct veining regimes and have been noted in each location. There are striking similarities in the morphology and mineralogy of the veins in all three areas apart from the similarity in a dominant northeast trend. The veins exhibit splay morphologies in all locations. Brecciation and cementing of earlier generations of quartz veins by a gossan matrix is noted in both the Boschhoek Prospect and along the Wonderkop Fault.

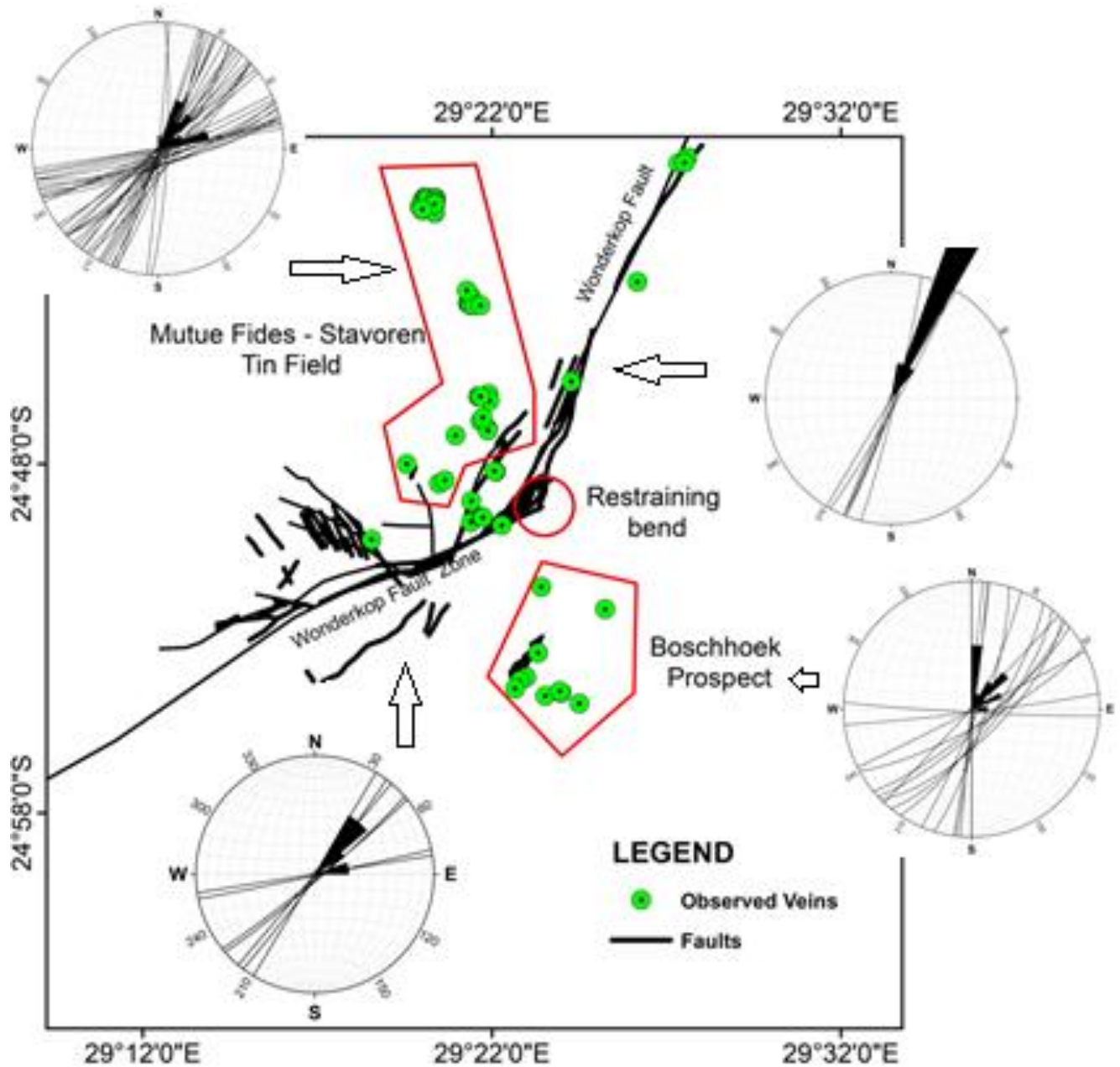


Figure 4.17: Structural map of the study areas and the corresponding stereonet diagrams showing the structural character of the veins in each location (Stereonet used by Allmendinger et al., (2012) and Cardozo and Allmendinger, (2013)).

4.4.2. Principal stress axes and implications

The mean vector of the planes representing the overall trend of the veins in the study areas is calculated at 046° using the program Stereonet 11 (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013). The poles to the planes of the veins plot in the fourth quadrant with a calculated Fisher Mean Vector trending at 322° and plunging at 05° (Figure 4.18).

The Bingham Axial Distribution (BAD) tool in the Stereonet 11 was used to calculate the Principal Component Analysis (CPA) of poles to the veins. The BAD tool computes three eigen vectors representing three axial distributions of the poles and the corresponding trends and plunges of each distribution (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013). In a transform fault, the highest loading of three eigen vectors corresponds to the axial distribution of the majority of the poles and the plunge and trend of this vector is orthogonal to the mean vector (Figure 4.18). The trend and plunge of the second loading of the eigen vector corresponds to the mean vector of the planes. The principal stress axis (sigma one) corresponds to the mean vector of the planes and the calculated stress axis using BAD trends and plunges at 047° (similar plunge of 047° of the mean vector) and 03° respectively. The sigma two stress axis has trend and plunge of 89° and 85° respectively. The best-fit great circle of the poles trend at 315° and plunges at 5° representing the direction of the least stress axis. The euhedral syntaxial quartz fabrics are parallel to this stress axis (Figure 4.12).

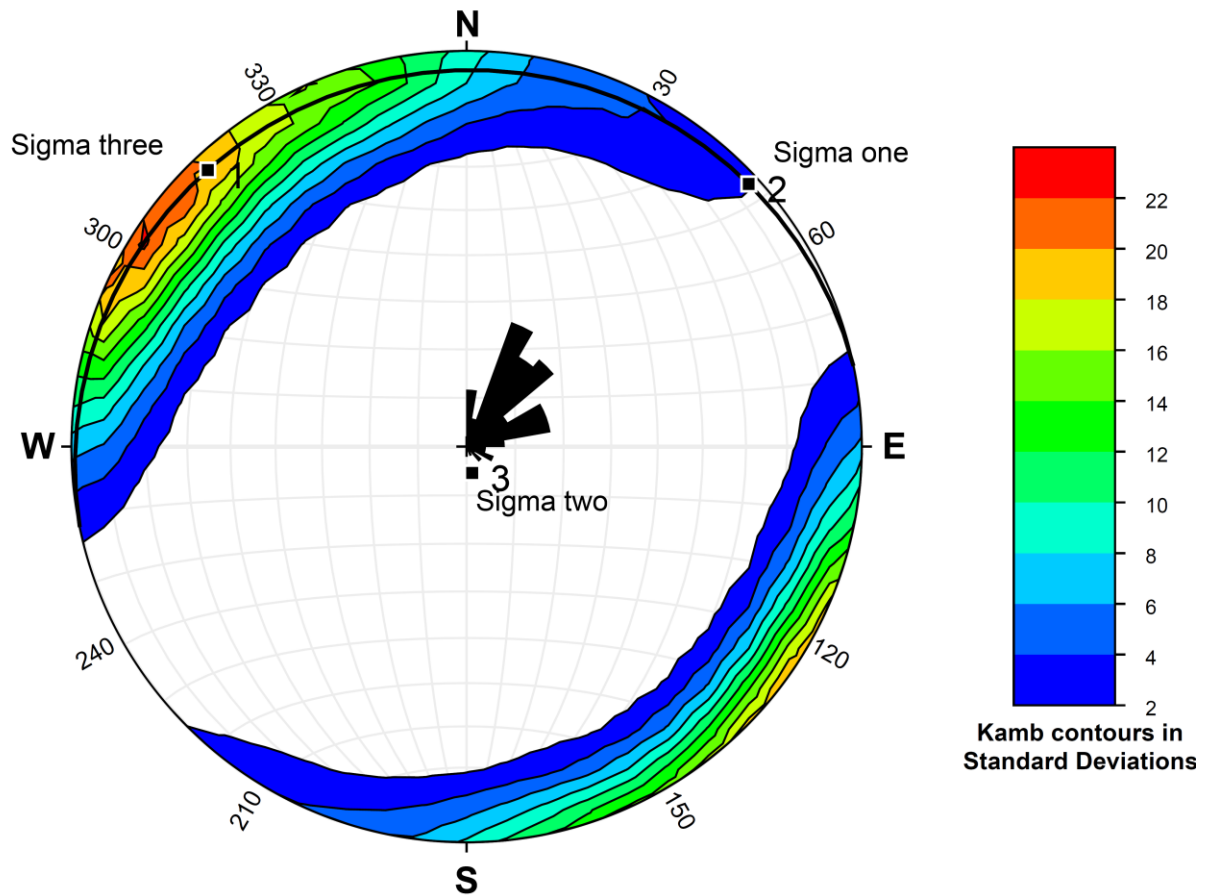


Figure 4.18. Stereonet diagram depicting contours to the poles of the structural data and the principal stress axis (Sigma 1-3) using the Bingham Axial Distribution in Stereonet 11. The eigen vectors are numbered 1-3 and their corresponding vectors together with strike and dip are as follows; 1 (047, 03) 2 (85, 85.) and 3 (317, 05). (Allmendinger et al., 2012; Cardozo and Allmendinger, 2013).

The structural data suggests that the tectonic structures in Stavoren Fragment, Boschhoek Prospect and along the Wonderkop Fault are a result of northeast-southwest compression (sigma one). This stress regime was also responsible for interference folding in the Stavoren Fragment characterised by folds (F1) with northeast-southwest axial planes as shown by Hartzler (1995). Holzer et al. (1998) attributed this syn-Bushveld Complex stress regime to craton-scale NW-SE compression due to the Limpopo belt. Silver et al. (2004) similarly attributed the compressional stress regime to the Magondi Orogeny (circa. 2.0 Ga) which arisen from reactivation of the Limpopo belt structures.

Chapter 5: Petrology of Boschhoek Prospect and Mutue Fides Tin

Two drill cores, BHDD 003 from Farm Boschhoek and 648 KS/1 from the Farm Mutue Fides were used for petrological studies to characterise the nature of the granites and subsequently unravel their effect as host rocks on polymetallic mineralization. This Chapter describes the granites and unravels the nature of alteration phases arising from hydrothermal interaction between the granites and the magmatic-hydrothermal fluids.

The drill cores were logged on the basis of colour, texture, mineralogy, chemical alteration of the mineralogy, structural fabrics and associated polymetallic mineralization. After logging, these cores were systematically sampled for representative samples from which polished thin sections were prepared for optical microscopy studies to characterise their petrological characteristics and also for geochemical studies. This chapter encompasses logging results and petrographic studies of the prepared 25 thin sections; twelve and thirteen from BHDD-003 borehole core and 648 KS/1 respectively.

Generally, the BHDD 003 core intersected granite with numerous cross-cutting alteration zones enclosing veins that comprise siderite, calcite, quartz and quartz micro-veinlets (Figure 5.1). Sulphides often occur within the quartz veins. The 648 KS/1 core intersected three granite types with numerous alteration zones. These alteration zones often enclose quartz and feldspar pegmatite bodies and/or quartz veins. Some of the pegmatite bodies contain mineralization including fluorite, cassiterite and sulphides (Figure 5.2).

**Farm Boschhoek 752 KS
BHDD 003**

Northing: 7244526.0 Easting: 740174.0

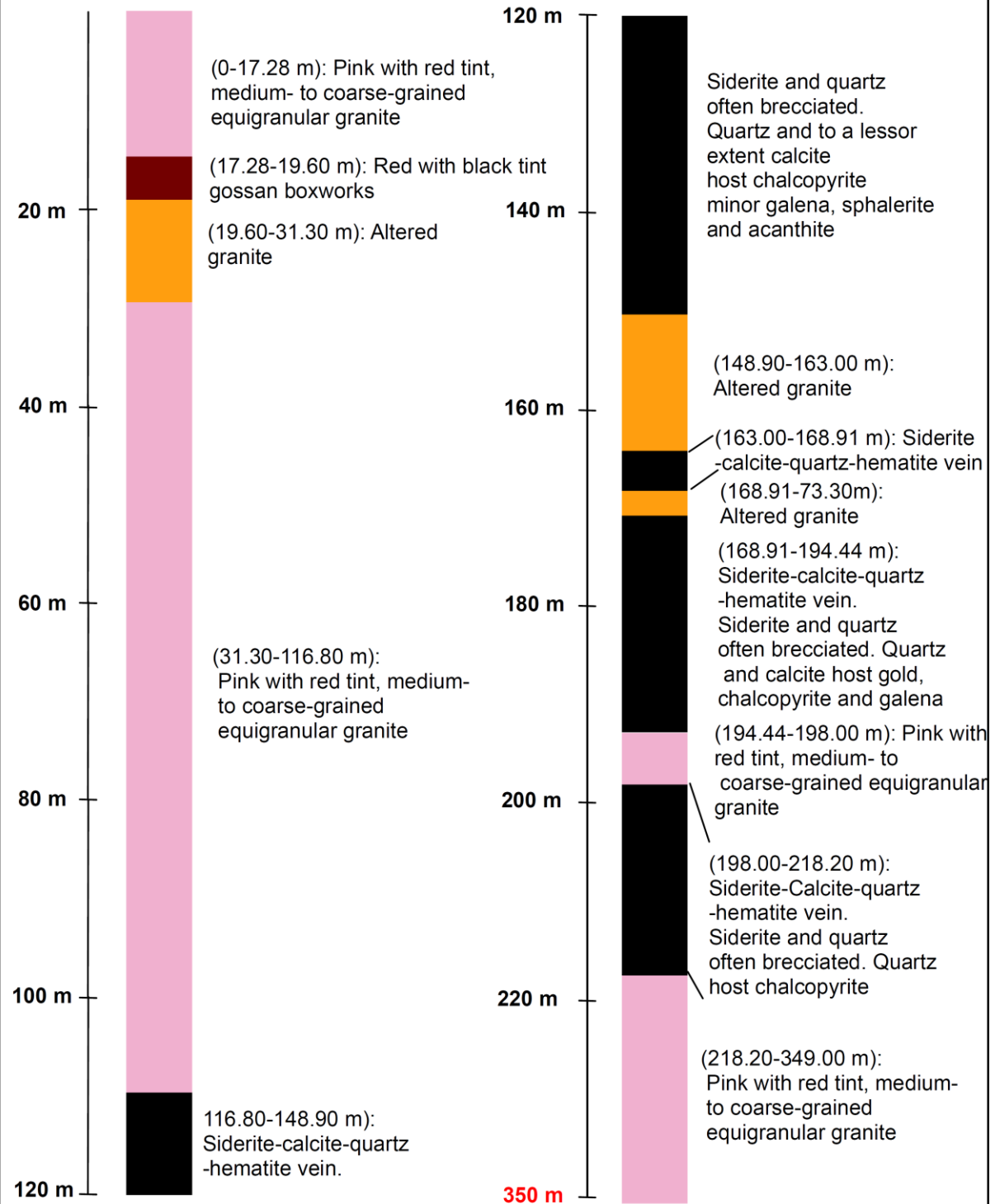


Figure 5.1: Drill log from the borehole BHDD 003 drilled on the Farm Boschhoek 752 KS. The core at depths between 218.20 to 350 m is not drawn to scale.

**Farm Mutue Fides 648 KS
648 KS/1**

X: -24.6865 Y: 29.3424

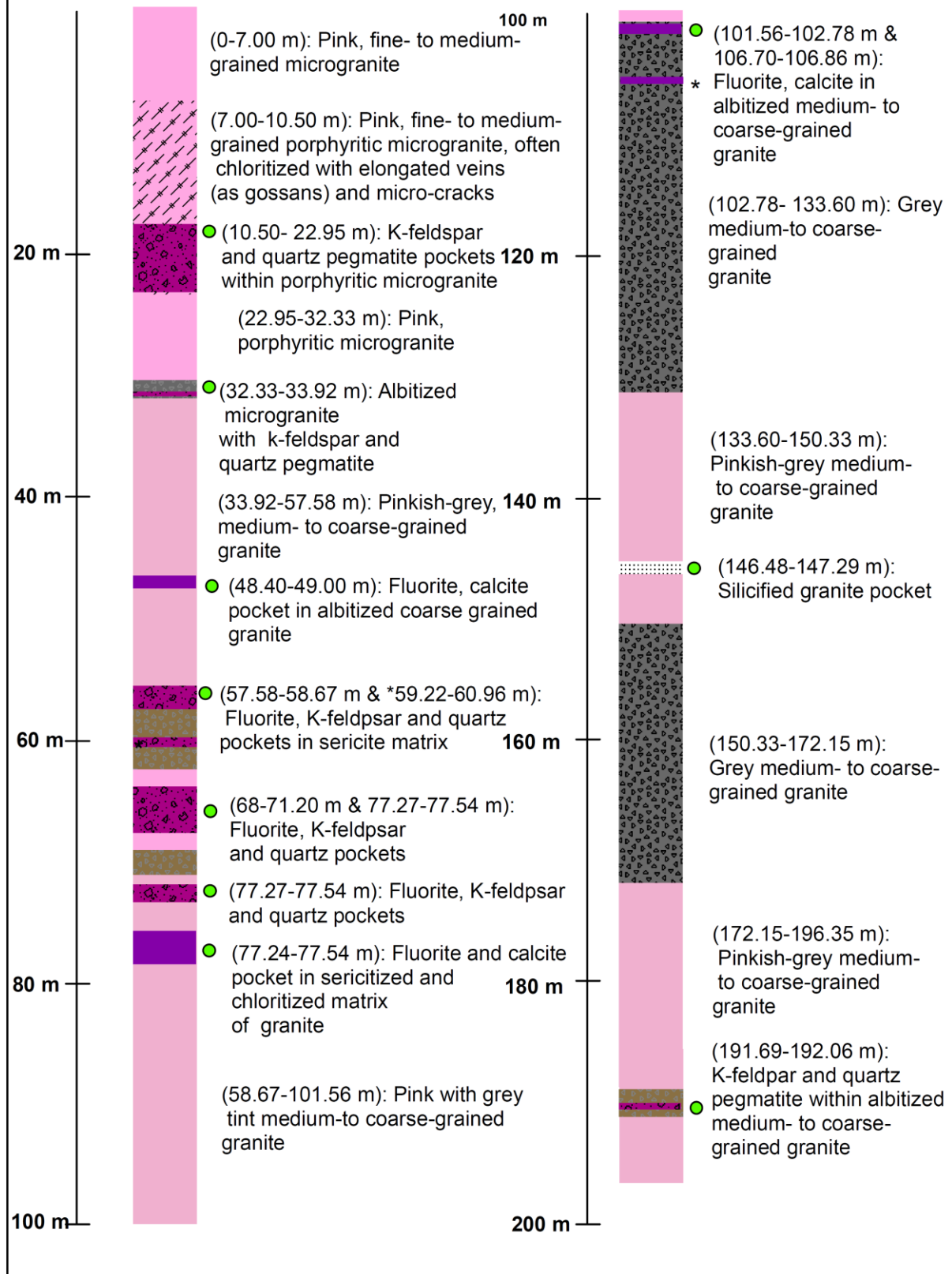


Figure 5.2: Drill log from the borehole 648 KS/1 drilled on the farm Mutue Fides.

5.1. BHDD 003 core

The BHDD 003 core from Farm Boschhoek is located at 740,174 mE and 72,444,526 mN (UTM Zone 35S), 10 km east of Marble Hall Fragment (Figure 2.3). The borehole was drilled at an inclination of -60° towards an azimuth of 157° and extends for 350 m apparent depth. It intercepts intervals of granite and altered granite enclosing several siderite-quartz-hematite veins. Weathered granite and ferruginous gossans cap the core at the top (Figure 5.3). The intercepted granite consists predominantly of pale-pink to rose-yellow, equiangular medium- to coarse-grained alkali feldspar and milky quartz with minor patchy hornblende and biotite (Figure 5.4). The granite often contains patches of green minerals (possibly epidote) and black ferroan minerals (Figure 5.5). This granite mineralogy is consistent with the description of Nebo granite by Kleemann and Twist (1989). It also fits the description of Evans (2015) of similar logged drill holes in the Boschhoek Prospect.

The silicified gossans comprise mainly of botryoidal hematite and network of weathered acicular-goethite prisms. The gossans cap the sub-vertical and vertical veins ranging between 1 and 20 m thick that predominantly comprise siderite, calcite, quartz and minor hematite. Primary siderite has been brecciated and later cemented by a second generation of siderite, calcite and quartz. Quartz and to a lesser degree calcite, host sulphide mineral assemblages including galena, sphalerite, chalcopyrite and bornite. Several narrow quartz veins are stained with hematite but are devoid of sulphide minerals (Figure 5.6).



Figure 5.3: Photographs from BHDD 003 core showing gossan-stained Nebo granite and gossans. A: botryoidal hematite and network of weathered acicular-goethite prisms (image taken between 17.28 and 19.60 m depth). B: Hematite stained calcite vein (Image taken between 19.60- 30.31 m) and gossans topping the BHDD 003 core.



Figure 5.4: Photograph from BHDD 003 core showing equiangular, medium- to coarse-grained granite with patchy black ferroan minerals and green minerals from BHDD 003 (core depth between ca 45.5 and 46.2 m).



Figure 5.5: Photograph of BHDD 003 core showing the transition of granite to altered granite. The altered granite often encloses veins (core depth between ca. 116.00 and 120.00 m).



Figure 5.6: Photographs from BHDD 003 core showing the typical mineralogy of veins crosscutting the Nebo granite. A: siderite-calcite-quartz-sulphides vein crosscutting the Nebo granite. B and C: Relatively small hematite veins and calcite veins and hematite vein-stringers often crosscut the Nebo granite core (Images represent depths between ca.163.00 and 194.00 m).

5.1.1. Nebo granite petrography and its altered variants

Typically, the granite comprises subhedral perthitic alkali-feldspar (1 to 6 mm; 60%) and plagioclase (0.5 to 1.5 mm; 5%) and subhedral to anhedral quartz grains (0.5 to 2 mm; 30%). Minor anhedral biotite and hornblende are present (both constitute ~5% averaging <0.5 mm in size) which fill the interstitial spaces between feldspar and quartz. These petrological characteristics are consisted with observations made by Smits (1979) and Evans (2015) of the Nebo granite. The average modal abundances of the Nebo granite samples are presented in table 5.1.

Table 5.1: Average modal concentrations of minerals in Nebo granite.

	RCB 01	RCB 02	RCB 14	RCB 15	RCB 16	RCB 17
K-feldspar	60	60	65	55	65	60
Plagioclase	5	5	<5	10	<5	5
Quartz	30	25	30	25	30	25
Biotite	<5	5	5	5	<5	5
Hornblende	<5	<5	<5	<5	<5	5
Chlorite	0	<5	<5	5	0	0
Apatite	trace	Trace	trace	trace	trace	trace
Zircon	trace	Trace	trace	trace	trace	trace
Rutile	trace	Trace	trace	trace	trace	trace

Over 60% of plagioclase grains are surrounded by perthite and other alkali feldspars. These plagioclase grains are characterised by polysynthetic twinning and exhibit minor sericite alteration (Figure 5.7). In rare cases, perthite exhibits irregular intergrowths of albite and orthoclase that form patches or lenses. Perthite and quartz grains form clusters characterised by a synneusis-texture with the latter grains showing undulose extinction as evidence of strain. Some quartz grains are annealed and sutured along the grain boundaries (Figure 5.8A). These sutured grain boundaries often possess

fluid inclusions and opaque minerals. Highly altered plagioclase and biotite form sericite and sericite together with chlorite and muscovite form saussurite assemblages (Figure 5.8B).

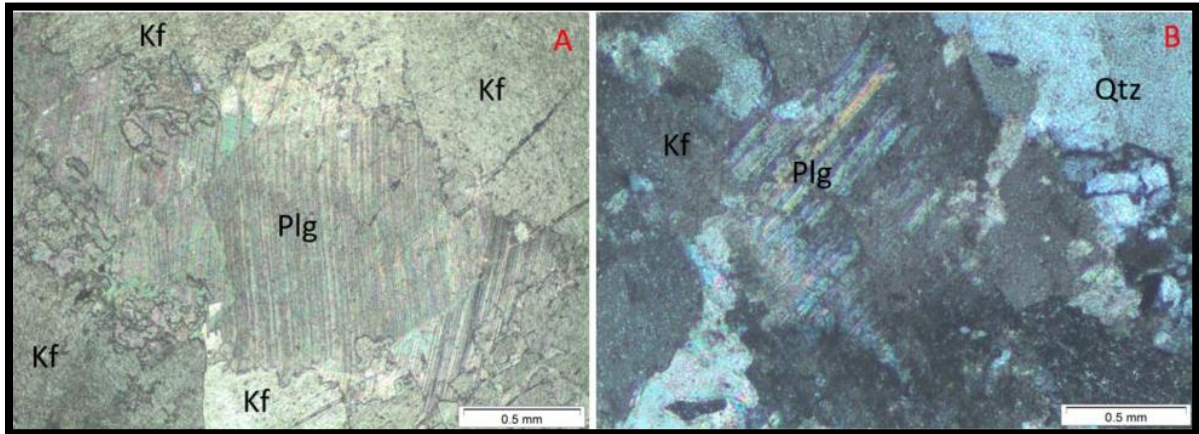


Figure 5.7: Photomicrographs taken in XPL of Nebo granite from BHDD 003 core. A: Plagioclase (Plg) grains surrounded by k-feldspars (Kf), sampled at depth 14.66 m, sample RCB 03. B: Selective altering of plagioclase (Plg) to sericite and leaving behind quartz (Qtz) and k-feldspar (Kf). Sampled at depth 137.60 m, sample RCB 04.

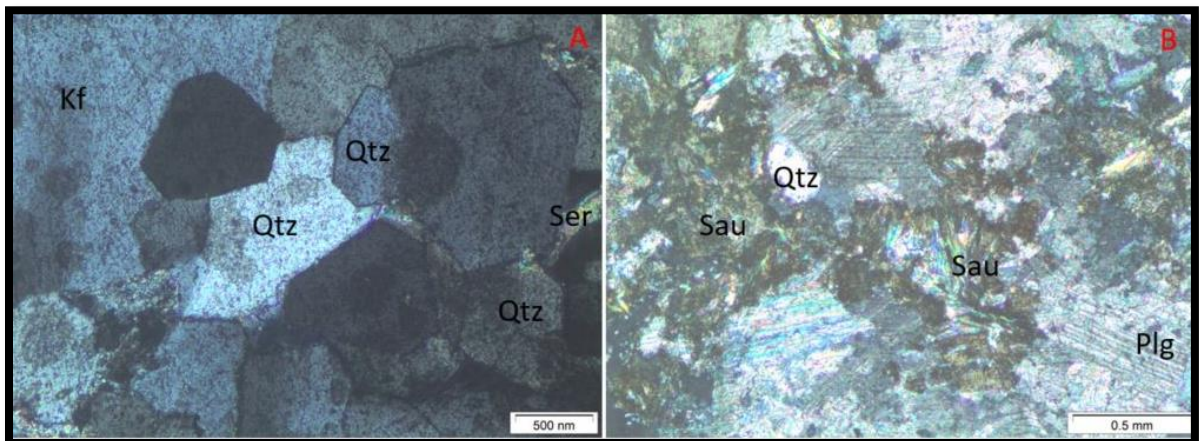


Figure 5.8: Photomicrographs taken in XPL of Nebo granite from BHDD 003 core. A: Annealed quartz grains along boundaries exhibiting undulose extinctions, sampled at depth 137.60 m, sample RCB 04. B: Altered plagioclase (Plg) and saussurite (Sau) assemblages, sampled at 137.60 m, sample RCB 04.

Biotite and to a lesser extent hornblende form clusters and fill interstitial spaces between k-feldspar grains (Figure 5.9A). These grains are chloritized in some cases. The chloritization in biotite mainly occurs along the cleavage planes and often exhibits inclusions of quartz and opaque minerals (Figure 5.9B). Other accessory minerals include zircon, apatite and rutile. The zircon crystals are typically euhedral.

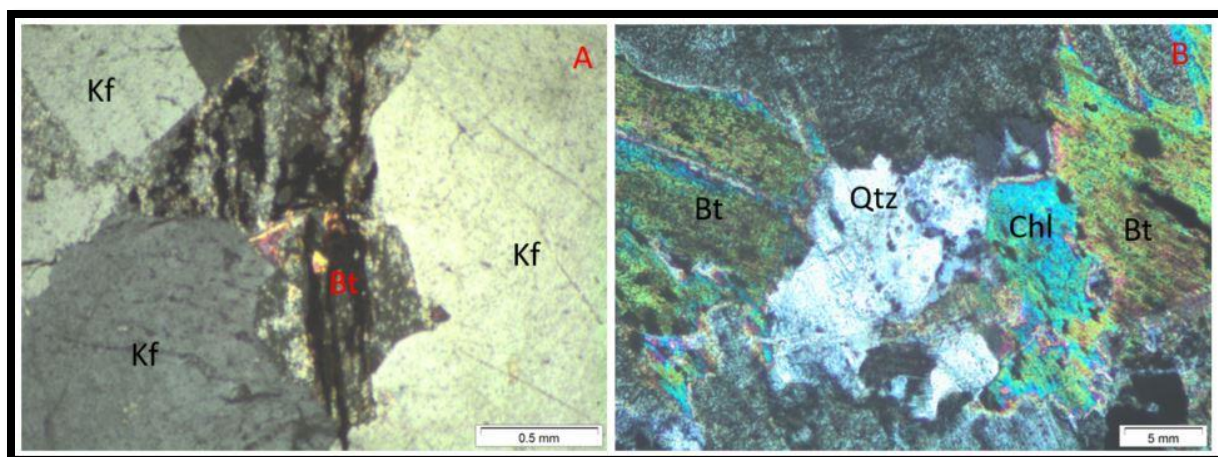


Figure 5.9: Photomicrographs taken in XPL of Nebo granite from BHDD 003 core. A: Biotite (Bt) clusters surrounded by k-feldspars (Kf) sampled at 18 m, sample RCB 01. B: Extensive biotite (Bt) alteration to chlorite (Chl), sampled at depth 18 m, sample RCB 01.

The altered Nebo granite samples occur adjacent to veins characterised by intensive metasomatic alteration brought upon by hydrothermal solutions. Pervasive sericitization and silicification characterise these samples. The altered Nebo granite is comprised predominantly of aggregates of fine-grained sericite and chlorite minerals with minor quartz and chlorite in addition to partially altered perthite grains (Figure 5.9B). Orthoclase and k-feldspar minerals are completely replaced by sericite and quartz aggregates. The perthite crystals that are not completely obliterated by alteration exhibit selective replacement. Principally, the sericite selectively replaces albite leaving behind orthoclase within perthite grains along the twin planes. Sericitization of perthite often precedes chloritization.

