THE GEOLOGY, GEOCHEMISTRY AND METALLOGENY OF THE FELSIC ROCKS OF THE BUSHVELD COMPLEX, NORTH OF BRONKHORSTSPRUIT, SOUTH AFRICA

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A dissertation submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science.

Johannesburg, 1997

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

R. H. Bailie

1st day of December 1997

ABSTRACT

The felsic rocks of the Bushveld Complex are host to abundant, small polymetallic mineralisation. The study involved mapping and metallogenic characterisation of an area north of Bronkhorstspruit, in the acid phase of the Bushveld Complex.

The upper Rooiberg Group shows an evolution from rhyodacites of the Kwaggasnek Formation to rhyolites of the Schrikkloof Formation. The Rooiberg Group formed from the same magma that formed the underlying granophyres. The granites represent further fractionation of the same parental magma, evolving from grey hornblende-rich granites at the base of the sheet to red biotite-rich granites at the top.

Mineralisation is derived from highly fractionated granites that evolved to water saturation. Structural controls also influenced hydrothermal fluid flow. The mineralisation progresses from a magmatic Sn assemblage through a Cu-Pb-Zn assemblage to a late meteoric Fe-U-F assemblage superimposed on earlier assemblages. Progressive fluid mixing from magmatic to meteoric characterised the development of the paragenetic sequence.

To my parents Glen and Jean Bailie for their unending support

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CHAPTER 1

INTRODUCTION

1.1 General

The Bushveld Complex, situated in the central northeast portion of South Africa, is the world's largest known intrusive complex. The Complex, situated north of Pretoria, occupies a total area of approximately 67 340 km^2, with a long axis of approximately 470 km and a short axis of 380 km. The Complex is developed in three distinct lobes (Figure 1.1). The western lobe stretches from just north of Pretoria to Zeerust in the west and north to Warmbaths. The eastern lobe stretches from Pretoria to Burgersfort and Steelpoort in the east, and the northern lobe is developed around and to the north of Potgietersrus.

From a geological point of view, the Complex is of major scientific interest, not only due to its size, but also due to the development of the world's largest layered mafic intrusion (the Rustenburg Layered Suite), as well as one of the world's largest subaerially developed felsic volcanic suites, the Rooiberg Group (Twist and French, 1984). Associated with these rocks are large volumes of granites and granophyres.

From an economic point of view, the Complex represents a vast repository for a large portion of South Africa's mineral wealth. The mafic rocks of the Rustenburg Layered Suite are host to chromium, platinum, nickel, titanium and vanadium, whereas the acidic rocks of the Lebowa Granite Suite and its associated roof rocks are host to fluorite and tin mineralisation as well as innumerable, small, polymetallic deposits. A number of these form one of the main focuses of the present project.

Over the years the Lebowa Granite Suite and its related roof rocks have been relatively neglected, both s ientifically and in exploration endeavours, in favour of the economically richer Rustenburg Layered Suite. However, recently geologists have begun to appreciate the large, mostly untapped potential of the felsic rocks, particularly as hosts to polymetallic deposits, often with unusual mineral associations.

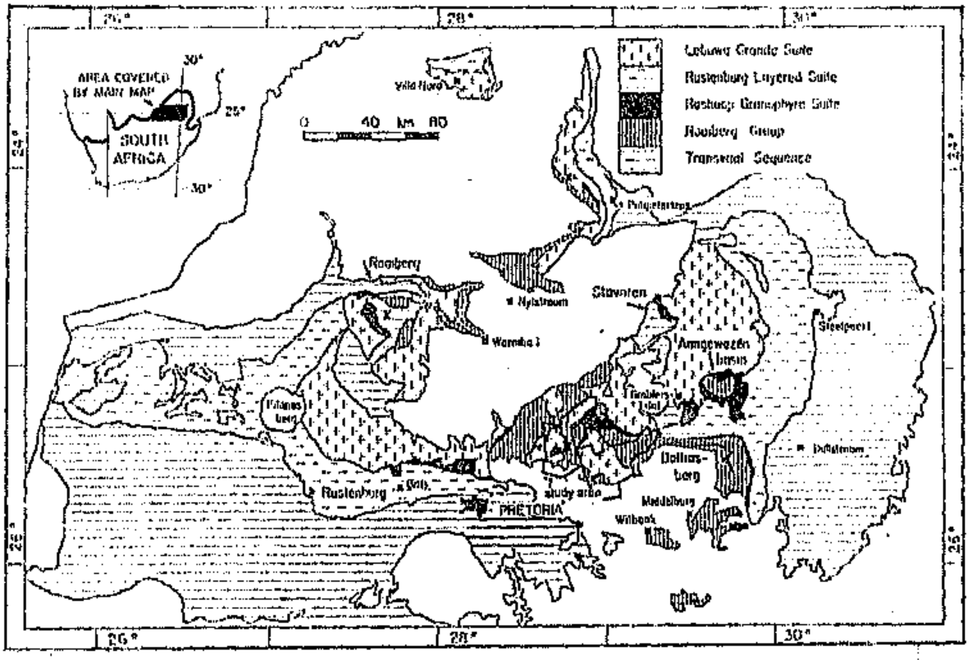


Figure 1.1: Location and generalised geology of the Bushveld Complex

(inset shows position of larger map)

1.2 Aims of study

The study was initiated by Rio Tinto Exploration Ltd., in conjunction with the University of the Witwatersrand, to examine the felsic rocks of the Bushveld Complex in an area north of Bronkhorstspruit as part of an exploration program of the Bushveld granites. The aims of the study were:

1. To map an area of felsic rocks of the Bushveld Complex, north of Bronkhorstspruit, consisting of volcanics of the Rooiberg Group, granophyres of the Rashoop Granophyre Suite, and the granitic rocks of the Lebowa Granite Suite. In addition to distinguish the different granite types in the area based on texture, mineralogy and colour. From this mapping a geological outcrop map of the area wa produced (see folder in back).
2. To study known mineral occurrences including their morphology, alteration assemblages, ore mineralogy, origin, relation to host rock and paragenetic sequences in an attempt to understand the nature of various polymetallic mineralisation styles in the felsic rocks of the Bushveld Complex. Along with this study a search for new mineral occurrences was carried out during the mapping.
3. An investigation, both petrologically and geochemically, of the rocks to determine their characteristics as an aid to exploration.
4. To investigate and consider the controls on mineralisation
5. Attempt a generalised model for polymetallic mineralisation within the felsic rocks of the Bushveld Complex.

The mapping was done on 1:10 000 aerial photographs and 1: 50 000 topographic maps. The outcrop data was then digitised at Rio Tinto Exploration Ltd. and printed at a scale of 1: 100 000 for use in this study (see folder in back).

Laboratory investigations, including petrographic and geochemical work was carried out at the Geology Department of the University of the Witwatersrand. Assaying and geochemistry of certain mineralised samples was carried out by Bergström and Bakker, Johannesburg, South Africa.

1.3 Locality and features of the study area

The study area is situated approximately 48 km north-east of Pretoria and 25 km north of Bronkhorstspruit as shown in Figure 1.2. The town of Groblersdal lies 28 km to the north-east and Witbank 28 km to the north-east of the margins of the study area. The area forms an arc 62 km in width from west to east, stretching from 28° 37' E to 29° 15' E, and approximately 45 km north to south along the longer western portion, stretching from 25° 13' S to 25° 40'S at its southernmost tip.

The area is arcuate owing to the presence of a number of settlements, namely Kwaggafontein, Tweefontein and Vlaklaagte 1 & 2 in the central portion of the arc, as well as the presence of two major nature reserves (see Figure 1.3). Mapping was not undertaken in and around the settlements in the central portion of the arc, and access to the nature reserves was restricted. This limited the size and shape of the study area. Nevertheless there are three major settlements within the study area. These are Moloto on the western border of the study area, KwaMhlanga in the west and Verena in the eastern central portion.

Other minor settlements such as Kameelpoort, Wolvenkop and Leeuwfontein also occur within the study area as well as extensions of Tweefontein and Vlaklaagte. Figure 1.3 shows the study area in greater detail.

The area covers rocks of the central acidic phase of the Bushveld Complex including granites of the Lebowa Granite Suite, granophyres of the Rashoop Granophyre Suite and rhyolites of the Rooiberg Group, and contains numerous small mineral occurrences of generally minor importance.

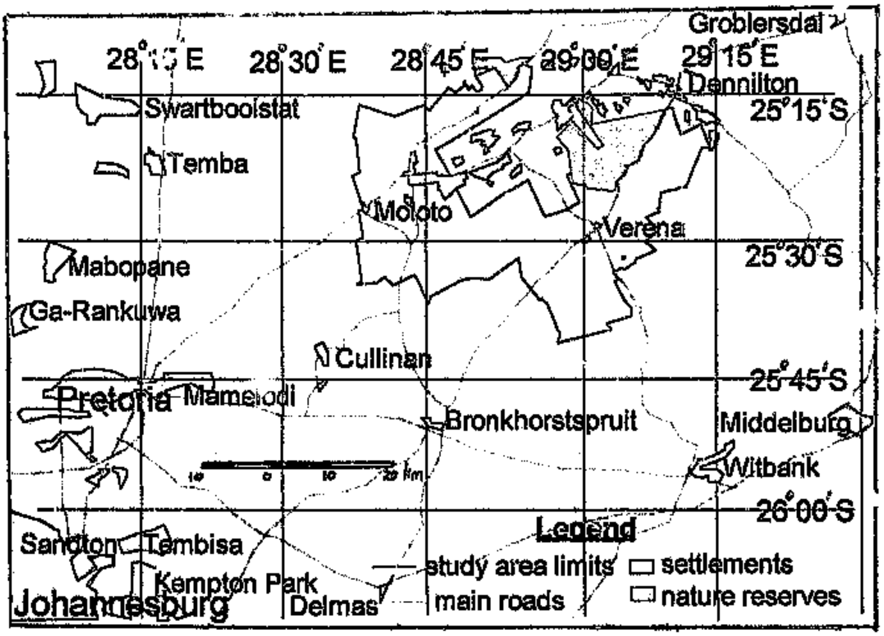


Figure 1.2: Location of the study area

1.3.1 Drainage

The area falls in the drainage basin of the easterly-draining Limpopo River on the South African - Zimbabwe border, and is thus drained by rivers flowing northwards or eastwards, which are tributaries to this river. The major river in the study area is the Wilge River that flows through the southern central portions of the area. To the east of the southern limb of the study area it flows into the Olifants River, which to the northeast flows into Loskop Dam and hence flows northwards (see Fig. 1.3).

The Moses River to the north drains the central portions of the study area where it flows in a northeasterly direction before flowing northwards. It flows to the west of Groblersdal where it joins up with the Olifants River. The Enkeldoringspruit drains the northwestern portion of the study area, flowing in a northerly direction before flowing into the Elands River, to the north of the study area. The Elands River subsequently

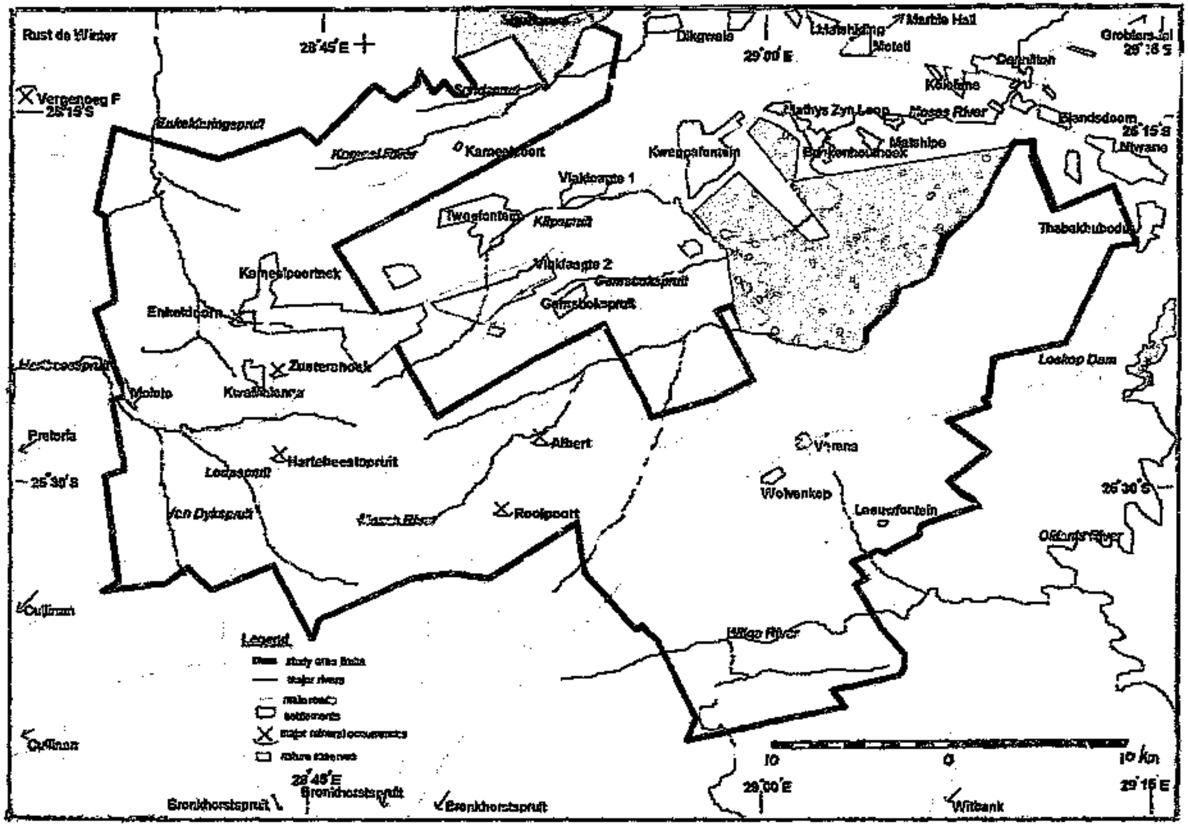


Figure 1.3: The study area and its major rivers

flows into the Olifants River. The southwestern portion of the study area is drained by a number of tributaries of the Elands River, which flows north to the west of the study area. The Van Dykspruit and Loopspruit both flow into the Hartbeesspruit which flows through Moloto westwards to the Elands River (see Fig. 1.3).

The northern portions of the study area are drained by the Kameelriver, with its tributary the Sandspruit, which flows into the Elands River to the north of Dikgwale (see Fig. 1.3). These rivers have influenced the topography and outcrop of the area.

1.3.2 Topography

The study area is on a plateau with an elevation of approximately 1350 m. In the northern extremities of the study area an escarpment is developed on the farms Zandspruit 189 JR and Malock Zyn Kop 58 JS (see Fig. 1.4). North of this escarpment, around Dennilton, Matsuiding and Dikgwale (see Fig. 1.3), the land drops off to form the low flat-lying country of the Springbok Flats.

The escarpment is developed along a ESE - WNW trend stretching from the area to the east of Vreemdeling 65 JS all along to Zandspruit 189 JR (see Fig. 1.4 and folder for farm positions), before it turns to the southwest. The land rises from elevations of approximately 950 m on the Springbok Flats to 1400 m along the escarpment (see Fig. 1.4 below).

To the south of the escarpment the land rises gently, with local highs on the farms Engelschedoornboom 95 JS and Rooipoort 440 JR. Rivers such as the Kameel River, the Enkeldoringspruit and the Wilge River have cut down into the plateau. In the extreme southern portion of the study area the land rises to above 1500 m, where sediments of the Waterberg Group are developed to the south of the Wilge River. It is found that the granite plutons generally form lower, gently undulating country with the roof rocks of granophyres and rhyolites forming higher, hilly country.

A notable topographic landmark is Rhenosterkop found in the south central portion of the study area near the Verena - Bronkhorstspruit road (see folder and Fig. 1.4). Rhenosterkop forms a distinctive hill, rising 270 m above the surrounding countryside, with a gentle slope on its southern side and a steep slope on its northern side. The hill is the site of spectacular agglomerates, and hence has led previous workers (Twist, 1983) to consider it as a volcanic vent for the Rooiberg Group, developed to the northeast of the hill.

1.4 Previous Investigations

Abundant work has been done on the more important tin and fluorite deposits such as the Rooiberg and Zaaiplaats tin deposits hosted elsewhere in the Bushveld Complex. However, relatively little work exists on descriptions of the rocks in and around the study area. The most notable work, that borders onto the present study area, is that of De Bruiyn (1980), who investigated the rhyolites, granophyres and granites north of Pretoria, with the easternmost portion of his study area coinciding with the western portion of the present study area.

De Bruiyn (1980) described the different rock types, both petrographically and geochemically, and then used geostatistical techniques to study their interrelationships. He concluded that the acidic rocks are all genetically related to each other, and formed by progressive evolution of a granitic magma.

Walraven (1986) attributed compositional layering, seen as stratigraphic variations in mineralogy and composition, to differentiation of the parent magma. Walraven's (1986) trace element differentiation index (TEDI) given as Ba × (Sr / Rb), can be used to determine the level in the granite sheet, and can be used in exploration, since ore deposits will be found in the more differentiated portions of the sheet where incompatible elements such as tin, copper and lead will be concentrated. Walraven *et al* (1990b) suggested that Rb and Sr isotopes could also be used as indicators of

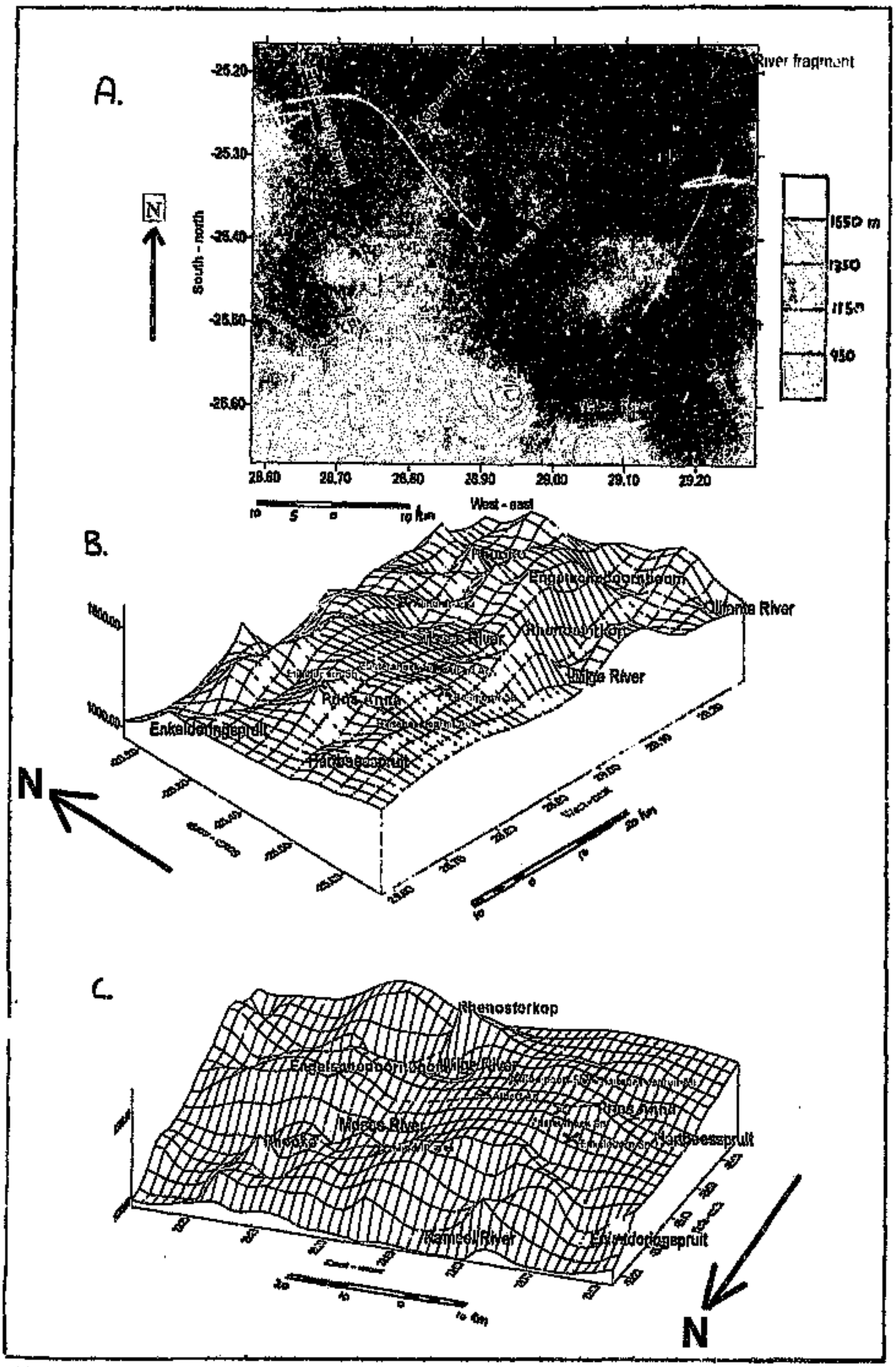


Figure 1.4: Topography and drainage of the study area. A: Topographic plan of the study area with oranges and yellows representing higher ground and purples lower ground. B: Topography seen from the southwest. C: Topography seen from the northwest. Vertical exaggeration about 25 times.

mineralisation in the granites, as their ratio changes with increasing fractionation of the granitic magma.

Lenthall (1972c) proposed a tentative model for the evolution and development of the Bushveld granites. Lenthall (1975) undertook geological mapping and sampling of the granites in the Moloto, Zusterstroom and Dennilton areas, in an attempt to demarcate potential tin-bearing areas and to determine the characteristics of both mineralised and non-mineralised Bushveld granites. Hunter and Lenthall (1971) described the geochemistry of the acid phase of the Bushveld Complex, but concentrated more on the geology around Zaaiplaats.

De Bruiyn and Rhodes (1975) described the Makhutso granite, the youngest granitic phase of the felsic rocks, found immediately to the north of the central portion of the study area, while Walraven (1988) determined the age of the Makhutso granite as approximately 2049+69-72 Ma (Pb-Pb whole rock). This placed an upper age restriction on the age of intrusion of the Bushveld granites as Walraven and Hattingh (1993) showed that the age of the granites of the Lebowa Granite Suite are 2054,4 ± 1,8 Ma years old, using Pb-Pb evaporation techniques on single zircons.

Walraven (1982) studied only the granophyric rocks of the Complex, with the granophyric rocks in the study area forming part of his study. He concluded that the Stavoren Granophyre, in his nomenclature, is the most prominent and abundant granophyric rock in the Bushveld Complex, and was emplaced as a magmatic intrusion below the volcanic rocks of the Rooiberg Group, with which it is cogenetic. Lenthall (1971) proposed a nomenclature system for the granophyres, which used the nature of the under- and overlying rocks for its classification. De Bruiyn (1980) used a similar scheme in his study of the acid rocks north of Pretoria. The age of the Rooikop Granite Porphyry was recently determined to be 2060±2 Ma (Walraven, 1997). This unit is considered to be contemporaneous with the Rashoop Granophyre Suite.

French and Twist (1983) gave a generalised description of the Rooiberg Group. Clubley- Armstrong (1977) described the geology of the Rooiberg Group around Loskop Dam, to the east of the study area, and proposed a new stratigraphic subdivision of the Group based on the relations exposed around the Dam. Schweitzer *et al* (1995a) re-evaluated the rocks of the Rooiberg Group, and concluded that they should be sub-divided into the Dullstroom, Damwal, Kwaggasnek and Schrikkloof Formations based on lithology and geochemistry. Only the upper Rooiberg Group comprising the Kwaggasnek and Schrikkloof Formations is found in the study area. Recently Walraven (1997) determined the age of the rhyolites of the Rooiberg Group to be 2061±2 Ma using a single zircon Pb-Pb method.

Mellor (1905) described the geology of Rhenosterkop, a possible volcanic vent for the Rooiberg Group. Clubley - Armstrong and Sharpe (1979) examined the structural evolution of the Dennilton Dome and its relationship to the intrusion of the Bushveld Complex.

Merensky (1908) described the rocks of the Bushveld Complex in which tin could be expected, and gave brief descriptions of some of the occurrences in the study area. Twist (1983) evaluated the economic potential of the Rooiberg Group, and concluded that it could be a host to mineralisation in its own right, and not simply a repository for mineralisation derived from the underlying granites, as is usually found. He described possible exploration models and target types for mineralisation in the Rooiberg Group. Schweitzer *et al* (1995b) also evaluated the economic potential of the Rooiberg Group but concluded that mineralisation in the rhyolites is derived from the underlying Rustenburg Layered Suite or the Bushveld granites. However, they did not rule out the possibility that the Rooiberg Group may be host to volcanogenic deposits derived directly from volcanic activity.