5.1.2. Vein petrography: gangue

The BHDD 003 drill hole intersects weathered Nebo granite prior to gossans in the supergene zone extending from surface until approximately 25 m depth. The gossans grade into oxidized siderite-quartz- calcite veins that host sulphide ores. Generally, the hypogene samples comprise siderite, quartz, calcite and several sulphide minerals.

Siderite exhibits two generations of precipitation. The first-generation appears brown, coarse-grained (1-5 mm) of subhedral to scalenohedral elongate crystals with a curved cleavage. These rhombic siderite grains often appear fragmented into brecciated medium-grained to fine-grained matrix cemented by quartz and/or second-generation calcite (Figure 5.10). This generation possess undulose extinction particularly the grains adjacent to altered granite. The second-generation siderite exhibits a brown to

black colour and a fine grained (<50 μm) texture. These second-generation aggregates of siderite possess uniform cathodoluminescence which is different from the first-generation of massive siderite.

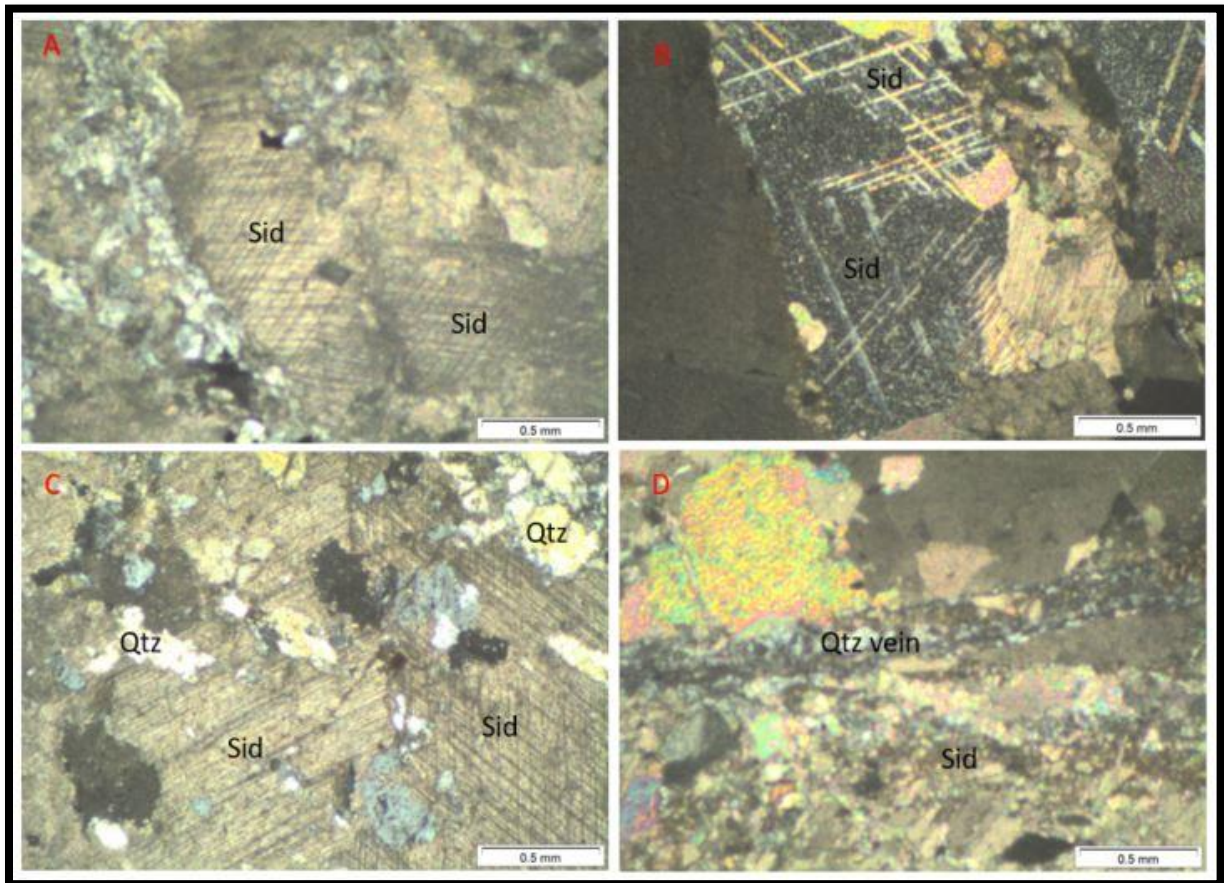


Figure 5.10: Photomicrographs of a siderite-calcite-quartz veins within the Nebo granite taken in XPL from BHDD 003 core. A: Subhedral elongate siderite (Sid) grains showing the characteristic two-cleavage planes, sampled at 169.10 m, sample RCB 10. B: Black siderite grains representing second generation of siderite with distinctive siderite luminescence, sampled at depth 168.40 m, sample RCB 09. C: Tinted quartz (Qtz) and isotropic minerals within fragmented siderite grains, sampled at 169.10 m, sample RCB 10. D: Brecciated siderite grains and siderite matrix adjacent to quartz vein (Qtz vein), sampled at depth 169.10 m, sample RCB 10.

Calcite exhibits semi-parallel crystal aggregates that grew towards the centre of the veins away from the siderite crystals. The aggregates appear white and show crack-seal textures filling fractures when adjacent to altered granite and vein contacts. Calcite fills interstitial pores of euhedral quartz grains (Figure 5.11). In rare cases, calcite is also included in quartz crystals.

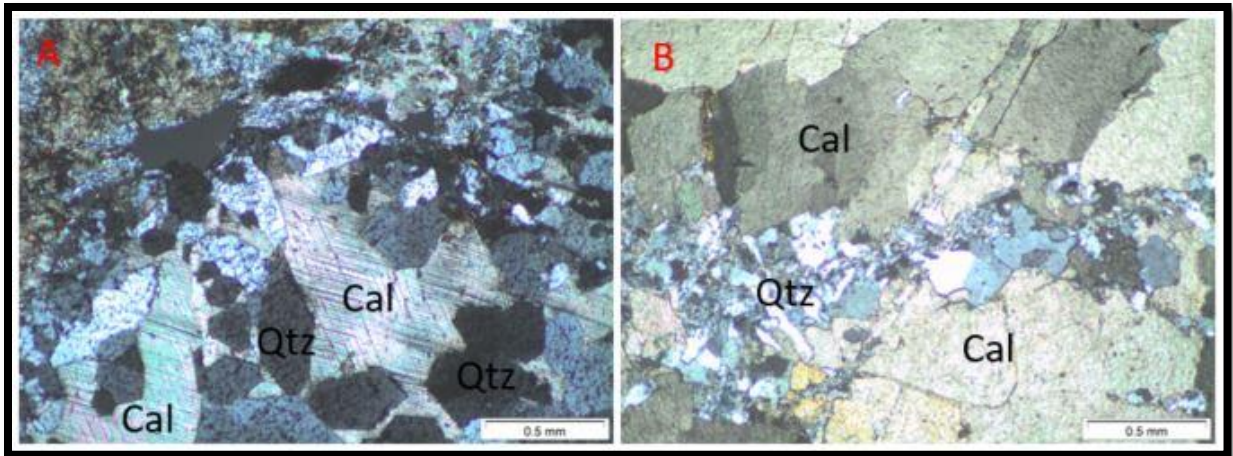


Figure 5.11: Photomicrographs of vein comprising siderite-calcite-quartz within Nebo granite taken in XPL from BHDD 003 core. A: Calcite (Cal) grains showing characteristic two angles cleavage-planes sampled at depth 137.60 m, sample RCB 04. B: Annealed calcite (Cal) grains with irregular quartz (Qtz) vein, sampled at depth 140.66 m, sample RCB 06.

Quartz precipitated in at least three episodes within the veins and followed the paragenetic sequence herein;

- (1) The first quartz generation exhibits subhedral and occasional euhedral grains (0.1-6 mm in size) accompanied by interstitial sulphide assemblages filling the fractures between the altered granite and the siderite and calcite (Figure 5.11A and Figure 5.12).
- (2) The second quartz generation occurs as quartz-sulphides assemblage that precipitated along weakened planes within the siderite-calcite veins. The quartz-sulphide assemblages exhibit crack-and-seal and crackle-breccia textures (Figure 5.11B).
- (3) The third quartz generation emanates from lateral extension created fractures within the siderite-calcite-quartz-(sulphide) veins and permitted euhedral-elongated quartz crystals (1-5 mm) to form (Figure 5.12). These white quartz crystals exhibit undulose extinction showing strain along the plumose prisms. This episode is responsible for precipitation of prominent sulphide assemblages. Anhedral fine quartz (<0.1 mm) accompanies the euhedral quartz grains.

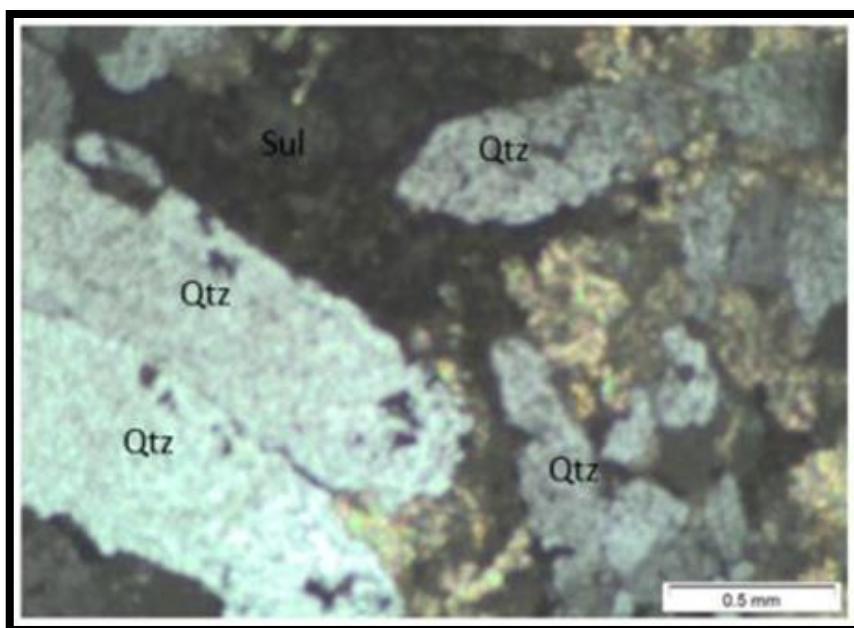


Figure 5.12: Photomicrograph showing elongated euhedral quartz grains hosting sulphides (Sul) with relatively finer anhedral quartz (Qtz) grains. Photomicrograph taken in XPL, sampled at depth 195. 40 m, sample RCB11 from BHDD 003 core.

5.1.3. Vein petrography: ore mineralogy

Sulphide mineralization encompassing pyrite, chalcopyrite, sphalerite and galena were observed in siderite-calcite-quartz-hematite ore zone samples. These sulphides are characterised by various morphologies and textures within the siderite-calcite-quartz veins. The sulphides occur as; (1) fracture infill of siderite-quartz veins, (2) crack-and-seal stringers of micro veinlets and (3) disseminations within the siderite-quartz veins. Pyrite textures are discussed in this section although they are not ore as they assist in defining various stages of mineralization.

Pyrite appears greyish-yellow exhibiting subhedral massive crystals (up to 2 mm). It also occurs as skeletal aggregates filling siderite-quartz fractures (Figure 5.13A). The skeletal texture of the pyrite aggregate emanates from the fragmentation due to single direction stress in the aggregates. Occasionally, anhedral pyrite crystals fill interstitial pores of the altered host rock forming disseminated gangue. A second generation of pyrite exhibits euhedral massive crystals related to the dissolution of chalcopyrite.

Chalcopyrite has a brass-yellow colour, exhibiting a fine to massive texture. It surrounds fractured pyrite crystals and pyrite aggregates are often included within massive chalcopyrite. Chalcopyrite crystals are less fractured compared to the pyrite crystals (Figure 5.13A). Quartz crystals often include chalcopyrite with the latter filling

interstitial spaces between quartz crystals and quartz-siderite contacts. In certain instances, the chalcopyrite occurs as micro veinlets in the altered granite wall rock and to a lesser extent in the siderite-quartz veins (Figure 5.13B). The micro veinlets exhibit a sinuous shape often following the grain boundaries of the siderite-quartz veins. In some instances, bornite replaces chalcopyrite (Figure 5.13C).

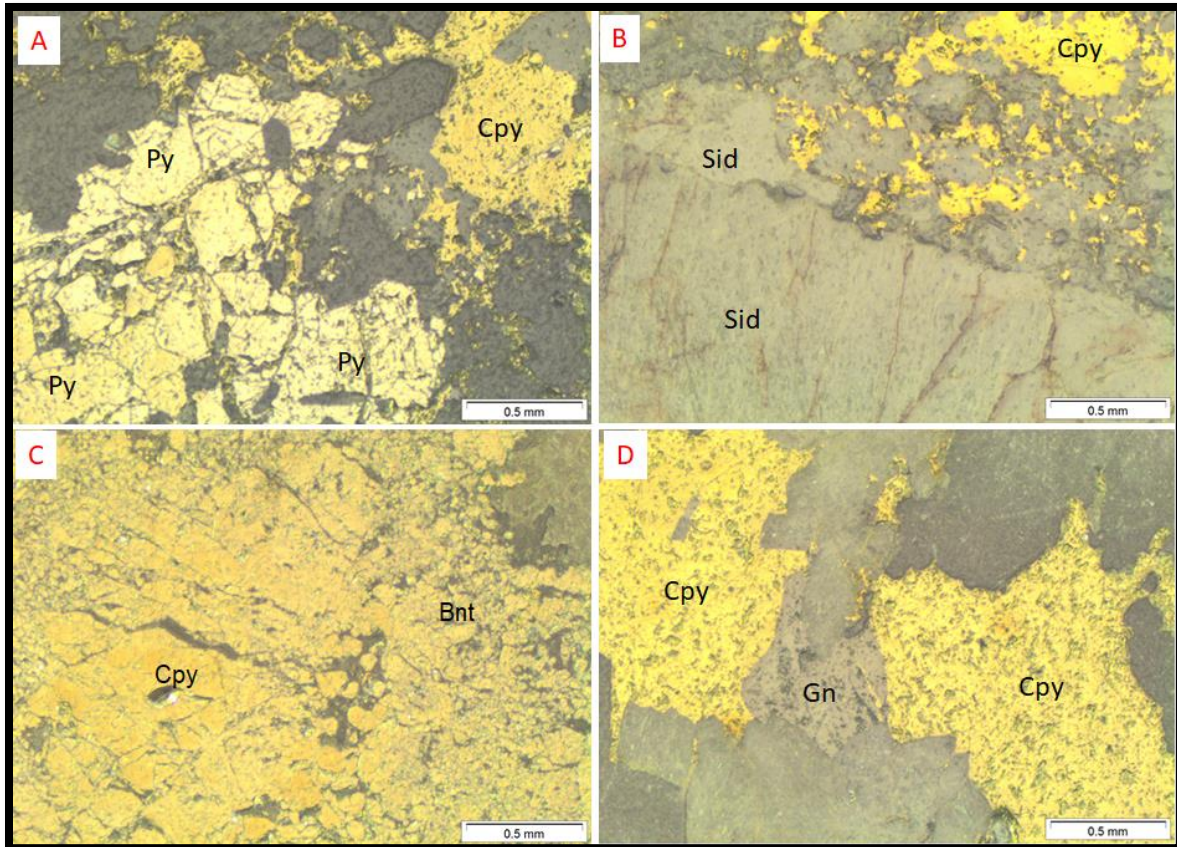


Figure 5.13: Photomicrographs of sulphides in BDD 03 core taken in plane-polarized transmitted light. A: Brecciated pyrite (Py) with calcite. Massive chalcopyrite (Cpy) in filling interstitial spaces of the siderite (Sid)-calcite (Cal)-quartz (Qtz) veins, sampled at depth 195.40 m, sample RCB11. B: Chalcopyrite (Cpy) in altered granite as irregular micro veinlets bordered by massive siderite grains, sampled at 144.60 m, sample RCB 8. C: Bronze brown bornite (Bnt) replacing chalcopyrite (Cpy), sampled at 196.40 m, sample RCB12. D: Galena (Gn) and chalcopyrite with siderite-calcite-quartz veins, sampled at depth 195.90 m, sample RCB 11.

5.2. KS/1 drill core

The 648 KS/1 drill is situated at -24.6865 latitude and 29.3424 longitude (decimal degrees) in the farm Mutue Fides, 5 km to the northwest of the Stavoren Fragment (Figure 2.4). The vertical drill core extends to almost 200 m depth and intercepts aplitic (often porphyritic) granite, granophyric microgranite and brick-red granite. These granite facies are intersected by mineralised pockets of feldspar and quartz pegmatite and vein-like structures.

The porphyritic aplitic granite consists predominantly of pink, fine- to medium-grained k-feldspar, quartz and minor biotite in addition to phenocrysts of quartz and pink k-feldspar (Figure 5.14A). The porphyritic granite often grades into brown with a black tint and black portions of alkali-feldspar and greenish-black chloritized-greisenized biotite (Figure 5.14B). The brown to pink granophyric microgranite contains fine to medium-grained alkali feldspar and quartz grains forming chains with lesser biotite and hornblende (Figure 5.15). Large pegmatite pockets often crosscut the pink variety. The brick-red granite exhibits brick-red, pinkish-red and brown varieties with medium- to coarse-grained k-feldspar, network chains of quartz and biotite (Figure 5.16).



Figure 5.14. Photographs from 648 KS/1 core of aplitic granite. A: Typical porphyritic aplitic granite. B: Altered aplitic granite (possibly albitized). The albitized portion is devoid of phenocrysts (core depth between ca. 116.00 and 120.00 m).



Figure 5.15: Photograph from 648 KS/1 core showing brown granophyric microgranite (top) grading into the pink variety (bottom), both microgranites are crosscut by large pegmatite pockets. Tray size =1.5m (core depth between ca. 53.00 and 60.50 m).

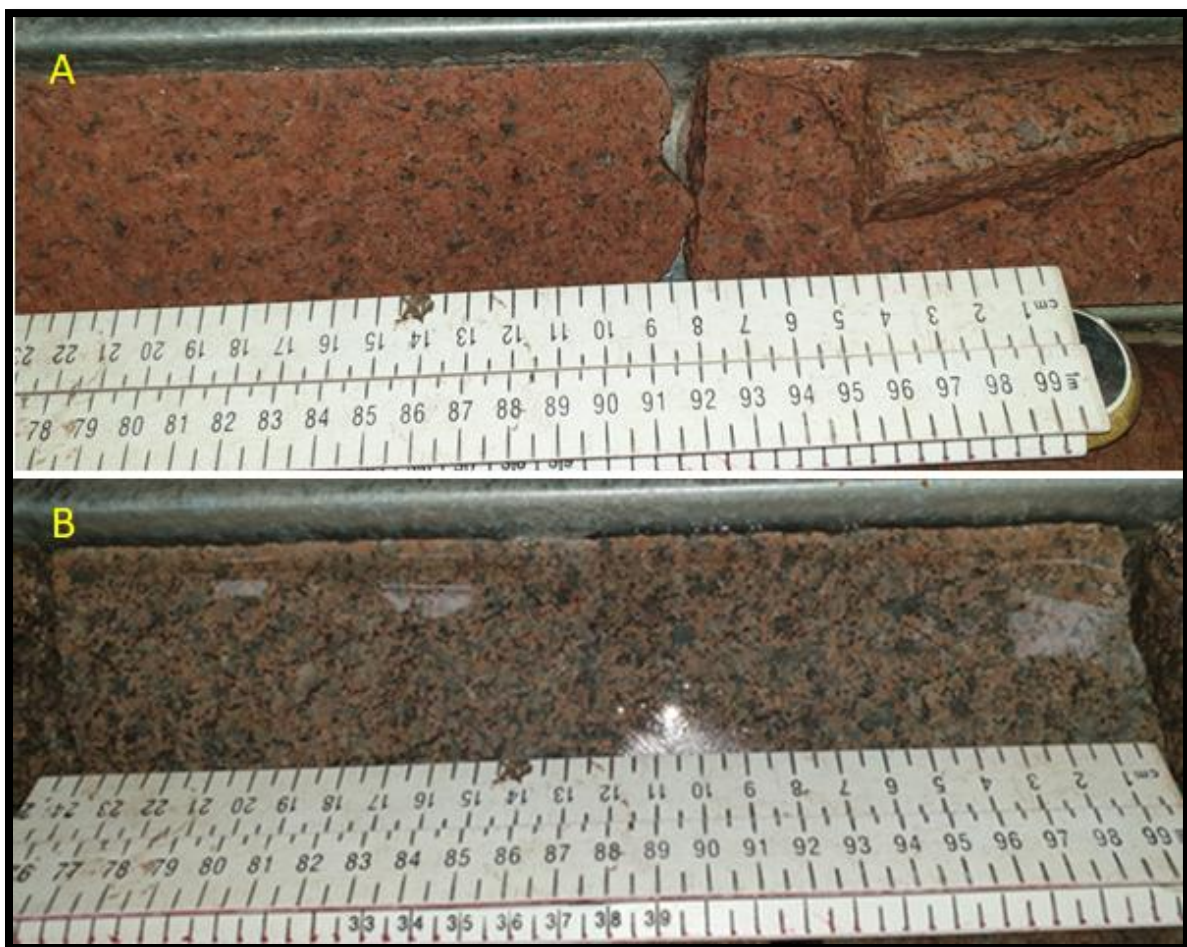


Figure 5.16: Photographs from 648 KS/1 core showing medium to coarse-grained granite. Typical brick red-granite (top) and its brown variety (bottom).

The pegmatite pockets take the form of; (1) large k-feldspar and quartz with sharp contacts with granophyric microgranite and (2) k-feldspar and quartz pegmatite adjacent to or within alteration zones in both phaneritic granite and aplitic granites.

The latter occurrence of pegmatite is often mineralised and adjacent to stringers of quartz veins (Figure 5.17).

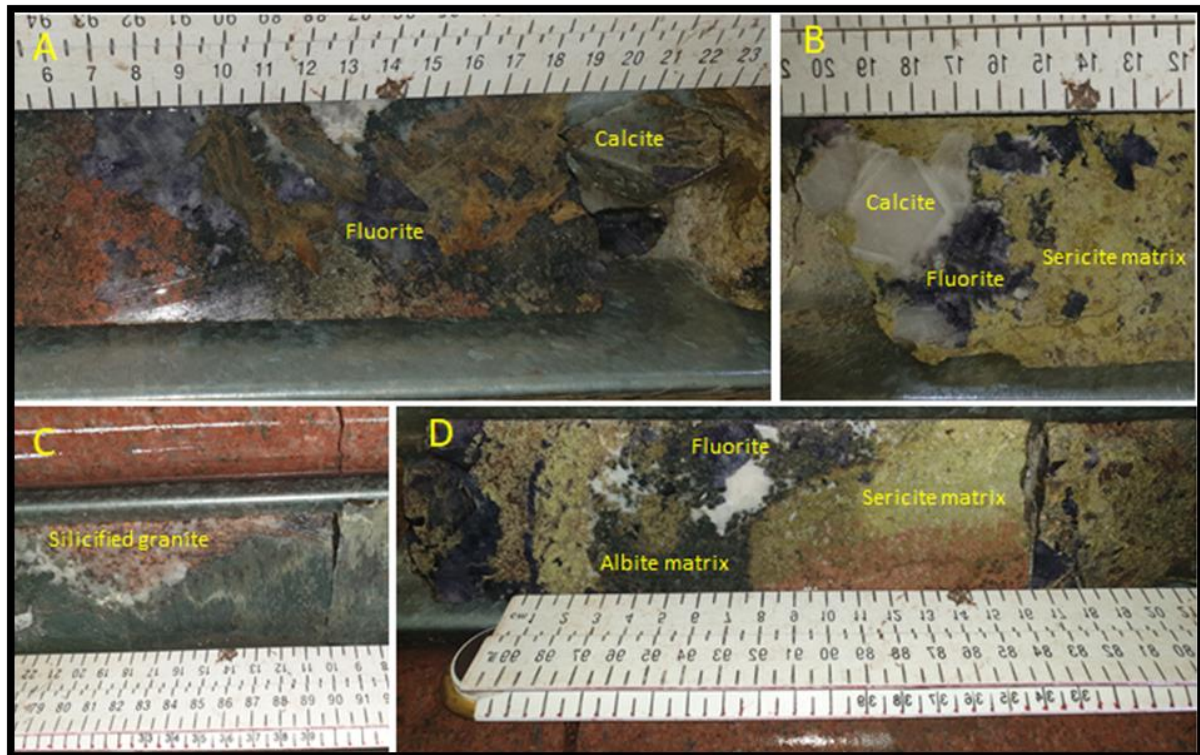


Figure 5.17: Photographs from 648 KS/1 core showing typical mineralogy of veins and pockets enclosed in the described granites. A: Calcite, fluorite and quartz pegmatite vein within albitized granite. B: Calcite and fluorite within chloritized and sericitized granite. C: Silicified granite. D: Albitized and silicified granite hosting fluorite.

Wagner (1921) termed the brick-red granite as the Red granite. The description of colour, mineralogy and modal abundances of the minerals in this granite type from 648 KS/1 core are consistent with both the findings of Wagner (1921) and Crocker et al. (2001). Crocker et al. (2001) concluded that the Red granite as described by Wagner (1921) in the Mutue Fides – Stavoren area resembles the Bobbejaankop granite from the Zaaipplaats Tin mine area. The aplitic (often porphyritic) granite described from the drill core resembles the Lease granite similar to descriptions of Crocker et al. (2001). The microgranite has the characteristics resembling the Stavoren granophyre as described by Crocker et al. (2001), however the absence of quartz and feldspar intergrowths in some samples fits the description from Kleemann and Twist (1989) of the Klipkloof granite. This granite will be referred to as microgranitic-Klipkloof granite. Average modal concentrations and sizes of minerals of the Bobbejaankop, Lease and microgranitic- Klipkloof granite samples are presented in table 5.2.

Table 5.2: Average modal concentrations of minerals in Bobbejaankop granite (B), microgranite (M) and Lease granite (L).

	RCM 01 (B)	RCM 02 (B)	RCM 03 (B)	RCM 04 (B)	RCM 05 (M)	RCM 06 (L)	RCM 07 (L)	RCM 09 (M)	RCM 11 (M)	RCM 12 (M)	RCM 14 (B)	RCM 15 (L)	RCM 16 (L)	RCM 20 (L)	RCM 21 (L)	RCM 22 (M)	RCM 23 (M)	RCM 24 (L)	RCM 26 (M)
K-feldspar	40	45	50	35	50	40	45	55	50	50	55	45	40	45	40	50	50	45	55
Plagio- clase	25	15	15	25	5	15	10	5	<5	5	<5	10	15	10	15	5	5	10	5
Quartz	30	25	30	25	40	35	35	35	35	35	30	35	35	35	35	40	40	35	35
Biotite	5	10	5	10	<5	5	<5	<5	5	5	5	5	5	5	5	5	5	5	5
Horn- blende	<5	5	5	5	0	5	<5	<5	<5	5	5	5	5	5	5	<5	<5	5	<5
Chlorite	<5	trace	<5	trace	trace	0	0	trace	trace	trace	trace	0	0	0	trace	trace	trace	0	trace
Apatite	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace
Zircon	trace	trace	trace	trace	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rutile	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace	trace

The Bobbejaankop granite comprises subhedral to anhedral alkali-feldspar (0.5 to 5 mm, 40%) and plagioclase (0.5 to 1 mm, 25%), subhedral to anhedral quartz grains (0.5 to 2 mm, 30%) with anhedral, chloritized biotite (<0.5 mm, 5%) filling interstitial spaces. The alkali feldspars are predominantly perthitic (0.5 to 2 mm) exhibiting patchy and irregular characteristics. The plagioclase shows polysynthetic twinning and is often sericitized resulting in micaceous aggregates. The plagioclase often appears exsolved within the perthite grains exhibiting patchy characteristics (Figure 5.18A and B). The microclinized plagioclase variants appear brown with a black tint owing to the colouration to Fe coating, a phenomenon attributed to hematite formation due to fluid-rock interaction (Figure 5.18D). The quartz grains exhibit granular, hypidiomorphic and synneusis-textures (Figure 5.18A).

The Bobbejaankop granite in the 648 KS/1 drill hole grades into fine- to medium-grained Lease granite. The Lease granite exhibits holocrystalline, seriate often porphyritic textures comprising k-feldspar (50%), quartz (40%), plagioclase (5%) and lesser biotite and hornblende (constitutes less than 5%) filling interstitial spaces. The porphyritic portions are characterised by k-feldspar and quartz phenocrysts (2 - 5 mm) exhibiting euhedral textures included within a 0.1 – 1 mm equigranular aplitic groundmass. The porphyritic k-feldspar and quartz crystals also exhibit poikilitic textures. The Lease granite shows similar mineral abundances to the Nebo granite, however the latter possesses more quartz crystals and less biotite and hornblende.

The granophyric microgranite forms part of the uppermost portions of the core. The largely fine-grained to medium-grained microgranite shows gradational contacts with both Bobbejaankop and Lease granite. The microgranitic-Klipkloof granite comprises subhedral k-feldspar (40%, 0.2 – 1 mm), anhedral quartz (35%, 0.2 – 1 mm), plagioclase (15%, 0.1 – 1 mm) and lesser subhedral to anhedral interstitial biotite and chlorite (both 10%, 0.2 – 5 mm). Perthitic k-feldspar and quartz exhibit graphical intergrowths. K-feldspar shows patchy and chessboard-like exsolutions which in some cases are intensively altered to sericite (Figure 5.18C). Biotite is partly altered to chlorite and often completely to sericite.

The granophyric microgranite granite possess miarolitic cavities often bound by a relatively finer-grained and altered facies of the microgranite granite. This altered facies possesses greenish-black albite accompanied by pervasive sericite, greisen and minor silicification alterations. Quartz, muscovite and to a lesser extent tourmaline

have almost replaced the granite minerals (Figure 5.19A). In some cases, k-feldspar is intensively altered and replaced by greisen and sulphide minerals. Plagioclase on the other hand is completely obliterated and replaced by acicular mineral exhibiting epidote characteristics (Figure 5.19B).

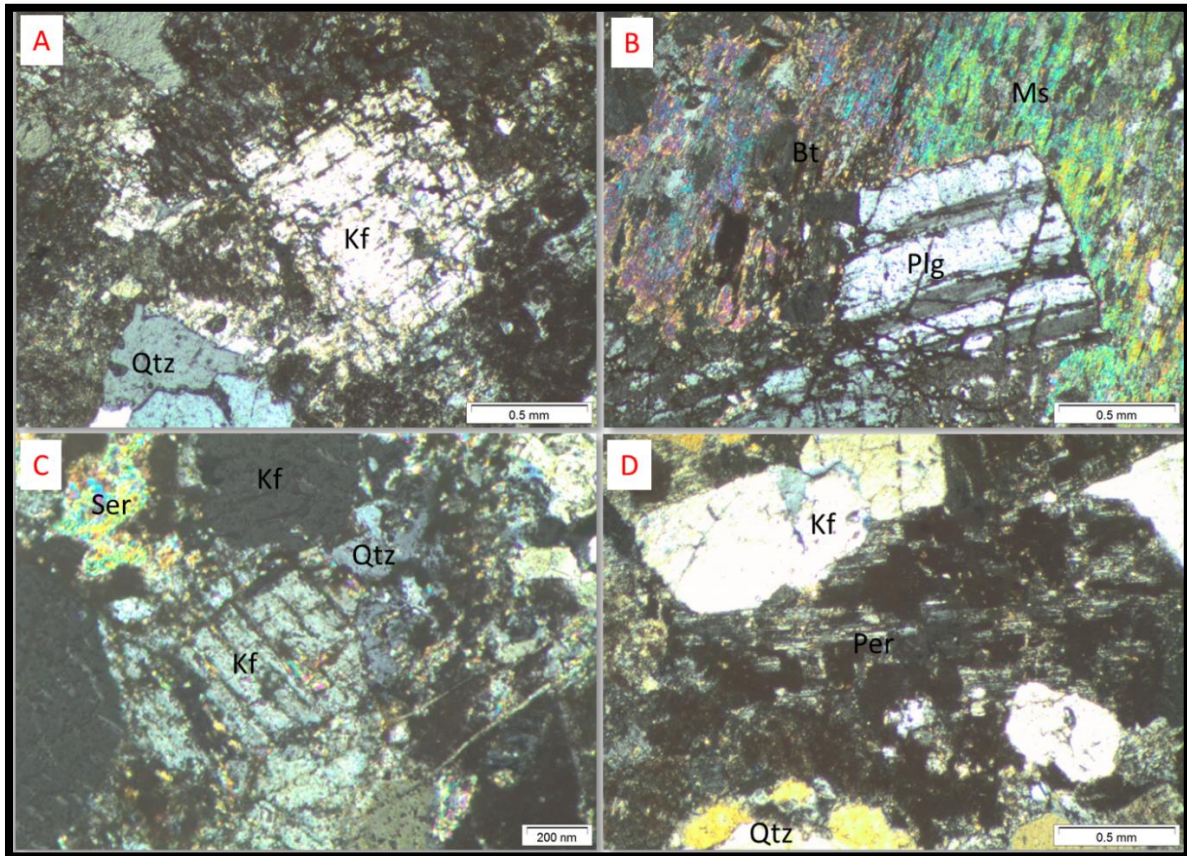


Figure 5.18: Photomicrographs from 648 KS/1 core taken in XPL. A: Patchy and irregular k-feldspar (Kf) and synneusis-textured quartz (Qtz) grains, sampled at depth 10.28 m, sample RCM 01. B: Typical polysynthetic twinning by plagioclase (Plg) often altered to micaceous aggregates, sampled at depth 10.28 m, sample RCM 01. C: Patchy and chessboard-like texture of k-feldspar, altered to sericite (Ser), sampled at depth 19.95 m, sample RCM 02. D: Altered perthite matrix within k-feldspar and quartz phenocrysts, sampled at depth 19.95, sample RCM 02.

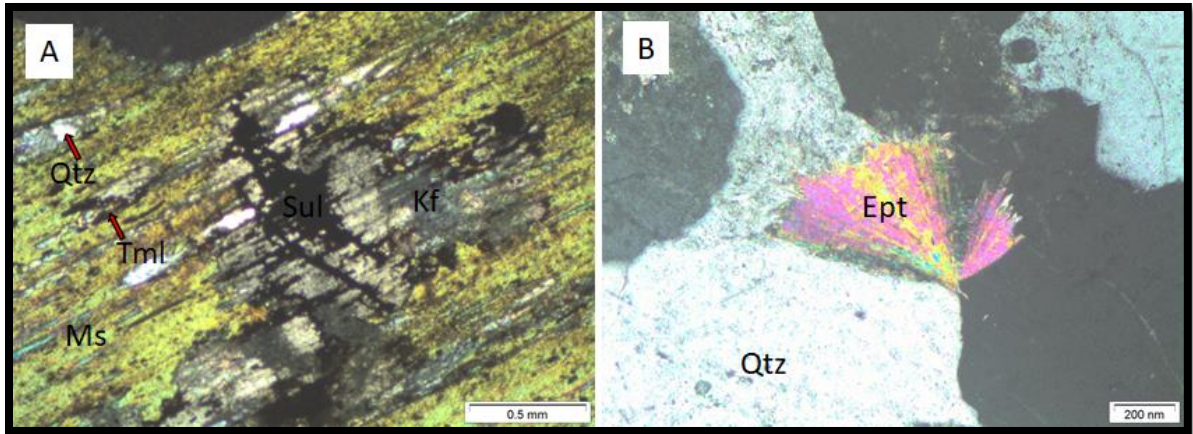


Figure 5.19: Photomicrographs from 648 KS/1 core depicting altered facies of microgranite taken XPL. A: Resultant greisen assemblage consisting foliated quartz (Qtz), muscovite (Ms) and tourmaline (Tml), sampled at depth 187.54 m, sample RCM 25. Sulphides (Sul) and greisen minerals replacing the k-feldspar (Kf). RCM25 (B) K-feldspar completely obliterated and replaced by acicular epidote (Ept) surrounded by microcrystalline quartz, sampled at depth 187.54 m, sample RCM 25.

5.2.1. Ore petrography

Ore minerals including cassiterite, fluorite and molybdenite occur in the miarolitic-cavities in the Bobbejaankop granite and associated microgranite and Klipkloof facies. These ore minerals occur in miarolitic cavities can form veins or pockets.

Cassiterite occur as massive euhedral grains which are brown with yellow tint (1 to 5 mm) within a black mica matrix in veins. These granular cassiterite crystals are often fractured and contain quartz inclusions (Figure 5.20A). In some instances, elongated granular subhedral cassiterite grains occur within a greisen matrix of green to black mica and quartz (Figure 5.20B).

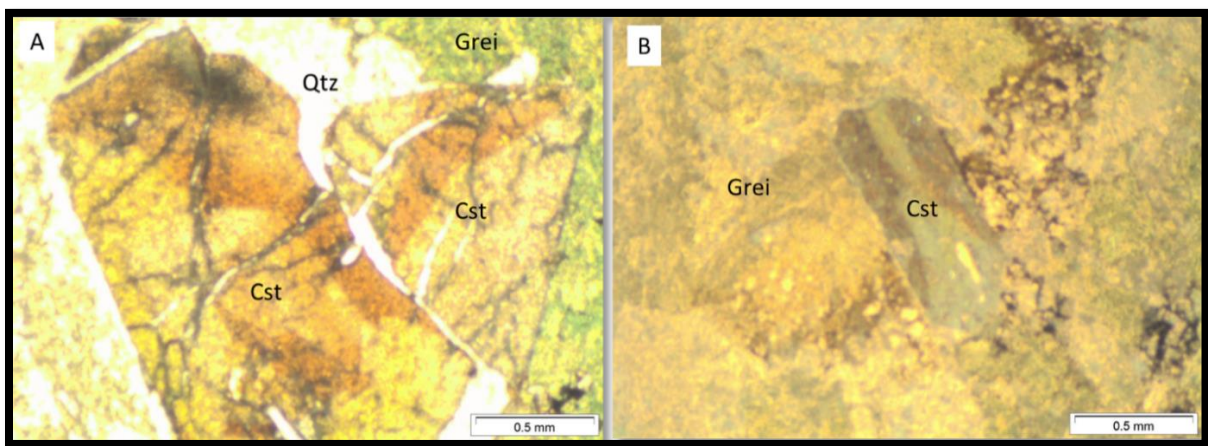


Figure 5.20: Photomicrographs from altered microgranite depicting granular cassiterite (Cst) from 648 KS/1 core. A: Fractured cassiterite grains cemented by quartz within greisen (Grei) matrix, sampled at 101.56 m, sample RCM 17. B; Elongated cassiterite grain within greisen matrix, sampled at 101.56 m, sample RCM 17.

Fluorite commonly occurs as shiny-grey fine-grained (<0.1 mm) subhedral to anhedral grains accompanied by calcite crystals within greisenized and chloritized granite veins (Figure 5.21). Calcite exhibits granular subhedral to anhedral textures filling interstitial spaces in association with the fluorite. Fluorite in pockets typically comprises purple, transparent and white varieties. These fluorite crystals exhibit massive and granular textures in association with calcite showing diffuse zonation of various colours (Figure 5.17A and 5.17B). Molybdenite exhibits silver-grey fine-grained subhedral to anhedral textures within greisenized and chloritized microgranite (Figure 5.22). Molybdenite and fluorite occur as massive subhedral grains in ore pockets associated with k-feldspar and quartz pegmatite.

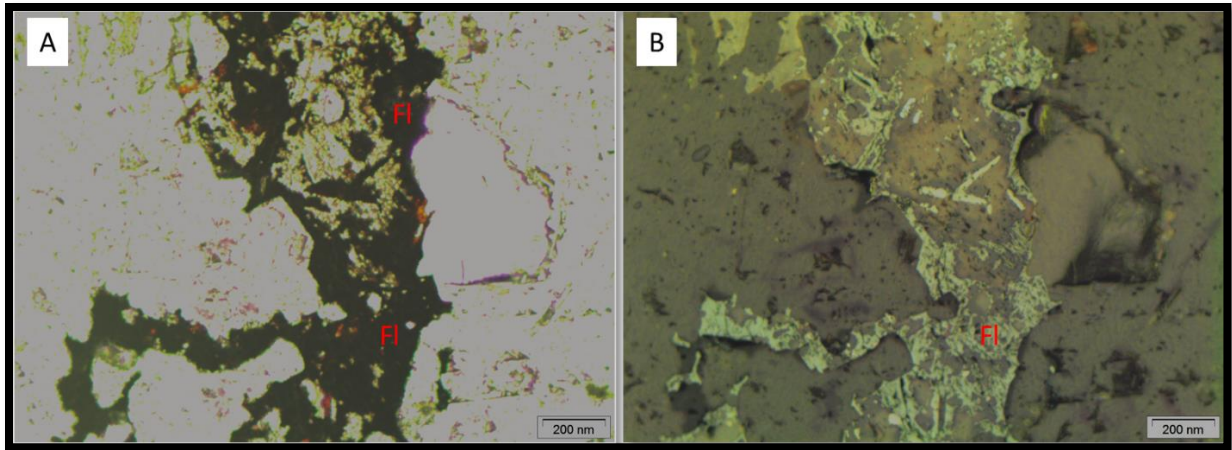


Figure 5.19: Photomicrographs of Fluorite (Fl) from microgranite from 648 KS/1 core. A: PPL image of fluorite with purple non-isotropic edges, sampled at depth 69.40 m, sample RCM 11. (B) Fluorite in plane-polarized transmitted light, sample at depth 69.40 m, sample RCM 11.

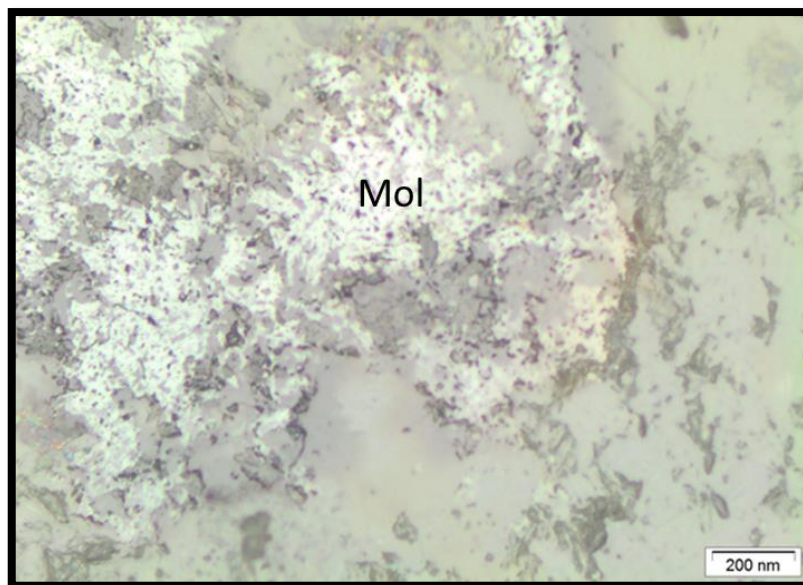


Figure 5.20: Photomicrograph in plane-polarized transmitted light of massive molybdenite (Mol) in greisen matrix, sampled at depth 77.32 m, sample RCM 13.

5.3. Discussion of Nebo granite and correlations amongst Bobbejaankop, Lease and Klipkloof granite

5.3.1. Nebo Granite (Boschhoek Prospect)

The granite in the Boschhoek Prospect is considered Nebo granite as first described by Smits (1980) comprising perthite (55 – 58%), quartz (25 – 30%), plagioclase (5 – 10 %), hornblende (2- 8%) and biotite (<2%). Evans (2015) in the same area confirmed the descriptions of Smits (1980) however, there is considerably more biotite and relatively less hornblende compared to the earlier studies. The considerable difference

in hornblende content may be attributed to the distance in stratigraphic height between the sampling locations of the two boreholes used by the authors. Kleemann and Twist (1989) noted an upwards decrease of hornblende content in Nebo granite. In this study, relatively less hornblende contents (<5%) are found and it is nearly absent in some samples. This implies that the Nebo granite in the Boschhoek Prospect is intermediate between the hornblende rich grey-granite described by McCaskie (1983) and the almost hornblende-free Evans (2015) found in the same locality.

5.3.2. Bobbejaankop Granite (648 KS/1 drill)

Studies by Vonopartis et al. (2020) of the Bobbejaankop granite from Zaaiplaats tin mine found the typical petrology of the granite comprises alkali-feldspar (averaging 35%), plagioclase (averaging 25%), quartz (35%) and biotite (<5%). The quartz grains exhibit a synneusis-texture which is characteristic of Bobbejaankop granite (Vonopartis et al., 2019, 2021). In the Mutue Fides area where 648 KS/1 core was drilled, Wagner (1921) description of the Red granite is consistent with the Bobbejaankop granite petrology. Crocker et al. (2001) referred to the Red granite as Bobbejaankop granite albeit the studies showed relatively less plagioclase than the reported average by Vonopartis et al. (2020). In this study, modal abundances and minerals present of the supposed Bobbejaankop granite are consistent with the observations by previous workers however, the synneusis texture of quartz grains is not as abundant.

5.3.3. Lease and Klipkloof granite (648 KS/1 drill)

The Lease granite shows cryptic contacts with the Bobbejaankop granite contrary to sharp contacts relationships noted by Bailie and Robb (2004) in the central southeastern lobe of the BIC. The Lease granite exhibits petrological characteristics akin to the Lease described in Zaaiplaats Tin mine (cf. Vonopartis et al., 2020). The porphyritic variety of the Lease granite resembles the Foothills granite first described by Strauss (1954).

The Klipkloof granite show transitional contacts with both the Lease and the Bobbejaankop granites and occurs in the upper portions of the cores. Its petrology is consisted with the description of Crocker et al. (2001). Some portions of the

microgranitic-Klipkloof granite are granophyric and resemble the Stavoren granophyre as described by Walraven (1987).

The identification of these granite facies of the Lebowa Granite Suite are further considered using geochemical data in the next chapter.

Chapter 6: Geochemistry

This chapter constitutes studies of whole-rock geochemistry of seventeen drill core samples from Boschhoek Prospect (BHDD 003) and twenty-six samples from Mutue Fides (648 KS/1) drill cores. These samples are complimented by historical data of geochemical studies of LGS rocks published by Kleemann and Twist (1989), Labuschagne (2004) and Vonopartis et al. (2020) and RGS studies by Labuschagne (2004). The study presents geochemical variations in each drill core to investigate magmatic fractionation, hydrothermal alteration and ultimately provide insights into their petrogenetic evolution, possible cogenesis and characteristic alteration signatures indicative of mineralization.

To establish the geochemical variations in each drill core, the samples are grouped into granites and late veins and pegmatites based on petrographic characteristics described in Chapter 5. In addition, the historical geochemical data is also adopted as a reference in the separation of the non-granitic samples from the granite samples and to further validate these distinctions made in Chapter 5. Although there is a general consensus that the Bobbejaankop granite, Klipkloof granite and Lease granite are to some extent all altered facies of the Nebo granite, in this chapter, the late veins and pegmatites refer to samples whose primary rock-forming minerals show evidence of alteration and their modal abundances are different from the typical Nebo and Bobbejaankop granites (cf. MacCaskie, 1983; Kleemann and Twist, 1989; Kinnaird et al., 2004).

Tables of the whole-rock major element and trace element concentrations are presented in Appendix A. Harker plots of Al_2O_3 , MgO , TiO_2 , CaO and FeO^T against SiO_2 of both drill cores are plotted in Figure 6.1 together with historical geochemical data. Numerous samples from both drill cores cluster within the historical data confirming their identification as various types of Bushveld granites. Samples from alteration zones, veins and pegmatites plot away from the characteristic areas delineated using the historical data by green ovals. These samples will be referred to as late veins and pegmatites and are presented in subsection 6.2., separately from the granites.

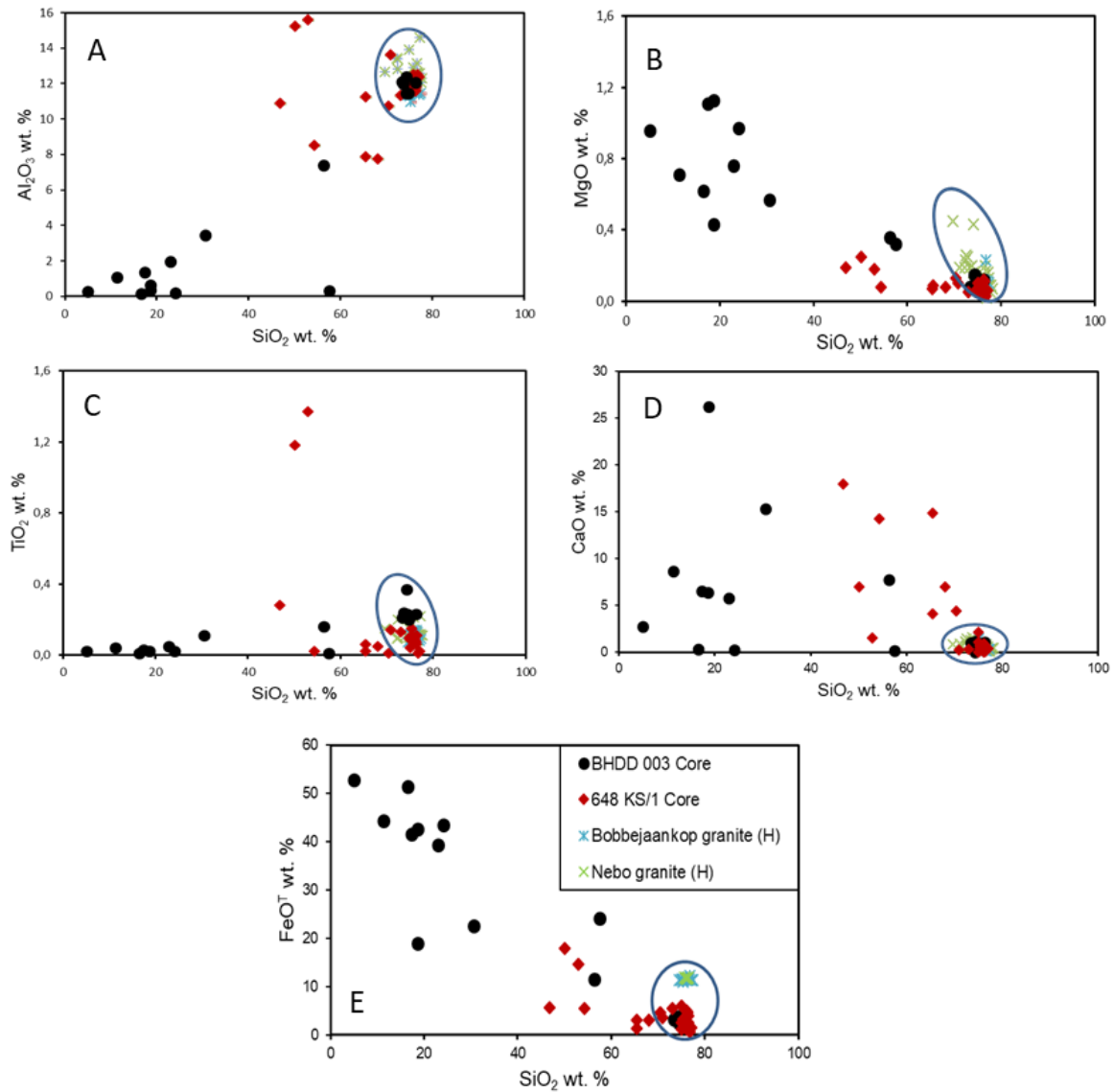


Figure 6.1: Major oxide element Harker plots of samples from BHDD 003 and 648 KS/1 drill cores. A: SiO₂ wt. % versus Al₂O₃ wt. % B: SiO₂ wt. % versus MgO wt. % C: SiO₂ wt. % versus TiO₂ wt. % and D: SiO₂ wt. % versus CaO wt.%. E: SiO₂ wt. % versus FeO^T wt. %. Historical published data of the Nebo granite from Kleemann and Twist (1989) and Labuschagne (2004) and historical Bobbejaankop granite data from Vonopartis et al. (2020). The blue ovals delineate areas within which all historical LGS granite data plot.

6.1. Granites

This subsection presents lithogeochemical data of six samples from BHDD 003 and nineteen samples from 648 KS/1 drill cores. The samples from BHDD 003 show affinities with the Nebo granite and the samples from 648 KS/1 are from the Bobbejaankop, Klipkloof and Lease granites discerned using petrographic studies in Chapter 5. The distinction amongst these granite facies from 648 KS/1 will be established using trace element geochemistry.

6.1.1. Major element geochemistry

The Nebo and the Bobbejaankop-like granites contain a high SiO₂ concentration ranging between 70.42 wt. % to 77.06 wt. % and 73.63 wt. % to 76.32 wt. % respectively. The silica concentration of Nebo granite averages 74.50% (n=6) and the Bobbejaankop-like granite averages 75.12% (n=19). Both granite types contain low concentrations of CaO ranging between 0.04 wt. % and 4.wt%, averaging 1 wt. % (n=25). The MgO and P₂O₅ contents are extremely low in both granites; they are less than 0.15 wt. % and 0.04 wt. % respectively.

The ranges and averages of major elements are consistent with the reported general geochemical concentration of the LGS, as reported by Kinnaird et al. (2004). The averages of K₂O, Na₂O and their ratios (K₂O/Na₂O>1), MgO and P₂O₅ contents are typical signatures for A-type granites (cf. Whalen et al., 1996; King et al., 1997; Kleemann and Twist, 1989). The Fe content and the FeO-MgO ratio also indicate their A-type ferromagnesian nature (Kleemann and Twist, 1989; Hill et al., 1996). Harker plots of some major oxides are presented in figure 6.2.

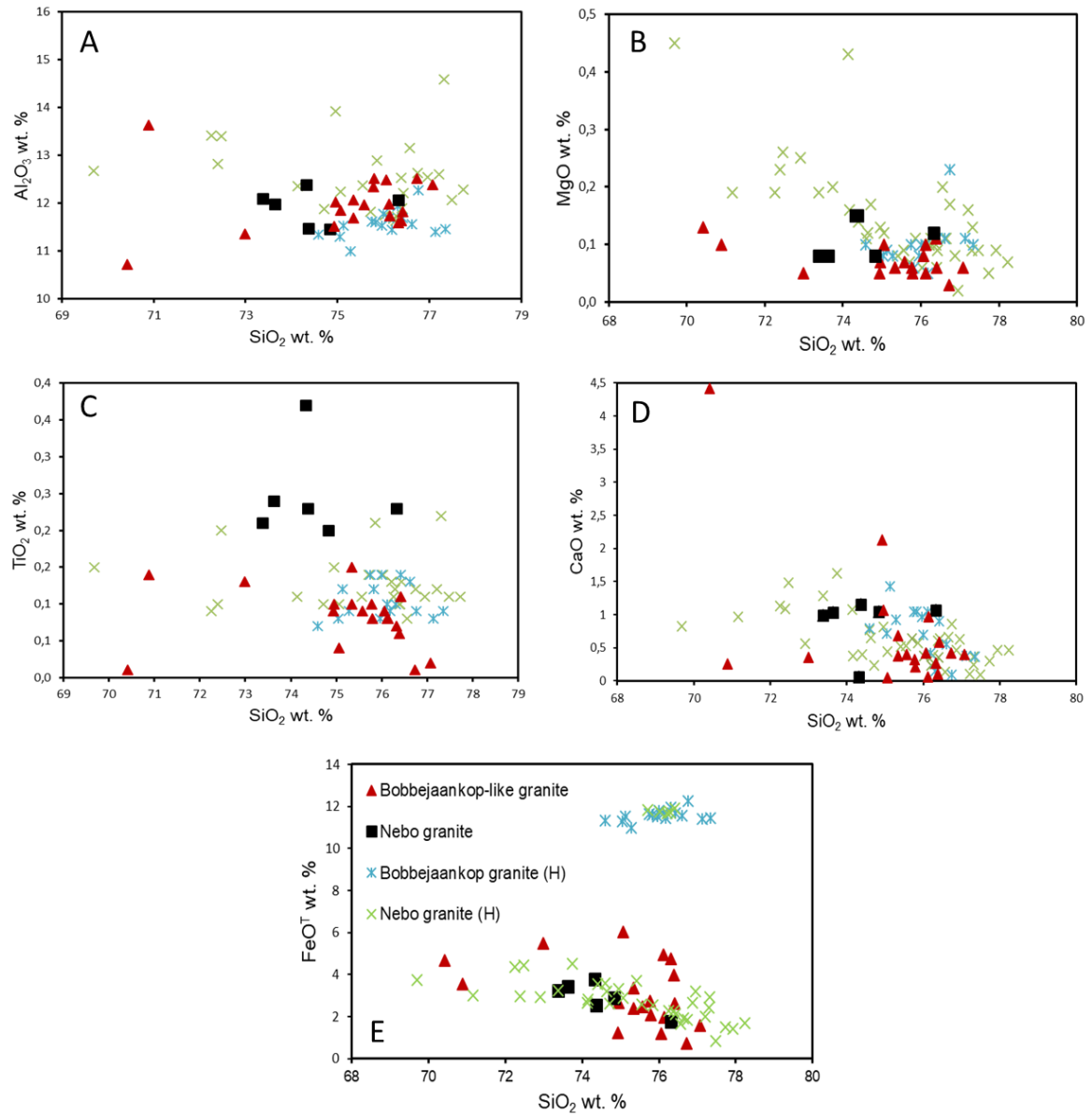


Figure 6.2: Major oxide element Harker plots of Nebo granite and Bobbejaankop-like granite. A: SiO_2 wt. % versus Al_2O_3 wt. % B: SiO_2 wt. % versus MgO wt. % C: SiO_2 wt. % versus TiO_2 wt. % and D: SiO_2 wt. % versus CaO wt. %. E: SiO_2 wt. % versus FeO^T wt. %. Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and Labuschagne (2004) and historical Bobbejaankop granite (H) data from Vonopartis et al. (2020).

The Fe-index ($Fe^* = FeO^T / (FeO^T + MgO)$) in both the Nebo and the Bobbejaankop-like granites satisfy the condition ($FeO^T / (FeO^T + MgO) > 0.486 + 0.0046 \times wt.\% SiO_2$) to be regarded as ferroan A-type granites after Frost et al. (2001) and Frost and Frost (2008) (Figure 6.3). The Alumina Saturation Index (ASI) ($Al_2O_3 / (CaO + Na_2O + K_2O)$), also known as the Shand Index (Shand, 1922); ranges from 1.28 to 3.67 suggesting that these A-type granites are peraluminous (Figure 6.4). The relatively high ASI implies oversaturation of alumina contents which is greater than the feldspar minerals can accommodate and therefore can subsequently form other alumina bearing minerals.

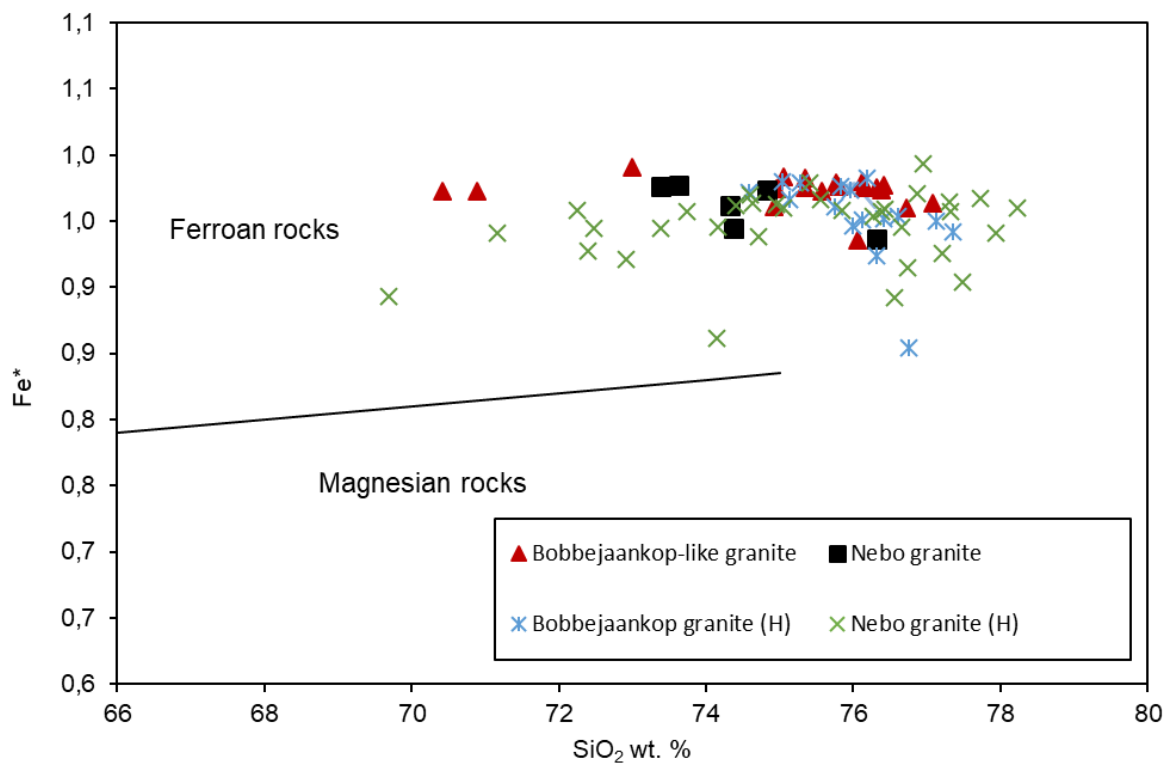


Figure 6.3. Fe^* versus SiO_2 plot depicting the Ferroan nature of the Nebo granite and Bobbejaankop-like granite. $Fe^* = FeO^T / (FeO^T + MgO)$. After Frost et al. (2001). Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and Labuschagne (2004) and historical Bobbejaankop granite (H) data from Vonopartis et al. (2020).