Crocker (1979) described various fluorite, tin and associated rare metal - carbonate mineralisation and alteration associated with mineral deposits throughout the Bushveld granites. Hunter (1971) examined some of the controls on tin mineralisation in the acidic rocks of the Bushveld Complex, whereas Lenthall (1974) described the tin production from the Bushveld Complex, including the small, now defunct workings in the study area. Scogings (1991) evaluated the base metal potential of the Bushveld Granites in the former homeland state of KwaNdebele, within which the study area is located.

Detailed descriptions, however, of the various mineral occurrences in the study area are limited and usually only deal with one occurrence and do not include similar deposits. Few authors have attempted a generalised model for mineralisation associated with the acidic rocks of the Bushveld Complex or within the associated roof rocks.

Champion (1970) described the mineralogy of the Albert Silver Mine in detail, whereas Van Ziyl (1965) studied the geophysical responses of the same deposit, but could not draw any specific conclusions. Robb *et al* (1994) re-examined the deposit and concluded that ore-bearing fluids had welled up beneath a fine-grained apical phase of the granite, thus forming the ore deposit. This mineralisation style can be genetically related to the origin of other well-known deposits in the Bushveld granites, such as the Rooiberg and Zaaiplaats tin mines.

Martini and Vorster (1994) described, in general, all the mineral occurrences found on the 1: 250 000 geological sheet of the area north and east of Pretoria. The mineral occurrences in the study area fall on this 1: 250 000 metallogenic map, and generalised descriptions of some of the occurrences are given by Martini and Vorster (1994).

1.5 Research Methods and Analytical Techniques

The study area was mapped on 1: 50 000 topographic maps and sampled, with a careful distinction made between the different granitic phases, in order to ascertain whether certain granite types are more likely to be mineralised than others. Known deposits were mapped, studied and sampled, and any features which may be related to, or indicate mineralisation were mapped and sampled. In doing so, a comprehensive geological outcrop map of the area was produced (see folder in back).

Polished thin sections, as well as polished sections, were cut so that the petrography of the various rock types and mineralisation styles could be studied and characterised.

The geochemistry of a representative group of samples, numbering 43, was determined by using a Phillips 1400 X-ray fluorescence (XRF) spectrometer at the University of the Witwatersrand, for both major and trace elements. Samples from the major mineral occurrences, such as the Zustershoek Tin Mine and the Albert Silver Mine, along with representative samples from all of the rock types, were assayed for base and precious metal values by Bergström and Bakker, Johannesburg, South Africa, using the fire assay method. Bergström and Bakker undertook assays on the most mineralised samples. All crushing, sample preparation and analyses were carried out by the author at the University of the Witwatersrand.

Determinations of whole rock Fe^{2+} / Fe^{3+} ratios, using the method described by Wilson (1960), were done to characterise differences in the ferrous to ferric ion in granites from different heights in the granite sheet, and varying degrees of alteration associated with mineralisation (for the analytical technique see appendix B). These determinations were carried out by the author in the geochemistry laboratory of the University of the Witwatersrand.

Petrographic fluid inclusion studies were undertaken at the University of the Witwatersrand to determine the nature of the ore-bearing fluids, and to test the hypothesis of two fluids of differing origin mixing to form a wide range of metal associations in mineralised areas.

CHAPTER TWO

STRATIGRAPHY

2.1 Stratigraphy of the Study area

The study area consists predominantly of the felsic rocks of the Bushveld Complex, which includes the Rooiberg Group, which in many areas forms the roof rocks to the Complex, the Rashoop Granophyre Suite, mostly underlying the rhyolites of the Rooiberg Group, and the Lebowa Granite Suite, comprising a number of different lithological types. The mafic rocks of the Rustenburg Layered Suite are not developed in the area. Sedimentary rocks of the Waterberg Group, dated at 1735±50 Ma (Burger and Coertze (1973), Pb-Pb and Pb-U methods) and Karoo Supergroup, dated at 187±7 Ma for Drakensberg basalts in Lesotho (Fitch and Miller, 1971, K-Ar), are found in the area, but do not directly form part of the studied rocks.

The Bushveld Complex is exposed in three major lobes. A western lobe is developed between Pretoria and Warmbaths, and stretches westwards beyond Rustenburg and the Pilanesberg into Botswana. The eastern lobe stretches from northeast of Pretoria to Middelburg and Steelpoort in the east. The northern lobe, which outcrops on a smaller scale, is exposed to the west and north of Potgietersrus.

A fourth southern lobe is known to exist to the south of Witbank and Middelburg, by the presence of inliers of Rooiberg Group and Nebo granite in younger Karoo strata, such as the Balmoral Granite north-northeast of Argent (SACS, 1980).

The Bushveld Complex is subdivided into two major suites: the mafic rocks of the Rustenburg Layered Suite, and the felsic rocks of the Lebowa Granite Suite and its related roof rocks. The Lebowa Granite Suite outcrops over a large area in the central part of the Bushveld Complex (Fig. 1.1). Age data for the two main suites as well as other dates for the Transvaal Supergroup, the Rooiberg Group and the Rooikop Granite Porphyry, thought to be an equivalent age to the Rashoop Granophyre Suite (Walraven, 1997), are given in Table 2.1.

The Transvaal Supergroup, which covers most of the northeastern portion of South Africa, has the Wolkberg Group, developed in the Eastern Transvaal (Truter, 1950, SACS, 1980), at its base, overlain by the extensive Black Reef Quartzite Formation (SACS, 1980). The predominantly calcareous Chuniespoort Group overlies this horizon (SACS, 1980). Unconformably overlying this Group are the alternating argillaceous and arenaceous sediments of the Pretoria Group (SACS, 1980). This group contains volcanic horizons within it, such as the Hekpoort lavas (SACS, 1980), dated at 2224±21 Ma (Burger and Coertze, 1973) and the Machadodorp volcanics (Button, 1973).

Numerous doleritic and gabbroic sills intrude into the upper levels of the Pretoria Group, and are believed to be feeders to the Bushveld Complex (Cawthorn *et al*, 1981). The end of Pretoria Group sedimentation was marked by extensive volcanism, beginning with the Dullstroom Formation developed on the margins of the Bushveld Complex, particularly in the area surrounding Loskop Dam. Overlying this is the Damwal Formation developed exclusively in the Loskop Dam area (Clubley-Armstrong (1977)). SACS (1980) previously regarded these two formations as being the uppermost formations of the Pretoria Group, before the extrusion of the volcanics of the Rooiberg Group. However, Schweitzer *et al* (1995a) have argued for their inclusion into the Rooiberg Group, where they form the lower part of the Rooiberg Group overlain by the Kwaggasnek and Schrikkloof Formations of the upper Rooiberg Group (Schweitzer *et al*, 1995a).

These latter two formations were previously termed the Selons Rivier Formation by SACS (1980). Only the upper Rooiberg Group (the Kwaggasnek and Schrikkloof

ROCK UNIT	Age (Ma)	No.	Method	Material	Reference
Bushveld complex and post-Transvaal intrusives					
Makhutso granite	2049+69-72		Pb-Pb	whole rock	Walraven (1988)
Nebo granite, Lebowa Granite Suite	2054±2		Pb-Pb	single zircon	Walraven and Hattingh (1993)
Upper Zone, Rustenburg Layered Suite	2061±27	33	Rb-Sr	whole rock	Walraven *et al* (1990a)
Stavoren Granophyre, Rashoop Granophyre Suite	2053±12		U-Pb	bulk zircon	Coertze *et al* (1978)
Rooikop Granite Porphyry	2060±2		Pb-Pb	single zircon	Walraven (1997)
Rooikop Granite Porphyry	2066±10	8	U-Pb	bulk zircon	Faurie (1977)
Transvaal Supergroup					
Rhyolite, Selons River Formation, Rooiberg Group	2061±2		Pb-Pb	single zircon	Walraven (1997)
Dullstroom Basalt Formation	2234±443	9	Rb-Sr	whole rock	Walraven (1987)
Dullstroom Basalt Formation	2101±28		Various	whole rock	Schweitzer (1986)
Hexpoort Andesite Formation	2224±21		Rb-Sr	whole rock	Burger and Coertze (1973)
Timeball Hill Formation, Pretoria Group	2208±63	10	Rb-Sr	whole rock	Hunter and Hamilton (1978)
Oak Tree Formation, Chuniespoort Group	2550±3	32	Pb-Pb	single zircon	Walraven and Martini (in press)
Abel Erasmus Formation, Wolkberg Group	2138+46/-47	6	Pb-Pb	whole rock	Armstrong (1987)
Godwan Formation	2325+69/-73	9	Pb-Pb	whole rock	Armstrong (1987)

Table 2.1 Age determinations for various rock units within the Transvaal Supergroup and making up the Bushveld Complex

Formations) is found in the study area. The Rooiberg Group forms the roof of the Bushveld Complex and has an age of 2061±2 Ma, determined by Pb-Pb single zircon work by Walraven (1997).

Massive, seemingly homogeneous rhyodacites and rhyolites of between 1500 m to 2500 m thickness dominate the Kwaggasnek Formation, forming the lower part of the upper Rooiberg Group. Its top is marked by a conspicuous zone of quartzite xenoliths, ranging in size from a few cms up to 5m in size, in a zone approximately 20 m thick (De Bruiyn, 1980). A prominent agglomerate layer overlies this, and is in turn overlain by a tuffaceous shale layer, that comprise the Union Tin Member of the Kwaggasnek Formation. Overlying this is the predominantly flow banded rhyolites of the Schrikkloof Formation, which has a prominent ash flow tuff and agglomerate at its top (De Bruiyn, 1980).

Conformably developed above the Schrikkloof Formation is a sequence of shale, sandstone, conglomerate, granophyre and rhyolite known as the Loskop Formation (Coertze *et al*, 1977). This formation, having an age of deposition between 2100 and 2200 Ma (SACS, 1980), marks the end of volcanism and sedimentation in the Transvaal Basin (Coertze *et al*, 1977), so that it was deposited around the time of intrusion of the Bushveld Complex and prior to Waterberg Group sedimentation at about 1750 Ma (Burger and Coertze, 1973).

The Rashoop Granophyre Suite, which is intimately associated with the Rooiberg Group and Lebowa Granite Suite, is found to take up different stratigraphic positions. The predominant type is that which is found between the Bushveld granite below and the Rooiberg Group above. De Bruiyn (1980) called this type the Stork River Granophyre. The second type is found between the Bushveld granite and the overlying Transvaal Sediments, and was called the Stavoren Granophyre by De Bruiyn (1980). The third type, which is of limited extent, is the Blinkwater Granophyre (De Bruiyn, 1980), which is developed between the Rustenburg Layered Suite and the Lebowa Granite Suite.

Walraven (1982), who undertook a detailed study of the granophyric rocks, preferred the term Stavoren granophyre for those rocks representing the magmatic intrusion below the Rooiberg Group. This granophyre type is the most abundant of the types found in the Bushveld Complex, and is considered to be syngenetic with the Rooiberg Group.

The Rustenburg Layered Suite, dated at 2061±27 Ma (Walraven *et al* (1990b) Rb-Sr whole rock), intruded into the uppermost levels of the Pretoria Group. Its roof rocks consist of Pretoria Group sediments such as at Potgietersrus, Rooiberg Group rocks such as the area to the north of Loskop Dam, the Rashoop Granophyre Suite such as the area north of Brits, and the Lebowa Granite Suite such as in Sekhukhuniland to the east of Groblersdal.

The last phase of the Bushveld Complex was marked by the intrusion of the Lebowa Granite Suite, with the age of the Nebo granite given as 2054±2 Ma (Walraven and Hattingh (1993)(single zircon Pb-Pb dating). This granite, which in the past has been called the Red Granite or Bushveld granite, is now recognised as being made up of different granite types, which differ slightly in composition, appearance, texture and field relations. The predominant type is known as the Nebo granite, which is a grey to red coarse-grained granite. Various local terms for this granite in specific geographic locations, such as Sekhukhuni granite for the grey coarse-grained granite found predominantly on the Sekhukhuni plateau to the east of Groblersdal, or the coarse porphyritic Verena granite developed in a pluton to the west of Verena township. are taken to be textural varieties of the Nebo granite.

Specific names are given to two distinct granite types of the Lebowa Granite Suite. One of these is the Bobbejaankop granite, whose type area is in the vicinity of the Zaaiplaats Tin Mine near Potgietersrus (Strauss, 1955). This granite variety is a dark red, coarse-grained granite characterised by deep red earthy K-feldspars, abundant coalesced quartz with a chain-like appearance, and a very low mafic mineral content. The Bobbejaankop granite is intimately associated with tin mineralisation at

Zaaiplaats. De Bruiyn (1980) preferred to call granites of this type Klipvoor granite in his study area, preferring to keep the name Bobbejaankop granite as specific to the Zaaiplaats type area.

The second special granite type is the Klipkloof granite, a fine-grained, aplitic, pinkish brown granite that is found as dykes or sills in the Nebo granite, and is considered to be the fractionated end member of the Nebo granite. It has an age of 2038+170-192 Ma (Pb-Pb whole rock, unpublished data-F. Walraven).

Other granite names, such as the Main and Lease granites, are very specific to certain type localities, and will not be considered. Recent studies by Walraven and Hattingh (1993) have established the age of the Nebo granite at 2054,4 ± 1,3 Ma using single zircon Pb-Pb dating.

A younger granite, known as the Makhutso granite (De Bruiyn and Rhodes, 1975), is developed in an area to the north of the Verena granite. Its field relations, composition and age suggest that it is not part of the Nebo granite sheet, but that it intruded after all the other granites, and was probably not related to the magma forming the Nebo granite (De Bruiyn and Rhodes, 1975). Its age is 2049 + 69 - 72 Ma (Pb-Pb whole rock)(Walraven, 1988). This age is younger, within a margin of error, than the Nebo granite.

Table 2.1 gives ages of various units in the Transvaal Supergroup and Bushveld Complex. The Rooiberg Group, dated at 2061±2 Ma (Walraven, 1997) followed Transvaal Group sedimentation. This was followed shortly afterwards by the Rashoop Granophyre Suite, thought to have an equivalent age to the Rooikop Granite Porphyry of 2060±2 Ma (Walraven, 1997). The Rustenburg Layered Suite (RLS) followed shortly after (2061±27 Ma)(Walraven *et al*, 1990b), owing to the recognition of granophyre xenoliths in the RLS (Walraven, 1987). The Nebo granite intruded at 2054±2 Ma (Walraven and Hattingh, 1993) so that it intrudes into both the Rooiberg lavas and the granophyres, as suggested by contact relationships (see Chapter 4). The

Makhutso granite has a younger age; but has a large error margin; of 2049+69-72 Ma (Walraven, 1988), making it a later, separate intrusion.

The Rooiberg Group is overlain conformably by sandstones, shales and conglomerates of the Waterberg Group (SACS, 1980), which were deposited soon after intrusion of the Bushveld Complex. To the south of the study area glacial tillite of the Dwyka Formation and the coal-bearing horizons of the Ecca Formation of the Karoo Supergroup outcrop. Table 2.2 gives a stratigraphic subdivision of the units developed in and around the study area.

Table 2.2: Stratigraphy of the study area

Rock Group	Sedimentary Rocks		Igneous Rocks	
Karoo Supergroup	Ecca Group	sandstone, shale, conglomerate, coal		
	Dwyka Formation	tillite, shale		
			undifferentiated diabase / dolerite sills	
			porphyritic biotite granite, fine-grained in places	Makhutso Granite
			pinkish brown aplitic fine-grained granite	Klipkloof Granite
Waterberg Group	Wilgerivier Formation	sandstone, shale, conglomerate	red medium to coarse-grained granite	Bobbejaankop Granite
			pinkish white coarse-grained porphyritic granite	Nebo granite (var. Verena Granite)
			grey, pink to red medium to coarse-grained granite	Nebo granite (var. Sekhukhuni granite)
			granophyre, micro-granophyre, porphyritic granophyre	Rashoop Granophyre Suite
	Loskop Formation	shale, sandstone, conglomerate	rhyolite, granophyre, pyroclastic volcanics	
Rooiberg Group	Schrikkloof Formation	impersistent volcanic breccia, tuff and agglomerate near base, sandstone lenses	red, brown and pale coloured rhyolite with flow-banding	
	Kwaggasnek Formation	scattered quartzite xenoliths	red, dark brown and black rhyolite with locally developed contorted flow-banding near top	

CHAPTER 3

DESCRIPTION OF THE ACIDIC ROOF ROCKS

3.1 Introduction

The Rooiberg Group and the Rashoop Granophyre Suite are major components of the roof rocks to the Bushveld Complex. They will be considered together in this chapter. The relationship of the Rooiberg Group to both the mafic and felsic phases of the Bushveld Complex make it an important sequence to consider in any discussion of the felsic rocks of the Complex. The granophyres are intimately associated with both the granites of the Lebowa Granite Suite and the rhyolites of the Rooiberg Group and in most cases, but not all, form an intermediate suite between the two.

3.2 The Rooiberg Group

3.2.1 Introduction

The Rooiberg Group has significant interest in any study of the felsic rocks of the Bushveld Complex, as it often forms the roof rocks to the granites (SACS, 1980), as is seen in the study area, the Rooiberg Fragment and near Potgietersrus. The rocks of the Rooiberg Group are also significant, in that they represent a large volume, more than 300 000 km^3 (French and Twist, 1983), of felsic magmatism. In addition they have a thickness of more than 5 km in areas (French and Twist, 1983), and so represent one of the world's largest terrestrial acid volcanic provinces.

The Rooiberg Group is intimately associated with the Bushveld Complex, having been extruded approximately simultaneously with the intrusion of the Rustenburg Layered Suite. Extruded at 2,061±2 Ma (Walraven, 1997), the Rooiberg Group was subsequently intruded by the mafic, and later by the felsic phases of the Complex. The relatively large error in the Rb-Sr whole rock of the Rustenburg Layered Suite (RLS)(Walraven, 1997), as well as evidence for granophyre xenoliths in the RLS (Walraven, 1987) would point to Rooiberg extrusion and granophyric intrusion (at 2060±2 Ma (Pb-Pb single zircon)-Walraven (1997)) prior to RLS intrusion. As such, the Rooiberg Group acts as a host to mineralisation derived from the underlying granites and possibly the mafic rocks (Schweitzer *et al*, 1995b), such as the Union Tin Mine north of Nylstroom or the Swartkloof fluorite mine near Warmbaths.

3.2.2 Stratigraphy

The large extent of the Group, its uniform character, and lack of reasonably good outcrop in most of the Transvaal Basin, has in the past led to difficulties in subdividing the succession into subgroups and formations and in correlating lithologies from one area to the next. As a result, previous investigators have tended to devise their own stratigraphy for the sequence, using such criteria as texture, structure and colour. Thus difficulties have arisen when trying to correlate these formations and developing a uniformly acceptable stratigraphic column for the sequence.

Early workers used textural and structural features in their stratigraphic subdivision, but their subdivisions cannot be employed for regional stratigraphic correlations, due to the lateral variability of the criteria used (Schweitzer *et al*, 1995a). However, numerous workers have identified a prominent agglomerate unit underlain by a zone of quartzite xenoliths. Above this agglomerate, the rhyolites are strongly flow-banded, and overlain at the top by an ash-flow tuff. These observations have been made in widely separated areas, such as Nylstroom and Warmbaths, west of Potgietersrus, and north of Pretoria.

Workers such as Clubley-Armstrong (1977) and Twist (1985) have extensively studied the Bothasberg Plateau, in the area around and to the east of Loskop Dam. Clubley-Armstrong (1977) identified a breccia or tuff overlain by mudstone, sandstone, shale and / or tuff. Clubley-Armstrong (1977) used this horizon to subdivide his upper Selons River Formation into a lower Doornkloof and an upper Klipnek Member. At the base of the Selons River Formation, the same author identified a prominent quartzite unit, which he used to separate a lower Damwal Formation from an upper Selons River Formation. The Damwal Formation is only found on the Bothasberg Plateau, and is not found to the west of Loskop Dam.

SACS (1980) accepted Clubley-Armstrong's (1977) subdivision for the Rooiberg Group in the eastern Transvaal, but kept the terms Kwaggasnek and Schrikkloof Formations for the Group for the western Transvaal, where the agglomerate layer, underlain by quartzite xenoliths in a layer 1 to 3 m thick, separates the two formations. De Bruiyn (1980) preferred to use the subdivision of the Kwaggasnek and Schrikkloof Formations in his investigation of the felsic rocks north of Pretoria. He identified a prominent agglomerate horizon underlain by quartzite xenoliths, and used this to separate the two formations, where the lower Kwaggasnek Formation showed a more massive nature compared to the more flow-banded upper Schrikkloof Formation, which is capped by a volcanic tuff horizon.

Schweitzer *et al* (1995a) used all of the observations of previous workers, as well as their own observations, to propose a new subdivision for the Rooiberg Group. The criteria they used were marker horizons such as:

- the pyroclastic flow at the top of the Schrikkloof Formation / Klipnek Member
- pronounced flow-banding throughout the Schrikkloof Formation / Klipnek Member
- an agglomerate and / or volcanic breccia at the top of the Kwaggasnek Formation / Doornkloof Member,
- a shale / tuff horizon at the top of the Kwaggasnek Formation / Doornkloof Member, and
- quartzite xenoliths at the top of the Kwaggasnek Formation / Doornkloof Member.

They proposed that Clubley-Armstrong's (1977) Selons River Formation be disregarded, and that the sequence be subdivided into the lower Kwaggasnek and the upper Schrikkloof Formations. This would also make Clubley-Armstrong's (1977) Doornkloof and Klipnek Members obsolete. The Damwal Formation, found beneath the Kwaggasnek Formation, is developed only in the Loskop Dam area and it, together with the Dullstroom Formation forms the lower part of the Rooiberg Group, which is, in turn, overlain by the Kwaggasnek and Schrikkloof Formations. The proposed subdivision (after Schweitzer *et al*, 1995a) is given in Table 3.1.

Table 3.1: Proposed subdivision of the Rooiberg Group

(after Schweitzer *et al*, 1995a)

GROUP	FORMATION	MEMBER
UPPER ROOIBERG	Schrikkloof	
	Kwaggasnek	Union Tin
LOWER ROOIBERG	Damwal	
	Dullstroom	

The Union Tin Member is found at the top of the Kwaggasnek Formation, and consists of the agglomerate and shale horizon found above the quartzite xenoliths. The uppermost tuff, agglomerate and quartzite horizon, found at the top of the Schrikkloof Formation, called the Rust de Winter Member by De Bruiyn (1980), is found outside the study area, to the northwest, around the Rust de Winter dam.

Lying above the Rooiberg Group and below the Waterberg Group is the Loskop Formation, which represents the final stages of sedimentation in the Transvaal basin, before the Waterberg Group was laid down. For convenience the Loskop Formation is placed into the uppermost portions of the Rooiberg Group, due to the presence of large amounts of volcanics, along with sediments, in the sequence. It is always found between the Rooiberg Group and the Waterberg Group, suggesting that it is a transitional horizon from the volcanic succession of the Rooiberg Group to the clastic sedimentation of the Waterberg Group.

The Loskop Formation consists of purplish black shales, reddish-brown sandstones, conglomerates as well as coarse agglomerate, black rhyolite and granophyre in places. The Loskop Formation outcrops in the southwestern portion of the study area and, notably, at Rhenosterkop, on the farms Rietfontein 446 JR and Rhenosterkop 462 JR in the south central part of the study area. This hill, rising 270 m above the surrounding landscape, has been considered a possible volcanic vent to the Rooiberg Group (Twist, 1983), but to date has only been investigated once (Mellor, 1905a).

Figure 3.1 shows the general distribution of the different formations of the Rooiberg Group in the study area. Figure 3.2 shows an approximate stratigraphic column of the Rooiberg Group and Loskop Formation as found in the study area.