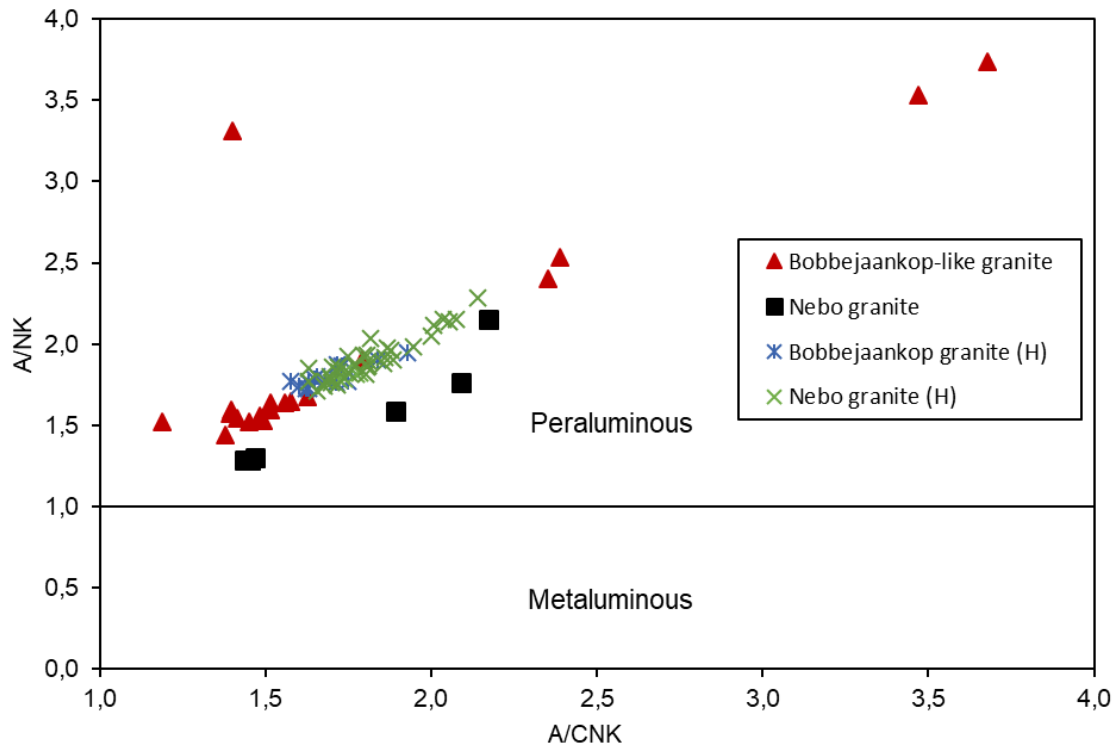
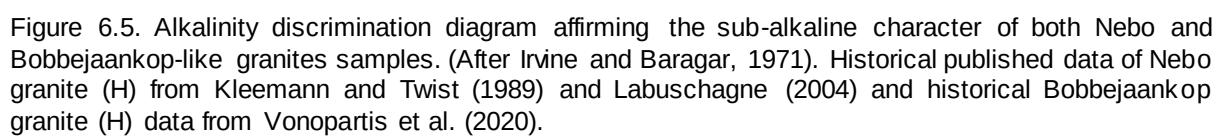


Figure 6.4: ASI discrimination plot classifying the Nebo granite and Bobbejaankop-like granite as peraluminous granites. A/CNK = molar $Al_2O_3/(CaO+Na_2O+K_2O)$; A/NK = molar $Al_2O_3/(Na_2O+K_2O)$. (After Frost and Frost, 2008). Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and Labuschagne (2004) and historical Bobbejaankop granite (H) data from Vonopartis et al. (2020).

These suites are sub-alkaline with calc-alkalic to calcic composition as indicated in the Modified Alkali Lime Index (MALI) diagram after Frost et al. (2001) (Figure 6.5). The Nebo granite samples mainly plot within the calc-alkalic field extending from the calcic field. The Bobbejaankop-like granite samples also extend from the calcic to calc-alkali field however, they show a relatively wide spread compared to the Nebo granite (Figure 6.6). This implies that Bobbejaankop-like granite contains more variable compositions than the Nebo granite. Moreover, the widespread variation may represent fractionation trends and variable amounts of fractionation in addition to the variable compositions (cf. Frost and Frost, 2008).



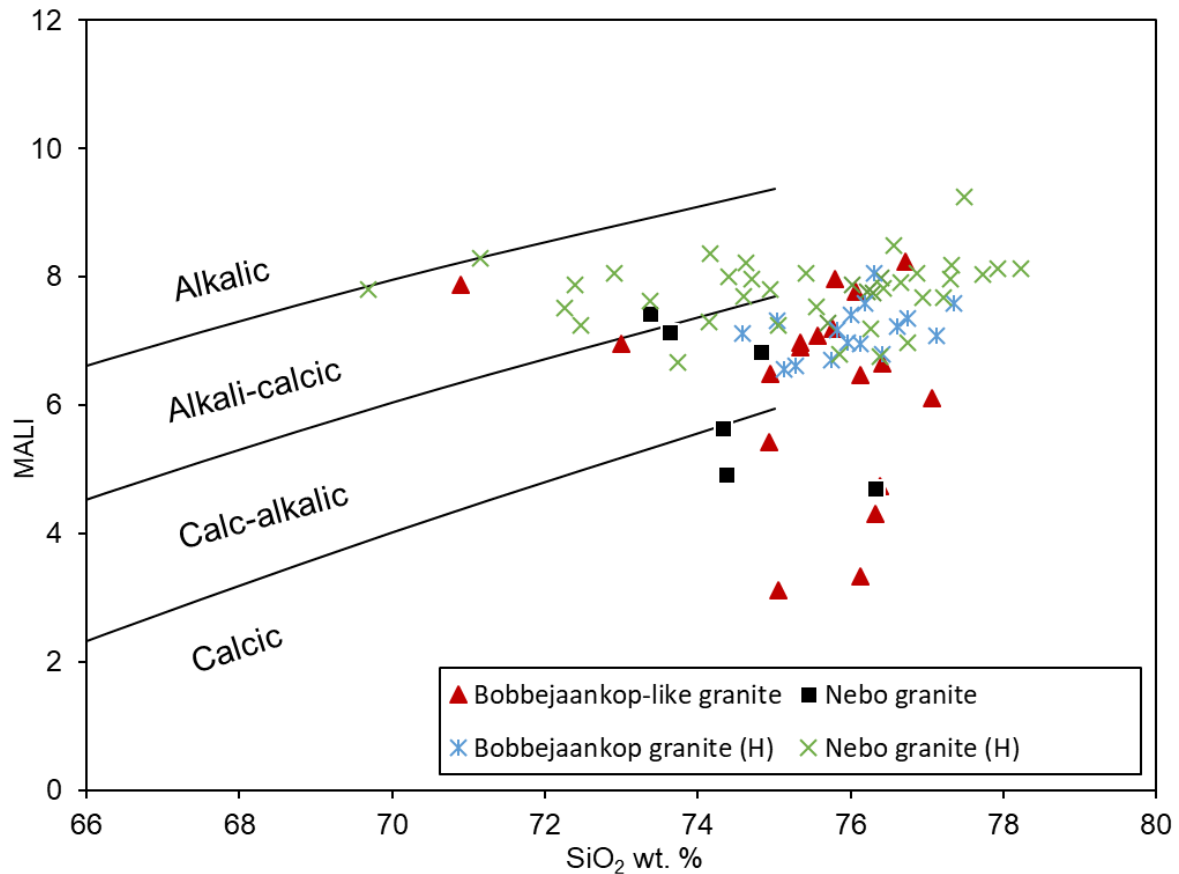


Figure 6.6: MALI discrimination diagram describing fractionation trends of Nebo and Bobbejaankop-like granite samples. MALI= $\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$ wt. % (After Frost et al., 2001). Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and Labuschagne (2004) and historical Bobbejaankop granite (H) data from Vonopartis et al. (2020).

Discrimination plots of major element compositions ascertain that the “unaltered” samples represent the LGS as they exhibit the typical A-type ferromagnesian nature of the suite with an anorogenic geochemical signature. The Nebo granite shows a relatively lower average and narrow range of SiO_2 concentration compared to the Bobbejaankop-like granites. The lower average concentration of SiO_2 is to be expected for the Nebo granite as it represents a more primitive composition (cf. Kleemann and Twist, 1989). The Bobbejaankop-like granite exhibits a wider spread in the MALI plot suggesting that it is more extensively fractionated than the Nebo granite (Figure .6.6).

The historical data from Labuschagne (2004) shows a wider range of SiO_2 and other major oxides such as MgO , Al_2O_3 and CaO in the Nebo granite. Due to these large variations of the major oxides, the dataset is then not usable to identify various varieties of the LGS and their respective degree of fractionation. As such, the

Kleemann and Twist (1989) historical dataset is favoured to provide a baseline for the trace element geochemistry of Nebo granite.

6.1.2. Trace elements

The Nebo granite samples show high Rb (138-186 ppm; averaging 158 ppm (n=6)), Th (19-30 ppm, averaging 24 ppm), U (4-6 ppm, averaging 5 ppm) but relatively depleted Ba (475 - 935 ppm, averaging 776 ppm), Sr (17 - 69, averaging 41 ppm) and Zr (185 - 322 ppm, averaging 248 ppm). The Nebo granite also shows an enrichment of REE such as Y, La, Ce, Gd and Nd when compared to non-A type granites with similar SiO₂ concentrations (Appendix A) (cf. Kleemann and Twist, 1989; Hill et al. 1996). The Bobbejaankop-like granite samples show comparably higher concentrations of Rb (235 - 619 ppm, averaging 407 ppm (n=19)), Th (3 - 75, averaging 32 ppm) and U (3 - 39 ppm, averaging 15 ppm) relative to the Nebo granite samples (Appendix A). The Bobbejaankop granites are also depleted in Ba (36-181, averaging 108 ppm), Sr (2 - 11 ppm, averaging 6 ppm) and Zr (165 - 878 ppm, averaging 360 ppm) when compared to non-A type granites (cf. Kleemann and Twist, 1989). Both granites further show low concentrations of compatible elements such as Cr, Co, Ni and V, which is typical of samples from the LGS (cf. Kleemann and Twist, 1989).

Using trace element discrimination diagrams, after Whalen et al. (1987), the Bushveld granites show an affinity to A-type granite trace element abundances (Figure 6.7A). Similarly, trace element ratios confirm the A-type nature of the granites as noted from major element geochemistry (Figure 6.7B). The binary discrimination diagrams after Eby (1992) show that the Bobbejaankop-like and Nebo granites overlap between the A1 (rift-related) and the A2 (post-collision) A-subtype fields (Figure 6.8).

The Nebo granite samples show a mantle-normalised Y/Nb ratio of above 1.2, which is consistent with the A2-granite classification (cf. Eby, 1990; 1992). On the other hand, the Bobbejaankop-like granite show ratios of less than 1.2, which is typical of the A1-granite type. According to Eby (1992), A1-granites are related to partial melting of and/or fractionation from the ocean island basalt-like source, whereas A2-granites emanate from partial melting of arc-type source or continental crust.

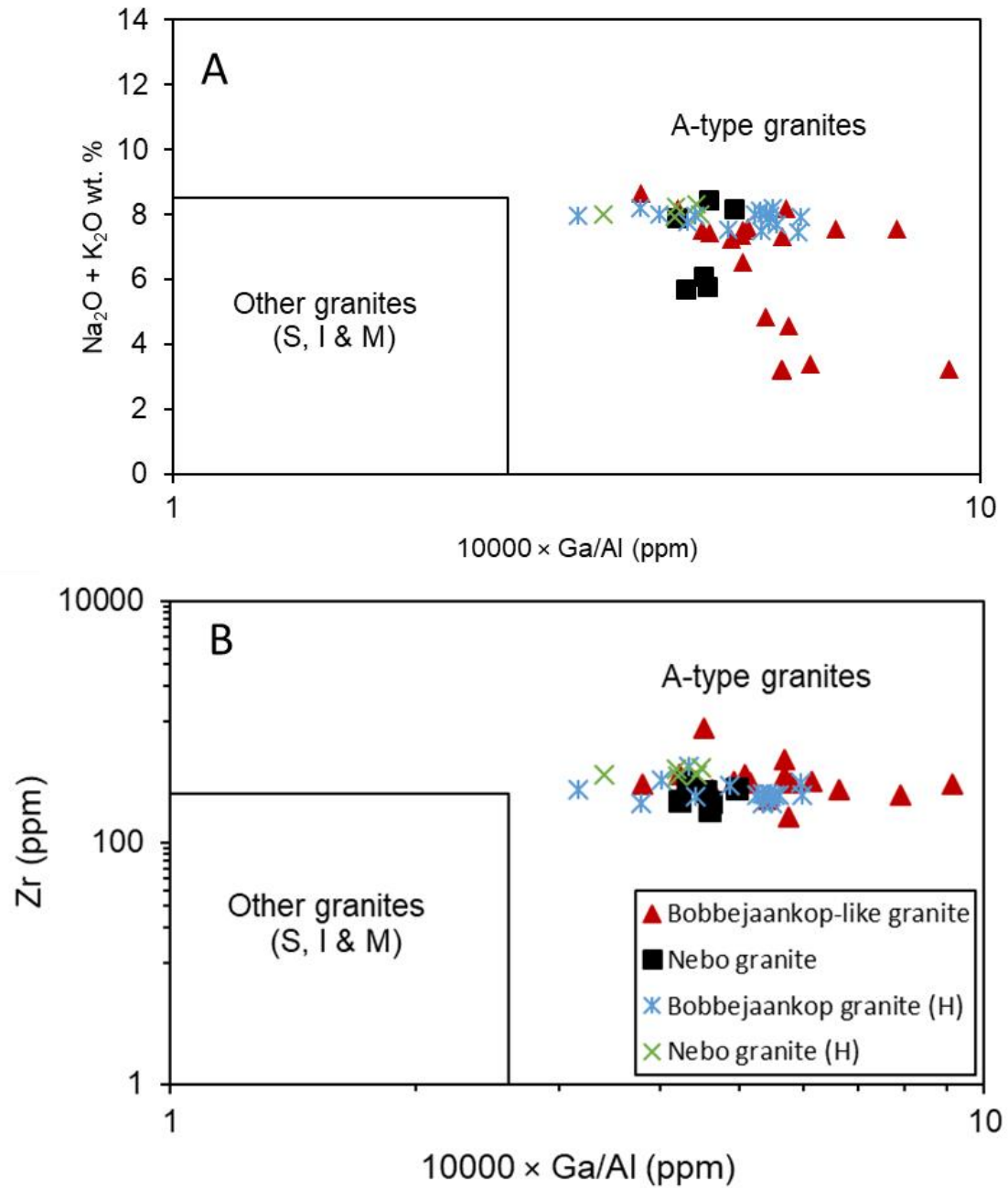


Figure 6.7: A: $10000 \times \text{Ga}/\text{Al}$ (Al in ppm) versus $\text{Na}_2\text{O} + \text{K}_2\text{O}$ wt. % and B: $10000 \times \text{Ga}/\text{Al}$ (Al in ppm) versus Zr (ppm) discrimination plots affirming both Nebo and Bobbejaankop-like as A-type granites (After Whalen et al. 1987). Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and historical Bobbejaankop granite (H) data from Vonopartis et al. (2020).

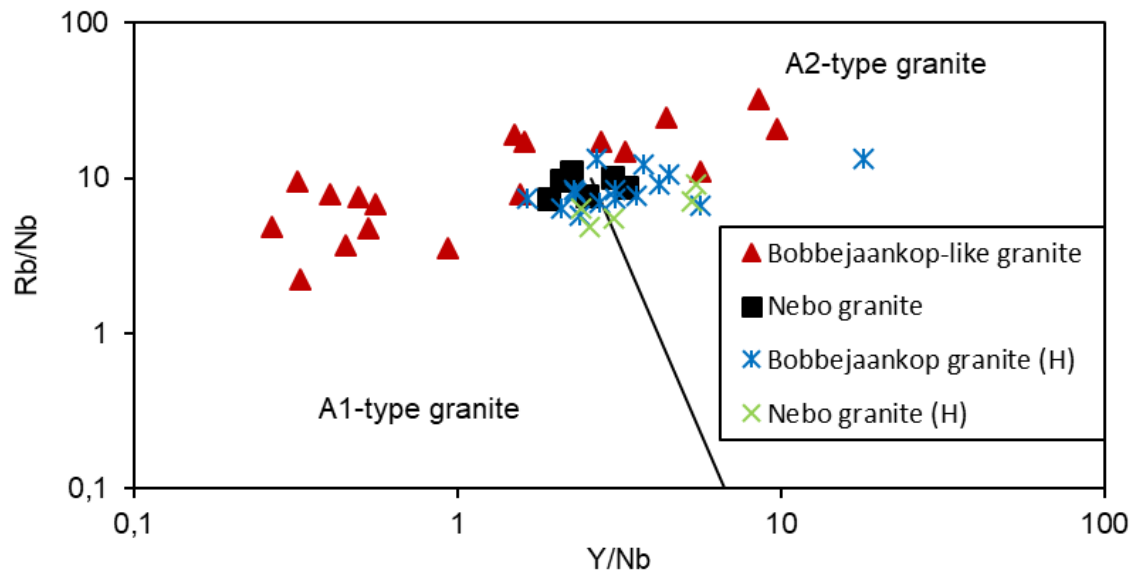


Figure 6.8: Y/Nb versus Rb/Nb discrimination diagram, showing overlap between the A1-type granite and A2-type granite fields of Nebo granite and Bobbejaankop-like granite respectively. (After Eby, 1992). Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and historical Bobbejaankop granite (H) data from Vonopartis et al. (2020).

The Nebo granite, shows Nb/Ta ratios between 15.41 and 21.56 (averaging 16.98). The Bobbejaankop-like granites show Nb/Ta ratios between 6.46 and 14.64 (averaging 10.10). According to Eby (1990) and Ballouard et al. (2020) Nb/Ta ratios are thought to remain constant in igneous magmatic suites including comagmatic suites owing to the similar geochemical character of Nb and Ta although Nb is preferred over Ta in evolving peraluminous magmatic systems (Linnen and Keppler, 1997). The lower Nb/Ta ratios in Bobbejaankop-like granite may signify the degree of magmatic fractionation and sub-solidus magmatic-hydrothermal processes.

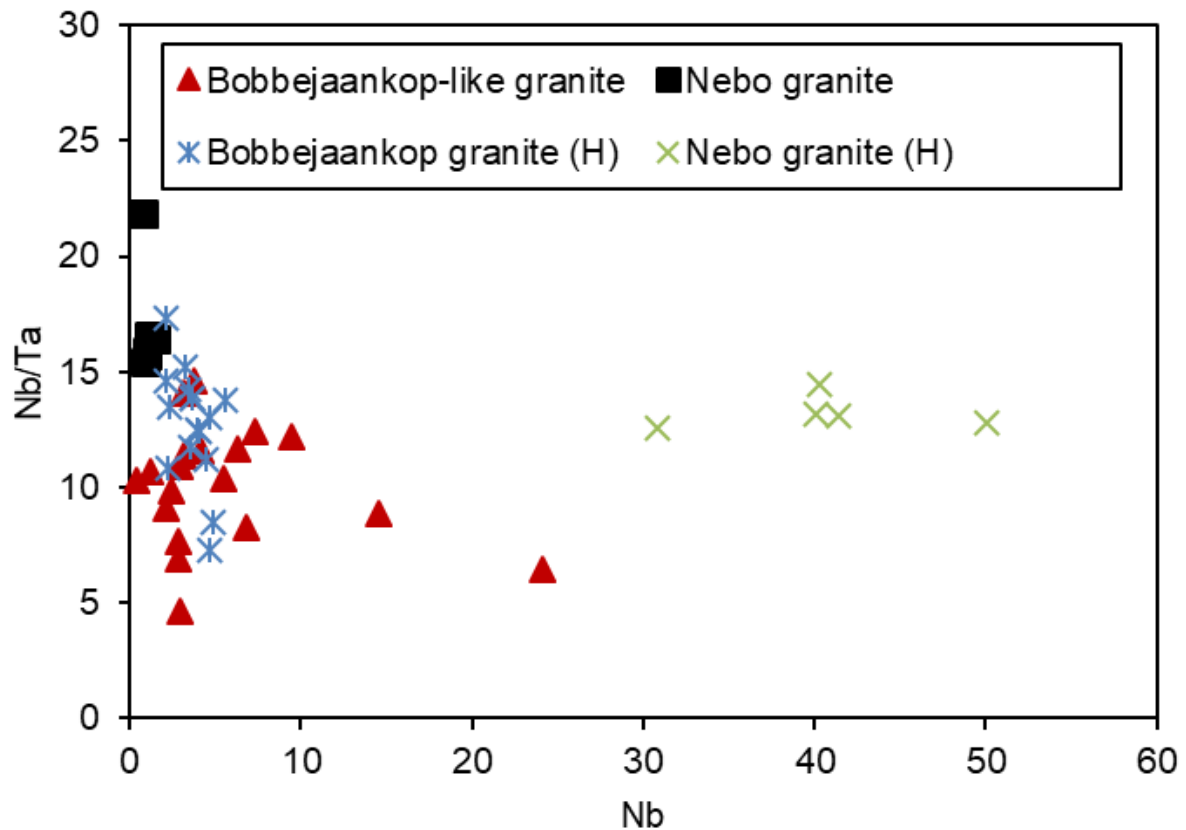


Figure 6.9: Nb versus Nb/Ta of Nebo granite and Bobbejaankop granite showing Nb-Ta fractionation from the Nebo granite. Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and historical Bobbejaankop granite (H) data from Vonopartis et al. (2020).

The Nebo granite shows Rb/Sr ratios ranging between 2 and 11 whereas the Bobbejaankop-like granite shows relatively higher Rb/Sr between 44 and 229 (Figure 6.10). Rb is relatively incompatible with respect to Sr and it partitions more into the melt than solid during crystallisation resulting in higher concentrations in the residual melt (Figure 6.10). Conversely, Ba and Sr are compatible and inherently decrease with increasing fractionation (El Bouseily and El Sokkary, 1975). Consequently, higher Rb/Sr ratios in the Bobbejaankop-like granite may be indicative of its highly fractionated nature relative to the Nebo granite.

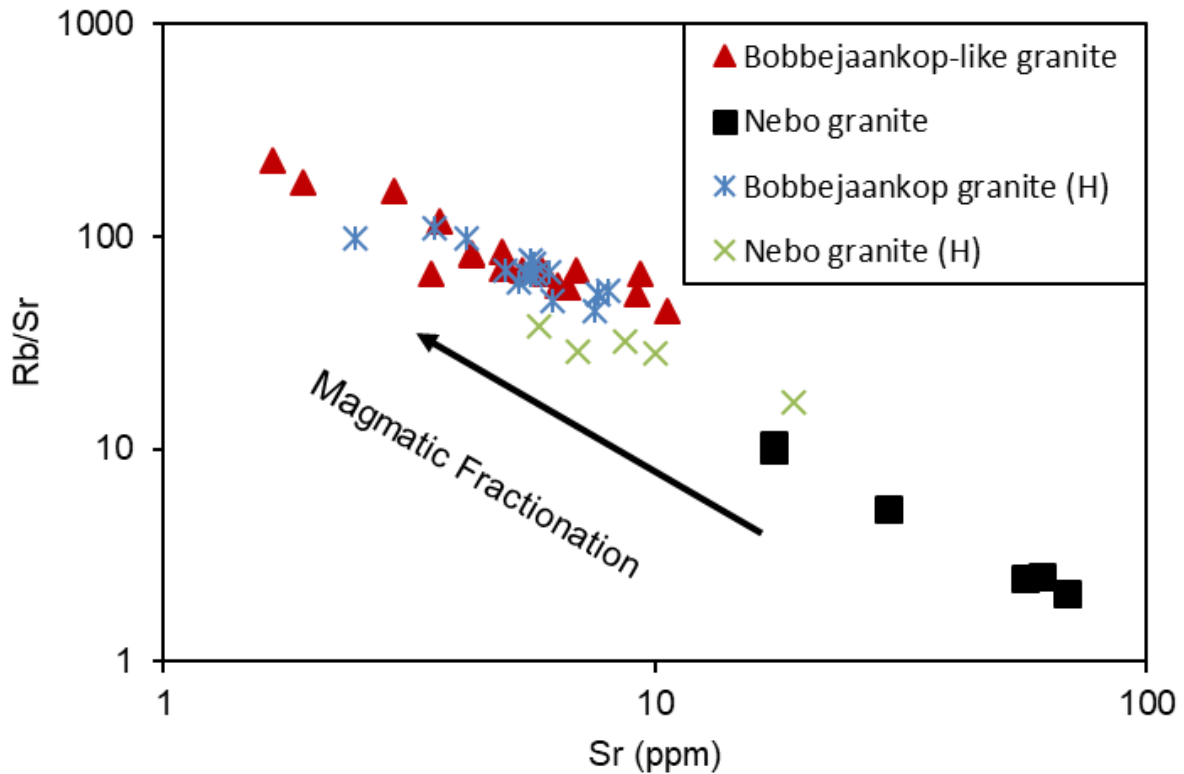


Figure 6.10: Sr (ppm) versus Rb/Sr plot showing magmatic fractionation trend of the Nebo granite representing the least differentiated variety and the more differentiated Bobbejaankop-like granite (cf. Walraven, 1986). Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and historical Bobbejaankop granite (H) data from Vonopartis et al. (2020).

The use of the Trace Element Differentiation Index (TEDI) developed by Walraven (1986) successfully distinguishes the relatively less fractionated Nebo granite and the fractionated granite facies such as the Klipkloof and Bobbejaankop (Walraven, 1986). The concept of TEDI was proposed and defined by Walraven (1986) as $Ba \times (Sr/Rb)$, with the values less than or equal to 100 indicating the least fractionated magma. Alternatively, TEDI values lower than 10 are indicative of highly fractionated magma (cf. Bailie, 1997; Freeman, 1998; Bailie and Robb, 2004). The Nebo granite shows TEDI values ranging between 70 and 399 whereas the Bobbejaankop-like granite shows a range between 0.1 and 4. These TEDI values confirm that the Bobbejaankop-like granite facies are relatively more fractionated and possibly extensively altered by magmatic aqueous solutions than the Nebo granite (Figure 6.11).

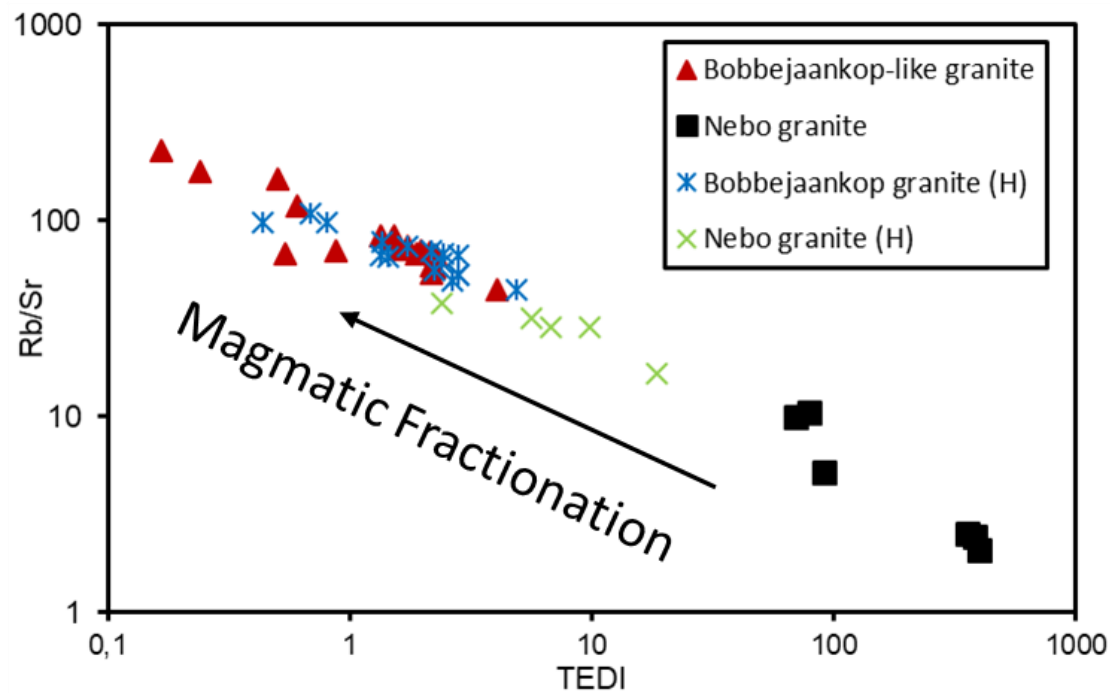


Figure 6.11: TEDI versus Rb/Sr binary plot showing the fractionation degrees of the Bobbejaankop-like and the Nebo granite. The Nebo granite shows the least fractionation and the Bobbejaankop-like granite is relatively more fractionation. Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and historical Bobbejaankop granite (H) data from Vonopartis et al. (2020).

The K/Rb ratio has been one of the effective tools in deciphering the evolution of granitic melt and fractionation trends (Dostal and Chatterjee, 2004 and references therein). Conceptually, the fractionation of granitic melt tends to increase the concentration of Rb in the residual melt with concomitant depletion of potassium as it partitions into silicate minerals hence the K/Rb ratio decreases with increasing degree of fractionation (Beus, 1968). The least differentiated granitic magmas tend to have K/Rb ratios of at least 170 (Beus, 1968), whereas the highly differentiated granites often show ratios of less than 150. At times, the lower ratios are not solely attributed to fractionation but also post-magmatic alteration such as in the hydrothermal environment (Shaw, 1968; Dostal et al., 2004). The Nebo granite shows a K/Rb ratio ranging between 231 and 283 whereas the Bobbejaankop-like granite shows a significantly lower ratio, ranging between 69 and 117. The lower Bobbejaankop-like granite K/Rb ratios suggest higher fractionation and evidently, the influence of aqueous fluid (Figure 6.12).