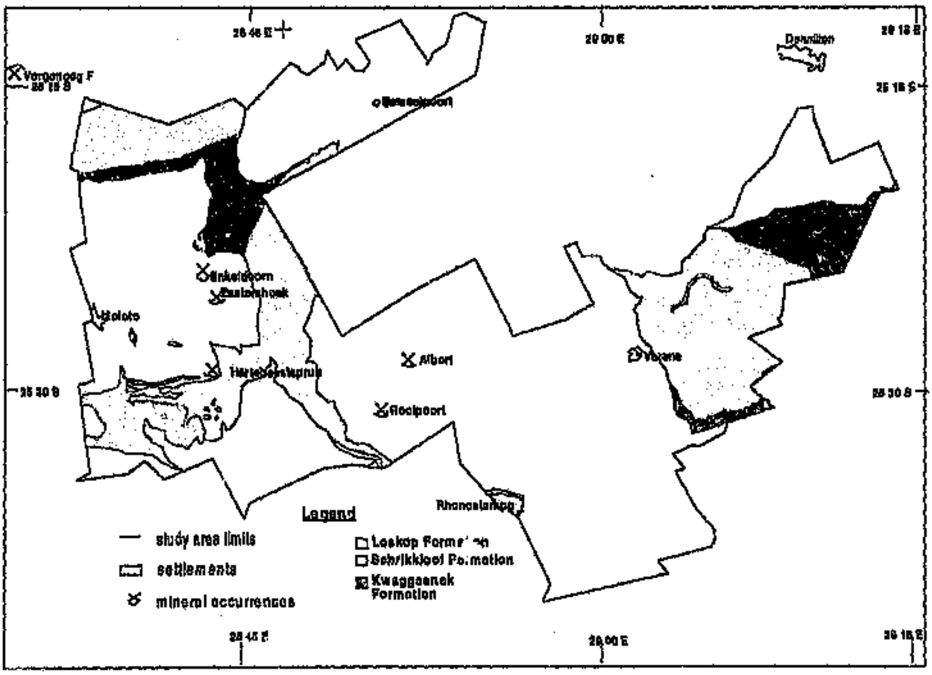


Figure 3.1: General distribution of the Rooiberg Group and the Loskop Formation in the study area

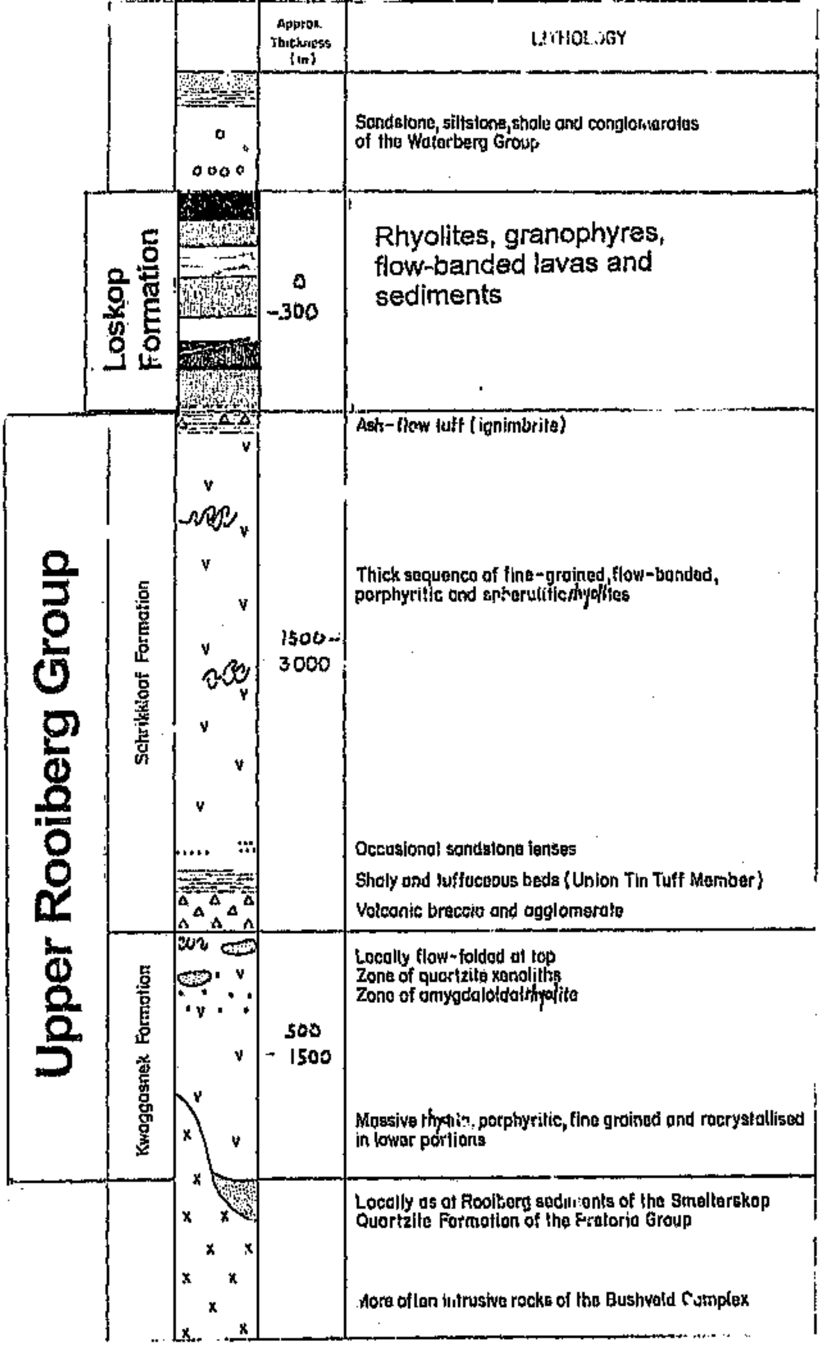


Figure 3.2: Stratigraphic column of the Rooiberg Group and Loskop Formation in the study area

3.3 The Rooiberg Group in the study area

3.3.1 Kwaggasnek Formation

3.3.1.1 General Description

The Kwaggasnek Formation is characterised by massive dark red, dark brown to black rhyolite. The rhyolite is often vesicular as well as porphyritic with plagioclase feldspar phenocrysts typically 2 mm in size. A distinctive feature of the formation is the lack of flow-banding, as well as interspersed agglomerates, tuffs or sedimentary lenses of any type. The rhyolite would seem to have been extruded under very quiet, non-explosive conditions, and to have been extruded subaerially due to lack of sedimentary intercalations.

Near the top of the formation a horizon, varying from a few centimetres up to 3 m in size, is found, consisting of quartzite xenoliths. These are mostly all recrystallised, but sometimes do show crossbedding, such as a large xenolith 3 m in diameter on the farm Rietfontein 90 JS. These xenoliths most likely derived from the underlying upper Pretoria Group, where quartzite units were broken up and disturbed during the passage of the magma to the surface.

Above this quartzite xenolith horizon, the rhyolite exhibits flow banding just beneath a prominent agglomerate horizon, separating it from the overlying Schrikkloof Formation. At this time, from the xenoliths through the agglomerate, the volcanism became more active (flow banding) and explosive (xenoliths and agglomerate).

3.3.1.2 Petrographic description

3.3.1.2.1 *Massive felsite*

The massive felsite is fine to very fine grained, with most groundmass grains less than 0,06 mm. The groundmass consists of quartz, feldspar grains, generally plagioclase feldspar and lesser potassium feldspar (K- feldspar), which have been extensively sericitised as well as altered to clay minerals. The plagioclase in the groundmass can reach 0,125 mm in size at its largest, but is generally smaller.

Dust fine ore, either magnetite (typically) or lesser hematite is also a constituent of the groundmass, and is typically very small in size (< 0,02 mm). Often the dust ore segregates together in clusters up to 0,25 mm in size.

The rhyolite is porphyritic in places, with plagioclase phenocrysts being the most dominant type. The plagioclase phenocrysts vary in size from 1 to 2,5 mm, and are euhedral in shape, though they are often highly sericitised, so that their exact composition could not be accurately determined. A few determinations of some lesser sericitised grains gave compositions of around An_{30} Plagioclase occasionally displays a swallow-tailed termination on laths 0,25 mm to 0,5 mm in size.

Other phenocrysts present include subhedral quartz 0.5 mm to 0,125 mm in size, though an euhedral quartz phenocryst 0,2 mm in size was found, and K- feldspar, which has been highly chloritised and sericitised, varying in size from 1 mm to 1,70 mm. Anhedral hematite and magnetite grains can grow to sizes of 1,45 mm, but are more often found in clusters, which can reach 1 mm in size. The magnetite is also often associated with the feldspar phenocrysts, where it is associated with chloritic alteration of feldspar. Hornblende occurs as dark rust red brown anhedral grains 2,5 mm in size, which have been extensively chloritised and hematised (see Plate I - B).

Chlorite is also found in the rhyolite, often as an alteration product of the feldspar phenocrysts, where it is associated with magnetite, and occasionally as grains 0,125 mm to 0,2 mm in size scattered throughout the groundmass. Iron oxyhydroxide staining is often found, particularly with hematite / magnetite alteration, and when in great abundance colours the rock red. Green-brown biotite, highly chloritised and with associated hematite alteration, occurs as anhedral grains 0,125 mm to 0,375 mm in size. The fine dust ore can cluster together to form a type of layering on a microscopic scale. The rhyolite in some cases shows a spherulitic texture with radiating laths, possibly indicating quenching of the lava.

3.3.1.2.2 *Quartzite xenoliths*

The quartzite xenoliths display interlocking quartz grains, varying in size from 0,125 mm to 0,5 mm, but usually around 0,25 mm (see Plate I - C). Fine-grained magnetite grains, 0,1 to 0,06 mm and less in size, are interstitial between the interlocking quartz grains. Despite the significant recrystallisation, bedding is preserved in some xenoliths. De Bruiyn (1980) described quartzite xenoliths showing sub-rounded to angular grains with dominant quartz and subordinate plagioclase and K-feldspar with lesser interstitial calcite and sericite. In these cases the xenoliths underwent little recrystallisation.

Highly recrystallised xenoliths, showing grain boundaries at 120°, were carried in magmas of higher temperature than those with more rounded grain boundaries, such as nearer a volcanic vent. It was found that the xenoliths in the eastern part of the area, such as on Rietfontein 90 JS, are highly recrystallised and larger than those in the western part of the study area. As this locality is approximately 25 km away from Rhenosterkop to the southwest (see folder), it may suggest that this hill is a possible volcanic vent for the Rooiberg Group. However, this is purely hypothetical.

3.3.1.2.3 *Flow-banded felsite*

This rock is developed just above the quartzite xenoliths, and below the agglomerate unit (see Plate I - D), and is fine to very fine-grained, with a groundmass of quartz, K-feldspar, plagioclase and hematite. The hematite is clustered along the flow bands with the more mafic minerals, with lesser amounts of hematite in-between the flow-bands. The flow-banding is between 1 to 1,5 mm thick and often contorted.

3.3.2 Schrikkloof Formation

3.3.2.1 General Description

The base of this formation is marked by a prominent agglomerate horizon, consisting of fragments of massive and flow-banded rhyolite, varying in size from a few centimetres up to 40 cm. These fragments are set in a very fine grained rhyolitic matrix (see Plate I - E). This agglomerate unit has been used to separate the Kwaggasnek and Schrikkloof Formations from each other. A thin shaly / tuffaceous bed occurs above the agglomerate horizon and is overlain by a thick succession of massive and flow-banded rhyolite.

The rhyolite varies in colour from dark brown through dark red / purple to black, and is occasionally porphyritic and vesicular. Thin tuff, agglomerate, and lapilli tuff horizons and sandstone lenses are occasionally found interbedded in the predominantly flow banded rhyolitic succession. However these were not readily identified, due to the rhyolite forming high hilly country often covered in scree and dense vegetation (e.g. Enkeldoornspoort 207 JR)(see Plate I - A). Elsewhere however, particularly in the area around Loskop Dam, to the east of the study area, the rocks are better exposed and the relationships clearer. The presence of these horizons, and the dominance of flow-banded rhyolite over the more massive rhyolite, indicates a more complex and explosive type of eruptive history of this formation, compared to the more homogeneous, older Kwaggasnek Formation.

3.3.2.2 Petrographic Description

3.3.2.2.1 *Agglomerate*

This unit, which forms part of the Union Tin Member, and separates the two formations of the upper Rooiberg Group, is dark brown in colour, and consists of fragments varying from 10 to 40 cm in size at the largest, down to a few centimetres and 1 cm and less at their smallest. In outcrop, the fragments, which are rounded to

PLATE I

A: View of hilly terrain formed by the Kooiberg Group, looking northwards onto Enkeldoornspoort 207 JR.

B: Photomicrograph of massive rhyolite with K-feldspar phenocryst set in fine-grained matrix of feldspar, quartz and chlorite. Kwaggasnek Formation. Crossed nicols. Field of view is 3,55 mm wide.

C: Photomicrograph of interlocking, recrystallised quartz grains of a quartzite xenolith. Kwaggasnek Formation, Rietfontein 90 JS. Crossed nicols; field of view is 3,55 mm wide.

D: Flow-banded rhyolite adjacent to the Union Tin Member agglomerate, Kwaggasnek Formation, Leeuwfontein 228 JS.

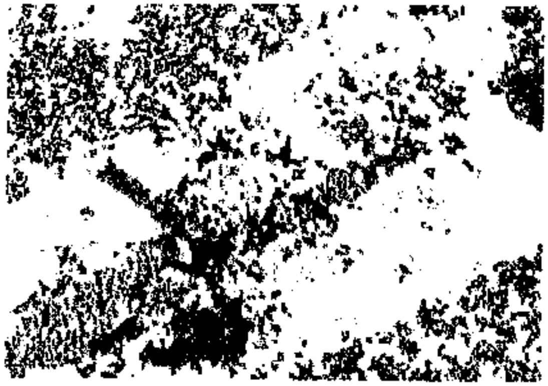
E: Union Tin Member agglomerate made up of a number of rhyolitic fragments of varying size, set in a rhyolitic matrix. Schrikkloof Formation, Leeuwfontein 228 JS.

F: Photomicrograph of fragments set in fine-grained quartzitic matrix. Union Tin Member agglomerate, Schrikkloof Formation. Parallel nicols; field of view is 3,55 mm wide.

G: Photomicrograph of massive rhyolite with plagioclase laths. Schrikkloof Formation, Van Dykspruit 431 JR. Parallel nicols; field of view is 3,55 mm wide.

PLATE I

A



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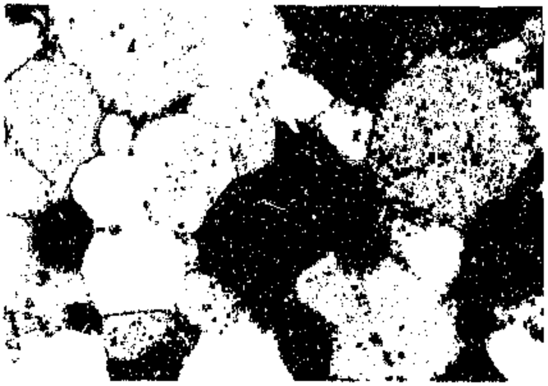

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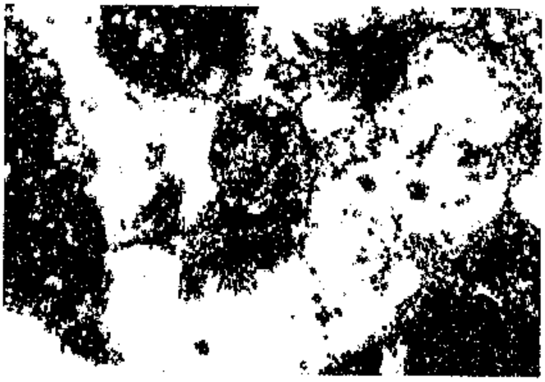

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sub-rounded, appear to consist of both massive and flow-banded rhyolite set in a fine-grained rhyolitic matrix (see Plate I - E).

The fragments of the agglomerate consist predominantly of chloritised and sericitised K-feldspar, which have been almost totally altered to hematite, as well as being extensively ferrohydroxide stained, which gives a yellow to red colouration.

Hematite, as anhedral to subhedral grains 0,25 to 0,5 mm in size, is found mostly in clusters along with ferrohydroxides, and m[illegible] most of the fragments, almost totally altering the K-feldspars. In some cases small fragments consist entirely of hematite and ferrohydroxides. Dark green / yellow green chlorite clusters, consisting of grains 0,03 mm in size, are associated with the oxides and ferrohydroxides.

Quartz, varying in size from 0,03 mm to 0,06 mm, is also found. Muscovite, 0,125 to 0,06 mm in size, is found in small open cavities 0,25 mm in size in the fragments, along with vugs 1,5 mm in size, infilled wi[illegible], suggesting a large amount of gas present in the fragments. Some fragments s[illegible]m to exhibit a spherulitic texture, though this is not distinct.

The fragments are darker in colour and more altered than the matrix, containing a greater abundance of oxides, particularly along their boundaries, which distinguish them from the matrix. The matrix is generally lighter coloured, consisting of sericitised K-feldspar and quartz 0,125 to 0,03 mm and less in size, along with hematite and chlorite 0,125 to 0,06 mm in size (see Plate I - F).

On the farms Zwartfontein 89 JS and Rietfontein 90 J[illegible] agglomerate consists of deep pink, highly sericitised fragments infilled by quartz veining 1 to 5 mm wide. The veins consist of euhedral interlocking quartz grains 0,06 to 0,25 mm in size, growing in from the margins of the vein, and accessory subhedral ore minerals 0,06 mm to 0,03 mm and less in size. Occasionally there is a concentration of euhedral to subhedral, 1,5 to 2 mm sized epidote grains near these quartz veins. Here hydrothermal fluids, possibly from the underlying granites, may have used the permeable agglomerate horizon as a conduit. The agglomerate horizon in this eastern region of the area, stretching from Lee.wfontein 228 JS and Langkloof 229 JS, all around through Rietfontein 90 JS and into Klipdrift 62 JS (see folder), is irregularly mineralised with sphalerite, pyrite, minor galena and arsenopyrite along a strike length of 40 km. This very low grade mineralisation may be due to upwelling solutions (Martini and Vorster, 1994). This will be dealt with again in chapter 6.

3.3.2.2.2 *Massive Rhyolite*

The massive rhyolite is porphyritic, dark red, dark brown to black in colour. The phenocrysts are set in a fine grained matrix. Quartz, 0,25 mm in size at the largest, but typically 0,12 mm and less, and sericitised, subhedral K-feldspar, 0,1 mm in size, are the major constituents. Other minerals include euhedral plagioclase (An_{25}), often as swallow-tailed laths 0,5 to 0,325 mm in size, and magnetite typically less than 0,06 mm in size. Some oxide rich zones are also found. Chlorite grains, 0,5 mm in size, are also typically found in the groundmass. Dark brown, subhedral to anhedral chloritised hornblende, 0,25 mm in size, is also occasionally found in the groundmass. The texture is typically hypocrystalline and porphyritic (see Plate I - G).

K-feldspar is the dominant phenocryst, varying from euhedral to subhedral in shape, and from 0,5 mm to 2,5 mm in size and 4 mm at its largest. The phenocrysts, which are occasionally zoned, are all highly deuterically altered, and are typically sericitised. Subhedral chlorite, 0,5 mm in size, associated with euhedral to subhedral hematite, 0,25 mm in size, often forms an alteration product of the phenocrysts (see Plate II - A). Sanidine, forming euhedral to subhedral grains 1 to 1,5 mm in size, are also occasionally found.

Other phenocrysts, present in lesser abundance, are anhedral quartz, 0,5 mm in size, hornblende, 1mm in size, and occasionally euhedral to subhedral plagioclase (An_{22}), 1,75 mm in size as well as subhedral magnetite 0,25 mm in size. Oxidation of magnetite to hematite gives rise to ferrohydroxides, such as goethite, and the red staining gives rise to the typical dark red-brown colour of the rock.

3.3.2.2.3 *Flow-banded Rhyolite*

This rock consists of dark flow bands, typically 1 to 0,5 mm in size, in a lighter coloured matrix. It consists of a fine-grained matrix composed of chloritised, sericitised, subhedral to anhedral K-feldspar 0,06 to 0,03 mm and less in size, plagioclase, subhedral quartz, 0,06 mm and less in size, and euhedral to subhedral hematite 0,06 to 0,03 mm in size. The rock has abundant chlorite, 0,016 mm and less in size, mostly forming clusters 0,06 to 0,25 mm in size. These are found in association with hematite, where the two form an alteration product of the feldspars.

The flow bands are formed by subhedral to euhedral hematite grains 0,06 to 0,75 mm in size, associated with blue-green chlorite and goethite clustering around the hematite. Away from the bands there is a lesser concentration of chlorite and goethite, and more quartz and feldspar. Subhedral feldspar grains, 0,25 mm in size, often highly chloritised, are occasionally found in the bands associated with chlorite.

3.3.2.2.4 *Tuff and agglomerate*

Tuffs comprise fragments 3 to 6 mm in size, with a devitrified centre of dark material. The shards are comprised of sericitised and chloritised K-feldspar and plagioclase, with no clear boundaries in the groundmass, along with subhedral to anhedral quartz grains 0,25 to 0,06 mm in size. Fine hematite and 0,03 mm sized chlorite, often clustering around the hematite, is dispersed throughout the groundmass. Blue-green chlorite clusters, in association with subhedral hematite, 0,06 mm to 0,03 mm and less in size, and associated goethite, is found at the centre of the shards.

Dark green chlorite is also found, along with hematite, in bands 0,5 mm wide, separating the shards. There is a greater abundance of hematite in the bands than is found in the devitrified centres of the shards.

The fragments, which are 3 to 0,5 mm in size, within the agglomerates are comprised of deuterically altered, chloritised, subhedral to anhedral K-feldspar grains, 2,5 to 0,25 mm in size, but typically 0,5 mm. Chlorite and hematite are common alteration products of the feldspars. Chlorite and hematite surround most grains. Perthite grains 2,5 to 1 mm in size are also found.

Quartz occurs as anhedral grains 0,75 to 0,06 mm in size, but typically 0,06 mm. Pleochroic dark green / light brown green chlorite occurs as 0,125 to 0,06 mm sized grains, interstitial between the other grains, and as large clusters 2 mm in size between the fragments. Anhedral hematite 0,125 to 0,06 mm in size, along with goethite, is found associated with the chlorite, with goethite causing red staining around the fragments (see Plate II - B). De Bruiyn (1980) described agglomerates consisting of rhyolite fragments in a fine-grained matrix of angular quartz, K-feldspar and plagioclase.

3.3.3 The Loskop Formation

3.3.3.1 General Description

This formation, regarded as a final sedimentary / volcanic phase, succeeds the volcanic activity of the Rooiberg group and terminates sedimentation in the Transvaal basin, prior to Waterberg Group sedimentation (Coertze *et al* 1977). It outcrops in the southern portion of the study area. Its best outcrop locality in the study area is at Rhenosterkop on the farm Rietfontein 446 JR (see folder and Fig. 3,1). The formation consists of volcanic units such as rhyolites and agglomerates, and sedimentary units such as shale, sandstone and conglomerate. More attention was paid to the volcanic members of this formation, but sedimentary units such as a fine-grained grey sandstone, consisting of K-feldspar and quartz, was mapped alternating with a fine-grained grey rhyolite on Hartebeestspruit 434 JR. What follows is a brief description of the volcanic rocks found at two localities in particular; a small wedge of Loskop Formation trending northwest on the farm Rooipoort 440 JR, and the volcanic / sedimentary succession at Rhenosterkop on the farm Rietfontein 446 JR.

PLATE II

A: Photomicrograph of massive rhyolite with K-feldspar phenocrysts exhibiting a glomeroporphyritic texture and set in a fine-grained feldspar, quartz, chlorite matrix. Schrikkloof Formation, Zwartfontein 89 JS. Crossed nicols; field of view is 3,55 mm wide.

B: Photomicrograph of rhyolitic fragments set in a chloritic matrix. Agglomerate, Schrikkloof Formation. Uncrossed nicols; field of view is 3,55 mm wide.

C: View of the northern flanks of Rhenosterkop, looking west from Rietfontein 446 JR.

D: Photomicrograph of sediment. Loskop Formation, Rhenosterkop, Rietfontein 446 JR. Uncrossed nicols; field of view is 3,55 mm.

E: View looking northeast from Rietfontein 214 JR to the escarpment made by the granophyre - granite contact on Kameelpoort 202 JR. The granophyre forms the hilly country while the granite forms the low-lying gently undulating topography in the foreground.

F: Photomicrograph of coarse-textured granophyre with an altered feldspar grain at the centre of the granophyric growth. Rashoop Granophyre Suite, Breytenbachs-rus 64 JS. Crossed nicols; field of view is 3,55 mm wide.

G: Photomicrograph of granophyre exhibiting a bow-tie texture. Rashoop Granophyre Suite, Leeuwfontein 248 JR. Crossed nicols; field of view is 3,55 mm wide.

LATE II

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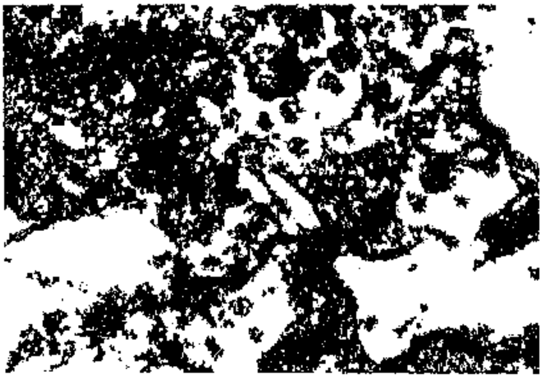

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Nearing the summit of the hill a pinkish yellow sericitised agglomerate is found with small angular fragments. The agglomerate varies from clast, tuffaceous to matrix supported in places, with angular clasts varying from 1 to 10 cm in size, with 3 cm an average size. This unit, which is more than 70 m thick, continues to the summit of the hill. At the summit of the hill the purplish-red agglomerate is matrix supported and consists of angular to sub-rounded fragments 5 to 10 cm in size. The fragments, which are pinkish brown in colour, consist of highly altered rhyolite. The matrix is a coarse and dark purplish red sandstone. The majority of the rock is made up of angular quartz grains 0,125 to 0,5 mm in size, along with lesser amounts of highly altered K-feldspar, some reaching 0,25 mm in size, and subhedral hematite grains, 0,06 to 0,03 mm in size, often forming clusters 0,25 to 0,5 mm in size. The matrix, which is arkosic in areas, exhibits trough cross-bedding in a few isolated areas, possibly suggesting reworking and sedimentary deposition in places.