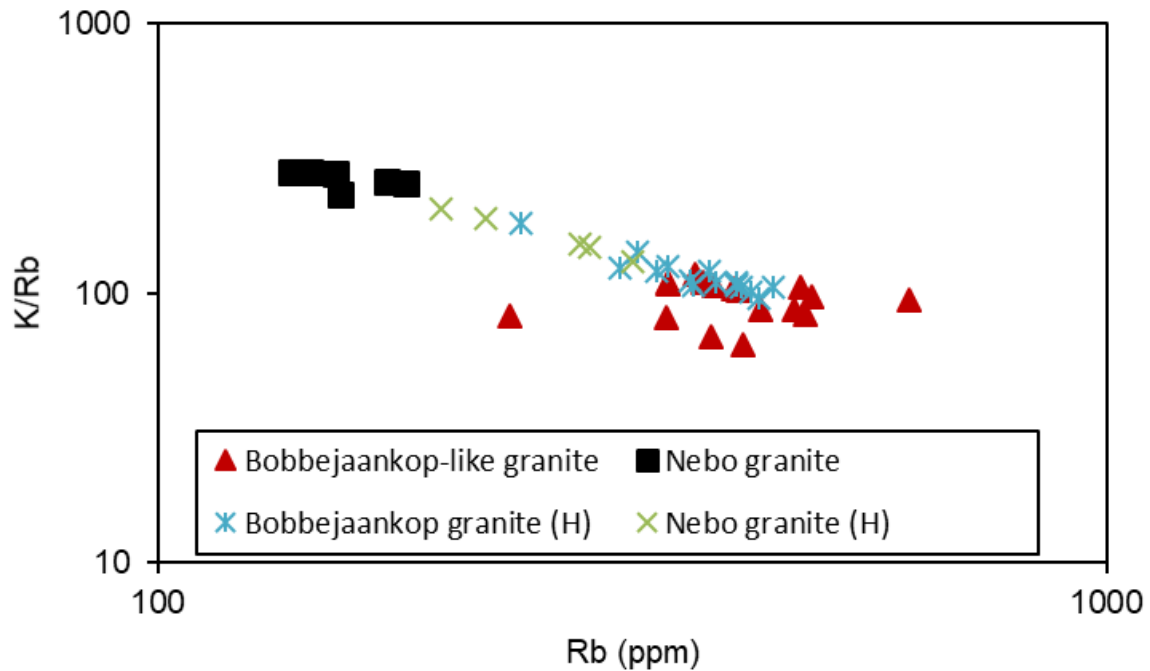


Figure 6.12: Rb (ppm) versus K/Rb plots showing variations of the Nebo granite representing the least differentiated variety and the most differentiated Bobbejaankop-like granite. Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and historical Bobbejaankop granite (H) data from Vonopartis et al. (2020).

Similar to Nb/Ta ratios, Y/Ho and Zr/Hf ratios maintain similar ratios with coherent partitioning behaviour owing primarily to their similar charge and radius and consequently, they retain their chondritic ratios in a geochemical system characterised by CHARGE-and-RADIUS-Controlled (CHARAC) trace element behaviour (Bau, 1996). Bau (1996) defined CHARAC of Y/Ho and Zr/Hf ratios between 23.27 - 25.70 and 32.40 - 40.53 respectively. Any ratios beyond this field imply that the magmatic suites may have been influenced by aqueous interference during fractionation.

The Nebo granites show Y/Ho and Zr/Hf ratios ranging between 23.27 - 25.07 and 32.40 - 40.53 respectively. The Bobbejaankop-like granite on the other hand shows Y/Ho and Zr/Hf ratios between 21.35 - 41.51 and 18.57 - 28.03 respectively. Thus the Nebo granite suite shows a relatively strong CHARAC character implying that these granites are the least altered by hydrothermal processes (Figure 6.10). The Bobbejaankop-like granite shows a non-CHARAC character with almost all samples plotting outside the CHARAC-field implying fractionation influenced and overprinted by late-magmatic fluids.

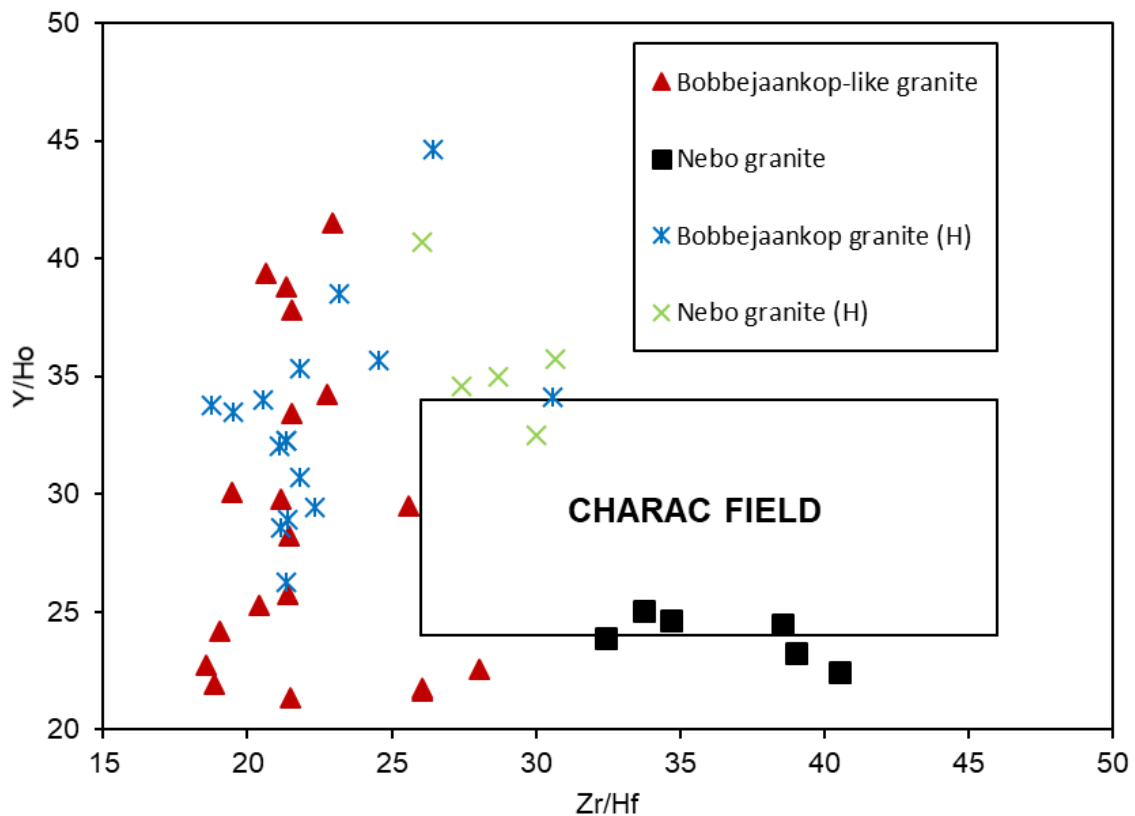


Figure 6.13: Zr/Hf versus Y/Ho diagram of Nebo granite showing CHARAC behaviour and Bobbejaankop-like granite plotting far from the CHARAC-field (After Bau, 1996). Historical published data of Nebo granite (H) was sourced from Kleemann and Twist (1989) and historical Bobbejaankop granite (H) data was sourced from Vonopartis et al. (2020).

The plots of Y versus Ho and Zr versus Hf exhibit distinct linear relationships between the pairs suggesting a coherent igneous suite with little or no hydrothermal fluid influence during fractionation (Bau, 1996) or at least the hydrothermal fluids did not change the ratios of these trace elements. The Nebo granite suite samples including the historical samples, each show a distinct linear trend implying little or no influence of hydrothermal fluids (Figure 6.14). On the contrary, the Bobbejaankop-like samples and the historical Bobbejaankop samples show multiple slopes which may be indicative of hydrothermal influence as observed also in figure 6.13. Further, the different proposed slopes of the Bobbejaankop-like granite may show various facies that the samples represent.

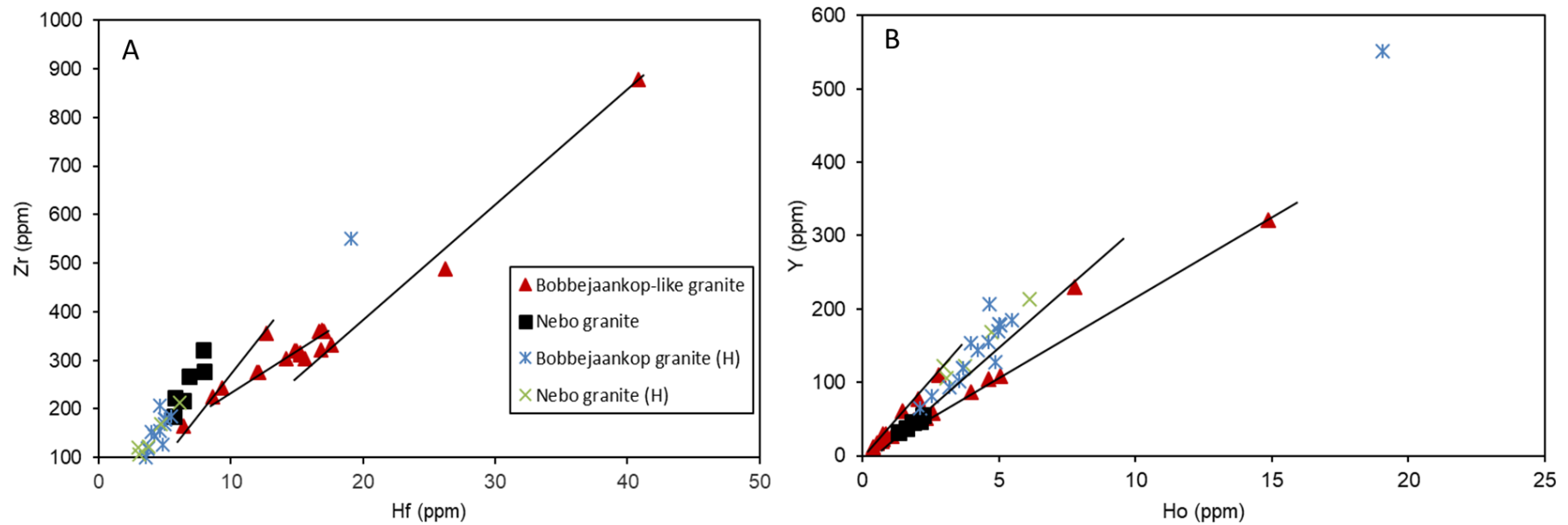


Figure 6.14: Trace elements bivariate plots. A: Hf (ppm) versus Zr (ppm) and B: Ho (ppm) versus Y (ppm) diagrams of Nebo granite and Bobbejaankop-like granite ascertaining their distinct magmatic characteristics. Historical published data of Nebo granite (H) from Kleemann and Twist (1989) and historical Bobbejaankop (H) and Lease (red crosses) granite data from Vonopartis et al. (2020).

The Nebo granite samples show coherent characteristics but do not plot in the same fields as the historical data of Kleemann and Twist (1989). In fractionation discrimination plots, the historical Nebo granite data show continuity from the trends of Nebo granite data from the current study, implying that the difference in plotting fields arises from a variance in fractionation (Figure 6.10 - 6.11).

The majority of Bobbejaankop-like granites plot in the same fields as the historical Bobbejaankop granite sourced from Vonopartis et al. (2020). In instance where some Bobbejaankop-like granite samples did not overlap with the historical data, such samples are interpreted as microgranitic Klipkloof granite and the aplitic Lease granite. However, these samples still show continuous fractionation trends implying that they are of the same origin but evolved slightly different (Figure 6.9 - 6.11) (cf. Kleemann and Twist, 1989). The Y versus Ho and Zr versus Hf plots, show distinct trends of these elements pairs in each Bobbejaankop-like facies. The rare element geochemistry will be employed to ascertain the distinctions of these facies and their degrees of fractionation relative to one another.

6.1.3. Rare earth elements

Rare Earth Elements (REE) and incompatible trace elements in this study were normalised using chondrite and primitive mantle values respectively, after Sun and McDonough (1989). The REE plots and incompatible trace element spider grams of Nebo and Bobbejaankop-like granite are used to try and establish the amount of fractionation and possible cogenesis. The differences in characteristics of microgranite, aplitic granite and medium- to coarse-grained granite within the previously regarded Bobbejaankop-like granite samples are also considered to establish genetic congruency amongst them.

The Nebo granite reflects the general trend of an A-type granite in the REE spider grams (Figure 6.12A) (cf. Hill et al., 1996; Chakhmouradian and Zaitsev, 2012 and references therein). The REE pattern for Nebo granite shows smooth, left-tilted “bird’s wing” enriched in LREE relative to HREE with a negative europium anomaly. The HREE on the other hand possesses relatively flat patterns. The negative europium anomalies $(Eu/Eu^*)_N$ of the Nebo granite samples range between 0.40-0.57. The chondrite-normalised values for Nebo granite are invariable; La_N and Yb_N range between 330.25-538.31 and 17.95-35.09. Sm_N and Gd_N have chondrite-normalised

values between 77.07 and 103.95 and 53.72-68.86. Calculated ratios of $(\text{La}/\text{Sm})_N$ and $(\text{La}/\text{Yb})_N$ range between 4.47-5.17 and 10.14-24.81 respectively.

The Bobbejaankop granite and the associated microgranite and aplitic granite REE patterns are relatively flat in comparison to general A-type granitoid patterns (Figure 6.12B). The corresponding HREE concentrations in the Bobbejaankop granite and associated microgranite and aplitic facies show enrichment relative to the corresponding LREE when compared to the Nebo granite spider grams. The negative europium anomalies (Eu/Eu^*) of Bobbejaankop-like granite are relatively large and variable, ranging between 0.06-0.23 in comparison with the Nebo granite. The La_N and Yb_N chondrite-normalised values for Bobbejaankop-like granite samples are noticeably variable, ranging between 19.73- 961.06 for La_N and 12.61-147.07 for Yb_N . Sm_N and Gd_N range between 4.96-1051.88 and 5.49-658.17 respectively. Bobbejaankop-like granite samples show La/Sm and La/Yb ratios of between 1.14-17.26 and 0.20-34.80 respectively. Gd/Yb values range between 1.59-1.89 and 0.17-7.14 for Nebo and Bobbejaankop granite samples respectively (Appendix A).

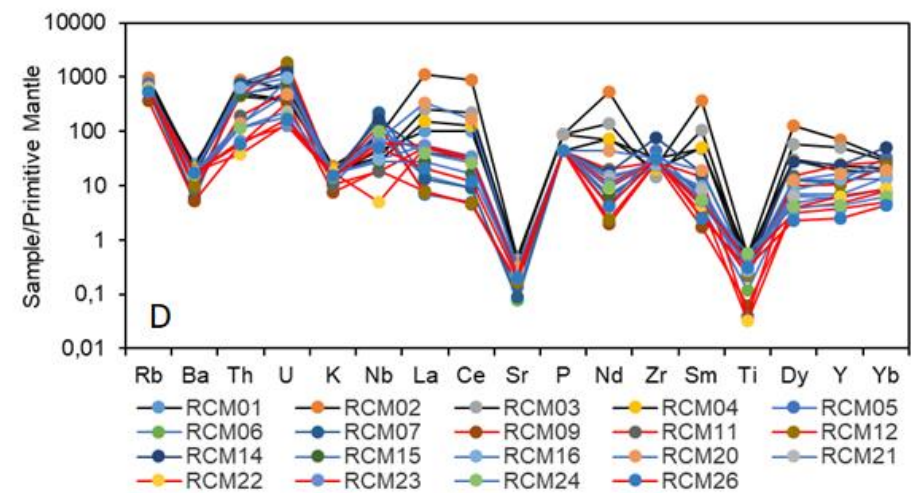
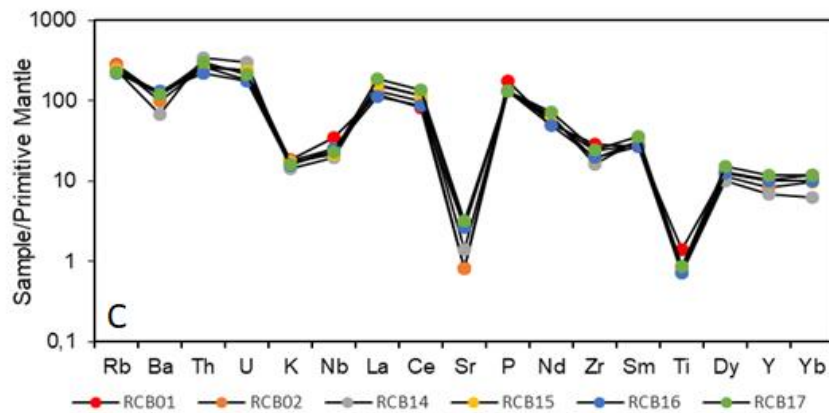
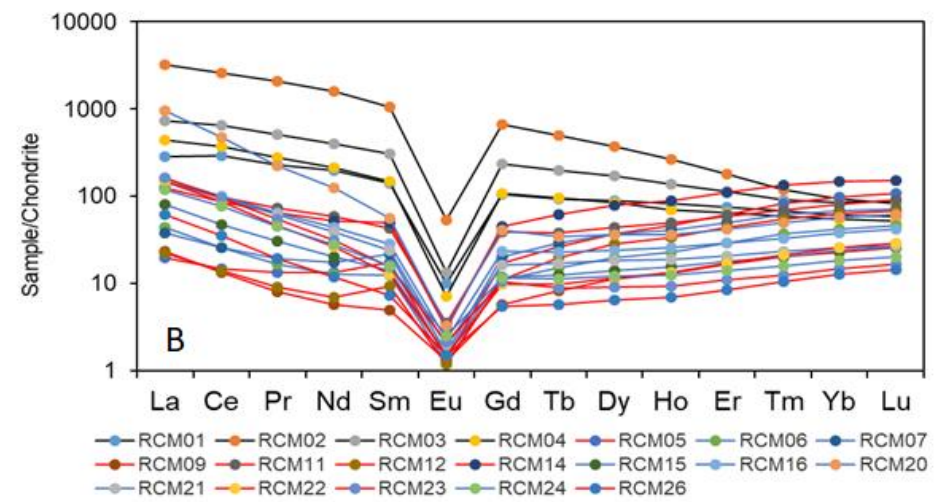
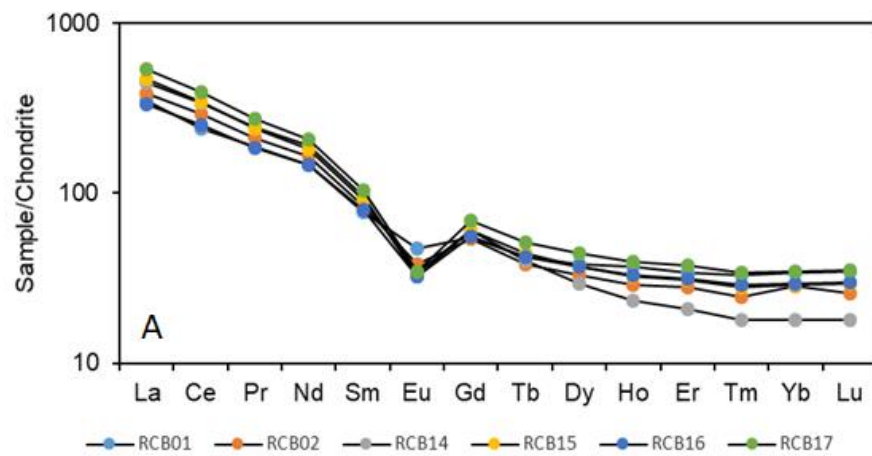


Figure 6.15: Chondrite-normalised REE plots for Nebo Granite (A) and Bobbejaankop-like granite (B) and primitive mantle-normalised spider plots for Nebo Granite (C) and Bobbejaankop Granite (D). Chondrite and primitive mantle values from Sun and McDonough (1989).

In the enriched HREE trends of the Bobbejaankop-like granite, two alignments in the data are observed; (1) one set of samples showing a gradual decrease from Gd to Lu which plots above the second set (black patterns in Figure 6.12B), (2) a second set which shows an increase from Gd to Lu. The second set is further distinguished into two subsets based on the gradients of their HREE increase; subset (2A) shows a relatively steep increase from Gd to Lu (red patterns in Figure 6.14B), while a subset (2B) show a steady increase in the same range of HREE (light blue patterns in Figure 6.14B).

As REE abundances are considered to increase with fractionation then the samples with the higher concentrations of REE are considered more fractionated than samples with lower concentrations (Figure 6.15B). The different REE patterns distinguish three Bobbejaankop-like granite facies; (1) the main Bobbejaankop facies characterised by relatively enriched LREE and corresponding larger Eu/Eu^* observed in RCM 01, RCM02, RCM03, RCM04 and RCM20 (black patterns). (2) Microgranitic Klipkloof granitic facies (2A), characterised by relative steep HREE gradients (RCM 05, RCM 11, RCM 14, RCM 16 and RCM 26) (red patterns). (3) Aplitic Lease granite facies (2B) with relative flat HREE gradients (RCM 06, RCM 07, RCM 16, RCM 20, RCM 21 and RCM 21) (light blue patterns). These differences in REE patterns help to validate the different granite facies observed in Chapter 5.

The Nebo granite samples possess congruent trace element spider gram patterns that are almost superimposed on one another (Figure 6.12C) and show notably low Sr, Ti, K, and Nb. Trace element patterns of the Bobbejaankop granite show much greater variation in U, Nb, La, Nd, Sm and Y although still show low Sr, Ti, K, and Nb concentrations. Both the Nebo and Bobbejaankop granites show trace element patterns similar to upper continental crust source patterns (Rollison, 1996).

The $(La/Yb)_N$, $(La/Sm)_N$ and $(Gd/Yb)_N$ ratios evaluate the degree of fractionation between REE and HREE. The $(La/Yb)_N$ ratios can also be studied to evaluate fractionation degrees in different granitic suites (Mikkola et al., 2010; Yusoff et al., 2013). Additionally, these ratios may give an indication of post-emplacement hydrothermal activities and/or assist in deciphering the petrogenetic sources. $(La/Yb)_N$, $(La/Sm)_N$ and $(Gd/Yb)_N$ in Nebo granite suggest LREE enrichment relative to HREE (Figure 6.14); conversely, Bobbejaankop-like granite samples show enrichment in HREE relative to LREE. Generally, Bobbejaankop-like granite samples show a higher

$(\text{La}/\text{Yb})_N$ average than Nebo element affirming that Bobbejaankop granite possesses higher degrees of fractionation as concluded from Rb/Sr, TEDI and K/Rb ratios. Furthermore, the $(\text{La}/\text{Yb})_N$ ratio distinguishes the main Bobbejaankop granite from the associated microgranite and aplitic facies. However, all these facies show similar La (ppm) versus La/Yb evolution suggesting they originate from partial melting of upper continental crust and underwent varying degrees of fractionation and evolution rather than in-situ fractionation (Figure 6.13) (cf. Janoušek et al., 2015 and references therein).

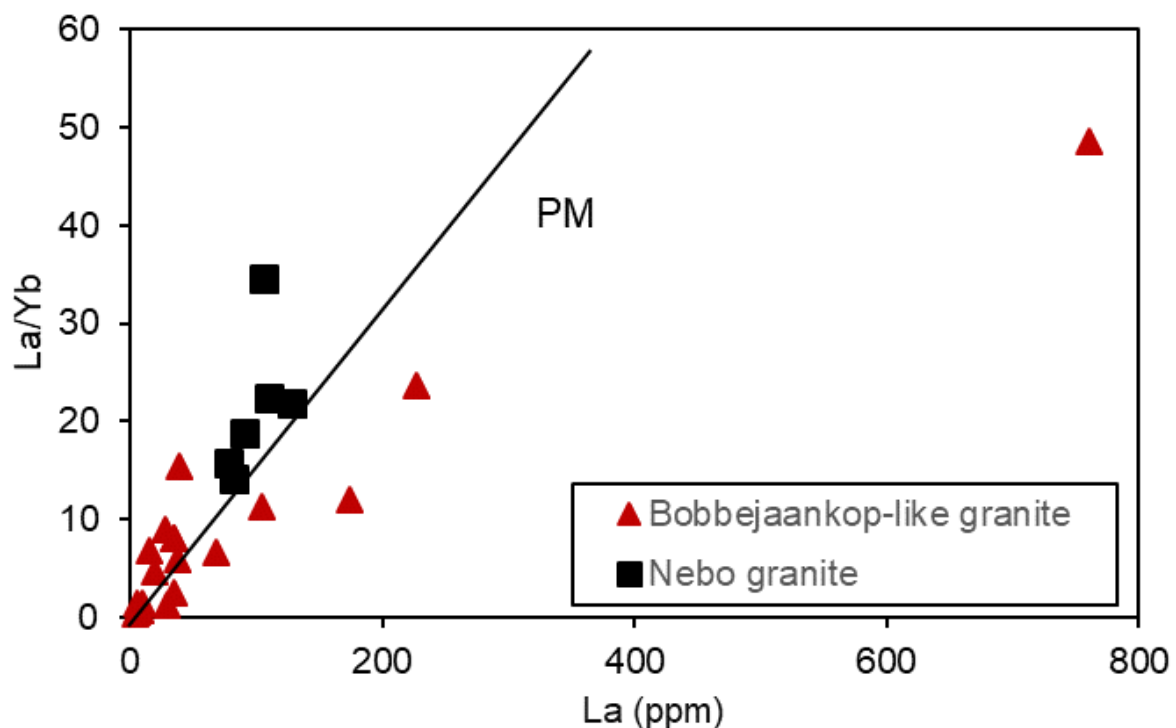


Figure 6.16: La (ppm) versus La/Yb diagram of Nebo and Bobbejaankop-like granite suggesting co-genesis from similar parental magma. PM represent partial melting trend.

6.2. Veins, pegmatites and mineralised zones

6.2.1. Major elements

Pervasive chemical alteration such as sericitization and chloritization characterise the altered contacts between the Nebo granite and the veins. The veins comprise mainly calcite, siderite, iron oxides and hydroxides and quartz. Samples RCB03, RCB04, RCB05, RCB06, RCB07, RCB08, RCB09, RCB10, RCB11, RCB12 and RCB13 represent these mineralised veins in the Nebo granite drill core (Appendix A). The geochemical data from these samples contains high concentrations of CaO (ranging between 0.09 - 26.20 wt. %) and FeO^{T} (1.40 - 52.82 wt. %) accompanied by relatively low SiO_2 contents relative to the granites (Figure 6.17).

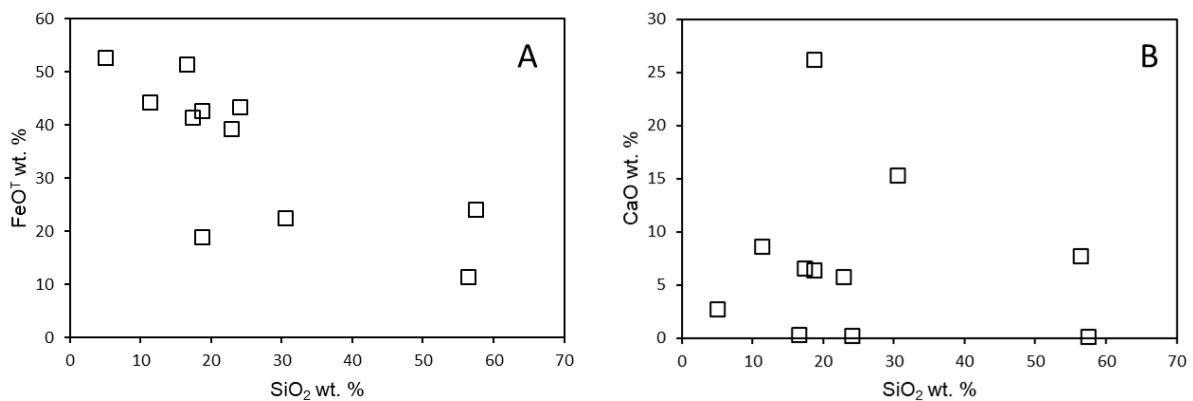


Figure 6.17: Major oxide element Harker plots of samples from mineralised zones from BHDD 003 drill core. A: SiO_2 versus FeO^{T} plot showing the elevated concentration of total FeO. B: SiO_2 wt. % versus CaO wt. % plot showing high concentration of CaO.

The mineralised pegmatites samples associated within Bobbejaankop-like granites show elevated concentration of CaO (ranging between 1.54 - 17.95 wt. %) and FeO^{T} (1.40 - 18.02 wt. %) with respect to low SiO_2 contents shown in granites (Figure 6.18). Samples RCM13, RCM17, RCM18, RCM19 and RCM25 represent transition zones to pegmatite zones of the Bobbejaankop-like granite (Appendix A).

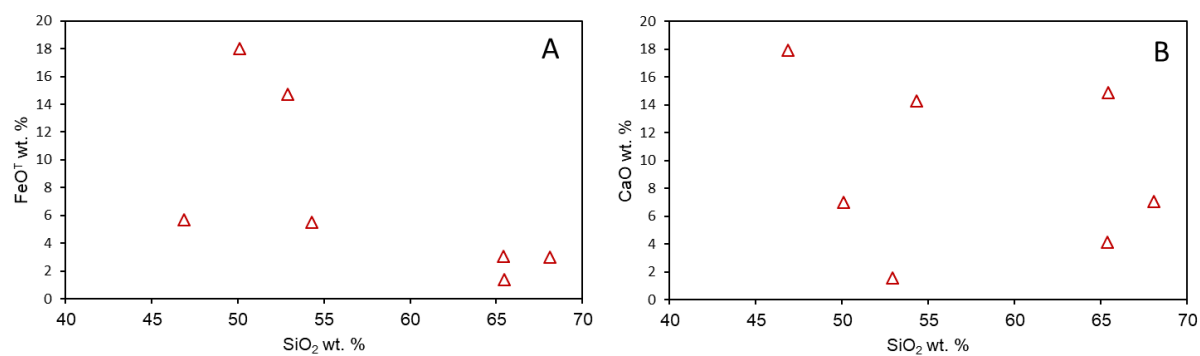


Figure 6.18: Harker plots of pegmatite zones samples from 648 KS/1 drill. A: SiO₂ versus FeO⁺ plot showing elevated concentration of total FeO. B: SiO₂ wt. % versus CaO wt. % plot showing high concentration of CaO.