The rhyolitic and sedimentary units continue unbroken across the northern side of the hill forming prominent sedimentary stratification which is easily visible from afar.

Mellor (1905a), who mapped the southern part of Rhenosterkop, noted a series of purplish-black shales approximately 122 m thick, with occasional greenish and reddish bands, and with occasional thin bands of breccia. In their upper portions these rocks become coarser textured and thickly bedded, passing into reddish-brown sandstones, typical of the Waterberg type. In passing upwards, these rocks contained an increasing number of pebbles and fragments and become conglomerates. Many of the fragments are a light green tuffaceous rock, while the matrix is green or purplish in colour.

Resting above these conglomerates Mellor (1905a) described a red massive breccia or agglomerate consisting of angular, sub-angular to rounded fragments and boulders, mostly of red banded rhyolite, ranging in size from a few centimetres up to 60 cm or more in diameter. Its thickness is anywhere from 60 m to 120 m. Overlying this is a conglomerate with a dark green igneous-like matrix and small fragments of various igneous rocks, some coarse basic igneous rocks. This conglomerate is comprised of well-rounded boulders of white quartzite, up to 1,25m in diameter, as well as boulders rhyolite, which gives way to a pinkish red rhyolite that becomes flow banded higher up. This is overlain by a reddish pink sandstone which grades into a grey quartzose sandstone, itself grading into a conglomerate with quartzite, rhyolite and lithic clasts set in a coarse matrix. A black rhyolite horizon approximately 50 m in thickness and alternating between massive and flow-banded overlies this thin conglomerate unit. The rhyolite horizon is overlain by a purplish red, massive and flow banded rhyolite. Overlying this is a grey banded tuff / ash flow with whitish bands. Microscopically the rock consists of a fine-grained groundmass of quartz, sericitised K-feldspar, and dust fine ore all less than 0,06 mm. The rock exhibits thick bands 0,5 to 1,5 mm thick, which have a greater concentration of opaque minerals, such as magnetite, as well as quartz, some of which are 0,125 mm in size. These bands have sediment-related features such as fluid escape and load structures and microfolding (see Plate II - D). In between the bands are quartz-rich areas with quartz grains 0,06 mm in size, along with lesser amounts of magnetite and little K-feldspar. The rock displays features of an ash-flow tuff which had experienced slumping and other sediment-type deformation during its formation. It has been subsequently altered and silicified.

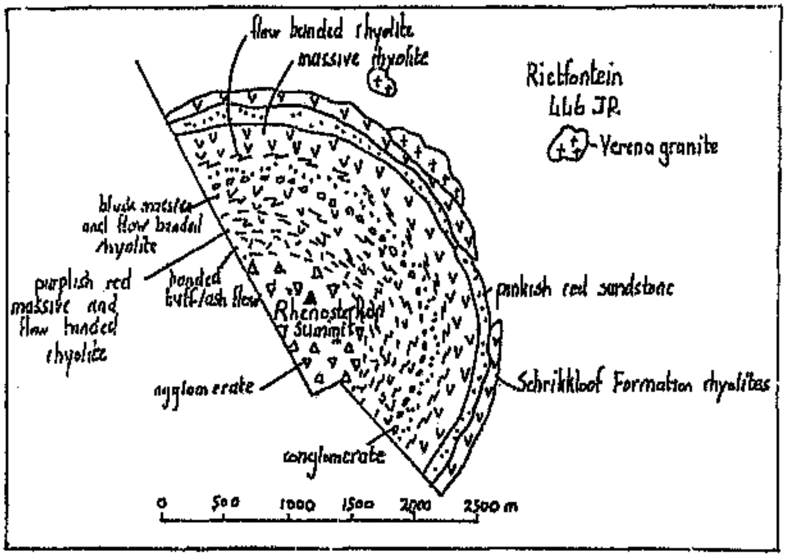


Figure 3.3 Simple geological sketchmap of the northeastern side of Rhenosterkop

3.3.3.2 Petrographic description

On Rooipoort 440 JR, a fine-grained light brown sandstone is overlain by an agglomerate, consisting of dark brown to yellowish-white rhyolitic fragments, and set in a dark red / brown rhyolitic matrix. The fragments, some of which exhibit typical shard shapes, are 2,5 mm to 0,5 mm in size, and are dominated by quartz 0,125 to 0,06 mm in size, in a very fine-grained altered groundmass, where individual grains could not be distinguished. Dust fine ore (hematite) is found as grains 0,056 to 0,03 mm and less in size in all the fragments. Fragments have varying grain size with some having hematite grains 0,125 mm in size. This imparts a darker colour to the fragment. The matrix is similar, but has a greater concentration of coarser hematite. There are also quartz-rich vugs 3 mm in size in the groundmass, associated with hematite, 0,25 mm in size, and associated ferrohydroxides.

This unit is overlain by a fine-grained dark grey to black tuff, which is itself overlain by a dark brown / orange flow-banded rhyolite, which is characterised by flow directions varying from 277° to 350°, suggesting the lava flowed from a source to the southeast, most likely Rhenosterkop. Microscopically the orange colour of the rock comes from the presence of iron hydroxides. The rock is fine grained, consisting of a groundmass of altered ferrohydroxide stained K-feldspar, quartz 0,12 mm in size and anhedral magnetite. There is also a large abundance of dark to olive green subhedral epidote, 0,12 mm in size, which sometimes forms clusters of radiating fibrous grains. Dark pleochroic olive / yellow green chlorite is occasionally found as grains 3 mm in size totally replacing accessory biotite. Hematite, 0,125 mm in size, is associated with the chlorite. The bands, which are typically 0,5 mm in size, are formed by ferrohydroxides derived from the oxidation of the magnetite, which originally formed the bands.

At the base of Rhenosterkop (see Plate II - C and Fig. 3.3) on the northeastern side, the flow-banded rhyolites of the Schrikkloof Formation of the upper Rooiberg Group, overlie coarse-grained red Verena granite. This unit is overlain by a fine-grained pinkish-red sandstone, which in turn is overlain by a fine-grained purplish red massive of red felsite, purplish-red syenitic rocks and indurated quartzose shales. Overlying this is a conglomerate horizon of the Waterberg type, with pebbles of a moderate size, in a coarse brown sandy matrix, which in turn is overlain by coarse-grained purple-brown Waterberg-type sandstones, with occasional beds of greenish fragmental material, mostly of igneous origin.

It would appear that the geology of Rhenosterkop has features compatible with the suggestion that this is a volcanic vent for the Rooiberg Group. Twist (1983) cited four main reasons supporting the hypothesis that Rhenosterkop was the site of a volcanic vent.

These are:

- the circular outcrop of a plug-shaped body of Loskop Formation rocks at Rhenosterkop.

- the south-westward extrapolation of the Steelpoort Fault passes directly through Rhenosterkop. The fault represents a major line of weakness which is known (Cameron (1971), Hertzer (1994)) to have been active during Bushveld emplacement times. It is well established that volcanic vents typically develop along strong regional lineaments, and therefore the siting of a feeder at Rhenosterkop is plausible.

- very coarse, prominent volcanic breccias have been reported at Rhenosterkop (Mellor, 1905a and this study).

- the area is geologically complex and locally disturbed; Mellor (1905b) described folded, faulted, vertically-dipping and structurally-overturned strata.

Rhenosterkop is a unique locality and requires a more detailed geological and petrographic study than has been attempted with this study.

3.3.4 Conclusions

The Rooiberg Group was extruded at 2061 Ma contemporaneously with the intrusion of the Rustenburg Layered Suite. Its vast volume and thickness make it an unique volcanic province. The upper Rooiberg Group, which is present in the study area, has at its base the lower, predominantly massive Kwaggasnek Formation, erupted under quite, stable conditions. This is overlain by the predominantly flow-banded rhyolites of the Schrikkloof Formation, which has interlaminated tuffs, agglomerates and sandstone lenses, and which was erupted under more violent, active conditions. The prominent agglomerate / tuffaceous Union Tin Member, between the two formations, represents a fundamental change in the style of volcanism, from more passive volcanism to a more active and explosive style of volcanism.

The sandstone lenses in the upper Schrikkloof Formation may also represent subaqueous sedimentation, so that at times pools of water covered the basin. The Loskop Formation, which developed between the underlying volcanic Rooiberg Group and the overlying sedimentary Waterberg Group, forms a transition between these two environments, being composed of both volcanic and sedimentary units.

Rhenosterkop has many features such as agglomerates, its situation along a major fault and its structural complexity which suggest that it may be a volcanic vent for the Rooiberg Group.

3.4 Rashoop Granophyre Suite

3.4.1 Introduction

The Rashoop Granophyre Suite represents the smallest volume of the various components making up the felsic rocks of the Bushveld Complex. Very few studies have focused primarily on these rocks, with Walraven's (1982) thesis being the most extensive work to date. Early workers argued on the origin of the granophyres. Some considered these rocks to be a product of magmatic crystallisation (e.g. Hall (1932), Lombaard (1932), De Bruiyn (1980)) , while others favoured a metasomatic origin (e.g. Strauss and Truter (1944), Strauss (1947), Du Plessis (1976)). Various localities suggest the granophyre to be a differentiation product, whilst others suggest a metasomatic origin.

Walraven (1982) regarded what he called the Stavoren granophyre as the predominant granophyre type, and suggested that it formed by crystallisation from a magma intruded below a roof comprising Rooiberg Group or sediments of the Pretoria Group. Walraven (1982) considered the Stavoren Granophyre to be co-genetic with the rhyolite of the Rooiberg Group, and to represent the shallow intrusive facies of the same magma which extruded to form the Rooiberg Group. The contact between the two is, in most cases, gradational, which concurs with this hypothesis. The Rooiberg Group and the granophyre, together form a magmatic cycle which preceded the Rustenburg Layered Suite and the Lebowa Granite Suite, with the granophyre having an age of 2060±2 Ma (Walraven, 1997), making it slightly older than the Rustenburg Layered Suite, which has an age of from 2061±27 Ma (Walraven *et al* (1990b), Walraven (1987)).

Walraven (1982) believed the granophyre-rhyolite magma to be derived from melting of lower crustal material, consisting of granitic rocks similar to some of the batholiths in the Barberton region. The granophyric rocks in the study area are believed to have been formed predominantly by hypabyssal fractionation of a magma derived from partial melting of the lower crust, owing to their stratigraphic position between the granites and rhyolites and that there is mostly a transition from the granophyres into the rhyolites. Some granophyric rocks in other localities are considered by Walraven (1982) to have been formed by other processes. These include recrystallisation of fragments of rhyolite of the Rooiberg Group by a hot magma, melting of roof rocks, magmatic fractionation and differentiation of the basic rocks of the Rustenburg Layered Suite, and by transformation of the sedimentary roof rocks of the Pretoria Group by intrusion of the Rustenburg Layered Suite.

De Bruiyn (1980) subdivided the Rashoop Granophyre Suite in his study area into three divisions, named the Sterk River, Stavoren and Blinkwater Granophyres, by virtue of their position in the stratigraphy. The Sterk River Granophyre is found between the Bushveld Granites and a roof of Rooiberg rhyolite. The Stavoren Granophyre occurs between Bushveld granites and a roof of Transvaal sediments, while the Blinkwater Granophyre is located between the Rustenburg Layered Suite and a roof of Bushveld granite.

The author will use De Bruiyn's (1980) subdivision for ease of use, since it is most applicable to the present study area. The author agrees that Walraven's (1982) Stavoren Granophyre is the predominant granophyre type in the Bushveld Complex and in the study area, as its name has no implications as to its stratigraphic level, only to its genesis. De Bruiyn's (1980) subdivision, given in Table 3.2, would indicate that in the study area the Sterk River Granophyre is the predominant type, with a small volume of Stavoren Granophyre being found on the farm Sybrandskraal 244 JR. Figure 3.3 shows the distribution of the various granophyre types in the study area.

Table 3.2: Subdivision of the Rashoop Granophyre Suite, based on relationships with the surrounding country rocks

(after De Bruiyn, 1980)

	Rashoop Granophyre Suite		
	Sterk River Granophyre	Stavoren Granophyre	Blinkwater Granophyre
Overlying rock type	Rooiberg Group	Pretoria Group	Lebowa Granite Suite
Underlying rock type	Lebowa Granite Suite	Lebowa Granite Suite	Rustenburg Layered Suite

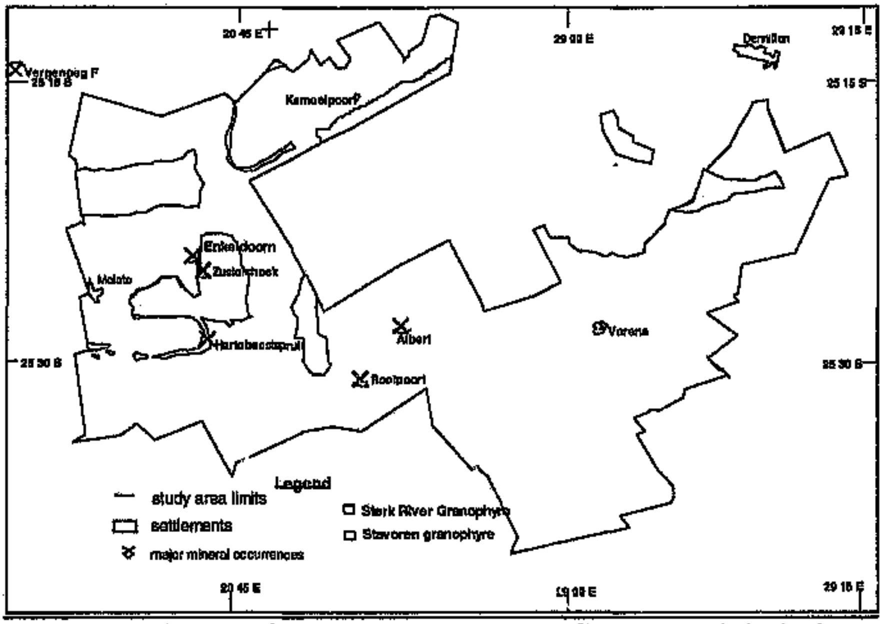


Figure 3.4: General distribution of the Rashoop Granophyre Suite in the study area

3.4.2 Petrography

The granophyre is a fine to medium-grained, dark pink to red rock, that varies from purplish red when it has a fine texture to reddish brown when it has a coarse texture. The outcrop forms low hilly country (see Plate II - E), and the rock often weathers to small rounded domical outcrops. In hand specimen the rock is made up of dark red, deuterically altered K-feldspar, quartz and hornblende, and in coarser textured varieties, the intergrowth of quartz and K-feldspar can be seen under close examination of the rock. Occasionally the granophyre is chloritised or contains hematite and may be deep red in colour. This occurs when the granophyre acts as a host to mineralisation, such as at the Zustershoek Tin Mine or the Hartebeestspruit gold prospect.

The granophyre tends to be coarser textured closer to the granite contact, and often granophyric granite is found underlying the granophyre, such as on Zustershoek 246 JR. In some instances the granophyre is found to be "pseudogranophyric" in texture, such as a thin wedge of granophyre found on Hartebeestspruit 434 JR. Here the texture is a fine-grained granitic type texture with small areas of granophyric intergrowth. It would appear in these cases that the granites caused recrystallisation of the immediately overlying rhyolite, rather than there being direct crystallisation from a magma as appears the case elsewhere.

Under the microscope the rock is made up of an intergrowth of dark red, earthy K-feldspar and quartz. The K-feldspar is typically highly deuterically altered, chloritised and sericitised. When found as grains not forming part of the granophyric texture it is subhedral (occasionally anhedral), reaching sizes of 0,125 to 2 mm and typically 1,5 mm. The grains are ferrohydroxide stained, with occasional ferrohydroxide alteration along grain boundaries. Perthite often forms distinct subhedral grains 2,5 to 2 mm in size. The K-feldspar may form the core of the granophyric texture (see Plate II - F), but typically the granophyric texture appears to have no large nucleation point. Quartz is also occasionally found as separate distinct grains, which are anhedral in shape, and vary in size from 0,06 to 1,75 mm and 2 to 3 mm at the largest and 0,2 mm typically.

The granophyric texture in the rock varies from a fine micrograpnophyric variety, with intergrowths of 0,1 mm and less, to a more coarse textured variety with intergrowths reaching 0,25 mm up to 0,5 mm in size. Highly altered K-feldspar and quartz form the intergrowth, growing from a central euhedral K-feldspar grain 0,5 mm in size. The texture then radiates outwards forming an intergrowth of quartz and K-feldspar, such that the grains are always in optical continuity with each other, and all go extinct in the same position on rotation of the stage. If a K-feldspar grain is present at the centre of the growth, the K-feldspar texture remains in optical continuity with this grain. Proceeding outwards the texture becomes coarser, with the K-feldspar visibly growing round the quartz grains (see Plate II - F).

The individual grains in the intergrowth reach sizes from 0,06 mm to 0,25 mm in the coarsest varieties with 0,25 mm being a typical size. The individual intergrown textured areas, in optical continuity, can reach sizes of 1,5 to 4 mm and 8 mm at the largest. It is occasionally found that the grains can grow out from a central point, and become coarser textured further away, but such that certain portions of the intergrown area have different optical continuities while still radiating out from the same central point in what is called a 'bow-tie' arrangement (see Plate II - G).

It is found that the coarse textured varieties are more predominant near the base of the succession, near the contact with the underlying granite, and become finer textured higher up in the succession. On Zustershoek 246 JR the granite directly beneath the granophyre often exhibits a coarse granophyric texture in places, so that there is a transition in some localities from the granite through a granophyric granite and into the coarse textured granophyre. This coarse textured granophyre outcrops as reddish brown dome-like outcrops. Higher up in the succession, nearer the rhyolites or sediments of the Pretoria Group, the rock has a finer texture, micrographic in places, and outcrops as rounded boulders with a purplish colour, as found on Rhenosterkuil 63 JS. The rock is often not totally granophyric, sometimes forming a fine-grained granitic texture in places.

Other constituents of the rock include accessory pleochroic yellow green / dark green, subhedral biotite, typically highly chloritised and sometimes skeletal in shape. It is typically 0,5 mm to 2 mm in size, with 3 mm being the largest size seen. Anhedral hornblende, 0,5 to 2,5 mm in size is also found. Euhedral to anhedral magnetite, 0,75 to 0,016 mm in size, often forming clusters 0,5 to 1 mm in size, is associated with hornblende and biotite alteration as well as with feldspar alteration. Dark-green chlorite is associated with alteration, as well as forming large clusters 7,5 mm in size, with individual grains 2 to 2,5 mm in size, where it has totally replaced hornblende. Magnetite accompanies the chlorite alteration and on one occasion, on Leeuwfontein 248 JR, pyrite is found within the granophyre. Goethite associated with rust red ferrohydroxide colouration occurs as accessory subhedral grains 0,375 mm in size.

3.4.3 Conclusions

The Rashoop Granophyre Suite is thought to have formed as a result of a magma intruding beneath the Rooiberg Group. The magma is thought to be the same as that which had been extruded to form the Rooiberg Group, so that the two suites are co-genetic. The Granophyre was intruded before the Rustenburg Layered Suite and the Lebowa Granite Suite. It varies from micrographophyric to granophyric, and is coarse textured near the underlying granite contact, and finer textured further up in its succession.

Other processes elsewhere in the Complex, such as metasomatic alteration of Pretoria Group sediments, magmatic fractionation of the Rustenburg Layered Suite, or incorporation and alteration of Rooiberg Group rhyolite also formed the granophyre into a magma (e.g. Walraven (1982)). The bulk of the granophyre formed by intrusion and crystallisation of a magma, co-genetic with the Rooiberg Group beneath a roof phase, comprising either Rooiberg Group rhyolites or Pretoria Group sediments. This type of granophyre Walraven (1982) termed Stavoren Granophyre.

De Bruiyn (1980) preferred to classify the granophyres according to their stratigraphic position, with no consideration in his classification for the genesis of the granophyre. His classification, used in this study, thus places the Sterk River Granophyre, developed between the Lebowa Granite Suite and the Rooiberg Group, as the predominant type in the study area, with a small volume of Stavoren Granophyre, developed between the Lebowa Granite Suite and the Pretoria Group sediments, found in the southwest corner of the study area.

The granophyres as such are not mineralised in their own right, but often host mineral deposits derived by fluid egress from the underlying granitic rocks.

CHAPTER 4
THE LEBOWA GRANITE SUITE

4.1 Introduction

The Bushveld Granites form a large laccolithic structure, approximately 290 km in width and 300 km in length, outcropping within the centre of the Bushveld Complex, and rimmed by the mafic rocks of the Rustenburg Layered Suite (Fig 1.1). Different compositional types exist in this granite suite, and it has been established by workers such as McCarthy and Hasty (1976), Groves and McCarthy (1978) and Kleeman and Twist (1989) that the granites form a sheet 2,5 km thick exhibiting features of progressive in situ fractional crystallisation towards its roof. During crystallisation a separate H_2O-rich fluid phase developed causing intensive deuteric alteration, which imparted a red colour to the feldspars due to the oxidation of hematite within the feldspar lattices. This feature is seen particularly toward the top of the sheet in phases such as the Bobbejaankop granite.

The Lebowa Granite Suite, formerly known as the Red Granite, Bushveld Granite and Main Granite, was subdivided by Coertze *et al* (1978) into a number of sub-types. The main granite type in the suite was termed the Nebo granite, which included the Veekraal granite variety in the west, as well as the Sekhukhuni granite variety in the east, and a locally developed variety called the Steelpoort Park granite near Steelpoort. Texture, mineralogy and other criteria distinguish these granites from each other.

A variety of Nebo Granite is developed in the study area, which has characteristics which distinguish it as a marginal phase of the Sekhukhuni Granite developed elsewhere in the study area. This granite outcrops in a pluton in the central region of the study area, near the township of Verena, and is therefore called the Verena Granite, a name also adopted in this study.

Also included in the suite are the Klipkloof and Bobbejaankop granites. Strauss (1955) first identified the Bobbejaankop granite in the Potgietersrus area, where he also identified the Foothills Granite, a locally developed fine-grained granite immediately above the Bobbejaankop Granite. The Bobbejaankop Granite hosts the mineralisation at the Zaaiplaats Tin Mine. Various authors, including De Bruiyn (1980) preferred to call granites of similar texture and appearance elsewhere in the Complex, the Klipvoor granite, preferring to reserve the name Bobbejaankop granite for its type locality near Potgietersrus. The author feels the name Bobbejaankop granite is a well-known name, and as it has been used by Rio Tinto Ltd. in their exploration study of the granites, it will be used in this study.

The Bobbejaankop granite is a dark red, K-feldspar, quartz-rich granite with a low mafic mineral content and is often associated with or host to mineralisation. The Klipkloof granite represents a highly fractionated phase of the Lebowa Granite Suite and occurs as a pinkish brown, fine-grained aplitic granite either as dykes or sills cutting across the Nebo granite or found in association with the Bobbejaankop granite.

De Bruiyn and Rhodes (1975) identified a new variety of Bushveld granite in the central regions of the Complex which showed crosscutting relationships to the other granites. The above authors called this new variety of Bushveld granite the Makhutso granite. Later investigations by Walraven (1988) indicated a younger age for this granite, post-dating the main Nebo granite, and representing the last phase of Bushveld Granite magmatism (see Table 2.1).

Table 4.1 shows the subdivision of the Lebowa Granite Suite (after Coertze *et al*, 1978), with an asterix behind those granite varieties occurring in the study area. The Makhutso granite is not found directly in the study area, but has its major outcrop just to the north of the study area on the farms Leeuwkop 228 JR, Gemsbokspruit 229 JR and Vlaklaagte 221 JR. A sample of this granite was taken for geochemical comparison with the other granite varieties. Figure 4.1 shows the distribution of the granite types in the study area.

Table 4.1 Subdivision of the Lebowa Granite Suite

(after Coertze *et al*, 1978)

LEBOWA GRANITE SUITE

NEBO GRANITE

Veekraal Granite

Sekhukhuni Granite*

Verena Granite*

Steelpoort Park Granite

Klipkloof Granite*

Bobbejaankop Granite*

MAKHUTSO GRANITE

4.2 Geographical Distribution and General Description

The Nebo Granite with its two varieties, the Sekhukhuni granite and the Verena granite, is the predominant granite type in the study area (see Fig. 4.1). The associated Bobbejaankop and Klipkloof granites are volumetrically less significant and are found as sills, dykes and plug-like areas in the Nebo granite. The Makhutso granite occurs as a plug just to the north of the Verena granite in the central part of the study area (Fig. 4.1).