6.2.2. Incompatible trace elements and rare earth elements

Generally, the trace element geochemistry of the vein samples within the Nebo granite show huge variations (Appendix A). The highest variations occur in Ba, Th, U, Sr, Sc, Nd and Y trace elements. Incompatible trace elements such as Rb (up to 120 ppm), Ce (208 ppm), P (up to 85 ppm) and Sr (up to 112 ppm) are moderately enriched relative to the base metals in some samples. Ba (9.63 – 355.67 ppm, averaging 59), Ti (6.74 – 816 ppm, averaging 176 ppm), Zr (1 – 164 ppm, averaging 29 ppm), Nb (0.11 – 12 ppm, averaging 2), U (0.01 – 3 ppm, averaging 1) and Th (0.02 – 14 ppm, averaging 2) show depleted concentrations. Similarly to the Nebo granite, the veins samples are depleted in Cr, Ni and V. Largely, the trace elements in the veins samples show different signatures when compared to the Nebo granite samples.

Trace element geochemistry of pegmatite samples in the Bobbejaankop-like granite show variations in Ti, Nb, Nd and Y. Rb (305 – 655 ppm, averaging 407 ppm), U (7 – 47 ppm, averaging 21 ppm), Nd (46 – 2720 ppm, averaging 1033 ppm) and Th (3 – 83, averaging 46) show enriched concentrations. Conversely, Ba (26 – 194 ppm, averaging 96 ppm), Sr (6 – 32 ppm, averaging 15 ppm) and Zr (143 – 300 ppm, averaging 221 ppm) are depleted in the pegmatite samples. Pegmatite samples are also depleted in Cr, Ni and V contents similarly to the Bobbejaankop-like granite. The concentration of trace elements are comparable to the Bobbejaankop-like granite samples in most instances.

Base metals such as Cu (72 – 13648 ppm, averaging 4362 ppm), Zn (27 – 8805 ppm, averaging 3868 ppm), Pb (8 – 336 ppm, averaging 139 ppm) and transitional metals Co (12 – 1041 ppm, 253 ppm) and Ni (3 – 1041 ppm, averaging 53 ppm) show enriched concentrations within the Nebo granite veins. The Cu, Zn and Pb concentrations in a ternary diagram plot mainly in a Cu and Zn boundary but clusters mainly towards the Cu apex (Figure 6.19). This implies dominance of Cu amongst the three base metals and consequently it was selected as a proxy to establish the base metals relationships with incompatible trace elements. However, the Cu metal as a proxy show indiscriminate correlations with incompatible trace element such as Ba including TEDI, Rb/Nb and Y/Nb ratios (Figure 6.20).

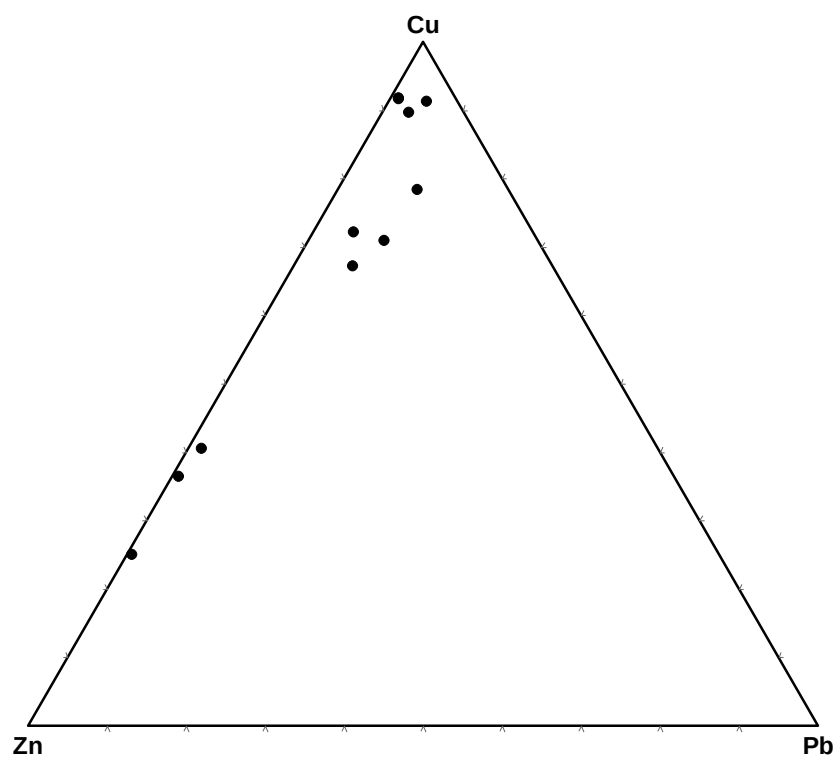


Figure 6.19: Ternary diagram of normalised Cu, Zn and Pb base metals depicting the concentration dominance of the former in the veins samples.

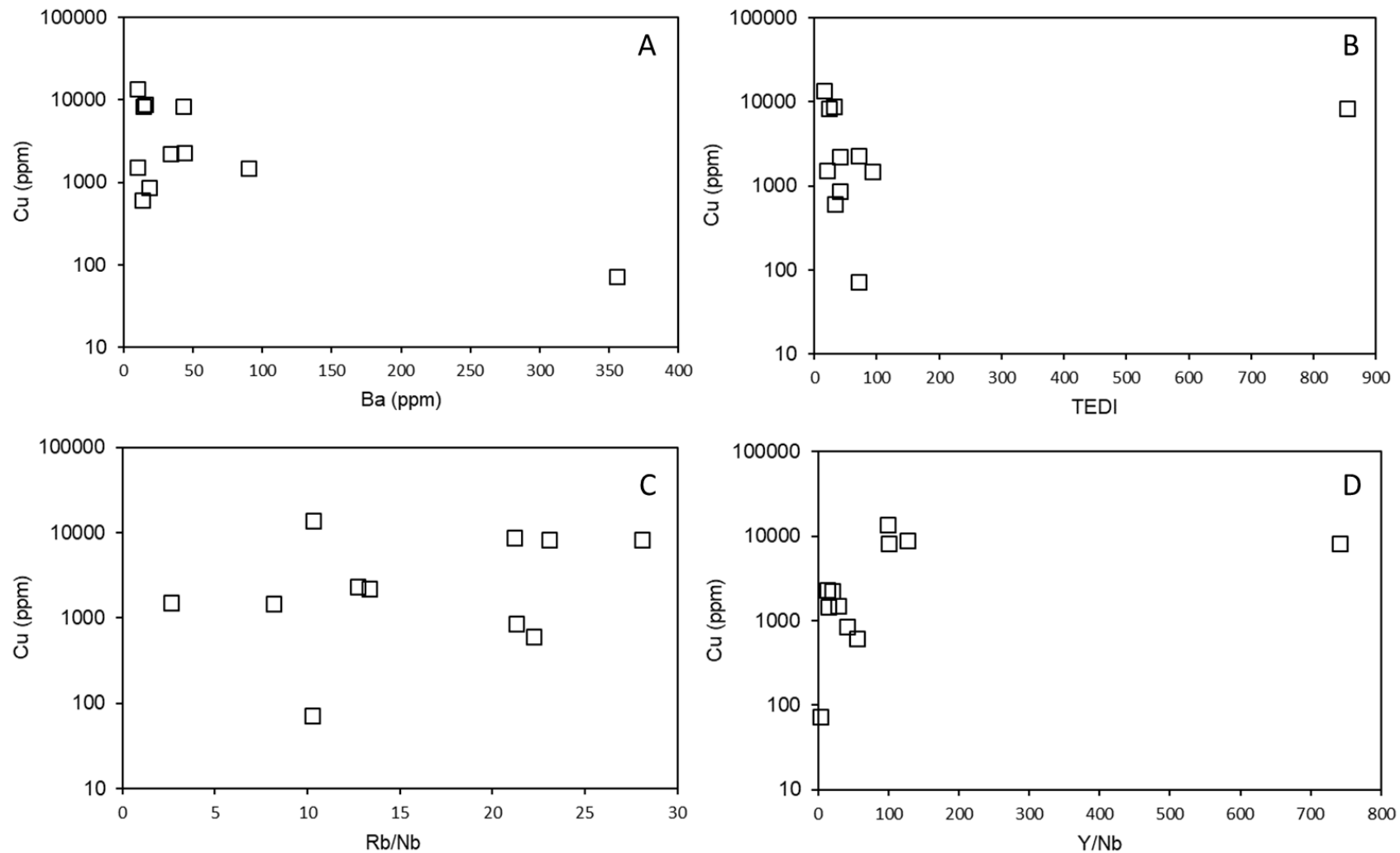


Figure 6.20: A-D: Various trace elements vs Cu (ppm) of veins samples within the Nebo granite showing little correlation between elements.

Sn (12 – 112 ppm, averaging 58 ppm) and W (1 - 15 ppm, averaging 13 ppm) show moderately enriched concentrations relative to their crustal abundances in the pegmatite samples. The concentration of these metals are however comparable to the Bobbejaankop-like granite samples (Appendix A). The trends of Sn (ppm) and W (ppm) versus Ti (ppm) resemble magmatic tin mineralization compared to some granite suites studied by Lehmann (2020) (Figure 6.21A and B). Ti (ppm) versus Ta (ppm) and Sn (ppm) versus Rb/Sr Harker plots suggests that these pegmatite samples represent a fertile environment for magmatic-hydrothermal tin mineralization as similarly studied by Lehmann (2020) (Figure 6.21C and D).

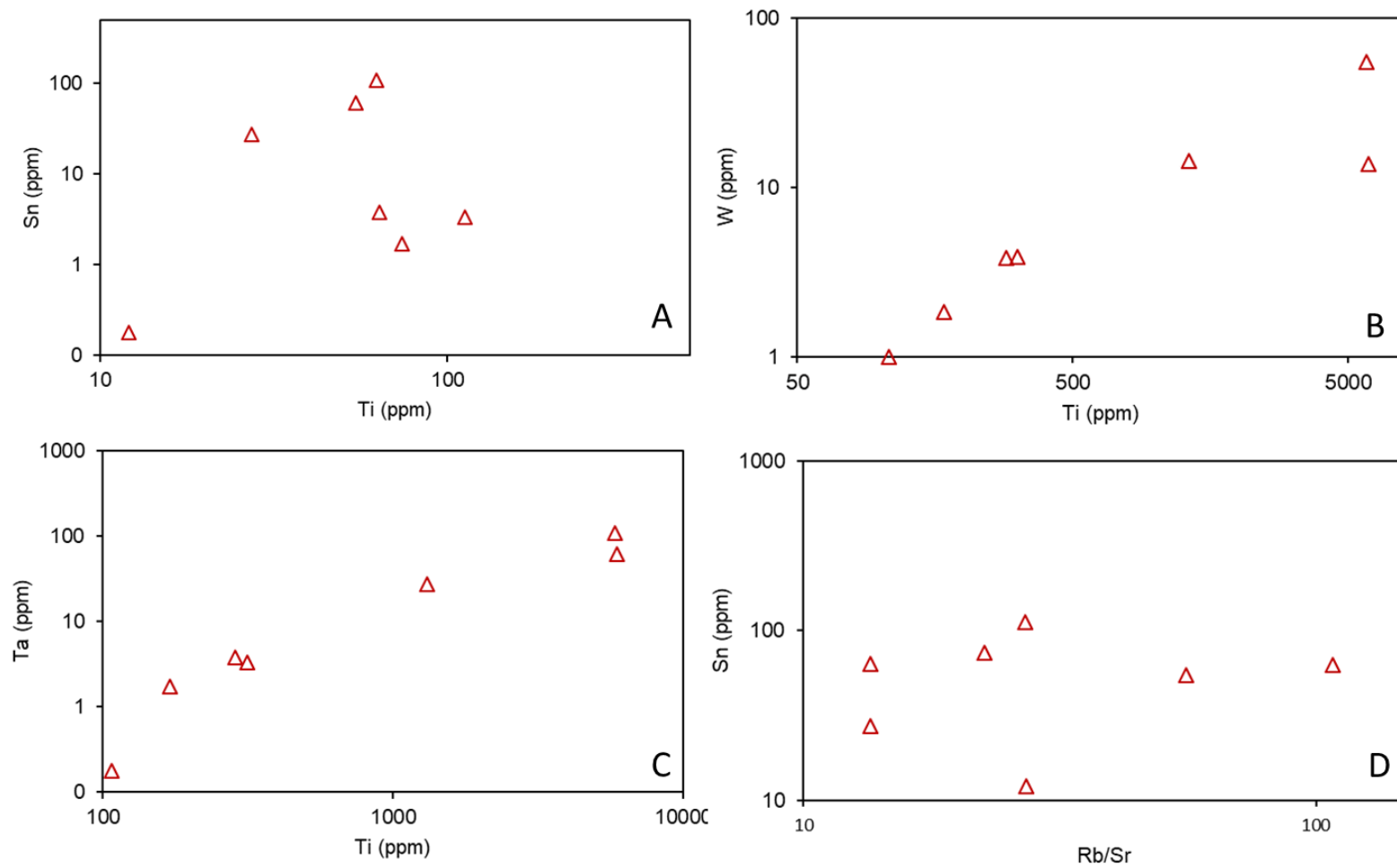


Figure 6.21: Binary plots of pegmatite samples in Bobbejaankop-like granite resembling the magmatic tin mineralization related to Pilok granite suite, Thailand (Lehmann, 2020). A: Ti (ppm) versus Sn (ppm). B: Ti (ppm) versus W (ppm). C: Ti (ppm) versus Ta (ppm) showing linear relationship. D: Rb/Sr versus Sn (ppm) showing the indiscriminate correlations.

The mineralised veins within the Nebo granite show Nb/Ta ratios between 2.84 and 21.83 (averaging 10.66). The pegmatite and mineralised zones of the Bobbejaankop-like granite on the other hand have ratios between 7.55 and 11.70 (averaging 9.44), excluding sample RCM 10 that shows uncharacteristic peraluminous granite with Nb/Ta ratios of 37.80, that is beyond the range described by Ballouard et al. (2020). These ratios are similar to the granites as described in 6.1.2. In fractionated peraluminous granites, Nb versus Nb/Ta with ratios less than five may show a transition from magmatic to a magmatic-hydrothermal system (Ballouard et al., 2016; Figure 6.22C and D).

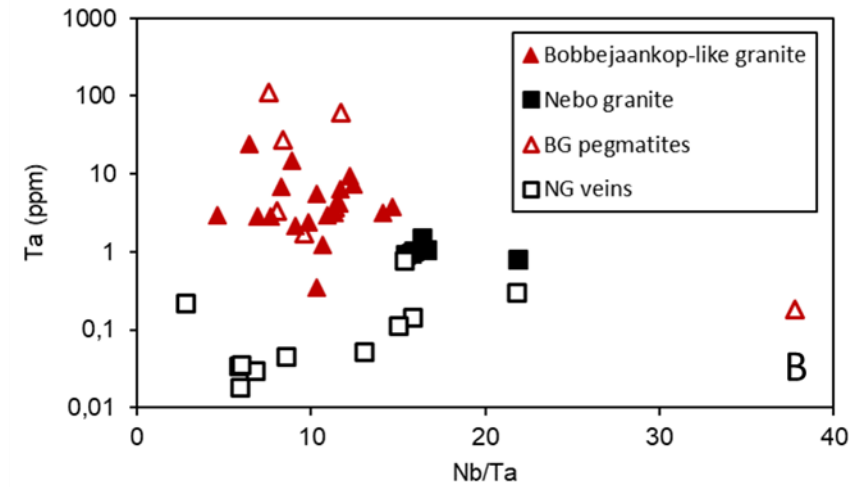
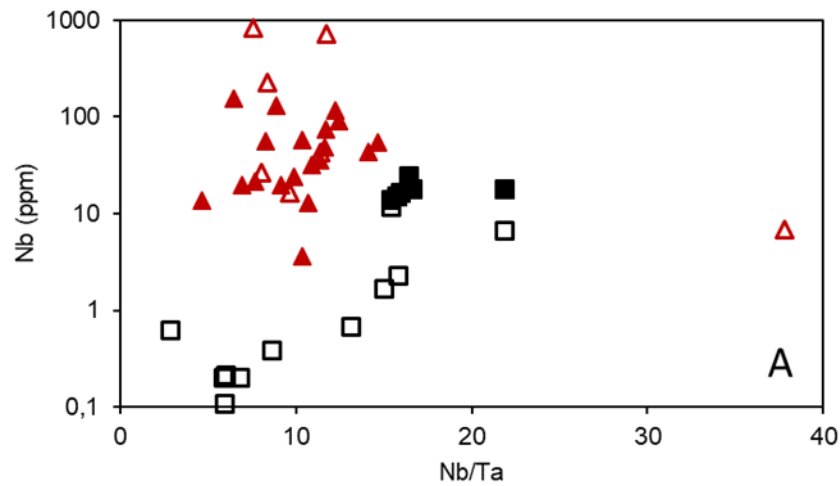


Figure 6.22: Nb/Ta differentiation variations of Nebo granite, Bobbejaankop-like granite, Nebo hosted veins (NG veins) and Bobbejaankop-like hosted pegmatites (BG pegmatites). A: Nb/Ta versus Nb (ppm) and B: Nb/Ta versus Ta (ppm) graphs of Nebo and Bobbejaankop granite discerning their cogenesis with each other and their respective veins and pegmatites.

The trace element geochemistry of samples from the mineralized zones in both drill cores show varied geochemical characters. To establish their geochemical character and their relationships to the granites and subsequently discern possible late/post-magmatic overprint on these vein and pegmatite samples; Sun and McDonough (1989) primitive mantle and chondrite values were used to normalise and study the incompatible trace elements and rare earth elements (REE) respectively.

Primitive-mantle normalised patterns of veins of Nebo granite show contrasting patterns in Th, U, Nd and Zr trace elements. Similar patterns are shown by Rb, Ba, Sr and Zr but with huge variations in normalised concentrations (Figure 6.23A). The primitive mantle normalised pegmatite samples are incongruent with variations in La, Nd and Sm trace elements. Rb, Ba, Sr and Ti trace elements show congruency (Figure 6.23B).

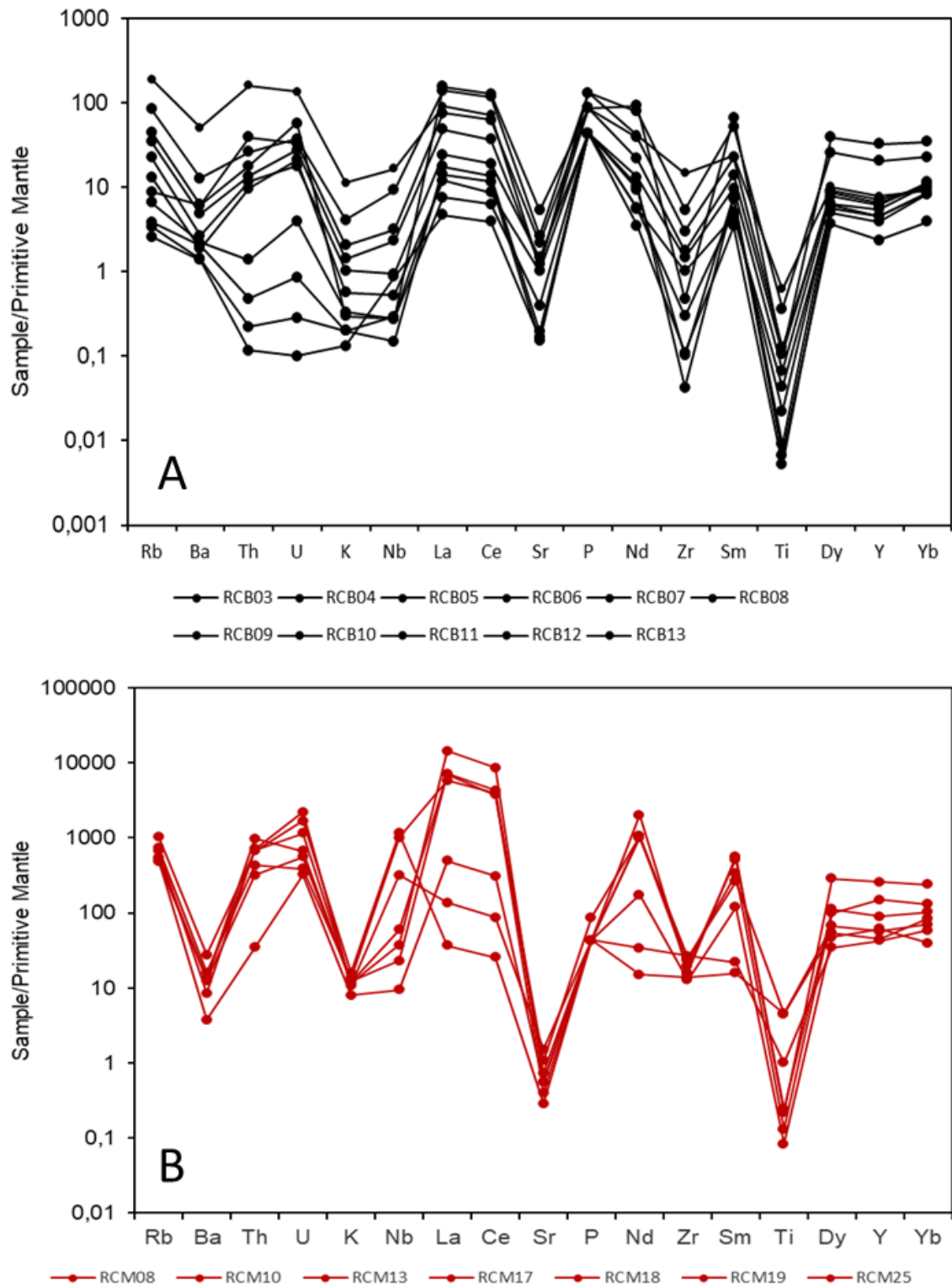


Figure 6.23: Primitive mantle normalised trace elements spider diagrams. A: Nebo granite veins samples showing stacking patterns with variations in some trace elements. B: Variations in trace elements of pegmatite samples.

Generally, the veins of the Nebo granite show enriched LREE relative to HREE with slightly positive and negative europium anomalies compared to the Nebo granite (Figure 6.24). The contact zones represented by samples RCB07 and RCB12 show slightly negative and positive europium anomalies respectively. Summarily, these veins show three characteristics; a set of samples with enriched LREE and positive europium anomalies (such as RCB07, RCB08 and RCB09), a second set which shows enriched LREE with a slightly negative europium anomaly (RCB10, RCB11 and RCB12) and the last set shows enriched HREE with a positive anomaly (RCB03 and RCB04). RCB06 shows enriched LREE without a europium anomaly and RCB13 shows enriched HREE with a slightly negative europium anomaly.

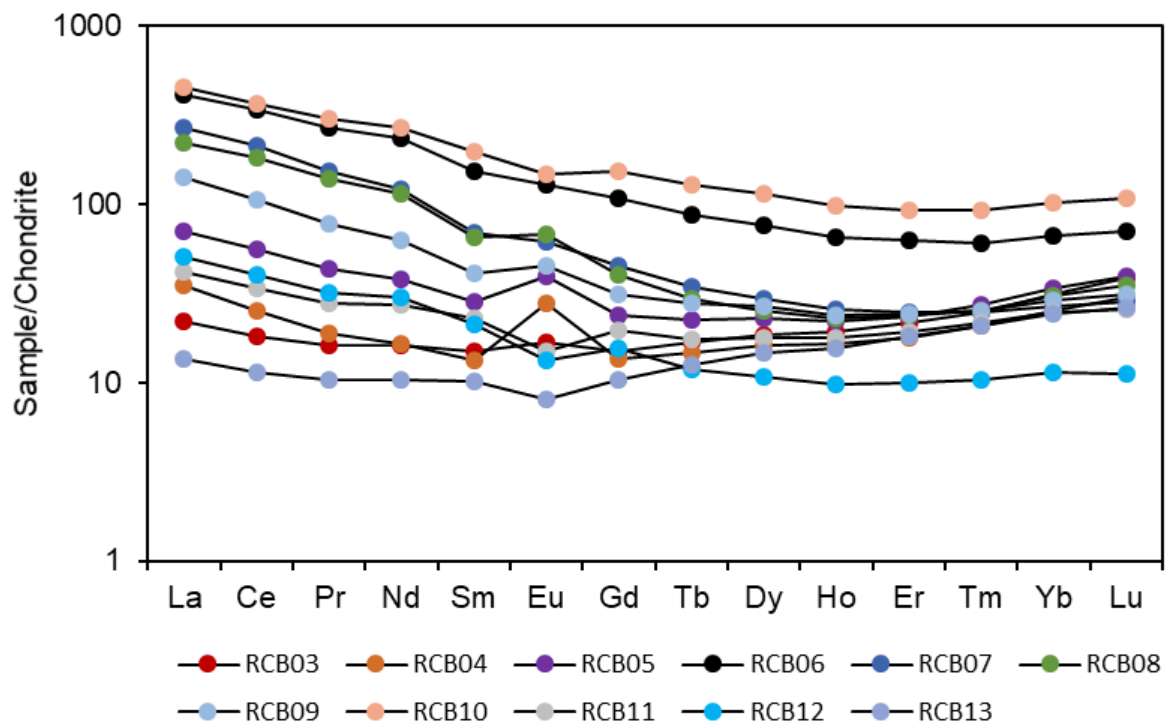


Figure 6.24: Chondrite-normalised REE of samples from the alteration zones of Nebo granite. Chondrite data attained from Sun and McDonough (1989).

The REE and trace element patterns representing pegmatite zones show a congruent nature similar to the Bobbejaankop-like granite but with relatively larger negative europium anomalies (Figure 6.25). These pegmatite samples show two

characteristics; one set with enriched LREE relative to the HREE (RCM10, RCM17, RCM18, RCM19 and RCM25) and the HREE wings (Gd to Lu) of these samples are correlated to the first set (set 1) of the granite zones. This set, as in the granites occurs above the second set. The second set shows an increase in HREE (RCM08, RCM09, RCM11 and RCM12). This set is correlated to both subsets (2A and 2B) of the set two in the granite zones. The LREE enriched set-one represents the fractionated porphyritic sections of the Bobbejaankop granite as described in Bobbejaankop-like granite samples. On the other hand, the second set with enriched HREE represents the porphyritic microgranite and aplitic facies. The pegmatite zones show similar fractionation trends observed in the Bobbejaankop-like granite samples.

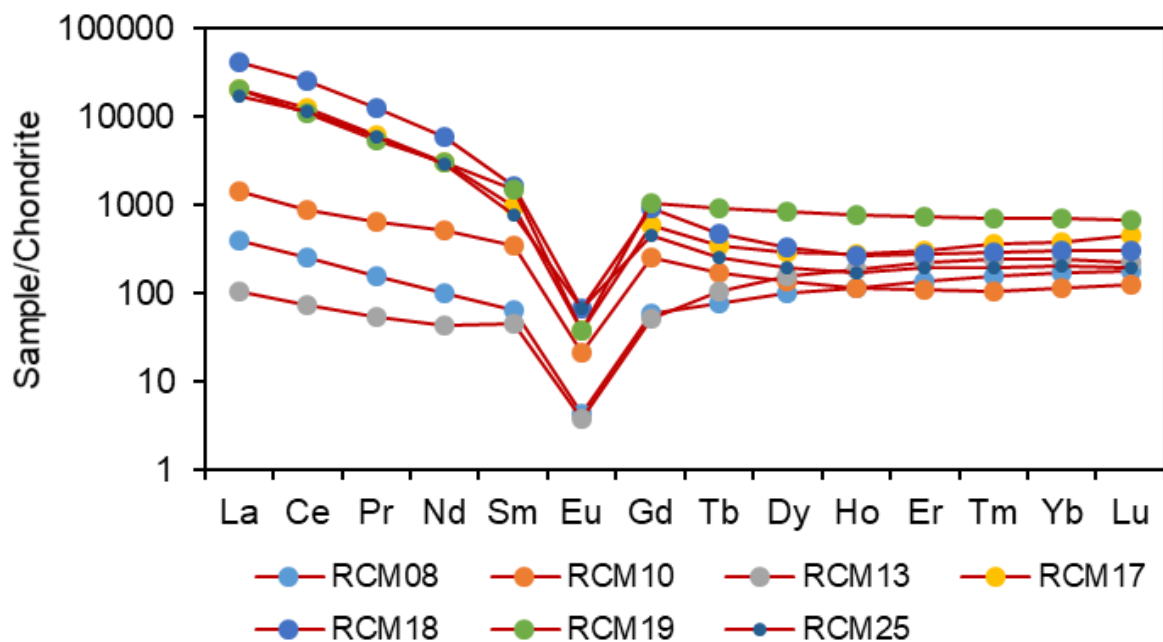


Figure 6.25: Chondrite-normalised REE of samples from the pegmatite zones of Bobbejaankop-like granite. Chondrite data attained from Sun and McDonough (1989).

Chapter 7: Discussion

7.1. Geophysics and Remote Sensing

The airborne magnetic data was employed to map out two aspects in the survey area; (1) the differences in magnetic intensities of the sedimentary rocks of the Marble Hall Dome and the Stavoren Fragment with the magmatic rocks of the LGS and (2) the structures truncating these lithologies. These lithologies have similar magnetic character and consequently they are not clearly distinguished. The magnetic data however successfully delineated possible dykes intruding the Marble Hall Dome as also interpreted by Babayeju (1999) (Figure 3.1). The vertical derivative transformation best delineates two sets of lineaments in the survey area; one set trending west-northwest and the other set trending northeast. The first set truncates the Transvaal inliers, the LGS rocks and the younger Karoo Supergroup to the northeast of the Stavoren Fragment (Figure 3.3). The first set also crosscuts and create offsets of the northeast and southwest trending sets. This observation suggests that the first set is younger than the second northeast trending lineaments. Furthermore, since the first set truncates the Karoo Supergroup rocks, it implies that their age postdates the Karoo Supergroup rocks and is not related to reactivation of the Wonderkop Fault that coincided with Bushveld magmatism.

The magnetic data was unable to directly delineate the Wonderkop Fault (Figure 3.1 – Figure 3.2). However, the Wonderkop Fault offsets the first set of lineaments trending west-northwest. The nature of the offsets suggests left-lateral strike-slip of the Wonderkop Fault (Figure 3.3) and implies that the last reactivation period of the Wonderkop Fault postdated the emplacement of the Karoo Supergroup.

The relatively local scale Boschhoek Structure was also not mapped by the magnetic data owing probably, to its small size in relation to the survey specifications (tie line spacing and flight line spacing are too far apart). However, the Boschhoek Structure's northeast trend is coincident with both the second set of lineaments and the Wonderkop Fault as described above. It can be conjectured that the Boschhoek Structure also postdates the west-northwest lineaments.

The Gamma-ray radiometric data was employed to delineate possible alteration haloes indicative of mineralization in the survey area. Total count imagery from K, eTh and eU and the ternary composite image of these three channels distinguished the sedimentary rocks from the igneous suite (Figure 3.5; Figure 3.9). In areas where the three channels are highest, the ternary composite image returned a white colour as radioelements are concentrated in felsic rocks of igneous suite (eg. Galbraith and Saunders, 1983; Figure 3.9).