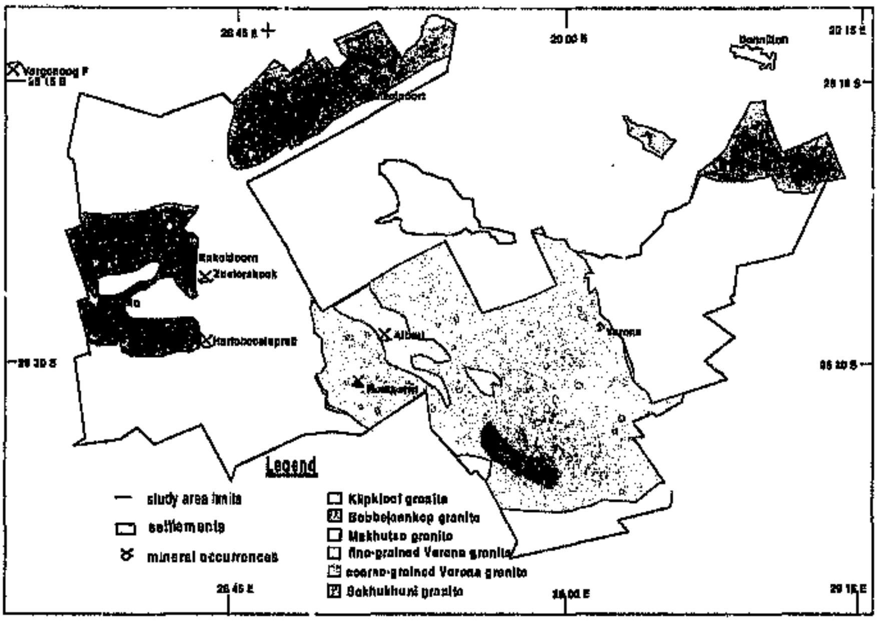


Figure 4.1 Distribution of the granite types in the study area

4.2.1 Nebo Granite

The Nebo Granite is locally subdivided into two different types, based on texture, mineralogy, colour, grain size and other features such as the abundance, nature and size of phenocrysts. The Sekhukhuni granite is found in the western and northeastern corners of the study area, and the Verena granite outcrops as a pluton 30 km across, forming the central region of the study area.

4.2.1.1 Sekhukhuni granite

The Sekhukhuni granite outcrops in three plutons in the study area. The first is in the northwestern corner of the study area on the farms Zandspruit 189 JR and Kameelpoort 202 JR (see folder), and will be called the Kameelpoort pluton in this study. The second, to the southwest, outcrops predominantly on the farms Enkeldoorn 217 JR and Zustershoek 246 JR in the study area (see folder) and the area around

Moloto township, and is called the Moloto pluton. The third pluton, in the far northeastern corner of the study area stretches northwards to Dennilton (see Figure 4.1 and folder) and the Transvaal and Karoo sediments preserved further north, and is hence called the Dennilton pluton.

The granites form low, undulating country, with hills of granophyre and rhyolite rising sharply from the flat plains created by the granites (see Plate II - E). The outcrop in both the Kameelpoort and Moloto plutons is typically poor but is found to improve closer to the rhyolite and granophyre contacts, where it forms low hills and outcrops as large angular blocks. Some small tors are developed on Enkeldoorn 217 JR. The Dennilton granite in the study area is marked by good outcrop, particularly on Maloek Zyn Kop 58 JS, where large domical hills are formed. A prominent hill named Phooko, rising 50 m above the surrounding landscape, occurs near the Klipkloof granite / granophyre contact, and is a well exposed granite outcrop. This and other hills form the escarpment, to the south of which is developed the plateau, and to the north of which the land drops to the flat, extensive Springbok Flats. To the north of Phooko, towards Dennilton, the land becomes flat and the outcrop is poor, until the hills of the Moses River fragment are reached just north of Dennilton.

4.2.1.1.1 *Contact relationships*

The contact of the granite with the overlying granophyre is, in most cases, a gradational one with the granite showing extensive granophyric texture near the granophyre contact. In one case, on Zandspruit 189 JR, the contact is marked by a fine grained whitish aplitic vein, with the overlying granophyre brecciated and infilled by quartz. The contact with the rhyolite, where it is developed, is sharp, such as on Hartebeestspruit 434 JR. The Dennilton granite shows a transition from a grey coarse-grained granite, through into a pinkish red coarse-grained granite similar to the Bobbejaankop granite in appearance. Further up in the succession the granite becomes finer grained and passes into Klipkloof granite which itself grades into granophyre.

4.2.1.1.2 *Macroscopic Description*

The Sekhukhuni granite forms low, rounded, exfoliated, domical and often well-jointed outcrop. Phooko on Maloek Zyn Kop 58 JS is a large rounded, exfoliated domical hill. In some outcrops, such as on Zandspruit 189 JR and Enkeldoorn 217 JR, the rock weathers to form large angular blocks which can develop into low tors.

The granite varies from coarse to fine-grained, but is typically coarse-grained, and ranges in colour from its typical pink colour to dull light pink to deep pink / red. In some areas it is also found to be grey, such as the granite outcropping at Phooko on Maloek Zyn Kop 58 JS. One outcrop, on Zustershoek 246 JR, just south of KwaMhlanga, shows a transition from reddish grey to red and into Bobbejaankop granite. The latter then becomes more granophyric further east, closer to the granophyre contact.

Another distinctive feature of this granite is that it is typically porphyritic, with K-feldspar phenocrysts 10 mm in size and quartz phenocrysts 3 mm in size, which stand out prominently on the weathered surface. The rock contains K-feldspar, quartz, lesser plagioclase, biotite and some minor oxide. Hornblende is also present along with biotite, particularly in the lower portions of the batholith. A feature of high-level granites is the dominance of biotite over hornblende, a greater abundance of quartz and little plagioclase. These mineralogical features are thought to be a function of fractional crystallisation toward the top of the granites.

The granites of the Lebowa Granite Suite shows a progression from a grey hornblende-rich granite at their base, where plagioclase feldspar is found in substantial amounts, upwards into reddish biotite-rich granites in the upper levels. In addition to the change in the colour and abundance of the feldspars with increasing height, plagioclase and hornblende decrease in abundance whereas biotite and quartz increase in abundance. As such, these colour, textural and mineralogical changes can be used on a broad scale to estimate a granite's proximity to the roof of the granites or its degree of fractionation. The Bobbejaankop granite, a reddish bimineralic granite, has features that suggest a highly fractionated nature and that it is likely to occur near the top of the granites.

In the Kameelpoort pluton the granite is K-feldspar rich and biotite is the predominant femic mineral, indicating that this pluton is a relatively unfractionated granite. The central portions of the Moloto dome granite exhibit mineralogical features, using the broad mineralogical criteria above, which suggest that it is less fractionated than the granites outcropping in the Kameelpoort pluton. The granites on the eastern margin of the Moloto pluton are red, however, and take on a Bobbejaankop-like appearance, suggesting higher level granites are exposed along this margin compared to those toward the centre of the pluton.

The granites of the central portions of the Dennilton granite pluton are grey in colour, have a greater abundance of plagioclase, often zoned, and contain approximately equal proportions of biotite and hornblende, indicating that these granites are not highly fractionated. Further south toward the granophyre, the granite becomes redder, more K-feldspar rich and hornblende becomes less abundant. Thus the southern margin of the Dennilton pluton is at a higher level than the northern, central regions.

4.2.1.1.3 *Petrographic Description*

The rock's predominant mineral is subhedral to anhedral K-feldspar which is highly sericitised, deuterically altered, chloritised in places and ferrohydroxide stained, so that identification was often difficult. The grains reach sizes of 0,25 mm at the smallest to 6,5 mm at the largest, but are typically between 1,5 to 2 mm in size. The K-feldspars of the granite near Dennilton are not as highly deuterically altered as elsewhere, and hence do not have the red colour of the other granites in the area. The grey K-feldspars impart a grey colour to this granite, indicating lower level granites are exposed here.

Phenocrysts of K-feldspar, also sericitised and deuterically altered, are subhedral reaching sizes of 5 to 6 mm to 10 mm at the largest. Some of these phenocrysts, such as at Phooko near Dennilton are zoned with a highly altered sericitised rim. Phenocrysts are not always present, but are more common in the coarser grained varieties. The orthoclase is often intergrown with albite to form perthite, which form subhedral grains growing to sizes of 0,75 mm to 2 mm. Perthite is often the predominant K-feldspar, particularly in higher level granites.

Quartz, typically anhedral, can reach sizes from 0,125 mm to 4 mm in size, but typically ranges from 0,5 mm to 1,5 mm. Quartz phenocrysts are also found, which are subhedral, and range in size from 3 mm to 10 mm but are typically 3 mm. Quartz-rich areas are also found, made up of quartz grains 3 to 4 mm in size. The Dennilton granite was also found to contain a greater number of quartz phenocrysts, which are of larger size than elsewhere.

In some cases, near the granophyre contact, the granite becomes distinctly granophyric, with up to 50 % of the rock being made up of granophyric texture.

Plagioclase grains, slightly altered and sericitised and typically subhedral, are found in accessory abundances, making up approximately 1 % of the rock. These grains, which have a composition of An_{25-35} can vary in size from 0,25 to 2 mm, but are typically 0,5 to 1,5 mm. The Dennilton granite, in some places, has plagioclase reaching an abundance of 10 % or more of the rock, but plagioclase typically makes up less than 1 % of the rock elsewhere. In some instance euhedral plagioclase laths (An_{27-35}), 0,5 to 1 mm in size, are found.

Biotite and hornblende are the main mafic minerals, with biotite being predominant over hornblende. This indicates that the granites of the study area are relatively high level granites, owing to the higher percentage of biotite over hornblende. Biotite, which varies from a pleochroic light yellow brown / dark brown and light green brown / dark green to red brown in colour, is subhedral and reaches sizes of 0,125 to 2,5 mm but is typically 0,5 to 1 mm. It is often highly chloritised, with dark green chlorite often totally replacing it. The chlorite is associated with magnetite, where it form grains 0,03 to 0,06 mm up to 1 mm in size at the largest, formed as part of the alteration of the biotite. Magnetite is also associated with chloritic alteration along the cleavage planes of biotite.

Hornblende, euhedral to anhedral in shape and pleochroic dark yellow brown / light yellow green to olive green / dark green and dark brown in colour reaches 0,25 to 1,75 mm and typically 0,5 to 0,75 mm in size. The hornblende is also often chloritised and is often associated with magnetite and hematite grains, forming part of the alteration assemblage of the mineral.

Subhedral to anhedral magnetite grains, varying in size from 0,06 to 0,5 mm to 1 mm at the largest, are found interstitially between the other grains and often in clusters. It is often associated with chloritic alteration of K-feldspar, biotite and hornblende, as well as often being associated with the latter two minerals. In some cases it shows an exsolution of ilmenite.

Accessory minerals include zircon, found in great abundance in the lower, central portions of the Dennilton granite, fluorite and apatite. Muscovite was found in one sample. These accessory minerals are typically euhedral in shape, reaching sizes of 0,25 to 0,5 mm, and are typically associated with the mafic minerals, particularly biotite. In the Dennilton granite the zircon may reach sizes of up to 1 mm. The Sekhukhuni granite is typically medium to coarse-grained, and equigranular in texture as shown in plate III - A.

4.2.1.2 Verena granite

The Verena granite, which represents a marginal phase of the Sekhukhuni granite, is developed in the central portion of the study area, around and to the west of Verena settlement (see Figure 4.1 and folder), and extends southwards to Rhenosterkop and beyond to the southeast.

The coarse-grained granite forms large rounded domes, and often has very good outcrop, such as on Zwartkopje 444 JR. The fine-grained apical phase forms smaller, more angular boulders.

4.2.1.2.1 *Contact relationships*

The granite, just like the Sekhukhuni granite, becomes finer grained and passes into a granophyric textured or fine-grained granite near the rhyolite contacts. Contacts with granophyre were not clear, and were always hidden so that this relationship was not clearly defined. At Rhenosterkop the contact with the overlying Schrikkloof Formation of the Rooiberg Group is sharp.

4.2.1.2.2 *Macroscopic Description*

The granite is coarse-grained, whitish pink to dark pink in colour, and is dominated by light pink K-feldspar, 5 to 10 mm in size, and quartz grains 3 to 8 mm in size, which stand out on the weathered surface, as well as euhedral K-feldspar phenocrysts 30 mm in size. The rock also contains plagioclase, books of biotite 2 mm in size and accessory hornblende and magnetite. Plate III - B shows the typical coarse-grained variety of the granite.

In the centre of the pluton, around the Albert Silver Mine on Roodepoortje 250 JR (see folder and Fig. 4.1), a fine-grained apical phase of the Verena granite is developed. This granite is greyish pink in colour, and porphyritic with K-feldspar phenocrysts 10 to 30 mm in size and occasional quartz phenocrysts 5 to 10 mm in size. The groundmass consists of K-feldspar, quartz, plagioclase, biotite and minor oxides. At the Albert Silver Mine this granite, which is the host to the mineralisation, is dark pink with dark red K-feldspar phenocrysts.

Plate III - C and III - D show a contact between the coarse-grained phase and the fine-grained apical phase of the Verena granite. Plate III - F shows xenoliths of fine-grained granite in coarse-grained granite indicating that the latter is truly intrusive into

PLATE III

A: Photomicrograph of Sekhukhuni granite showing quartz (upper right), K-feldspar (left corner), plagioclase feldspar (upper centre) and chloritised biotite (lower right). Maloek Zyn Kop 58 JS. Crossed nicols; field of view is 3,55 mm wide.

B: Photograph of typical coarse-grained Verena granite with K-feldspar phenocrysts 30 mm in size; Wolvengaten 255 JR.

C: Photograph of coarse-grained Verena granite intruding fine-grained Verena granite; Rooipoort 440 JR.

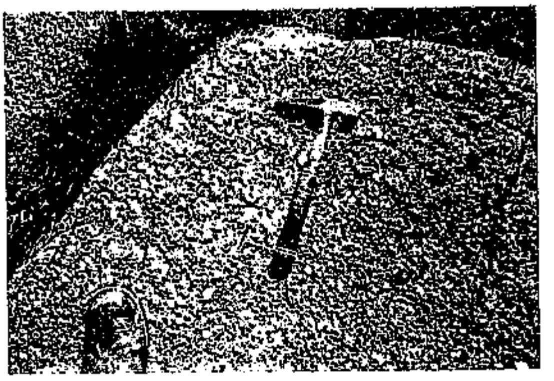
D: Photograph of coarse-grained Verena granite intruding fine-grained Verena granite; Zwartkopje 444 JR.

E: Photograph of fine-grained aplitic dyke cutting across coarse-grained Verena granite; Klipdrift 252 JR.

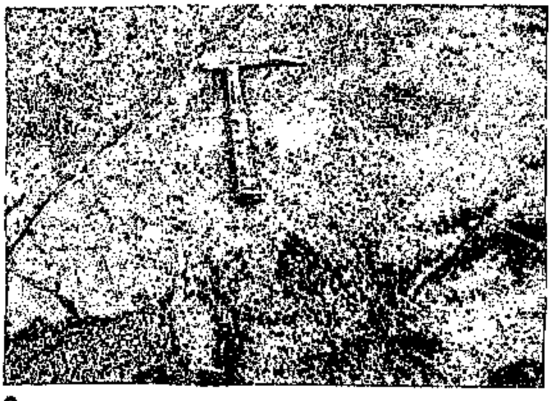
F: Photograph of xenoliths of fine-grained Verena granite in coarse-grained Verena granite, showing the latter to be clearly intrusive into the former; Zwartkopje 444 JR.

PLATE III

A



B



C

D

E

F

the former. The contact relationships all indicate that the coarse-grained granite intrudes the fine-grained granite (cf. Robb *et al*, 1994). It would appear that the fine-grained phase chilled against the pluton's country rocks, and was intruded from beneath by a coarse-grained phase that stoped its way into the fine-grained phase.

On Hartbeesfontein 441 JR the fine-grained phase contains pegmatoidal vugs 100 mm in size, with quartz 25 mm in size, and K-feldspar up to 38 mm in size, indicating the presence of late stage magmatic fluids or volatiles in the fine-grained phase at this locality. However, this granite has numerous characteristics of Klipkloof granite, and may represent dykes of Klipkloof granite cutting across the Verena granite at this locality.

Fine-grained aplitic leptite veins are found cutting through the coarse-grained granite, such as on the farm Klipdrift 252 JR (see Plate III - E).

4.2.1.2.3 *Petrographic Description*

The coarse-grained granite consists of K-feldspar, quartz, plagioclase, biotite, hornblende and magnetite. The K-feldspar phenocrysts, which reach sizes of 10 to 30 mm, are euhedral to subhedral and are deuterically altered and sericitised. Occasionally perthite phenocrysts 7,5 to 11 mm in size, with fine-grained, sericitised rims, are found. On one occasion a sanidine phenocryst 10 mm in size was seen. The K-feldspar in the matrix is subhedral to anhedral and highly deuterically altered and sericitised, reaching sizes of 1,5 to 5 mm, and are often zoned and chloritised in places. Perthite occurs as subhedral to anhedral grains, 2 to 5 mm in size, in the matrix and in some instances is the dominant K-feldspar. Albite sometimes occurs as euhedral to subhedral, sericitised grains 0,75 to 1 mm in size with 4 mm being the largest size observed.

The quartz grains are subhedral to anhedral, and reach sizes of 0,5 to 3 mm and up to 5 mm at the largest. Plagioclase, of composition An_{27-35} is typically subhedral to anhedral, and is sericitised forming crystals 0,75 to 2,5 mm in size and typically 0,5 to 1 mm. The plagioclase makes up about 10 % of the rock.

Biotite and hornblende are the primary mafic minerals with biotite being the more dominant mineral. Biotite forms skeletal to subhedral grains, pleochroic light yellow brown / dark green brown to dark brown / black in colour, and reaching sizes of 0,25 to 2,25 mm with 5 mm the largest. The biotite is often highly chloritised, and is often totally replaced by chlorite and hematite. Hornblende, which is also often chloritised, forms subhedral to anhedral grains, yellow green and pleochroic light red brown / dark red brown, to dark green in colour when highly chloritised. The hornblende, which is very much an accessory mineral, reaches sizes of 0,5 to 1,5 mm.

Magnetite forms as subhedral to anhedral interstitial grains 0,06 to 0,25 mm in size with 2 mm being the largest size. The magnetite grains are often associated with red ferrohydroxide staining, and typically occur as grains 0,06 to 0,25 mm in size when associated with chlorite alteration of the femic minerals. Chlorite is often found as anhedral grains or fibrous masses 0,125 to 0,75 mm in size, and often completely replacing biotite and hornblende. Accessory minerals include zircon, fluorite, sphene and apatite, which are typically euhedral, 0,5 to 0,25 mm in size, and often near or associated with the femic minerals. Plates IV - A and IV - B show typical coarse-grained Verena granite under the microscope.

The fine-grained apical phase consists of K-feldspar, perthite, quartz, plagioclase, biotite and magnetite. K-feldspar phenocrysts, typically subhedral in shape and 3 mm in size, are highly altered (mostly sericitised), and ferrohydroxide stained. Quartz phenocrysts, 4,5 mm in size, are also found, as well as patches of quartz-rich areas made up of quartz grains 1,5 to 2,5 mm in size. The K-feldspar in the groundmass is subhedral to anhedral, deuterically altered, ferrohydroxide stained and sericitised, reaching sizes of 0,25 to 1,5 mm and typically 0,5 to 1 mm. Perthite is found as subhedral grains 1 to 1,5 mm in size. Quartz grains are subhedral to anhedral reaching sizes of 0,06 to 2 mm. Accessory plagioclase, with composition An_{25-35} is found as euhedral to subhedral, sericitised laths 0,25 to 1,5 mm in size.

Biotite is found as subhedral pleochroic yellow green brown / dark green to dark brown / black grains, reaching sizes of 0,125 to 2,5 mm but typically 0,5 mm. The biotite is often highly chloritised, in which case it is found as dark green grains 0,25 to 0,75 mm in size. This highly chloritised biotite is often found associated with clusters of magnetite 0,06 to 0,125 mm in size. Magnetite occurs as subhedral interstitial grains 0,06 to 0,25 mm in size, and is often associated with chloritised biotite. Often it is accompanied by red ferrohydroxides.

Chlorite occasionally occurs as separate subhedral grains 0,25 mm to 0,75 mm in size, as well as replacing biotite. Accessory minerals, which are typically euhedral to subhedral in shape, and 0,03 to 0,5 mm in size, are fluorite, zircon and apatite. The rock has a fine-grained equigranular texture. The fine-grained granite has the exact same mineralogy as the coarse-grained granite, and it can be seen that the one is just the fine-grained phase of the other. Plate IV - C shows a photomicrograph of the fine-grained apical phase of the Verena granite.

The fine-grained granite, found near the Rooipoort tin occurrence on Rooipoort 440 JR (see folder), contains extensive granophyric texture, and may represent recrystallised leptite or Klipkloof granite.

4.2.2 Associated granites

The Bobbejaankop and Klipkloof granites are two granites associated with the Nebo granite in the study area. The Bobbejaankop granite in the study area is correlatable with the type granite in the Potgietersrus area, and exhibits the same basic features, so that it can be given the same name as the type granite. The Bobbejaankop granite is regarded as a highly fractionated phase of the Nebo granite, and is often host to base metal, particularly tin, mineralisation. The Bobbejaankop granite is believed to have formed in the presence of large quantities of volatiles, causing intense deuteric alteration of the crystallising granite, and suppressing crystallisation of mafic minerals (Crocker, 1979).

The Klipkloof granite is a fine-grained pinkish brown aplitic granite occurring as dykes and sills cutting across the main Nebo granite sheet, as well as often being associated with the Bobbejaankop granite. Various authors such as De Bruiyn (1980) and Walraven (1982) have pointed to the highly fractionated nature of this granite, inherent from its geochemical characteristics, and have suggested a younger age for this granite owing to its crosscutting relations. The cross-cutting relations would appear to have been brought about by press-squeezing of this late-stage fractionate into the crystallised to semi-crystallised surrounding Nebo granite. The Klipkloof granite is considered to represent a phase formed by crystallisation of the last remnants of granitic magma that formed the Lebowa Granite Suite.

The Lebowa Granite Suite contains other fine-grained granites that have often being misinterpreted as Klipkloof granite, such as the fine-grained Verena granite. Various authors such as Robb *et al* (1994) have made attempts to distinguish between the highly fractionated late-stage Klipkloof granite and other fine-grained granite varieties that do not exhibit the highly fractionated composition of the Klipkloof granite or may simply be chill phases, such as the fine-grained Verena granite.

4.2.2.1 Bobbejaankop granite

4.2.2.1.1 *Contact relationships and general description*

The Bobbejaankop granite or granites with a Bobbejaankop-like appearance are found in all four plutons, with the Moloto pluton having the greatest extent of this phase (see Figure 4.1). The Bobbejaankop granite is mostly associated with Klipkloof granite.

The Bobbejaankop granite forms transitional contacts with underlying Nebo granite and overlying granophyre, suggesting that this granite variety was formed after large amounts of fractionation of the granitic magma and in the presence of late-stage volatiles which had evolved with fractionation. On Vreemdeling 65 JS, the Sekhukhuni granite becomes redder, more quartz-rich and has less mafic minerals nearing the Bobbejaankop-type granite, indicating increasing degrees of fractionation

PLATE IV

A: Photomicrograph of coarse-grained Verena granite. The rock is composed of quartz (top), K-feldspar (central portion) and chloritised biotite (right margin) and hornblende (left). A zircon grain can be seen left of centre. Roodepoortje 250 JR. Uncrossed nicols; field of view is 3,55 mm.

B: Photomicrograph of coarse-grained Verena granite consisting of quartz (upper right margin), K-feldspar (upper left) and chloritised biotite (off centre right). Roodepoortje 250 JR. Crossed nicols; field of view is 3,55 mm wide.

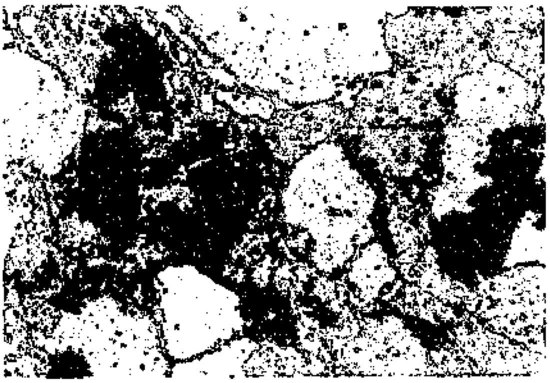
C: Photomicrograph of fine-grained Verena granite. Mineralogy is as for the coarse-grained Verena granite. Roodepoortje 250 JR. Uncrossed nicols; field of view is 3,55 mm wide.