Haematitic and phyllic alterations characterise mineralised areas in the Boschhoek and Mutue Fides areas (Chapter 5). Higher ratios of eTh/K highlight these alterations (Figure 3.10). The study areas however show very low ratios of eTh/K possibly due to the sizes of the mineralised bodies in relations to the survey specifications. In addition, exploration in the late 1940s around the Mutue Fides area (Figure 3.10, area 2) dug out all veins and destroyed any surficial features required for radiometric data acquisition.

Similar attempts by Landsat 7 and SENTINEL 2 to delineate surficial alteration haloes indicative of mineralization using band combinations did not yield desired results (Figure 3.14; Figure 3.16). Vegetation cover, unconsolidated quaternary sand and the localised nature of the alterations hindered the ability of remote sensing to characterise these alterations.

7.2. Structural regime

Several factors suggest similarities between the Wonderkop Fault and the relatively local scale structures observed at Boschhoek and the Mutue Fides - Stavoren tin field. These factors include similarities in morphologies of the structures, the characteristics of the veins and the conjectured similarity in time-period of the Wonderkop Fault reactivation in relation to the timing of polymetallic mineralization. The Wonderkop Fault preceded these local scale structures and it was active for long period (Hartzer, 1995); consequently, it may have created weakness planes from which the faults and veins emanated.

(1) The splay morphologies characterise the Wonderkop Fault (4.1). These steeply dipping large-scale structures generally strike northeast-southwest and are often interfered by perpendicular structures of a later event(s). Relatively small-scale structures in the Boschhoek Structure, veins in Mutue Fides - Stavoren and Mutue Fides tin field mimic the morphologies of the Wonderkop Fault and further, they plunge and trend in the same direction. It is thus inferred that the Wonderkop Fault reactivation syn-BIC created planes of weakness that hydrothermal fluid passed through to create veins.

(2) The Wonderkop Fault infill comprises brecciated quartzite, gossans and tinted quartz in addition to the quartz veins found in extension fractures with various morphologies. The latter quartz veins are often coarse-grained, euhedral and accompanied by imprints of iron-rich gossanous fluid (Figure 4.11). The gossan veins and iron-rich fluid imprint were also observed in the Mutue Fides - Stavoren and the surrounding areas although, they are not as well pronounced as in the Wonderkop Fault. These gossanous veins characterise the Boschhoek Prospect area. The similarities in the gossanous and iron-rich fluid imprint in the quartz veins suggest association amongst these geological structures as this phenomenon is attributed to one hydrothermal event responsible for this hydrothermal signature affected fractures of syn- and post- Bushveld period (Freeman 1998; Gleason et al. 2014).

7.3. Alteration types

At the Boschhoek Prospect, numerous alteration assemblages have been recognised. Sericite alteration characterises the Boschhoek Prospect, less predominant alteration types include chloritization and silicification (Smits 1980; Evans 2015; this study, Chapter 5). These alteration types are represented in various wall-rock alteration zones resembling porphyry ore deposits model by Lowell and Guilbert (1970) and Smits (1980) (Figure 7.1).

The oxidized and the supergene zones are characterised by highly oxidized ferruginous gossans, siderite-calcite-quartz-pyrite veins and various alteration assemblages. The gossans comprise hematite, goethite (evidence of hydration) and

cuprite that formed hypothetically from the following chemical reactions (1 and 2) in low-saline brines on the subsurface of the fractures.

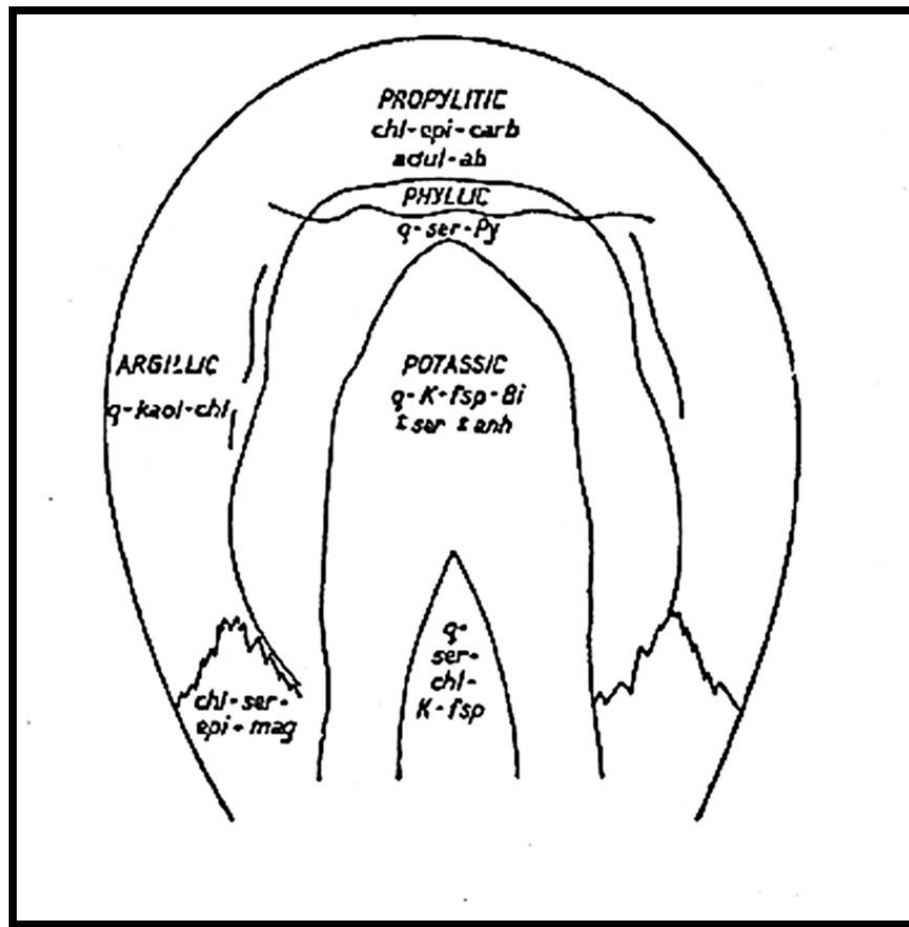
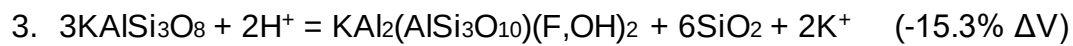


Figure 7.1. Alteration types zoning in porphyry ore model (modified after Lowell and Guilbert, 1970).

1. $\alpha\text{-FeOOH} + \text{H}^+ = \alpha\text{-Fe}_2\text{O}_3 + \text{H}_2\text{O}$
 Goethite Hematite
2. $\text{FeS}_2 + 15/4\text{O}_2 + 7/2\text{H}_2\text{O} = \text{Fe}(\text{OH})_3 + 2\text{SO}_4^{2-} + 4\text{H}^+$
 Pyrite Goethite

Pervasive sericite alteration characterises the oxidized and the hypogene zone of the Boschhoek Prospect. In this phyllic alteration zone adjacent to the vein-wall; sericite, zoned chlorite and muscovite have completely replaced the primary granite minerals such as feldspars and biotite (3, 4 and 5). The zoned chloritization is restricted to mineralised boundaries roughly within two metres of the vein peripheries. Although

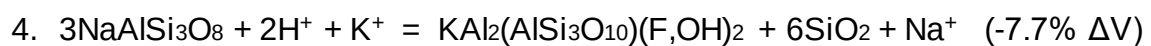
sericitization is pervasive but it is limited to five meters away from the veins. Silicic or epidote alteration usually accompanied the sericitization and are defined within the limits of the latter. The epidote alteration is prevalent throughout the mineralized zones. K-metasomatism extend to a broader scale (< 100 m) and albitization alteration spreads to regional scale and is much better delineated by remote sensing techniques (Figure 3.6)



K-feldspar

Muscovite

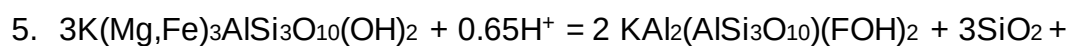
Quartz



Albite

Muscovite

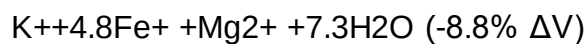
Quartz



Biotite

Muscovite

Quartz



Wagner (1921) and this study noted various alteration assemblages in the Stavoren-Mutue Fides Tin Field. Tin and associated polymetallic mineralization hosted in Bobbejaankop-like granite are distinguished by stanniferous greisen and sericite alteration. The stanniferous greisenisation is restricted to mineralised veins and/or ore pockets. Prior to the formation of ore-pockets, an acidic hydrothermal fluid front facilitated alteration reactions that improved porosity and permeability of the apical granite rocks and subsequently resulted in rock volume loss and density change (Launay et al., 2019). These alteration reactions entail modification of feldspars and biotite to form a muscovite (sericite) quartz assemblage (reactions 3, 4 and 5) which is characteristic of greisenisation. The resulting volume change (ΔV) created vugs that subsequently acted as physiochemical traps for Sn-W-Mo mineralization and later silicification.

Sericitization is well pronounced in conjunction with greisenisation but extends further away from the boundaries of the greisen. Similarly to greisen alteration, sericite formed

through feldspar replacement. Patches of pyrite formed at the expense of feldspar minerals and quartz in addition to sericite. In some cases, pyrite also replaces feldspars that escaped greisenisation and sericitization.

7.4. Geochemistry: cogenesis, fractionation and post magmatic processes

The Nebo and the Bobbejaankop-like granites show similarities in terms of major element geochemistry. Major element geochemistry affirmed their ferroan alkali-type nature and in addition the Shand Index categorised them as peraluminous A-type granites. These granites possess low abundances of P_2O_5 (less than 0.04 wt. %), a significant character of fractionated A-type granites according to Kleemann and Twist (1989). This geochemical character provided the basis to investigate their contemporaneous genetic and fractionation evolution(s).

The Bobbejaankop-like granites possess a wider range of silica content compared to the Nebo granite. This phenomenon suggests that the Bobbejaankop-like granite may be possibly more fractionated but also may have evolved from a more primitive parental magma source since some samples possess relatively less silica than lowest silica-bearing Nebo granite samples.

Both Nebo and Bobbejaankop-like granites plot in the sub-alkaline field in the alkalinity discrimination diagram after Irvine and Baragar (1971) (Figure 6.5). The Nebo granite plots mainly within the calc-alkalic field and the Bobbejaankop-like granite extends from calcic to calc-alkalic field in the MALI diagram after Frost et al. (2001) (Figure 6.5). The wider spread in the Bobbejaankop-like granite implies variable compositions of the feldspar bearing oxides (i.e. K_2O , Na_2O and CaO) and may also imply variable fractionation within the samples (cf. Frost and Frost, 2008).

The trace element geochemistry data of both the Nebo and the Bobbejaankop-like granites in the Eby (1992) discrimination diagram show an overlap between the A1-type and A2-type anorogenic granite fields (Figure 6.8.) It is likely that these suites show an average continental geochemical signature and formed through partial melting of continental crust as asserted by Hill et al. (1996). This is also evident in the La (pp) versus La/Yb diagram which supports a partial melting of continental crustal

as opposed to in- situ fractionation of relatively basaltic composition (Figure 6.16). There are however, features of fractional crystallisation in the geochemical signature of these suites which have been modelled by trace element geochemistry.

Trace element geochemistry distinguished petrogenetic evolution differences between the Nebo granite and Bobbejaankop-like granites. Elemental ratios such as K/Rb, Sr/Rb, Nb/Ta and TEDI discriminants show that Bobbejaankop-like granites are more fractionated than the Nebo granite (Figure 6.9 – 6.12). The Bobbejaankop granite and the associated microgranite and aplitic facies show coherent and somewhat progressive trace-element trends. Furthermore, K/Rb ratios in apical portions close to the pegmatite zone in the Bobbejaankop-like granites are below 150 implying that they were severely affected by late magmatic-hydrothermal alteration (Shaw, 1968; Dostal and Chatterjee, 2000; Ballouard et al., 2016 and references therein). This observation is confirmed by the CHARAC-field discriminant derived by Bau (1996) in which the Bobbejaankop-like granites plot away from the CHARAC-field implying a magmatic hydrothermal influence.

Chondritic normalised REE geochemistry of Nebo granite show an enrichment of LREE relative to HREE with smooth and relatively sharp trend towards the latter. The europium anomalies (Eu/Eu^*) of the Nebo granite samples are invariable, ranging between 0.40 and 0.57 (Figure 6.12A). The REE patterns and the corresponding trace elements patterns in the veins show contrasting geochemical characteristics to the Nebo granite. The samples representing contact zones between the veins and the granite show the general similar REE patterns but without the characteristic negative europium anomaly. The sericitic alteration in the contact zones may have consumed the feldspar responsible for incorporating europium into the crystal structure depicted by negative spike on the patterns. The veins mainly comprise carbonates; and the geochemical character of these carbonates and other hydrothermal fluids are observed in the spider diagrams and distinguished accordingly as sets with varying characteristics in the alteration zones. The Nebo granite and veins bear no geochemical genetic similarities.

The Nebo Granite contact zone samples showing positive europium anomalies and enriched LREE have higher total REE abundances than other samples. This phenomenon does not necessarily suggest a higher fractionation but may imply petrogenetic variance from the other sets of samples and also from the Nebo granite. The petrogenetic differences in the veins may affirm the various hydrothermal fluids associated with polymetallic deposits setting as alluded by Freeman (1998) and Gleason et al. (2016) using fluid inclusion studies. Samples RCB07, RCB08 and RCB09 exhibit carbonate REE character and concur with the concluded petrographic studies in the previous chapter (Harmer and Eglington, 1998).

The Bobbejaankop-like granite REE spidergrams portray the three granite facies as also observed in the drill-core and petrographic studies (Chapter 5). The main Bobbejaankop granite facies show enriched HREE relative to general HREE patterns of A-type granites as also observed by Hill et al. (1996) and this study (Figure 6.15B). This Bobbejaankop-like facies, generally shows a decrease from Gd to Lu and occurs above the other two facies in the REE spider diagrams. Microgranite and aplitic facies show steady-flat and a relatively sharp enriched HREE increase respectively, with no apparent evidence of distinction in fractionation between the two.

The Bobbejaankop-like granites have variable negative anomalies but are relatively larger ranging from 0.06 to 0.23 in comparison with the Nebo granite. The negative europium anomalies of the Bobbejaankop granite facies are larger than the associated microgranite and aplitic facies corroborating. REE patterns representing quartz-and-feldspar pegmatitic zones which exhibit REE patterns similar to the Bobbejaankop-like granite. These REE patterns of pegmatitic zones are generally more fractionated than their parent granite constituencies suggesting that they formed from residual cupola-like orthomagmatic rich fluids in closed systems (McNaughton et al., 1993; Kinnaird et al., 2004).

7.4.1. Heterogeneity in LGS facies and possible sources

The LGS constitutes a compositionally-zoned sheeted body of A-type granite magmatism that produced several varieties mainly through differentiation and

metasomatic alteration (Kleemann and Twist, 1989; Vonopartis et al., 2020). Kleemann and Twist (1989) concluded that these varieties are comagmatic and this study through an evaluation of the REE has shown that Nebo and Bobbejaankop-like granites are cogenetic despite heterogeneity in fractionation trends and hydrothermal alteration patterns (Figure 6.13-16). However, despite the consensus that all fractionated LGS varieties emanate from the parent Nebo granite, fractionation modelling techniques such as least-squares and Rayleigh Fractionation do not explicitly link the fractionated varieties such as Klipkloof and Bobbejaankop granites to the Nebo granite without assuming unrealistic modal concentrations of hornblende and the water content of the parental Nebo granite (e.g. Kleemann and Twist, 1989; Vonopartis et al., 2020). The heterogeneity of the LGS facies and the inability of models to unequivocally model fractionation prompt scholars to suggest that the source of these varieties is different rather than having a common source (Fourie and Harris, 2011; Zeh et al., 2020). Hill et al. (1996) attribute the heterogeneity of LGS to geochemical variations in the melted quartzofeldspathic crystalline rocks from continental crust remnants. Fourie and Harris (2011) suggests that LGS emanates from both fractional crystallization of mafic BIC components and partly assimilated crustal material. Zeh et al. (2020) suggests that LGS represent highly fractionated RLS derived from single or multiple sources including enriched subcontinental lithospheric mantle by Transvaal Supergroup contamination during magma chamber accretion, subduction and partly assimilated crustal material. assimilation of continental crust during magma ascent.

The genetic model proposed by Hill et al. (1996) suggests that quartzofeldspathic crystalline rocks from continental crust remnants are a common source and also attributes the heterogeneity of the LGS to geochemical variations in these remnants. Furthermore, inliers and the tectonic structures around the Bobbejaankop-like granite facies in the Mutue Fides area may have created a compartment during the emplacement of the LGS and caused this facies to evolve into disparate mineralogy and geochemistry. Alternatively, the Stavoren Granophyre that is spatially associated

with the Bobbejaankop-like granite facies may have been assimilated into the magma that was already isolated from the larger melt volume.

7.5. Implications for mineralization

There are fundamental differences between the mineralization hosted within the Nebo and Bobbejaankop-like granites. The differences are subject to several factors encompassing the petrology of the host rocks, the existence of fractures and micro fractures in host rocks, the fluid types and their metal budget percolating the fissures, the temperature and pressure of the fluid(s), fluid-rock interactions and timing (Pirajno, 1992). This subsection discusses the effect of the host rock petrology on mineralization and how the host rock petrology influences or is influenced by these mineralising system factors.

Geochemistry data from this study and numerous studies (cf. Hill et al. 1996; Wilson et al. 2000; Vonopartis et al. 2020) show that Bobbejaankop-like granites exhibit metasomatic alteration, and are typically more fractionated than the Nebo granite. Additionally, petrographic studies show that Bobbejaankop-like granites are chloritized with magmatic biotite and other hydrous minerals and are more susceptible to miarolitic cavities arising from degassing of the volatiles concentrated during fractionation (sub-section 5.2.1). The relatively fractionated nature of the Bobbejaankop-like granites imply that they are likely to have an enrichment of large-ion lithophile elements (LILE) and high field strength elements (HFSE) such as Sn Ta, Nb, Zr and Hf (Bau, 1996). The presence of hydrous minerals and cavities promoted migration and concentration of the incompatible HFSE that are often accompanied by acidic F⁻, Cl⁻ and Fe-rich fluids (Pollard et al. 1991). This acidic hydrothermal fluid-front sequestered the metal ligands and precipitated them in cupolas with favourable physico-chemical conditions (Taylor et al. 1993). During the build-up of volatiles, the rock-fluid interactions also increased the volume required for precipitation through formation of a sericite-quartz assemblage from feldspars and biotite (reactions 3, 4 and 5) (London, 1999; Drivenes et al., 2015). REE data suggests that these fluids emanated within the granites as shown by similarities of REE signatures between

pegmatitic-mineralised zones and unaltered Bobbejaankop-like granite samples (Figure 6.15B and Figure 6.25). The mineralising system is relatively closed and maintained equilibrium as substantiated by REE data and zoned pegmatite in hydrothermal vugs referred to as “ore boulders”, “pockets” and “eyes” (Wagner, 1921; Crocker et al., 2001). In cases where mineralization takes the form of “tabular” or “pipe-like” ore-bodies, fluids were channelled through isolated fissures and still maintained to a certain extent, a closed system (Wagner, 1921).

The Nebo granite-hosted mineralization exhibits a different mineralising system in comparison to the Bobbejaankop-like granite system. The Nebo granite-hosted mineralization is largely controlled by fractures and hydrothermal fluids percolating through the host; and the alteration products manifested in the host rock are indicative of rock-fluid interactions rather than facilitation of mineralization (Robb et al. 2000). Due to a low metal ligand budget, low acidity and volatiles in the hypersolvus Nebo granite relative to the subsolvus Bobbejaankop-like granite, the former is restricted in creating robust fluid-rock interactions and sufficient redox front to subsequently sequester the metal ligands compared to the Bobbejaankop-like granite (Freeman, 1998). This assertion does not rule out the possibility that prolonged rock-fluid interaction facilitated by fissures may have altered the physico-chemical conditions of metal ligands-sulphide complexes and triggered precipitation of ores.

The Boschhoek Structure, in comparison to the isolated fissures in the Bobbejaankop-like granite mineralisation, forms a sigmoidal array of interconnected veins that adequately promoted fluid migration. The fluid migration and mineralization thereof occurred in episodes and these mineralization regimes are manifested in the Boschhoek Structure veins (Smits, 1980; Evans, 2015). Smits (1980) noted a three-staged paragenetic sequence comprising (1) early-stage pyrite, siderite, pyrrhotite and marcasite assemblage, (2) main stage characterised by sulphides such pyrite, galena, sphalerite and chalcopyrite in addition to calcite and (3) late stage comprising second generation galena and sphalerite assemblage. The source of these phased metal ligands-sulphides complexes includes orthomagmatic, connate and meteoric waters (Robb et al., 2000). REE data representing alteration zones (veins) of Nebo granite

show contradicting patterns corroborating the varied nature of fluid sources (Figure 6.24). The presence of massive siderite and calcite that cannot be attributed to the chemistry of Nebo granite chemistry further validates the assertion of mixed fluid sources.

Fluid inclusion studies in similar deposits suggest that mineralogical assemblages of the Mutue Fides deposits represent high temperature (>400°C), high salinity (35-50 wt. %) and high volatile content (Ollila, 1981; Freeman, 1998). The Boschhoek Prospect assemblage on the other hand represents a mesothermal deposit with low salinity and relatively low volatile content (equivalent to Spoedwel deposit) (Freeman, 1998). A complete comparison of the mineralization styles and factors influencing the mineralization are presented in Table 7.1.

Table 7.1. Comparison of mineralization styles between Boschhoek Prospect and Mutue Fides deposits (Freeman, 1998; Crocker et al., 2001, this study).

Factors	Boschhoek Prospect	Mutue Fides Deposit
Host rock	Nebo granite	Bobbejaankop granite
Alterations	Sericitic,	Sericitic, greisenization,
Ore mineralogy	Pyrrhotite, chalcopyrite, sphalerite, galena, pyrite, argenite, bornite, digenite,	Cassiterite, fluorite, chalcopyrite, pyrite, bornite
Mineralization morphology	Veins, breccia	Pipe-like and ore-boulders in pegmatite
Fluid(s) source	Hydrothermal, connate, meteoric	Ortho-magmatic
Structure type	Prominent sigmoidal array of fissures	Isolated fissures

Physico-chemical conditions	Mesothermal temperatures between 400 and 200°C	Hypothermal temperatures (>400°C)
	Low salinity (<35 wt. % eNaCl)	High salinity (35-50 wt.% eNaCl)
	Low volatile content	High volatile content

Chapter 8: Conclusions and metallogenic model of polymetallic mineralization

The reactivation of the Wonderkop Fault during and post BIC intrusion caused major warping along the fault-line and consequently caused rheological failures that created relatively local scale faults, folds and veins in adjacent lithologies. These local scale faults and veins morphologically and geodynamically mimic the regional scale Wonderkop Fault. The warping and fracturing of the lithologies along the Fault was contemporaneous with the BIC hydrothermal event. Prominent structurally controlled polymetallic deposits flank the Wonderkop Fault. The episodes of the fracturing and fluid migrations are well preserved within the Wonderkop Fault zone and the Boschhoek Prospect. The fracturing in the Mutue Fides was relatively limited probably due to shielding provided by older and rheologically competent Stavoren Granophyre and the Marble Hall Dome.

The geochemistry of the Nebo granite and the main Bobbejaankop granite together with associated microgranitic Klipkloof and aplitic facies demonstrate characteristics of a peraluminous A-type granite. There is no evidence suggesting that the Nebo and Bobbejaankop granite evolved concomitantly however, they are petrogenetically cogenetic as shown by similar normalised La/Yb ratios ascertaining the same source. Geochemical variations between the Nebo granite and the Bobbejaankop-like granite facies exist. (1) Silica contents of the Nebo granite fall within a wider range of Bobbejaankop granite silica range and prompt the consideration that the latter formed from a more primitive parental magma source. However, that is not confirmed by La/Yb ratios and is thought to have undergone more extensive fractionation. (2) These granite suites show distinct K/Rb, Rb/Sr (Ba) and Nb/Ta trends. These ratios suggested higher degrees of fractionation in Bobbejaankop-like granites than the Nebo granite. (3) Chondrite normalised REE and mantle normalised trace elements also exhibit distinct fractionations and suggest that the Bobbejaankop-like granite is more highly fractionated than the Nebo granite. (4) Y/Ho and Zr/Hf ratios suggest that

Bobbejaankop-like granite facies underwent considerable and extensive late magmatic-magmatic alteration (Bau, 1996; Pack et al., 2007).

In summary, the Bobbejaankop-like granites are more fractionated than the Nebo granite and the former have also undergone extensive magmatic-hydrothermal alteration. Furthermore, these suites emanate possibly from one crustal source with a heterogeneous composition and consequently evolved in isolation to form disparate mineralogical and geochemistry. Hill et al. (1996) attributed the geochemical variations to the varied nature of discrete Archean quartzo-feldspathic crystalline rocks melted the by RLS intrusion to form the LGS. Kleemann and Twist (1989) suggest both Nebo granite and Bobbejaankop granite (extending from the interpretation that Klipkloof and Bobbejaankop share similar characteristics) emanate from one magmatic source. However, extensive and late-/post-magmatic alteration affected the latter and enhanced the intrinsic geochemical characteristics. The Y/Ho and Zr/Hf ratios show that even the extensively hydrothermally affected Bobbejaankop granite samples do still maintain geochemical characteristics that are somewhat traceable back to the parent Nebo granite (Figure 6.13). Recent studies such as Zeh et al. (2020) and Gudelius et al. (2020) corroborate multiple reservoirs such as subcontinental lithospheric mantle and early felsic terranes to have brought heterogeneity to the BIC magmas.

The microgranite and aplitic facies share similar characteristics with the Bobbejaankop granite particularly the exposure to magmatic hydrothermal alteration in late stages. The Bobbejaankop granite is generally more fractionated than both microgranite and aplitic facies. The genesis of the porphyritic aplitic follows the textural genetic model of the relationship between porphyritic Klipkloof and the Nebo granite proposed by Kleemann and Twist (1989).

8.1. Boschhoek Prospect summary

The Boschhoek Prospect is located on the periphery northeast of the Marble Hall Dome (Figure 1.2). The Prospect is an epigenetic mesothermal Cu-Zn-Pb-Ag deposit hosted within fractured Nebo granite of the LGS (Freeman, 1998; Robb et al., 2000).

Borehole data shows that sulphide-bearing carbonate and quartz hydrothermal veins filled the fractures (this study; Smits 1986; Evans 2015). The fractures are exposed as steeply dipping gossanous bodies that strike northeast (Smits, 1986 and this study). The fracture system is parallel to the Wonderkop Fault and reflects the sense of movement coherent with the regional structural regime.

Three major fracturing events are noted in the Boschhoek Prospect fracture system. The first Boschhoek Prospect episode exhibiting a steeply dipping composite fracture system primarily due to LGS rheological failure caused by Wonderkop Fault movement. Subsequently, large interstitial siderite and calcite crystals together with earlier disseminated pyrite and pyrrhotite filled the fractures (Smits 1980 and this study). Brittle fracturing characterised the second episode of the Wonderkop Prospect system. Gradual stress release in the fractured veins permitted magmatic and connate fluids mixing (Evans, 2015). The resultant silica-rich hydrothermal fluid formed sulphide mineralization and quartz veins post pervasive sericite alteration. Brecciated gossans in addition to the secondary sulphide minerals marked the third episode of fracturing.

8.2. Summary of Mutue Fides and Stavoren Fragment mineralization

The Mutue Fides-Stavoren Tin Field spreads across various lithological units northeast of the Stavoren Fragment periphery (Figure 1.2). The tin (Sn) and associated polymetallic mineralization within the Tin Field is hosted in Kwarriehoek Formation of Makeckaan Subgroup, the Stavoren Granophyre of RGS and the Nebo and Bobbejaankop granites of LGS. Prominent areas include the farms Mutue Fides, Stavoren, Kwarriehoek and Gaasterland. The prominent tin deposits occur in various forms as discussed in Chapter one (Wagner 1921; Crocker et al., 2001). Borehole data from Mutue Fides show ore pockets comprising cassiterite, fluorite and minor sulphides hosted in pegmatites. In most cases, the mineralization is accompanied by pervasive greisen alteration. Field observations concur that these deposits are often adjacent to veins striking at northeast (045°N), east-northeast (068°N) and southeast (120°N).

The Bobbejaankop granite and the associated apical facies were dominated by vugs emanating from the escape of volatiles in cupola regions of the granites. These vugs were subsequently filled by k-feldspar and quartz pegmatite with incompatible metals such as Sn-W-Mo-F creating tabular ores. Greisen and sericite alterations created volumes shrinkages in these granitic facies that permitted metalliferous fluid to precipitate Sn-W-Mo-F assemblages in replacement veins.

8.3. Metallogenic model of polymetallic mineralization with emphasis on Boschhoek Prospect

De Launay (1905) described metallogeny as a scientific study focussing on genesis of ore deposits with respect to their geological period and regional space of occurrence on the Earth's crust. In the context of polymetallic deposits in the LGS, the Bushveld Igneous Complex becomes the regional space (the metallogenic province), the timing of the LGS intrusion at 2054.2 ± 2.8 Ma (Harmer and Armstrong, 2000) and the accompanying hydrothermal circulation and large-scale fracturing that prevailed define the geological period. In the broad sense, previous models captured the genesis of the polymetallic mineralization from the intrusion of the LGS into Pretoria Group, Rooiberg Group and RGS and the subsequent fractionation that enabled metallic fluid build-up into the apical portions. Subsequently, these magmatic fluids formed disseminated to higher-grade lode endogranitic–orthomagmatic deposits (e.g. Zaaiplaats Tin deposit) (Robb et al., 2000). In some cases, the orthomagmatic fluids mixed with meteoric or connate waters through fissures in the host rocks to form either endogranitic or exogranitic structurally controlled deposits (Figure 8.1) (Robb et al., 2000).