D: Photomicrograph of coarse-grained Bobbejaankop granite consisting of quartz forming coalesced chains, and K-feldspar. Enkeldoorn 217 JR. Crossed nicols; field of view is 3,55 mm.

E: Photomicrograph of Klipkloof granite composed of quartz, K-feldspar, magnetite and chloritised biotite. Enkeldoorn 217 JR. Uncrossed nicols; field of view is 3,55 mm.

F: Photomicrograph of medium-grained Makhutso granite composed of quartz, K-feldspar, biotite (upper margin) and plagioclase (left centre). Hartebeestfontein 224 JR. Crossed nicols: field of view is 2,2 mm.

PLATE IV



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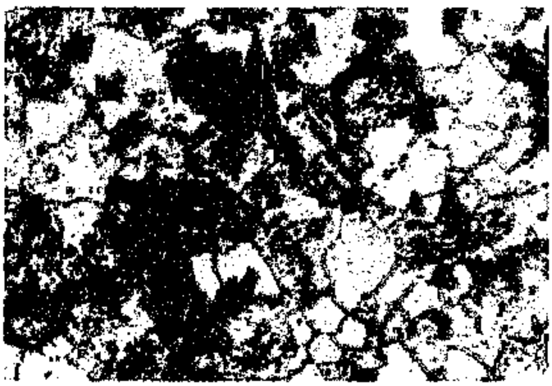

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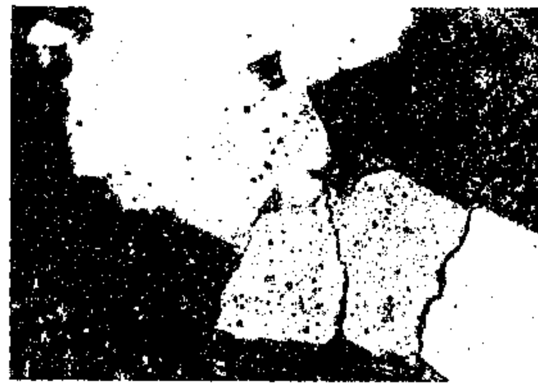

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toward this granite type. The Bobbejaankop-type granite subsequently becomes finer grained as one nears the Klipkloof granite contact. However, at this locality the granite may not be strictly Bobbejaankop granite but rather Sekhukhuni granite.

It is found that in all three Sekhukhuni granite plutons, the Sekhukhuni granite becomes darker red in colour and takes on a Bobbejaankop-like appearance near the granophyre contact. On Zandspruit 189 JR, the Sekhukhuni granite, found between a Klipkloof granite sill and the overlying granophyre, looks very much like Bobbejaankop granite. The Verena granite is also found to take on a Bobbejaankop-like appearance, such as at the Rooipoort tin occurrence and the coarse-grained granite at depth associated with the north vein near the Albert Silver Mine. The Verena granite contains an area of Bobbejaankop granite, 7 km in length, adjacent to Rhenosterkop, which is the host to the Rietfontein tin occurrence (see Chapter 6).

4.2.2.1.2 *Macroscopic Description*

The granite is a dark red colour due to the dark red colour of the constituent K-feldspar grains. The dark red colour is caused by exsolution of magnetite along the cleavage planes of the feldspar. On oxidation, the magnetite is oxidised to red hematite, which imparts a deep red earthy appearance to the feldspars.

The granite is virtually a two-mineral rock consisting of dark red K-feldspar and quartz grains coalesced together around the K-feldspar grains, so that it appears as if the quartz forms long chains on the weathered surface. There are very few mafic minerals in the rock, although biotite and hornblende are occasionally present near the Nebo granite contact.

In outcrop, the rock forms low, rounded domical boulders, and can often look like Sekhukhuni or Verena granite, apart from its deep red colour and low mafic mineral content.

4.2.2.1.3 *Petrographic Description*

Under the microscope the rock consists predominantly of deuterically altered, deep red, subhedral to anhedral, ferrohydroxide stained K-feldspar, 0,75 to 6 mm in size and typically 2 to 4 mm. The K-feldspar is often rimmed by magnetite grains, and is often highly chloritised. Perthite grains are often the predominant K-feldspar occurring as subhedral to anhedral grains 2 to 2,5 mm in size. The quartz grains are coalesced together to form long chains (see Plate IV - D). The quartz grains are subhedral to anhedral, and range in size from 0,25 mm at the smallest to 7 mm at the largest, with 1,5 to 2,5 mm being the typical size. On Zustershoek 246 JR the K-feldspar and quartz are granophyrically intergrown near the granophyre contact.

Altered, sericitised, euhedral to subhedral plagioclase with composition An_{25-35}, and varying in size from 0,5 to 2 mm, is found as an accessory mineral. On some occasions K-feldspar overgrows and totally replaces the plagioclase, suggesting more than one period of crystal growth.

Mafic minerals, which are accessory in abundance, include subhedral to anhedral, often skeletal, dark brown biotite, which is often highly chloritised and hematised on occasion, and 0,75 to 1,5 mm in size. Orange green, subhedral to anhedral, often highly chloritised hornblende 0,75 to 2,5 mm in size is also found. The hornblende is often associated with magnetite.

Magnetite, euhedral to anhedral in shape, is interstitial and can reach sizes from 0,06 mm to 1 mm but has a typical size of 0,75 mm. The magnetite is often associated with chlorite alteration, as well as found separately with chlorite grains in the rock. Chlorite occurs as 1 to 3 mm sized clusters in the rock, as well as replacing K-feldspar, biotite and hornblende. It is also associated with occasional quartz veining intersecting the rock. Accessory minerals include fluorite, apatite and some epidote associated with quartz veining cutting across the rock in some areas.

4.2.2.2 Klipkloof Granite

The Klipkloof Granite has limited outcrop in the study area, and is most often found associated with the Bobbejaankop granite (see Fig. 4.1). It is found as a sill between the Sekhukhuni granite and Bobbejaankop-like granite and granophyre on Zandspruit 189 JR, where its contact with the Nebo granite is relatively sharp. On Enkeldoorn 217 JR the coarser Bobbejaankop granite seems to be intruded by the fine-grained Klipkloof granite and the contact is sharp. However, the exact relationships in outcrop are not clear.

On Rietfontein 446 JR the two granites are also intimately associated with each other, and are found in close proximity to each other. On the farms Maloek Zyn Kop 58 JS and Rhenosterkuil 63 JS the Klipkloof granite is found between the granophyre and Bobbejaankop-like Sekhukhuni granite. Its contacts with the underlying Nebo granite and overlying granophyre is more transitional in these areas.

4.2.2.2.1 *Macroscopic Description*

The Klipkloof granite forms low, smooth, domical hills and is a fine-grained, aplitic, pinkish brown rock. It is porphyritic in places with K-feldspar phenocrysts from 3 to 10 mm in size, as well as containing lesser quartz phenocrysts, and in some areas contains tourmaline spheroids, such as on Zandspruit 189 JR, and pegmatitic vugs, as on Enkeldoorn 217 JR. The tourmaline spheroids reach 5 cm in size, and consist of tourmaline crystals intergrown with K-feldspar and quartz crystals, which reach sizes of 5 mm and more. Freeman *et al* (1997) suggest that these features formed as a result of interaction of boron-rich, magmatically derived fluids and Fe - Mg-rich connate fluids. The pegmatite vugs consist of coarse K-feldspar, quartz and biotite (now chloritised) 10 mm in size. The rock consists of K-feldspar, quartz, plagioclase, biotite and minor hornblende.

4.2.2.2.2 Petrographic Description

The rock consists of subhedral to anhedral, sericitised K-feldspar grains 0,25 to 1,5 mm in size, but typically 0,5 mm. Perthite grains of the same size are also sometimes present. K-feldspar phenocrysts, from 2 to 7 mm in size, are subhedral to euhedral in shape, and are also often highly sericitised. Quartz is found as anhedral grains 0,25 to 2 mm in size at the largest but are typically 0,5 mm. Quartz phenocrysts, which are subordinate to K-feldspar phenocrysts, are subhedral to anhedral, and can be from 4 to 5,25 mm in size but are typically 2,5 mm. On Rhenosterkuil 63 JS the Klipkloof granite, developed near overlying granophyre, shows extensive granophyric texture.

Plagioclase is found as 0,25 to 2 mm sized, typically 0,5 to 0,75 mm, subhedral, slightly sericitised grains with a composition An_{30-37}, and is usually only present in minor amounts. Biotite and hornblende are the main femic minerals. Biotite, which is predominant, occurs as pleochroic subhedral to anhedral, light yellow brown / dark brown to dark brown / black grains, where it has extensive oxides. It reaches sizes of 0,25 to 0,75 mm and up to 2 mm. It is often highly chloritised, where it exhibits a light yellow green / dark green pleochroism. Hornblende occurs as subhedral to anhedral grains, pleochroic light yellow green / dark green to light brown / dark reddish brown in colour, and reaching sizes varying from 0,5 to 1,5 mm but typically 0,5 mm. These grains are also often highly chloritised.

Chlorite is found on occasion as subhedral grains 2 mm in size, often forming part of the alteration of K-feldspar grains or phenocrysts, or of the femic minerals. Magnetite is found as subhedral grains 0,25 to 0,5 mm in size, interstitial to the other grains, or associated with hornblende, or with chlorite, where it forms part of the alteration assemblage of the femic minerals. Accessory minerals include fluorite, apatite and euhedral zircon grains, 0,25 mm in size. Plate IV - E shows a photomicrograph of Klipkloof granite.

4.2.3 Makhutso granite

The Makhutso granite is found as a pluton, 5 km by 10 km in size, just to the north of the central region of the study area, where it is in contact with Verena granite (see Fig. 4.1). This, however is not its only mode of occurrence, as Coertze *et al* (1978) found a few dykes cutting across the Sekhukh i granite. It is a grey biotite-rich granite, which in the area north of the Verena granite fo s tor-like outcrop. The K-feldspars are a whitish grey colour, unlike the typical red colour of the other Bushveld granites, and it has a greater abundance of biotite than the other granites found in the study area.

De Bruiyn and Rhodes (1975) report that the southern contact with the Verena granite is not well exposed. This pluton is found to consist of a fine-grained marginal phase, grading into a coarse-grained biotite-rich granite, which is porphyritic in places (De Bruiyn and Rhodes, 1975). The fine- to medium-grained marginal phase is what has mpled in this investigation.

Walraven (1988) studied the age of the granite and found it to have an age of 2049 + 69/- 72 Ma from Pb-Pb whole rock dating. This age disproved the far younger age of 1670 ± 70 Ma reported by Coertze *et al* (1978). The field relationships and its trace element chemistry, led Walraven (1988) to conclude that the Makhutso granite did not evolve by fractional crystallisation of the other acid rocks, but that it represents a magma formed during the final stage of Bushveld magmatism, possibly by renewed partial melting of the source region, probably located in the lower crust. The Makhutso granite is the youngest of all the granitic phases found in the Bushveld Complex, and thus it places an important constraint on the upper age of the Bushveld granites.

4.2.3.1 Petrographic Description

A medium-grained phase near the fine-grained marginal phase of the Makhutso granite pluton north of the Verena granite was sampled. The Makhutso granite consists of subhedral to anhedral slightly sericitised, but not deuterically altered, grey K-feldspar 0,5 to 1 mm in size but typically 0,5 mm. Perthite forms a minor component of the K-feldspar grains. Anhedral quartz 0,25 mm to 1 mm in size, but typically 0,75 mm is the other major constituent.

Subhedral plagioclase with a composition of An_{35-39} is a minor constituent and forms grains 0,5 to 1 mm in size. Subhedral, chloritised biotite, pleochroic light green / dark green in colour and 0,5 to 1,5 mm in size is a major constituent of the rock. Anhedral to subhedral, pleochroic dark green / brown green hornblende 0,25 to 1,5 mm but typically 0,5 mm, is also abundant. Magnetite is found as subhedral grains, 0,25 mm in size, interstitially between the other grains and as grains 0,03 mm in size associated with chloritisation of the femic minerals. The rock has an equigranular medium-grained texture. Plate IV - F shows a photomicrograph of medium-grained Makhutso granite.

4.3 Conclusions

The Lebowa Granite Suite is found as a number of different compositional types that vary in grain size and texture as well as chemistry. It is found that the granites vary from a grey K-feldspar, hornblende-rich granite at their base to a more quartz- and biotite-rich rock, with red deuterically altered K-feldspars near their top. The dark red K-feldspar, quartz-rich Bobbejaankop granite follows this trend and is closely associated with mineralisation in the granites, as it is formed from amongst the last remnants of magma, which are enriched in incompatible elements such as tin. The level of exposure within the granites determine, to a large extent, the extent of mineralisation potential of the granite pluton.

The Sekhukhuni granite is found in three plutons in the study area, and is found to have both sharp to gradational contacts with the overlying granophyre and rhyolite. Some plutons, such as the Moloto dome area, which represent higher level granites, are found to be more inherently susceptible to mineralisation.

The Verena granite, a marginal phase of the Sekhukhuni granite, differs in texture but otherwise shows similar relationships as the Sekhukhuni granite. It has a prominent fine-grained apical phase developed on Roodepoortje 250 JR and Zwartkopje 444 JR, which hosts the mineralisation at the Albert Silver Mine.

The Bobbejaankop and Klipkloof granites have limited outcrop but are usually found associated with each other and are typical hosts for mineralisation. The Bobbejaankop granite is found near the roof of the granites, as is the Klipkloof granite, which is also often found as dykes and sills cutting across the Nebo granite.

The Makhutso granite represents the youngest acid intrusion in the Bushveld Complex, owing to its younger age as well as having intruded into the Verena granite. It thus represents an upper age constraint on the age of the Lebowa Granite Suite.

CHAPTER 5

GEOCHEMISTRY OF THE FELSIC ROCKS

5.1 Introduction

The felsic rocks of the Bushveld Complex have been studied geochemically by many authors, such as Lenthall (1972, 1975), McCarthy and Hasty (1976), De Bruiyn (1980), Twist (1983, 1985), Walraven (1982) and Schweitzer *et al* (1995a) to name a few. Some of these authors have concentrated on specific felsic rock types in the Bushveld Complex. The granophyres were extensively studied by Walraven (1982), and the Rooiberg Group by Twist (1983, 1985) and Schweitzer *et al* (1995a). Others, such as De Bruiyn (1980), have studied the whole felsic rock suite and ha· considered the origin and emplacement of these rocks.

This study will not attempt to model the genesis of any of the felsic rocks of the Bushveld Complex, but will use the chemical data to classify the felsic rocks, as well as to highlight features of the rocks relevant to an exploration program. The lack of a comprehensive data set on any one particular rock type also precludes an intensive study on the origin of any particular rock type.

Table A1 (Appendix A) gives the major and trace element compositions of the granites in the study area. The composition of the roof rocks are given in Table A2 (Appendix A).

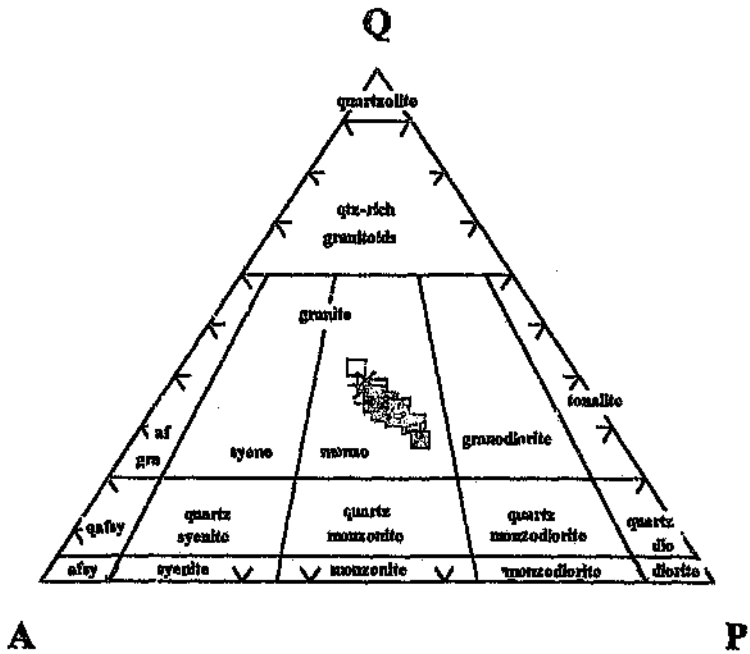
5.2 Rock Classification

5.2.1 Granite Classification

The granites of the Lebowa Granite Suite are subdivided in the field into a number of textural and compositional varieties. Chemically these different granite varieties are found to differ from one another in terms of major and trace element contents. All the granite varieties, however, are found to be granite *sensu stricto* in nature, as illustrated in Fig. 5.1 where a Q-A-P diagram, as used by Streckeisen (1975), is plotted. Streckeisen (1975) used this diagram to differentiate between the various plutonic rocks encountered in the earth's crust. The granites plot within the monzogranite field of the Q-A-P diagram in that they, in general, contain equal amounts of K-feldspar, quartz and plagioclase.

5.2.2 Roof Rock Classification

Discrimination diagrams, as used by Winchester and Floyd (1977), identify the felsic volcanic rocks of the Bushveld Complex as rhyolites to rhyodacites (Figure 5.2 a and b). The volcanics of the upper Schrikkloof Formation are predominantly rhyolitic in composition with the Kwaggasnek Formation composed of predominantly rhyodacites. Thus, there is an evolution in the volcanics in passing upwards, from a dacitic composition at the base of the volcanic pile to a rhyolitic composition toward the top. This trend has been noted by other authors, such as Twist (1983) and De Bruiyn (1980). The diagrams also include the granophyres, and indicates that if extruded as volcanics the granophyres would be rhyolitic in composition, and thus represent a more fractionated portion of the parental magma, than that which gave rise to the lower levels of the volcanic pile.



Legend

- Makhutso granite
- Klipkloof granite
- Bobbejaankop granite
- Sekhukhuni granite
- fine-grained Verena granite
- coarse-grained Verena granite

qtz: quartz af gra: alkali feldspar granite

qafsy: quartz alkali feldspar syenite afsy: alkali feldspar syenite

dio: diorite

Fig. 5.1 Q-A-P diagram, after Streckeisen (1975), indicating the granite *sensu stricto* nature of the granites of the Lebowa Granite Suite in the study area

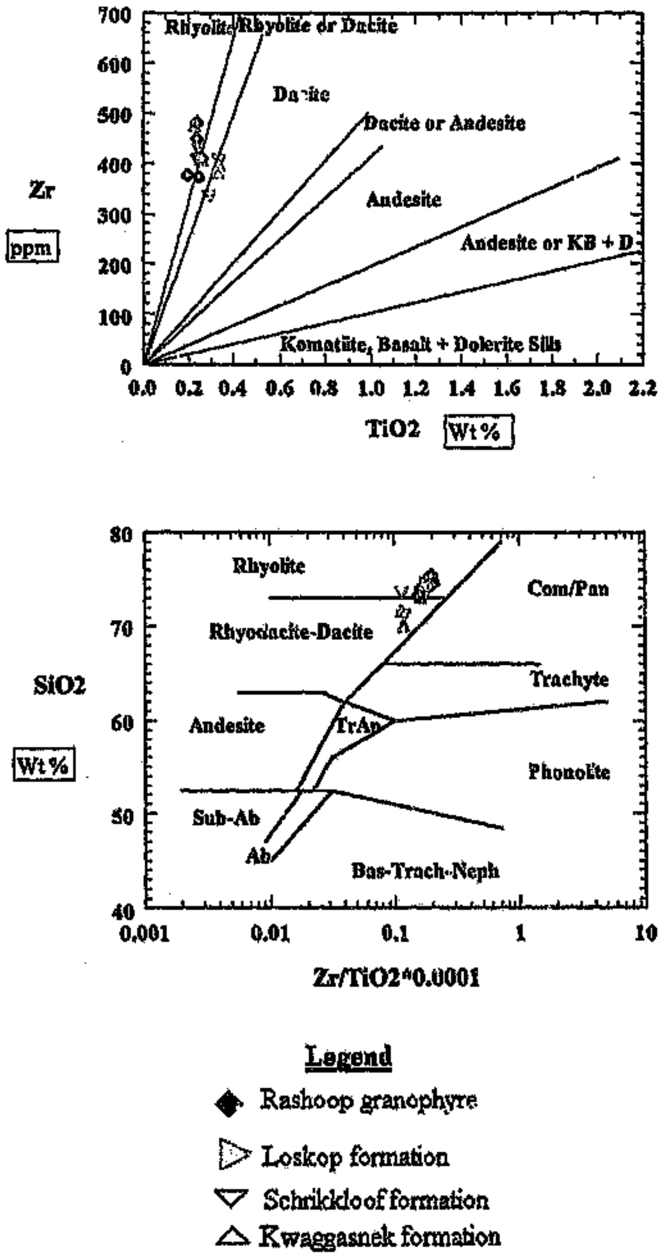
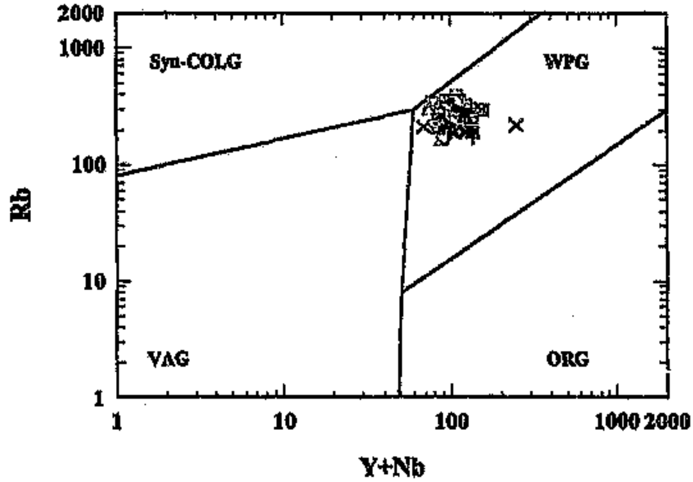


Figure 5.2 Discrimination diagrams, as used by Winchester and Floyd (1977), indicating the predominantly rhyolitic nature of the roof rocks (Data from Appendix A2)

5.3 Tectonic Setting of the felsic rocks in the study area

Attempts have been made over the years to consider the tectonic setting of the Bushveld Complex. Theories have ranged from a rift setting to meteorite impact. This section deals with the classification of the felsic rocks within a tectonic setting, the nature of the granites (i.e. S-, I- or A-type granites), and a brief look at the tectonic environment which may have prevailed during emplacement of the felsic rocks.



Legend

Syn-COLG: Syn - Collision granites
VAG: Volcanic Arc granites
WPG: Within - Plate granites
ORG: Ocean Ridge granites

- Makhutso granite
- Klipkloof granite
- Bobbejaankop granite
- Sekhukhuni granite
- fine-grained Verena granite
- coarse-grained Verena granite
- Rashoop granophyre
- Loskop formation
- Schrikkloof formation
- Kwaggasnek formation

Fig. 5.3 Log (Y + Nb) vs. Log Rb diagram, after Pearce *et al* (1984), indicating the tectonic setting of the felsic rocks in the study area

The diagram indicates that the felsic rocks were emplaced in an anorogenic environment.