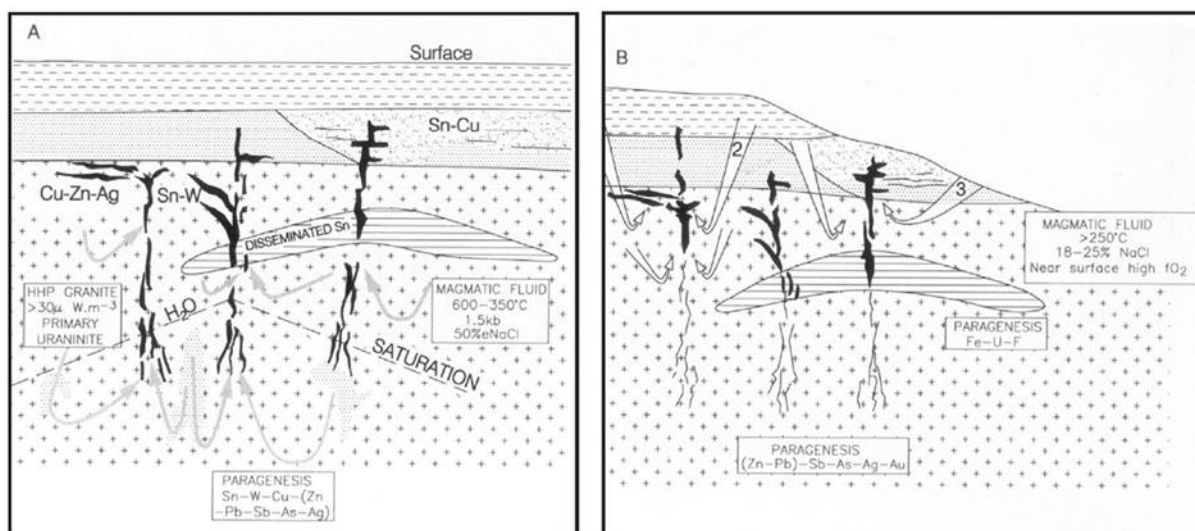


Figure 8.1: Generalised polymetallic mineralization model in the LGS. (A) Hypothermal orthomagmatic deposits dominate the early mineralization stages. (B) Mesothermal mixed hydrothermal fluid characterise the later stages of the mineralization (Robb et al., 2000; Bailie and Robb, 2004).

This subsection seeks to expand these metallogenic parameters of the polymetallic deposits in the LGS with emphasis on the Boschhoek Prospect in comparison with Mutue Fides. In the context of the favoured model of LGS, as proposed by Hill et al. (1996), the intrusion of the RLS triggered melting of the quartzofeldspathic crystalline rocks from continental crust remnants (Hill et al., 1996). The subtle geochemical variations in the continental crust, structural discontinuities brought upon by regional structures such as the Wonderkop Fault and Steelpoort and the Transvaal inliers created compartments that enabled disparate evolution of the Nebo granite into various fractionated and hydrothermally altered facies. The fractionation of the Nebo granite into various facies coincided with some reactivation phases of the Wonderkop Fault. Several warping events and rheological failures in response to this reactivation created relatively small-scale fractures adjacent to the Wonderkop Fault, some fractures occurred in isolation as noted in Mutue Fides and others occurred as an array of fissures as it is the case in the Boschhoek Structure. The magmatic fluid build-up and cavities in the isolated and highly fractionated Bobbejaankop-like granite concentrated fluids to produce disseminated and lode “pipe-like” ore-bodies comprising cassiterite, fluorite, chalcopyrite, pyrite and bornite. In the Boschhoek Prospect, these magmatic fluids together with meteoric and/or connate fluids carrying

metal ligands were channelled along these fractures, resulting in base metals deposition comprising a pyrrhotite, chalcopyrite, sphalerite, galena, pyrite, argenite, bornite and digenite assemblage. The deposition of the assemblage occurred in episodes as the system moved from mesothermal to epithermal with increase in external fluids.

Numerous attempts to constrain polymetallic deposition to a definite geological period yielded contrasting results. McNaughton et al. (1993) suggested that the accompanying hydrothermal systems driven by high-heat producing LGS lasted for 100 million years after intrusion although this is unlikely as a continuous process. Radiogenic isotopic data suggests that the long-lived hydrothermal systems circulated as open-system chemical re-equilibration and selectively homogenised the isotopic ratios (Robb et al., 2000). The timing of the hydrothermal fluid-flow and various metallic entrapment episodes can be restricted to between the 2.054 Ga intrusion of the LGS (Walraven and Hattingh, 1993) and 961 ± 129 Ma (McNaughton et al., 1993). The magmatic-dominated hydrothermal fluid lasted for at most 5 million years after emplacement of LGS. Unpublished SHRIMP age data for cassiterite by Armstrong from the Rooiberg mine restrict the mineralization to 2049 ± 5 Ma, which is within the limits of the period of magmatic-dominated fluid circulation (Robb et al. 2000 and references therein). Boschhoek Prospect, Mutue Fides and adjacent Stavoren Fragment and Speedwel deposits are no exception, they are restricted to within the period of LGS emplacement and the subsequent hydrothermal circulation period as expressed above.

8.4. Recommendations

The outcomes of this study supports previous findings of Smits (1986) and Freeman (1998) that Bushveld polymetallic mineralization, including the Boschhoek Prospect, originated from hybrid fluid of magmatic-hydrothermal and connate fluid. This is reflected in the REE spider grams of veins samples. In order to draw conclusive interpretations of the nature of the fluid, the following future study is recommended:

fluid inclusions studies in carbonate and quartz minerals in order to evaluate fluid composition and temperature.

Core logging and petrographic studies indicated the occurrence of fluorite in the Bobbejaankop-like granite pegmatite samples. The pegmatite show similar trace element geochemistry patterns as the granite, radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ isotope studies in fluorite to provide age of mineralization.

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APPENDIX A

Table A1: Whole rock major element concentrations of the BHDD 003 core samples. S#= sample number, N=Nebo granite (black text), V= vein (mineralised zones in red text).

S#	RCB01	RCB02	RCB03	RCB04	RCB05	RCB06	RCB07	RCB08	RCB09	RCB10	RCB11	RCB12	RCB13	RCB14	RCB15	RCB16	RCB17
TYPE	N	N	V	V	V	V	V	V	V	V	V	V	V	N	N	N	N
SiO ₂	74,32	74,37	5,04	18,65	11,32	30,56	56,31	22,91	17,36	18,68	24,07	57,48	16,52	76,32	73,38	74,83	73,63
Al ₂ O ₃	12,38	11,47	0,26	0,63	1,06	3,46	7,41	1,95	1,37	0,37	0,19	0,31	0,14	12,07	12,1	11,46	11,98
Fe ₂ O ₃	3,78	2,54	52,82	42,71	44,36	22,57	11,59	39,31	41,57	18,95	43,44	24,2	51,51	1,78	3,24	2,9	3,44
MnO	0,15	0,12	3,01	1,99	2,22	1,39	0,58	2,05	1,85	1,59	1,79	1,08	2,79	0,03	0,05	0,04	0,06
MgO	0,15	0,15	0,96	1,13	0,71	0,57	0,36	0,76	1,11	0,43	0,97	0,32	0,62	0,12	0,08	0,08	0,08
CaO	0,06	1,15	2,72	6,4	8,63	15,29	7,76	5,8	6,54	26,2	0,26	0,14	0,34	1,07	0,99	1,04	1,03
Na ₂ O	0,08	0,61	0	0	0	0	0,01	0	0	0	0,63	0,33	0,03	1,43	3,24	3,16	3,26
K ₂ O	5,62	5,45	0,1	0,17	0,31	1,23	3,43	0,62	0,43	0,09	0,06	0,06	0,04	4,34	5,18	4,71	4,9
TiO ₂	0,37	0,23	0,02	0,02	0,04	0,11	0,16	0,05	0,03	0,02	0,02	0,01	0,01	0,23	0,21	0,2	0,24
P ₂ O ₅	0,04	0,03	0,01	0,01	0,01	0,03	0,03	0,02	0,02	0,02	0,01	0,01	0,01	0,03	0,03	0,03	0,03
Cr ₂ O ₃	0,01	0,01	0,02	0,02	0,02	0,02	0,01	0,02	0,02	0,02	0,02	0,01	0,02	0,01	0,01	0,01	0,01

NiO	0	0	0,01	0,01	0,01	0,01	0	0,01	0,06	0,01	0,01	0,01	0,01	0	0	0	0
LOI	2,3	3,05	28,53	26,39	29,76	23,26	12,33	24,15	23,3	28,8	22,81	12,49	26,28	2,09	1,68	0,97	1,24
Total	99,24	99,17	93,5	98,13	98,46	98,49	99,98	97,65	93,66	95,18	94,26	96,44	98,31	99,51	100,19	99,42	99,90

Table A2: Whole rock trace element concentrations of the BHDD 003 core samples (Nebo granite). S# = sample number, N = Nebo granite (black text), V = vein (mineralised zones in red text).

S#	RCB01	RCB02	RCB03	RCB04	RCB05	RCB06	RCB07	RCB08	RCB09	RCB10	RCB11	RCB12	RCB13	RCB14	RCB15	RCB16	RCB17
TYPE	N	N	V	V	V	V	V	V	V	V	V	V	V	N	N	N	N
Li	4,35	3,39	1,74	4,74	2,74	4,20	3,63	5,09	3,12	4,52	4,36	11,82	3,62	4,11	3,20	2,24	6,74
P	106,78	65,61	12,56	10,04	11,00	85,38	68,50	53,95	37,03	45,95	4,65	2,39	8,00	91,81	76,04	90,79	97,87
Sc	3,81	3,02	25,32	7,12	13,04	16,81	4,86	10,14	8,31	16,92	1,84	1,01	2,43	2,32	2,83	2,60	3,32
Ti	1818,10	1098,87	29,23	55,94	88,19	472,64	816,24	163,31	141,88	138,17	11,82	8,83	6,74	954,99	1076,27	945,08	1151,52
V	2,69	1,59	1,76	3,86	1,11	2,16	1,71	1,01	2,57	0,97	0,77	0,21	0,32	1,44	1,49	1,28	1,67
Cr	2,55	4,20	1,46	1,86	0,46	2,12	3,88	1,33	1,92	1,17	0,87	2,50	1,63	2,22	3,57	1,76	1,40
Co	7,31	2,97	11,74	83,66	43,38	363,88	29,98	88,58	635,91	181,60	217,25	1041,35	82,60	0,65	1,57	0,92	1,44
Ni	2,15	1,82	9,03	32,49	6,85	42,69	12,64	15,23	404,95	19,01	18,10	15,91	2,69	0,73	2,87	0,93	1,59
Cu	448,32	114,84	8805,41	606,16	857,63	1471,41	71,87	2307,02	2221,45	8237,05	13647,61	8242,86	1508,06	6,96	14,42	19,09	25,66
Zn	197,98	42,69	693,41	47,48	127,28	62,34	27,02	723,61	612,36	652,77	23417,01	11710,72	4475,03	34,55	99,75	78,09	117,26
Ga	28,34	27,57	1,57	2,51	4,59	19,31	19,38	11,27	7,04	16,81	2,12	2,18	0,95	29,40	29,51	25,61	31,44
Rb	182,61	174,29	4,20	8,41	14,24	53,98	120,68	28,65	22,08	5,62	2,17	2,47	1,65	155,71	153,78	138,29	144,75
Sr	17,39	17,46	8,39	21,42	30,99	56,07	23,86	46,43	25,95	111,76	3,20	4,11	3,51	29,76	61,37	56,52	69,08

Y	47,23	37,72	25,03	20,86	27,76	93,15	35,63	30,00	32,47	148,36	20,88	10,78	17,89	31,66	45,86	45,29	54,78
Zr	321,89	267,49	3,35	11,46	16,55	61,05	164,24	34,06	19,79	5,29	1,15	0,47	1,23	184,71	216,87	222,26	277,91
Nb	24,68	17,93	0,20	0,38	0,67	6,59	11,79	2,25	1,65	0,20	0,21	0,11	0,63	14,10	15,26	17,93	16,48
Sn	9,21	8,49	0,84	2,76	0,64	2,64	5,69	3,86	2,38	1,13	3,86	2,69	1,05	10,18	8,45	7,07	9,28
Sb	3,91	4,06	2,06	13,78	4,48	14,12	5,08	10,10	40,72	7,76	18,14	37,43	11,33	1,34	0,94	0,76	0,87
Cs	2,18	2,96	0,14	0,20	0,24	0,62	1,50	0,60	0,30	0,12	0,17	0,28	0,18	2,61	2,75	2,62	2,63
Ba	824,99	697,71	15,50	13,17	18,61	89,97	355,67	43,57	34,01	42,89	9,92	14,34	9,63	474,75	886,79	935,14	835,33
La	82,33	90,81	5,24	8,32	16,68	96,63	62,92	52,15	33,63	106,86	9,83	12,10	3,24	105,41	110,55	78,27	127,58
Ce	146,81	179,33	11,15	15,47	34,04	208,44	128,57	112,02	65,14	225,02	20,57	24,65	6,93	207,32	208,37	154,59	239,45
Pr	17,66	19,93	1,54	1,80	4,11	25,18	14,54	13,08	7,35	28,69	2,66	3,05	0,98	23,13	22,74	17,53	25,73
Nd	68,39	76,06	7,54	7,63	17,76	108,20	56,85	53,40	29,51	124,70	12,71	13,89	4,80	88,37	84,30	67,90	96,77
Sm	11,88	12,76	2,28	2,03	4,31	23,46	10,51	10,00	6,21	29,83	3,49	3,26	1,54	14,62	14,00	12,21	15,90
Eu	2,73	2,23	0,97	1,60	2,27	7,43	3,58	3,94	2,60	8,57	0,86	0,78	0,46	1,89	1,98	1,87	2,00
Gd	11,24	11,04	3,09	2,76	4,90	22,01	9,26	8,31	6,45	31,58	4,00	3,21	2,13	12,42	12,46	11,40	14,15
Tb	1,59	1,44	0,62	0,55	0,84	3,25	1,28	1,11	1,04	4,82	0,65	0,44	0,47	1,50	1,65	1,58	1,93
Dy	9,71	8,36	4,71	4,13	5,77	19,24	7,43	6,38	6,77	28,80	4,56	2,73	3,69	7,49	9,44	9,40	11,23
Ho	2,10	1,62	1,09	0,94	1,25	3,70	1,46	1,30	1,36	5,52	1,00	0,55	0,88	1,33	1,83	1,85	2,22
Er	5,63	4,60	3,55	2,95	3,88	10,43	4,10	3,95	4,00	15,35	3,21	1,64	2,98	3,43	5,07	5,16	6,21
Tm	0,84	0,62	0,63	0,53	0,69	1,54	0,63	0,65	0,64	2,34	0,55	0,26	0,53	0,46	0,72	0,74	0,87
Yb	5,82	4,83	5,32	4,32	5,69	11,24	4,56	5,19	4,92	17,12	4,24	1,94	4,14	3,05	4,93	4,97	5,84
Lu	0,88	0,65	0,98	0,76	1,00	1,78	0,73	0,90	0,80	2,73	0,65	0,28	0,67	0,46	0,74	0,75	0,89

Hf	7,94	6,86	0,10	0,37	0,54	1,70	4,88	1,08	0,67	0,25	0,05	0,02	0,05	5,70	6,42	5,77	8,01
Ta	1,51	1,08	0,03	0,04	0,05	0,30	0,77	0,14	0,11	0,03	0,04	0,02	0,22	0,92	0,97	0,82	1,04
W	0,51	0,96	0,11	0,08	0,29	0,67	2,28	0,32	0,40	0,08	0,23	0,32	0,83	0,37	0,44	0,46	0,45
Ti	1,66	1,68	0,01	0,07	0,11	0,45	1,08	0,21	0,12	0,06	0,02	0,03	-0,01	1,25	1,41	1,30	1,36
Pb	28,28	17,13	95,45	23,42	110,44	77,20	7,96	161,80	299,33	93,38	287,71	336,00	37,72	5,28	28,80	19,97	27,37
Th	22,69	22,01	0,12	0,83	0,99	2,25	13,63	3,36	1,16	1,51	0,02	0,04	0,01	29,59	23,28	18,92	25,74
U	3,80	5,05	0,08	0,45	0,38	0,78	2,85	0,70	0,58	1,21	0,01	0,02	0,00	6,26	4,96	3,71	4,53

Table B1: Whole rock major element concentrations of the 648 KS/1 core samples. S# = sample number, Bobbejaankop granite, M=Microgranitic Klipkloof, L=Lease granite, P= pegmatite (mineralised zones in red text).

S#	RCM 01	RCM 02	RCM 03	RCM 04	RCM 05	RCM 06	RCM 07	RCM 08	RCM 09	RCM 10	RCM 11	RCM 12	RCM 13	RCM 14	RCM 15	RCM 16	RCM 17	RCM 18	RCM 19	RCM 20	RCM 21	RCM 22	RCM 23	RCM 24	RCM 25	RCM 26
TYPES	B	B	B	B	M	L	L	P	M	P	M	M	P	B	L	L	P	P	P	L	L	M	M	L	P	M
SiO ₂	72,99	70,89	74,93	76,06	76,38	75,06	76,12	46,85	77,07	65,45	70,42	76,32	52,9	75,34	75,57	76,13	54,31	65,39	68,09	74,95	75,77	76,72	76,41	75,34	50,09	75,79
Al ₂ O ₃	11,35	13,63	11,51	12,48	11,63	11,84	11,97	10,91	12,38	7,86	10,72	11,59	15,58	11,68	11,96	11,73	8,53	11,27	7,77	12,02	12,34	12,51	11,82	12,06	15,22	12,52
Fe ₂ O ₃	5,5	3,55	1,22	1,17	3,98	6,04	4,93	5,66	1,59	1,4	4,68	4,73	14,73	2,37	2,48	1,95	5,5	3,07	3,01	2,66	2,75	0,72	2,61	3,34	18,02	2,08
MnO	0,04	0,03	0,01	0,01	0,16	0,14	0,08	0,5	0,05	0,05	0,21	0,06	0,43	0,08	0,09	0,07	0,24	0,09	0,06	0,04	0,03	0,01	0,04	0,08	0,38	0,05
MgO	0,05	0,1	0,05	0,08	0,11	0,1	0,1	0,19	0,06	0,09	0,13	0,12	0,18	0,06	0,07	0,05	0,08	0,07	0,08	0,07	0,06	0,03	0,06	0,06	0,25	0,05
CaO	0,35	0,25	2,13	0,42	0,1	0,05	0,06	17,95	0,4	14,85	4,42	0,27	1,54	0,68	0,4	0,97	14,27	4,1	7,03	1,06	0,32	0,42	0,58	0,38	6,99	0,21
Na ₂ O	2,36	1,09	1,79	2,16	0,03	0	0,02	0,6	4,18	0	0,01	0,03	0,01	2,49	2,5	2,46	0,45	2,4	0,96	2,61	2,44	3,47	2,73	2,96	0,64	3,63

K ₂ O	4,94	7,04	5,76	6,03	4,81	3,17	3,37	3,28	2,33	2,4	3,23	4,55	4,86	5,09	4,99	4,98	3,7	3,53	3,59	4,94	5,07	5,19	4,49	4,39	4,09	4,55
TiO ₂	0,13	0,14	0,09	0,09	0,06	0,04	0,08	0,28	0,02	0,02	0,01	0,07	1,37	0,1	0,09	0,08	0,02	0,06	0,05	0,1	0,1	0,01	0,11	0,15	1,18	0,08
P ₂ O ₅	0,02	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	0,01	0,02	0,01	0,01	0,01	0,01	0,01	0,01	0,01
Cr ₂ O ₃	0,01	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	0	0,01	0	0	0	0	0,01	0
NiO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LOI	1,61	2,21	1,66	1,31	2,34	2,77	2,36	11,08	1,09	4,1	4,53	1,97	8,66	1,37	1,44	1,39	6,22	4,09	4,2	1,29	1,05	0,64	1,02	1,35	1,7	0,96
Total	99,36	98,97	99,17	99,82	99,59	99,21	99,11	97,34	99,17	96,23	98,37	99,72	100,28	99,28	99,61	99,83	93,37	94,09	94,87	99,74	99,94	99,73	99,89	100,12	98,58	99,93

Table B2: Whole rock trace element concentrations of the 648 KS/1 core samples. S#= sample number, Bobbejaankop granite, M=Microgranitic Klipkloof, L=Lease granite, P= pegmatite (mineralised zones in red text).

S#	RCM 01	RCM 02	RCM 03	RCM 04	RCM 05	RCM 06	RCM 07	RCM 08	RCM 09	RCM 10	RCM 11	RCM 12	RCM 13	RCM 14	RCM 15	RCM 16	RCM 17	RCM 18	RCM 19	RCM 20	RCM 21	RCM 22	RCM 23	RCM 24	RCM 25	RCM 26
TYPE	B	B	B	B	M	L	L	P	M	P	M	M	P	B	L	L	P	P	P	L	L	M	M	L	P	M
Li	7,56	16,30	8,79	9,09	16,04	42,92	39,63	37,37	11,29	16,94	31,41	28,57	22,41	10,54	8,74	10,99	33,24	25,04	20,09	14,97	17,69	4,48	15,96	10,20	61,02	6,91
P	10,73	18,22	6,40	9,46	13,28	5,55	11,29	11,94	9,01	6,09	3,97	5,66	7,78	8,02	6,22	12,49	8,49	7,72	10,19	9,65	6,77	3,58	6,20	14,02	5,23	8,86
Sc	2,10	1,98	1,25	1,49	2,59	1,66	1,93	2,27	1,47	0,91	2,05	1,76	2,76	4,28	1,37	1,31	1,98	1,36	1,38	1,83	1,59	1,39	1,65	2,00	5,05	1,85
Ti	634,56	686,59	413,24	365,12	279,83	152,73	378,32	1315,50	80,67	107,71	51,60	298,79	5842,11	455,73	429,51	350,32	170,12	316,11	285,78	428,63	471,98	42,08	525,93	752,83	5922,41	401,05
V	0,81	3,91	0,31	0,31	0,40	0,36	0,20	0,13	0,25	0,72	0,35	0,26	0,17	0,22	0,49	0,21	0,22	0,33	0,44	0,33	0,30	0,26	0,36	0,28	0,53	0,42
Cr	1,78	1,40	1,49	1,08	1,75	2,13	1,15	0,90	1,00	5,48	1,06	0,81	0,78	0,94	2,43	1,07	1,54	1,40	1,88	1,35	1,03	0,88	1,59	0,97	0,71	4,85
Co	0,73	0,54	0,48	0,40	0,43	0,49	1,37	5,46	0,98	0,59	0,44	0,70	0,97	2,27	0,83	0,56	0,59	0,78	2,64	0,88	0,49	0,50	0,70	0,86	3,17	0,57
Ni	1,97	1,74	1,39	1,47	2,05	1,91	1,12	0,79	1,21	1,63	1,16	1,11	0,56	0,85	1,30	3,40	1,21	1,04	1,98	1,51	1,52	1,43	1,55	1,22	0,67	1,57
Cu	46,18	120,22	1051,87	42,69	19,90	5,33	275,41	871,14	597,96	179,90	76,23	10,75	47,79	255,63	11,79	459,71	738,86	647,12	1044,89	175,76	94,72	189,00	452,28	447,29	66,80	143,17
Zn	43,72	70,96	97,95	46,60	179,47	199,40	372,24	149,59	163,24	33,84	38,87	56,59	142,69	217,35	25,19	239,18	314,93	385,01	388,33	127,74	107,46	31,05	77,00	236,59	315,65	49,96
Ga	34,16	135,52	48,00	37,92	33,34	35,68	38,96	75,29	33,24	66,44	51,85	35,57	107,98	31,90	28,60	28,74	535,50	1058,44	487,59	42,14	33,17	25,14	30,76	32,27	549,13	28,01
Rb	468,43	619,28	489,68	475,39	480,94	382,80	343,46	428,94	235,18	317,44	414,09	431,45	655,78	404,52	375,07	371,16	351,09	321,07	305,90	385,32	409,39	368,64	345,29	352,47	467,76	344,47
Sr	10,57	9,33	9,17	6,92	2,93	1,67	1,93	31,80	3,50	11,65	5,86	3,65	6,08	6,02	5,37	6,33	15,57	11,87	22,59	6,65	4,87	4,95	4,88	4,25	8,37	4,25
Y	104,68	321,41	229,61	86,50	58,57	31,45	50,87	195,98	22,20	280,00	109,92	48,28	203,81	108,00	29,59	60,08	680,48	406,31	1182,89	76,40	27,16	29,28	17,68	19,68	259,83	11,58
Zr	355,56	243,67	164,52	225,14	487,46	320,85	331,74	300,13	303,62	143,03	314,60	311,19	156,62	877,71	275,49	275,22	266,90	178,89	219,78	359,62	303,66	318,68	319,01	361,60	284,23	360,39
Nb	31,80	56,79	23,65	19,46	129,32	56,34	155,98	228,93	13,70	6,77	12,92	91,37	824,45	115,68	19,65	21,54	16,37	26,75	42,81	48,83	54,72	3,64	43,95	73,34	715,74	36,10
Sn	16,78	33,64	17,87	15,92	25,44	43,54	39,46	27,38	25,29	12,14	32,79	34,40	62,47	23,29	23,98	22,68	74,14	112,04	63,64	16,65	22,97	10,87	12,66	23,42	54,47	47,55
Sb	1,40	2,10	3,16	1,28	2,97	3,40	4,65	7,45	6,57	5,03	3,81	2,66	6,65	4,32	1,34	1,45	1,75	2,30	3,81	2,41	1,66	1,57	1,63	1,84	2,98	1,88

Cs	2,19	2,81	1,55	2,25	7,70	3,49	2,92	3,26	1,80	13,77	4,99	3,36	5,07	1,44	3,75	1,34	1,42	1,63	1,31	1,33	1,44	1,10	1,10	1,29	4,03	1,20
Ba	180,70	149,96	116,43	148,15	82,12	38,07	42,66	59,46	36,15	26,10	61,77	71,73	193,60	127,34	136,95	126,54	88,48	93,37	96,31	129,82	129,01	128,93	115,00	111,34	112,53	121,73
La	68,05	760,19	173,77	104,09	4,68	10,37	9,07	94,66	5,50	337,63	34,90	5,25	25,43	29,19	19,06	37,90	4919,09	9896,27	4781,52	227,77	34,72	35,10	38,83	27,92	4016,94	14,77
Ce	176,95	1591,48	400,30	229,32	9,10	15,90	15,92	154,81	8,07	549,80	59,38	8,49	45,44	52,92	29,06	62,03	7592,20	15247,60	6621,06	292,85	57,77	52,55	58,40	47,23	7005,85	21,41
Pr	21,85	198,17	48,50	26,60	1,27	1,56	1,81	14,93	0,76	60,16	6,87	0,85	5,24	6,10	2,87	6,12	592,82	1173,98	521,44	21,13	5,88	4,41	5,12	4,31	573,10	1,84
Nd	92,77	739,96	188,81	98,27	6,23	5,87	8,06	46,06	2,64	236,43	27,40	3,25	20,34	24,19	9,51	20,59	1417,60	2719,74	1428,92	58,79	17,93	12,26	14,64	12,90	1358,49	5,58
Sm	21,30	160,94	47,35	22,85	2,63	1,88	3,35	9,83	0,76	53,10	6,49	1,43	6,96	7,64	2,16	4,29	147,41	253,21	230,41	8,52	3,62	1,93	2,36	2,44	116,66	1,10
Eu	0,58	3,06	0,77	0,41	0,08	0,07	0,09	0,25	0,08	1,23	0,20	0,07	0,22	0,18	0,09	0,13	2,16	3,92	2,23	0,19	0,11	0,09	0,12	0,15	3,95	0,09
Gd	21,42	135,25	48,40	22,23	3,50	2,27	4,13	12,26	1,17	52,59	7,99	2,27	10,79	9,31	2,43	4,82	122,37	192,88	216,14	8,33	3,36	2,02	2,16	2,36	91,22	1,13
Tb	3,52	18,70	7,46	3,53	0,99	0,57	1,08	2,89	0,31	6,43	1,43	0,74	3,86	2,28	0,47	0,84	13,14	18,10	34,02	1,29	0,64	0,36	0,33	0,43	9,50	0,21
Dy	22,79	95,38	43,57	21,50	9,47	5,04	9,51	25,59	2,83	34,90	11,21	7,27	40,04	20,12	3,59	6,12	73,69	82,66	211,34	9,11	4,67	2,94	2,32	3,09	49,62	1,65
Ho	4,63	14,87	7,78	3,98	2,58	1,30	2,32	6,50	0,74	6,52	2,79	1,91	10,48	5,06	0,86	1,45	15,59	14,99	42,73	2,02	1,06	0,76	0,53	0,70	9,90	0,39
Er	12,24	30,03	18,49	10,59	10,21	4,86	8,19	22,85	2,73	17,88	9,80	7,27	36,30	18,34	2,93	4,84	50,40	46,31	122,20	6,95	3,42	2,82	1,82	2,33	32,53	1,40
Tm	1,72	3,04	2,34	1,49	2,10	0,94	1,56	4,00	0,51	2,65	1,77	1,39	6,20	3,39	0,52	0,84	9,09	7,55	18,08	1,26	0,59	0,53	0,32	0,41	4,98	0,27
Yb	10,34	15,67	14,47	9,20	16,74	7,12	11,60	28,98	3,90	19,57	13,73	10,68	41,36	25,00	4,03	6,47	64,28	51,00	118,51	9,64	4,34	4,33	2,52	3,11	34,95	2,14
Lu	1,48	2,11	2,28	1,31	2,72	1,16	1,82	4,58	0,66	3,20	2,31	1,74	5,57	3,84	0,66	1,07	11,28	7,60	17,45	1,57	0,69	0,74	0,42	0,51	4,92	0,36
Hf	12,69	9,36	6,43	8,64	26,25	16,85	17,58	13,76	15,60	7,19	15,24	15,26	7,28	40,82	12,12	12,00	11,91	7,97	10,70	16,71	14,20	14,94	14,80	16,87	12,26	17,02
Ta	2,92	5,49	2,41	2,14	14,58	6,81	24,14	27,32	2,97	0,18	1,21	7,34	109,23	9,47	2,85	2,81	1,71	3,33	3,77	4,21	3,74	0,35	3,12	6,27	61,13	3,18
W	2,40	1,46	0,93	0,86	4,01	3,49	9,55	14,37	1,32	1,00	1,50	4,12	55,26	3,80	4,65	3,62	1,85	3,88	3,82	4,41	5,81	1,13	4,14	2,45	13,81	5,26
Tl	3,77	5,27	4,13	4,14	4,22	3,34	2,90	2,94	1,13	2,23	3,34	3,40	3,14	2,76	3,33	3,40	2,64	2,76	2,64	3,57	3,78	3,51	2,90	3,27	3,72	3,48
Pb	11,79	14,97	285,12	8,98	17,21	6,90	45,68	18,75	37,96	1,91	0,97	3,71	6,46	79,42	55,83	34,12	303,78	55,60	152,50	58,47	11,59	19,30	14,30	27,55	4,03	6,03
Th	41,01	74,90	43,48	38,41	10,70	57,95	65,53	60,62	4,86	2,93	16,09	39,64	56,57	60,20	39,27	55,72	27,00	82,67	58,91	11,87	9,95	3,30	5,77	10,07	36,70	4,95
U	14,55	13,13	7,96	7,95	19,11	26,35	32,23	46,50	6,97	6,80	11,10	38,68	35,48	25,62	17,07	20,38	11,67	14,08	24,23	10,41	4,91	2,98	2,68	3,94	8,11	3,57