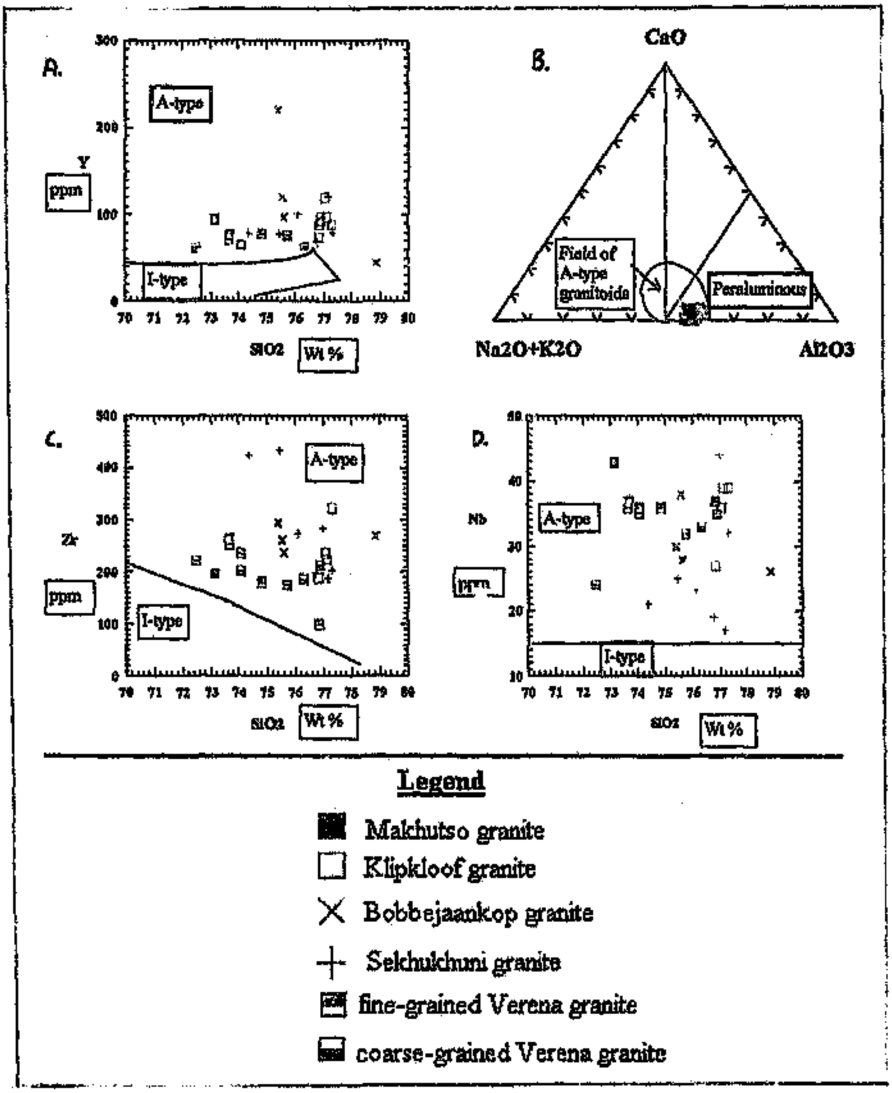


Fig. 5.4 Diagrams illustrating the A-type nature of the granites. B. Derived, and after Kleeman and Twist (1989). A. C, and D are diagrams derived by Collins *et al* (1982) to distinguish A-type granites from I-type granites.

Fig. 5.3 is a diagram used by Pearce *et al* (1984) to distinguish tectonic settings of granites. The felsic rocks in the study area have the compositions of within-plate granites (WPGs), which corresponds with the emplacement of the Bushveld Complex within the middle of the Kaapvaal Craton after collision of the Kaapvaal and Zimbabwe cratons (Courtnage, 1995). The A-type, post-collisional, within-plate nature of the rocks is confirmed by plotting the data on Y+Nb-Rb diagrams (not shown), as used by Sylvester (1989). On Y-Nb and Y/ Nb-Rb/ Nb diagrams (as plotted by Eby (1992))(not shown), the granites plot as A2 granitoids from postcollisional, postorogenic and anorogenic environments. The A-type nature of the granites is also confirmed, to a lesser extent, by plotting the rocks on SiO_2-CaO, SiO_2-(Na_2O+K_2O)/ Al_2O_3 and SiO_2-K_2O/ Na_2O plots as used by Patiño Douce (1997).

Figure 5.4 illustrates four diagrams used to discriminate between A-type and I-type granites. The granites in Fig. 5.4B plot in the A-type granitoid field (after Kleeman and Twist, 1989). Collins *et al* (1982) point to the alkaline composition of A-type granites along with their high Ga / Al_2O_3, Fe / Mg, SiO_2, Zr, F, low Ca and Sr and a Sn-Mo-Bi-Nb-W-Ta-F metallogenic association. The granites plotted in Fig. 5.4 A, C and D all fall within the field of A-type granitoids as defined by Collins *et al* (1982). CaO-poor peraluminous granites are those formed in an anorogenic environment, i.e. they are not emplaced during mountain building, plate collision or subduction. This concurs with Figure 5.3 as A-type granites are more readily formed within a plate whereas S- or I-type granites are formed at plate margins during plate collision and / or subduction.

Batchelor and Bowden (1985) used R1-R2 diagrams, first used by de la Roche *et al* (1980), to distinguish various tectonic settings of granitic rocks (Fig. 5.5). The diagram makes use of two different formulae R1 and R2 , first derived by de la Roche *et al* (1980) where:-

$$R1 = 4\,Si - 11(Na + K) - 2\,(Fe + Ti)$$
$$R2 = 6\,Ca + 2\,Mg + Al$$

Nearing the top of the Pretoria Group, volcanic successions start to predominant over the sediments and a large number of diabase sills intrude the sediments, increasing in abundance upwards. Authors, such as Sharpe and Snyman (1980), have postulated that the Bushveld magmas intruded as a result of subsidence involving the Transvaal Supergroup rocks, which began to occur in late Pretoria Group times. Sharpe *et al* (1981) postulated that the Bushveld magmas intruded into the sedimentary units of the Transvaal Supergroup at a late stage in the subsidence of this basin, possibly as a result

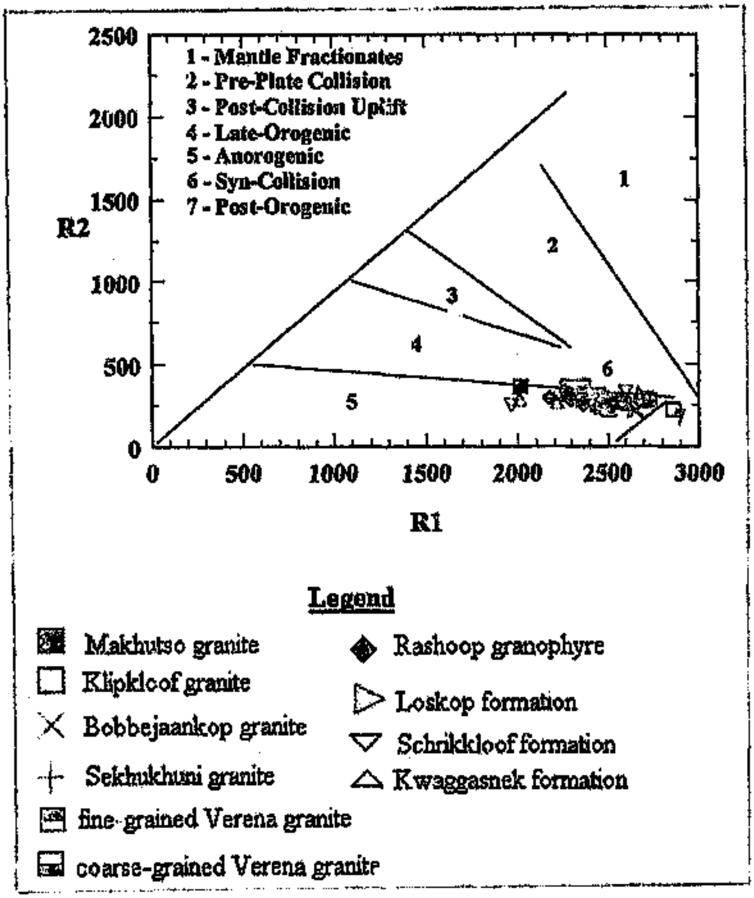


Fig. 5.5 Plot of R1 vs. R2, after Batchelor and Bowden (1985), showing the tectonic setting of the Bushveld Complex in the study area

of multi-stage conical fracturing of the crust. The Rooiberg Group was the initial volcanism and the granites represent later intrusion of the more highly fractionated parental magma.

5.4 Differentiation of the felsic rocks

Workers, such as Walraven (1982), Kleeman and Twist (1989) and Twist and Harmer (1987), suggest that the Rooiberg Group volcanics and the Rashoop Granophyre Suite represent a single magma formed by partial melting of the lower crust. The granites of the Lebowa Granite Suite were derived from further fractionation of this same parental magma, which then intruded these roof rocks. These arguments agree with field relationships, where it is evident that the granites intruded beneath a roof of rhyolites and in many areas granophyre.

Much of the granophyre in the Complex owes its origin to fractionation from a magma intruded beneath a layer of volcanics extruded from the same magma (Walraven, 1982). Only in some cases is the granophyre derived from a different origin, such as metasomatism or melting and recrystallisation of the rhyolites. The Rooiberg Group was extruded at 2061±2 Ma ago (Walraven, 1997), with contemporaneous hypabyssal intrusion of the granophyres beneath the rhyolites.

Recent studies have placed the age of intrusion of the Nebo Granite at 2054.4 ± 1.8 Ma (Walraven and Hattingh, 1993). Thus a time span of only 5 Ma occurred between extrusion of the Rooiberg volcanics, dated at 2061±2 Ma (Walraven, 1997) and intrusion of the Lebowa Granite Suite.

Geochemically the major elements do not record changes in the degree of fractionation particularly well. However, trace elements such as Rb, Ba, Sr, Zr, Y, and Nb are more useful, as trace elements exhibit more significant changes in their contents during fractionation than do the major elements. Rb, being an incompatible element, increases its abundance during fractionation, whereas Ba and Sr, which are both compatible elements, decrease in abundance with increasing degrees of fractionation. The ternary plot of Rb, Ba and Sr, as defined by El Bouseily and El Sokkary (1975), shown in Figure 5.6 indicates that the granites were derived from a magma which had und-, gone greater degrees of fractionation (higher Rb, lower Ba) than the roof rocks, with which it is coeval. This may also be a determining factor as to why the granites

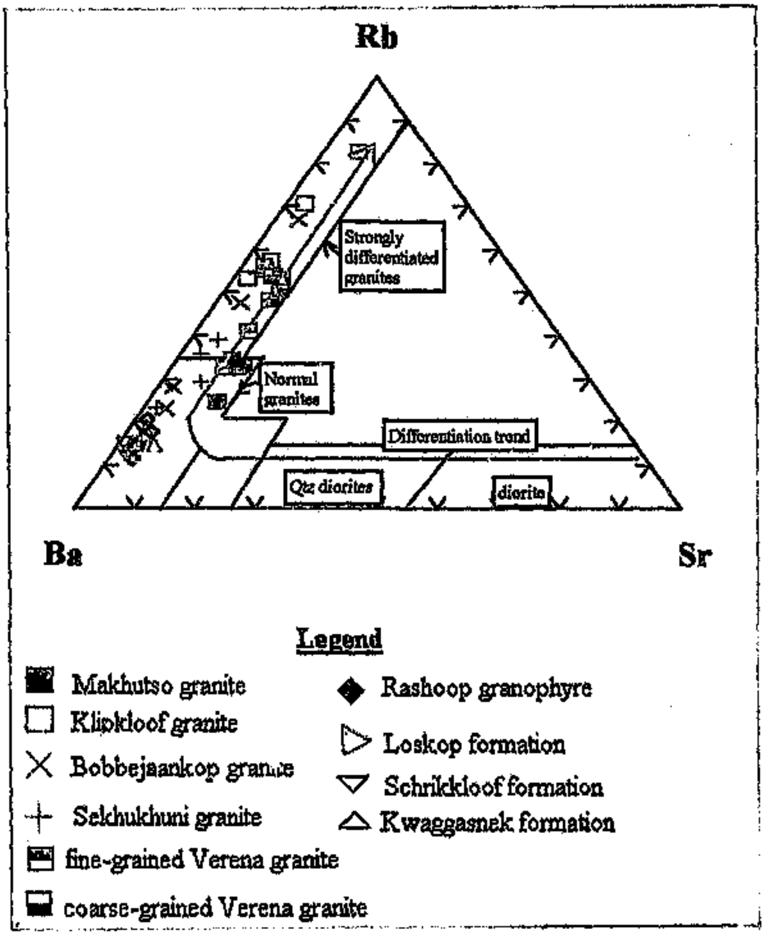


Figure 5.6 Rb - Ba - Sr ternary diagram, as used by El Bouseily and El Sokkary (1975), showing the more fractionated nature of the granitic rocks .

are the main host to mineralisation, whereas the rhyolites and granophyres act as repositories for mineralisation derived from the underlying granites, and appear not to be sources of mineralisation in their own right.

Another point worth noting in Fig. 5.6 is that the Klipkloof granite tends to have the highest Rb and the lowest Ba, and indicates that it is the most fractionated of the granitic rocks.

The Loskop Formation rocks are not included due to exhibiting variable results. Tapping of magma that had undergone differing degrees of fractionation may have led to the variable rock compositions of the Loskop Formation samples.

5.4.1 Major element geochemistry (Harker diagrams)

Harker diagrams, where SiO_2 is plotted against the other major elements often show fractionation trends well. As SiO_2 increases fairly substantially in going from the base of the granite sheet to its upper reaches, as well as increasing upwards in the volcanic succession, it is used as the independent variable in the Harker diagrams shown in Figure 5.7. Ba, Rb and Sr are plotted against SiO_2 in Figure 5.8.

With increasing degrees of fractionation of a granitic magma there are increases in SiO_2 and K_2O and decreases in TiO_2, Al_2O_3, Fe_2O_3, CaO and P_2O_5. The granites of the Lebowa Granite Suite of the study area exhibit fractionation trends from Sekhukhuni granite, through coarse grained Verena granite through to Klipkloof granite, which is the most highly fractionated. The Makhutso granite has a low SiO_2 content, and shows that the magma responsible for this granite had not undergone much fractionation before emplacement.

It is generally seen that the granophyres have higher silica contents and generally higher alkali contents (see Table A2) than the Rooiberg Group, indicating the more fractionated nature of the granophyres compared to the rhyolites of the Rooiberg

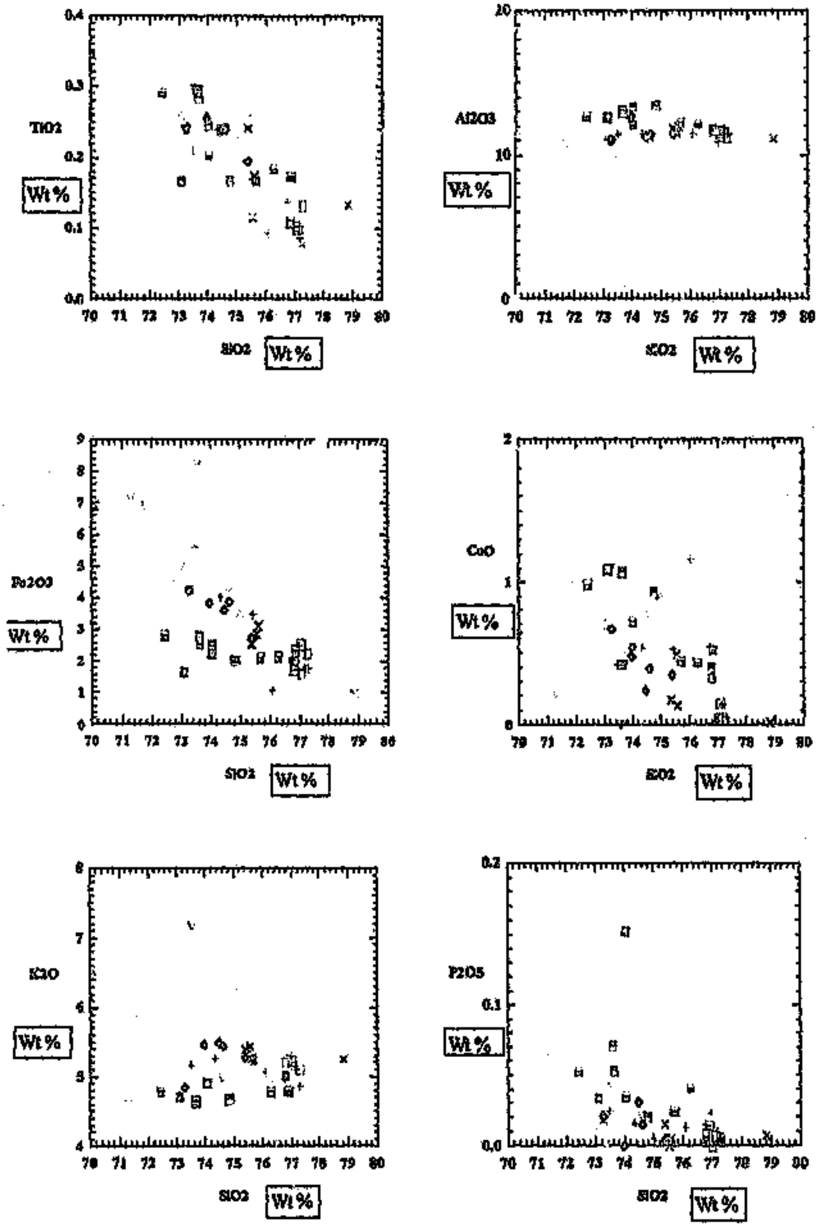


Figure 5.7 Harker diagrams for the felsic rocks of the Bushveld Complex in the study area. Legend as for Figure 5.8.

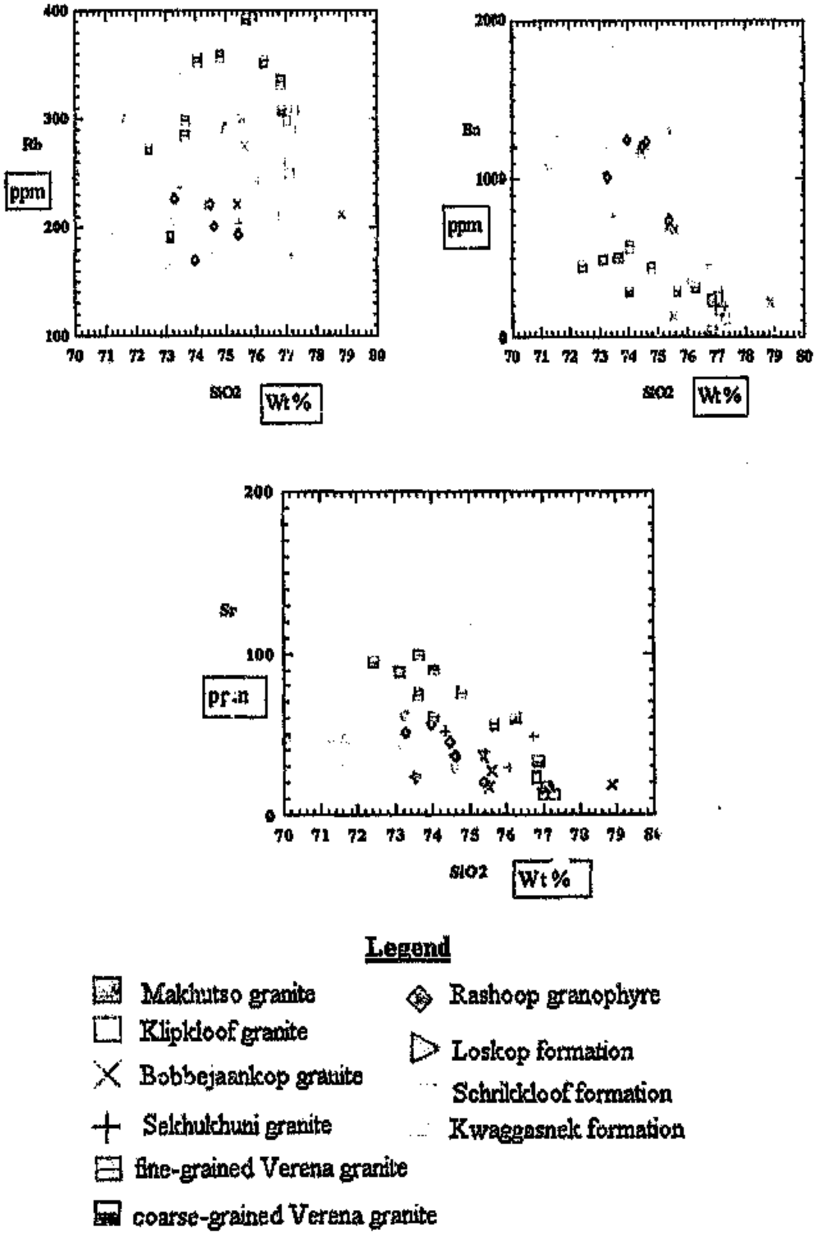


Figure 5.8 SiO_2 vs. trace element diagrams for the felsic rocks of the Bushveld Complex in the study area

Group. Note too that the volcanics of the upper Schrikkloof Formation are more silica rich than the lower Kwaggasnek Formation, and indicates progressive fractionation of the parental magma during the eruption of the Rooiberg Group in passing from its base upwards.

With regards to the roof rocks, the Harker diagrams tend to show fractionation trends better than the trace element plots. The trace element plots with regard to the roof rocks tend to show a greater variation due to more variable trace element contents in the roof rocks compared to the granites.

The Harker diagrams, in terms of the roof rocks, show reasonably good trends, with the granophyres typically showing the best trends. It is found that SiO_2, and to some extent Al_2O_3, increase with height in both the granophyres and Rooiberg Group, whereas Fe_2O_3, TiO_2, Ba and Sr decrease in content. In the case of the Rooiberg Group, this is as would be expected for rocks which had been extruded from a progressively fractionating parental magma, and in this regard they show similar geochemical trends to the granites.

The plots involving trace elements do not have clearly defined fractionation trends for the roof rocks, and Rb is generally found to decrease with height in the volcanic pile (using TEDI values as a general guide to height in the stratigraphy). This trend is totally opposite to that expected, as Ba and Sr are found to generally decrease in content with stratigraphic height, while Rb generally increases in content with stratigraphic height, as may be expected for a succession of volcanics tapping a progressively fractionating parental magma. Some other influence may have caused the Rb to decrease in content with height in the volcanic pile.

With regards to the granitic rocks the SiO_2 versus Ba and Sr diagrams both show a negative correlation with regards to SiO_2, which is particularly well illustrated in the Sr diagram. This is as would be expected for a progressively fractionating granitic magma.

All the granophyre samples shown occur between the Lebowa Granite Suite and the overlying Rooiberg Group. The granophyre may have originated by fractionation from the base of a magma chamber upwards beneath a roof of rhyolite. Initial crystallisation of the lowermost granophyre occurred beneath a roof of rhyolites erupted from the same parental magma. With time residual magma, which was either trapped in-between the underlying crystallising granophyre and the overlying rhyolites, or was successively injected in-between the granophyric rocks and the rhyolites from an underlying fractionating magma chamber, gave rise to the granophyres which exhibit a fractionation trend from base to top.

The granites intruded the granophyre-volcanic pile after the hypabyssal intrusion of the granophyre and extrusion of the volcanics of the Rooiberg Group. Granophyric granite formed by the intrusion of the granites into the granophyre pile, and the gradual assimilation at the contact of the still relatively hot granophyre.

5.4.2 Trace element geochemistry

Binary plots of Rb, Ba and Sr against each other, as shown in Figure 5.9, also indicate fractionation trends in the felsic rocks.

Two distinct trends can be seen on the Rb - Sr diagram. The first to the left consists of samples of Sekhukhuni granite, Bobbejaankop granite, some coarse-grained Verena granite and Klipkloof granite, and illustrates the progressive fractionation from Nebo granite through Bobbejaankop granite to Klipkloof granite. The second trend in the upper right corner consists predominantly of fine-grained Verena granite. The melts in equilibrium with the crystallising solid are always more enriched in Rb and less enriched in Ba and Sr than the solid with which they are in equilibrium (see Fig. 1, McCarthy and Hasty, 1976). This is due to the differing degrees of differentiation of Rb, Ba and Sr into the crystallising minerals, so that the incompatible nature of Rb, and the compatible natures of Ba and Sr influence the abundance of these elements in the melt. Thus samples plotting with a higher Rb content are generally less

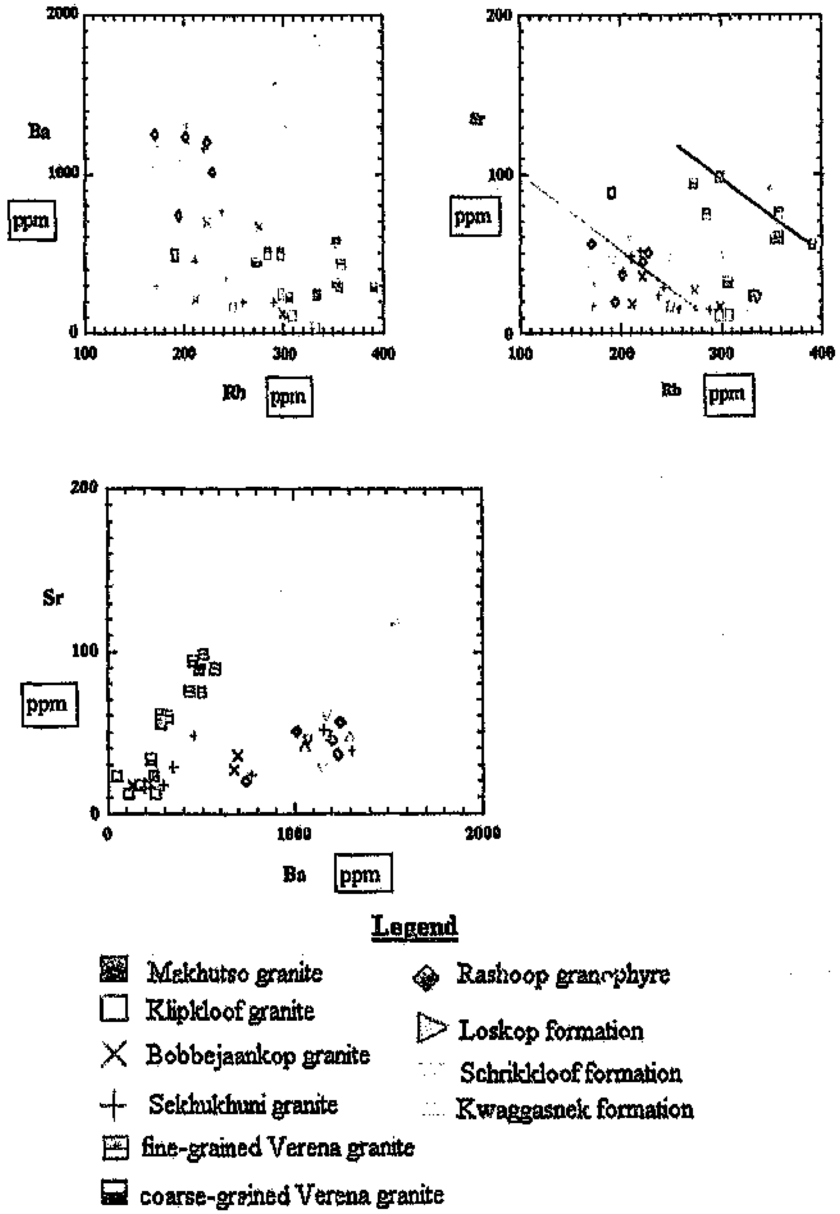


Figure 5.9 Binary trace element plots indicating fractionation in the felsic rocks of the Bushveld Complex in the study area

fractionated and are closer to the initial melt composition, as illustrated by McCarthy and Hasty (1976). Thus the fine-grained Verena granite samples represent a less fractionated chill phase, where the granitic magma chilled beneath roof rocks and was intruded by a more fractionated granitic magma, which slowly cooled giving rise to the coarse-grained phase of the Verena granite.

Owing to the limited number of samples analysed fractionation trends in the roof rocks of the study area are not well defined. A factor to bear in mind is that the samples also come from across the whole area, and not from one particular portion of the study area, and hence wide discrepancies between the samples will be observed. The Loskop Formation, which forms the uppermost part of the Rooiberg Group, is omitted. The roof rocks, however, generally have lower Rb and higher Ba and Sr than the granites indicating lesser degrees of fractionation than the granites. The granophyres generally appear to be more fractionated than the Rooiberg Group volcanics.

5.4.3 The Trace Element Differentiation Index (TEDI)

Walraven (1986) defined a trace element differentiation index (TEDI) to determine the amount of fractionation a granite of the Lebowa Granite Suite had undergone. To this end the trace elements Rb, Ba, and Sr proved most useful. The trace element differentiation index (TEDI) is defined as:

$$\text{TEDI} = \text{Ba} \times (\text{Sr} / \text{Rb})$$

Investigations by numerous workers (e.g. McCarthy and Hasty (1976), El Bouseily and El Sokkary (1975) and Walraven (1986)) have shown that with increasing fractionation in a granitic magma, Rb increases in content while Ba and Sr decrease in content. Thus with increasing amounts of fractionation the TEDI value decreases. Walraven (1986) reported that TEDI values of between 4000 and 1000 represent the lowest portions of the granite sheet, whereas values less than 10 are found in the very upper parts of the sheet. Values of around 500 would be reasonable for the middle of the granite sheet. Table 5.1 gives the TEDI values for the different granite types in the study area.

Despite there being relatively few samples for each pluton or granite type the TEDI values illustrate that the Nebo granite in the area has relatively low TEDI values,ranging from 170 to 10. This indicates that the granites in the study area are high level granites and relatively highly fractionated. Where TEDI values are low, the mineralisation potential of the granite is far greater as incompatible elements, such as the base metals, are concentrated in the most highly fractionated portions of the granite.

Of the three Sekhukhuni granite plutons the Kameelpoort pluton has the lowest TEDI values. This, however, would appear to be a function of the sampling positions, as samples were collected from near the pluton margins on the northwestern portion of Kameelpoort 202 JR.

The Kameelpoort pluton is situated on an antiform trending NE - SW, parallel to the Zebediela anticline, that passes through into the Moloto pluton to the southwest and is partly responsible for the doming of the latter. Thus, present levels of erosion have exposed deeper level granites (with higher TEDI values) in the center of the Kameelpoort pluton along the line of the antiform. Higher level granites are preserved along the margins of the pluton, particularly along the northwestern margin. It is also worth noting that a small Cu - F occurrence is found on the northwestern margin near a Klipkloof granite sill where the TEDI values are low.

The Moloto pluton has TEDI values ranging from 134 to 60, indicating that the granites are highly fractionated, a feature that is confirmed by its mineralogy. The granites with TEDI values ranging from 134 to 118 are nearer the center of the pluton, with values less than 100 being nearer the margins. The numerous mineral occurrences along the eastern margin of the pluton is explained by the fact that higher level granites, in the form of Bobbejaankop granite, are preserved here. Due to the domical nature of the Moloto pluton high-level rocks are preserved along the margins, particularly the eastern margin (see Fig. 6.2).

The samples from the Dennilton granite pluton are lis in Table 5.1 in a north to south fashion so that sample 58-163 is at Phooko (see folder), and closer to the center of the pluton, whereas sample 65-151 is much south near the Klipkloof granite contact, where the granite takes on a Bobbejaankop-like appearance. From the TEDI values it is apparent that in moving from north to south, one is passing into the upper portions of the granites and up into the Klipkloof granite (see sample 63-161). This upward progression is reflected in both the topography as well as the texture and colour of the granites. To the south of Dennilton the granite is grey and hornblende-rich. Southwards the land rises to an escarpment a granite passes into a deep red Bobbejaankop-like granite. This granite becomes rained passing into Klipkloof granite, and up into granophyre. Further south a plateau is formed by Rooiberg Group rocks on Zwartfontein 89 JS and Rietfontein 90 JS, and south onto Engelschedoornboom 95 JS. It is also worth noting that all the mineral occurrences associated with the Dennilton granite are found along its margin, in the upper portions of the granite sheet, as reflected by the low TEDI values.

The Verena granite has TEDI values generally less than 100 and hence are high-level anites, despite being at an approximately equivalent topographic height as its neighbour, the Moloto pluton. The Verena pluton is more hig actionated than the Moloto pluton. The Verena pluton intrudes Schrikkloof Formation rocks of the Rooiberg Group along both its eastern and western margins. The Moloto pluton, however, intruded granophyres and the lower Kwaggasnek Formation. Thus different plutons intruded the volcanic pile at different stratigraphic positions.

The fine-grained phase of the Verena granite in the vicinity of the Albert Silver Mine on Roodepoortje 250 JR, has an average TEDI value of 136, whereas the surrounding

Table 5.1 TEDI values for the various granite types in the study area

Nebo granite (var. Sekhukhuni)					
sample	Ba	Sr	Rb	TEDI (Ba x (Sr/Rb))	min. occ.
Kameelpoort pluton					
189-24	215	19	212	19	
202-15	293	17	173	29	
202-19	351	29	242	42	
Moloto dome					
ED. 3	720	47	281	120	
ED. 4	707	43	232	131	
ED. 5	690	41	211	134	
ED. 6	680	30	233	88	
ED. 7	637	41	222	118	
ED. 8	678	32	290	75	
ED. 9	750	25	300	63	
ED. 10	574	24	230	60	
ED. 11	787	24	235	80	
Dennilton granite					
58-163	461	48	211	105	
63-159	201	16	259	12	
65-161	198	15	290	10	
Nebo granite (var. Verena)					
fine-grained apical phase					
250-108	572	90	352	146	
250-110	512	99	299	170	
250-115	437	76	358	93	
250-113	507	75	285	133	Albert
441-103	245	24	335	18	Rooipoort
coarse-grained phase					
93-136	285	56	392	41	
227-117	455	95	273	158	
250-109	316	60	354	54	
441-102	229	33	307	25	
441-104	108	10	330	3	Rooipoort
444-116	285	61	367	49	
Bobbejaankop granite					
217-37	678	27	275	67	
217-49	771	24	238	78	
246-76	131	17	300	7	
Klipkloof granite					
63-161	116	12	309	5	
189-23	168	17	250	11	
217-39	249	12	299	10	
447-130	47	23	332	3	
Makhutso granite					
MAK-1	492	89	191	229	

samples ED. 3 to 11 from Lenthall (1975). Sample numbers (see Appendix A, Table A1) coarse-grained phase has an average TEDI value of 65. Thus the TEDI values reflect the observation that the fine-grained granite is an apical chill phase, that formed by relatively rapid cooling of a relatively unfractionated granitic magma. The coarse-grained phase represents a more evolved, slower cooling magma.

It is also worth noting that the granites near the granophyre / rhyolite contact have lower TEDI values (e.g. sample 93-136), compared to those toward the center of the pluton (e.g. samp. e 227-117). This reflects the fact that higher-level granites are preserved near the granophyre / rhyolite contact, whereas erosion in the center of the plutons exposes lower level granites. Thus the TEDI values to a certain extent reflect the topography of the granite pluton.

The Bobbejaankop granite has low TEDI values reflecting its highly fractionated nature (cf. McCarthy and Hasty, 1976). The increasing volatile content of the magma which crystallised to form the Bobbejaankop granite caused the intense deuteric alteration characteristic of this granite. The volatile-rich magma also suppressed crystallisation of the mafic minerals giving rise to the bimineralic nature of the Bobbejaankop granite.

The Klipkloof granite has very low TEDI values (less than 10 typically), confirming that it is the very last remnants of crystallised magma.

The Makhutso granite has a high TEDI value and so, despite being the youngest granite in the Lebowa Granite Suite, was derived from a different magma caused by renewed partial melting of the lower crust. This would explain its different chemistry compared to the other granites of the Lebowa Granite Suite.

The granites hosting the Rooipoort tin occurrence (samples 441-103 and 104) have markedly low TEDI values, which possibly reflect a trace element redistribution brought about by the mineralising fluids. Walraven *et al* (1990b) discussed the behaviour of Rb and Sr isotopes near tin mineralisation, and the markedly different values of these trace elements in mineralised granites compared to unmineralised, barren granites. Walraven *et al* (1990b) discovered a direct correlation between the degree of ^{87}Sr loss, the severity of alteration and the proximity of the rocks to Sn mineralisation. Late-stage, low temperature hydrothermal fluids which had evolved from the earlier high-temperature fluids responsible for Sn mineralisation caused a lowering of the Rb-Sr whole-rock ages (Walraven *et al*, 1990b). Hence these fluids would affect the TEDI value of these rocks.

Alteration by hydrothermal fluids involves sericitisation and / or chloritisation of the feldspars, chloritisation of the mafic minerals hornblende and biotite and introduction of chlorite, epidote and possibly carbonates. Rb is able to substitute for K and to a lesser extent Na. Sr can substitute for Ca and to a lesser extent Mg and Fe^{2+}. As such, during alteration Ca is preferentially lost in chloritisation and sericitisation of the feldspars. Na is also affected to a lesser degree. The Mg and K content is relatively unaffected. As a consequence there is a smaller Sr content in the chloritised and sericitised granites than in the unaltered granites, whereas the Rb content is affected to a far lesser degree. As such highly chloritised samples will have low TEDI values due to preferential leaching of Sr caused by alteration. As phyllic alteration begins to predominate with decreasing hydrothermal fluid temperatures, Sr is not preferentially leached and the TEDI value is not as severely affected. Hence, TEDI values of altered rocks, that differ substantially from the immediately surrounding unaltered rocks, may indicate the passage of mineralising fluids and may indicate the presence of mineralisation. If so, TEDI values are useful in any exploration program as indicators of possible mineralisation.

The trace element differentiation index (TEDI) can be used in the roof rocks to determine stratigraphic height. Even though Walraven (1986) first used it to determine the height in the granite sheet of the Lebowa Granite Suite the concept can also be used for the roof rocks. The ratio is particularly valuable for work in the granophyres, where stratigraphic height cannot be easily correlated from one area to another. Even the Rooiberg Group, despite some marker horizons, is relatively homogenous and may not be well exposed. This may not be necessarily true in widely separated areas, such as at Loskop Dam and Rooiberg, as separate extrusions may have occured in separate areas. Nevertheless within a certain area TEDI values may be useful in determining the volcanic stratigraphy. Table 5.2 lists TEDI values for the roof rocks analysed.

Table 5.2 TEDI values of the roof rocks

Rooiberg Group (Schrikkloof Formation)					
sample	Ba	Sr	Rb	TEDI (Ba x Sr/Rb)	
95-134	1151	29	176	190	
439-98	1071	46	191	258	
89-140	1171	61	207	345	
90-138	1845	22	336	121	agglom.
Rooiberg Group (Kwaggasnek Formation)					
228-133	1295	48	301	207	
228-132	1194	48	250	229	
205-22	1058	42	166	268	
434-89	1550	119	291	634	
Rashoop Granophyre Suite					
63-162	739	20	194	76	
434-90	1011	51	227	227	
248-94	1234	37	201	227	
214-32	1205	45	222	244	
205-27	1247	57	170	418	

The samples as listed in Table 5.2 do not show a decreasing TEDI value from the lowermost samples of the Kwaggasnek Formation to the uppermost samples of the Schrikkloof Formation. Rather they show decreasing trends in the separate formations. Hence, determination of which formation the volcanic rocks fell into was determined by field relationships alone.

The agglomerate layer sample (sample 90-138) has a low TEDI value. As this sample is taken from the mineralised agglomerate layer that is sporadically mineralised along a strike length of 40 km, the low TEDI value may be explained by the influence of fluids moving along the permeable agglomerate layer, and giving rise to the low grade mineralisation within it. The mineralising fluids would have influenced the Rb and Sr contents of the rock and hence the TEDI value.

The TEDI values can help give an overall stratigraphy to a field area and may help in determining the tectonic, structural or intrusive history of an area. The TEDI values indicate that the Verena pluton intruded at high stratigraphic levels in the volcanic pile, whereas the Moloto pluton intruded at lower levels, and the Kameelpoort pluton at even lower levels.

The TEDI values also indicate which roof rocks are lowest particularly in areas where no underlying granites or Rustenburg Layered Suite rocks are exposed. High TEDI values in this case indicate roof rocks low down in the stratigraphy, and hence closer to the granites or mafic rocks. These rocks are of greater exploration potential as hosts to mineralisation derived from the immediately underlying granites or mafic rocks.

5.5 Conclusions

The Rooiberg Group was extruded from a progressively fractionating rest liquid, firstly as a passive type of volcanism to form the Kwaggasnek Formation, followed by a more explosive volcanism to form the Schrikkloof Formation. The style of volcanism may have changed due to the magma becoming more viscous due to fractionation. The Rooiberg Group samples show a progressive fractionation of the parental magma, giving rise to more fractionated lavas being extruded higher up in the volcanic succession.

Magma which intruded beneath this volcanic pile crystallised as the Rashoop Granophyre Suite, often metasomatising and recrystallising the immediately overlying rhyolite of the Rooiberg Group. The lowermost granophyres crystallised from the magma first. With time, restite liquid got progressively trapped between the overlying rhyolites and the underlying crystallising granophyre. This restite liquid gave rise to the granophyre suite, and explains why the granophyre exhibits similar geochemical trends to the granites.

Continued fractionation of the now progressively fractionated magma gave rise to the granites. The magma intruded beneath the roof rocks of rhyolite and granophyre and was often chilled and metasomalised in places giving rise to granophyric granite near the granophyre contact.

Fractionation of the magma gave rise to the distinct trends noted in passing from the bottom of the granites to their top. These include changes in texture, colour and mineral content, particularly the dominance of one or the other mafic mineral. The uppermost granites are marked by deep red K-feldspar and quartz rich granites, with little mafic mineral content and often host to tin mineralisation. The Klipkloof granite, often associated with the Bobbejaankop granite, is a fine-grained, pinkish-brown, aplitic granite, and represents the most highly fractionated portion of the granitic magma. The Klipkloof granite often shows pegmatoidal vugs of tourmaline, quartz and K-feldspar. The same textures were found in the granites at the Zaaiplaats Tin Mine (Groves and McCarthy, 1978).

The Makhutso granite represents the last intrusive event in the emplacement of the Bushveld Granites. It has a different chemistry to the other granites, and would seem to have been derived from a second partial melting of the lower crust.

The upper, most fractionated portions of the granites contain the greatest abundance of incompatible elements, i.e. the metals, and hence are more subject to mineralisation than lower level, less fractionated granites.

TEDI values are useful indicators of height not only in the granites but also in the roof rocks. TEDI values are a useful exploration tool as they can be used, in conjunction with field observations, to delineate areas of mineralisation potential.

CHAPTER 6

METALLOGENY OF THE FELSIC ROCKS

6.1 Introduction

The acid phase of the Bushveld Complex is host to numerous small mineral occurrences, as well as important deposits such as the Rooiberg and Zaaiplaats tin mines. The study area is no exception, having several mineral occurrences with numerous, different commodities, and hosted in a variety of different rock types. The various commodities found include the base metals, precious metals and rare earth elements. It is found that the granite suite is the principal host to the bulk of the mineral occurrences, especially those of possible economic significance in the study area. The Rashoop Granophyre Suite does not offer any potential in its own right, but is rather a repository for mineralisation originating from the underlying granites. The Rooiberg Group has a potential to host mineral deposits, but it too is often host to mineralisation derived from either the underlying granites and could possibly host mineralisation derived from the Rustenburg Layered Suite (Schweitzer *et al*, 1995b).

Figure 6.1 shows the various mineral occurrences found in and around the study area. The name of each occurrence in Fig. 6.1 is given according to the farm on which it is located, followed by the major commodity found at the occurrence. For convenience the study area has been divided into four regions, namely:

1. the Moloto pluton area, consisting of the Sekhukhuni granite pluton developed in and around the settlement of Moloto, as well as the immediate surrounding rocks
2. the northwestern Verena granite pluton, which is the granitic terrain of the Verena pluton to the west of 29° E
3. the Rhenosterkop area, which includes deposits in the area adjacent to this prominent hill and

4. the southern Dennilton granite pluton area, which is found in the upper northeast portion of the study area.

These four areas are further subdivided into major mineral occurrences in that area e.g. the Enkeldoorn tin field in the Moloto pluton area. Any mineral occurrence outside of these four areas is described in a separate section.

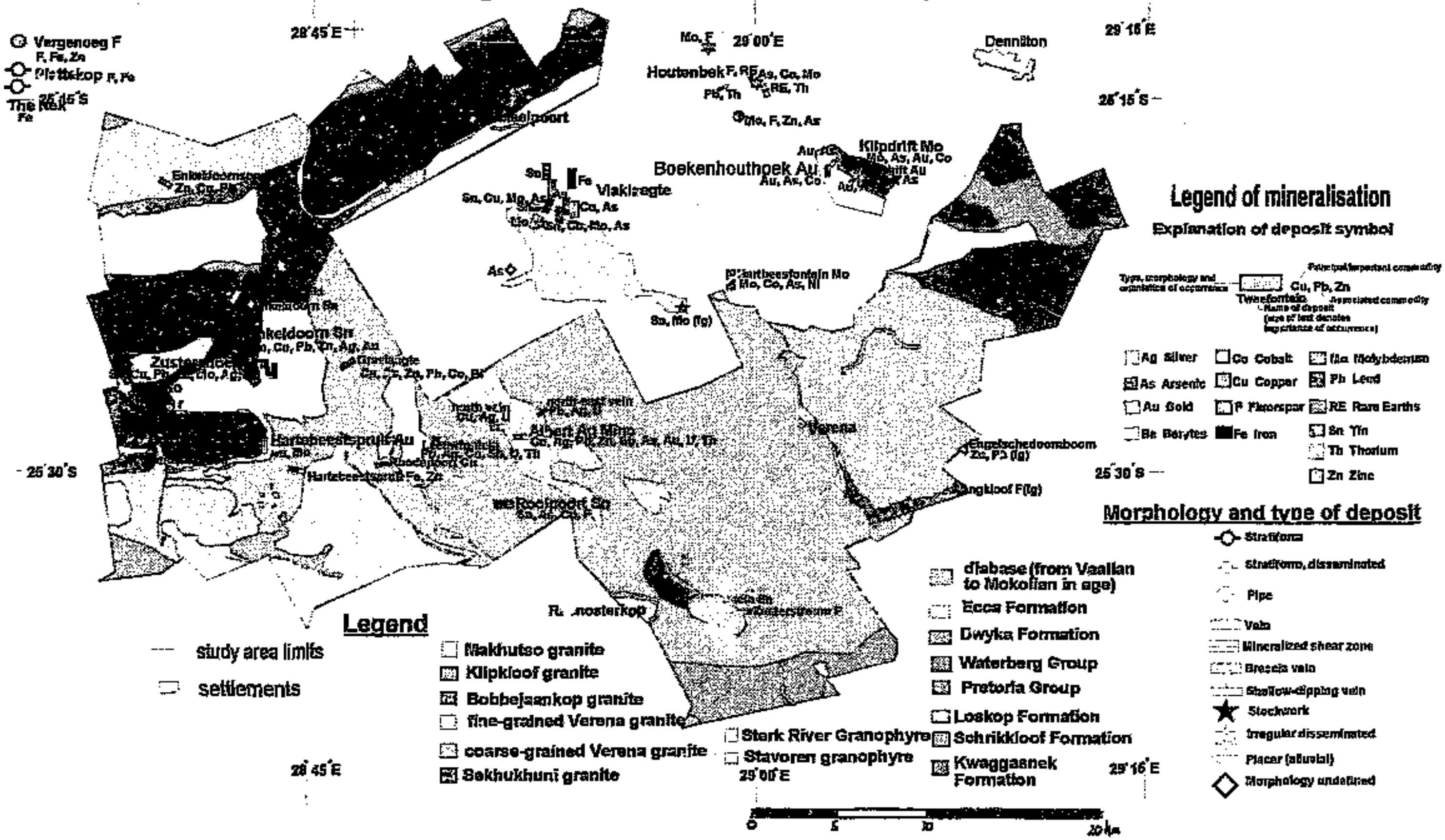
6.2 Moloto Pluton

The Moloto pluton area includes the Sekhukhuni granite found around the settlement of Moloto on the border of the study area, as well as the granophyric and Rooiberg Group rocks immediately adjacent to this pluton (see Fig. 6.1). This area hosts three minor mineral occurrences, namely the Enkeldoorn tin field, the Zustershoek Tin Mine, and the Prins Anna structure which hosts Pb-Zn mineralisation. Other mineral occurrences in the area include the Hartebeestspruit gold occurrence, the Rietfontein and Enkeldoorn barite occurrences, and a copper occurrence on Sybrandskraal 244 JR.

The area is underlain by coarse-grained Sekhukhuni granite, a variety of Nebo granite, and is surrounded by granophyre to the north, east and southeast, and by rhyolite of the Rooiberg Group to the northeast and south. In the centre of the pluton a wedge of Ecca Group sediments is preserved. Bobbejaankop granite is extensively developed along the eastern margin of the pluton, where it acts as host to the Enkeldoorn tin field and Rietfontein and Enkeldoorn barite occurrences (see folder). It underlies the granophyre hosting the mineralisation at the Zustershoek Tin Mine on Zustershoek 246 JR.

Klipkloof granite is found in the upper northeast corner of the pluton (see Fig. 4.1), where it is associated with Bobbejaankop granite. The base and precious metal

Figure 6.1 Mineral occurrences in the study area



contents of the mineral occurrences found within the Moloto pluton and surrounding rocks are given in Table 6.1. Some values are obtained from Scogings (1991).

Table 6.1 Base and precious metal contents for the mineral occurrences in the Moloto pluton area

occur.	ppm Sn	ppm Mo	ppm Cu	ppm Pb	ppm Zn	ppm As	ppm Sb	ppm Ag	ppm Au	ppm F
Enkeldoorn	202	-	2618	1150	1508	403	<10	4.8	0.02	85
Zustershoek										
sample 1	64412	62	20.90%	7870	850	0.11%	30	12.3	0.37	11
sample 2	21700	9	4230	6633	148	1208	20	1.15	0.15	-
sample 3	9567	-	3686	143	93	873	-	-	0.02	-
Prins Anna										
sample 1	20	<5	147	459	2385	134	21	10.3	< 0.01	<10
sample 2	-	-	67	0.56%	0.84%	30	-	24	-	-
sample 3	-	-	-	1.27%	1.65%	-	-	-	-	-
Harte' Au										
sample 1	166	139	2007	2323	233	118483	416	<1.0	0.01	462
sample 2	77	-	271	1223	179	2922	347	-	5	-
sample 3	27	-	83	-	41	241	14	-	-	-
avg. content	12021	-	24679	4233	2761	13933	-	10.5	0.93	-

6.2.1 Zustershoek Tin Mine

The Zustershoek Tin Mine is found on the farm Zustershoek 246 JR, directly to the south of Tweefontein settlement and directly east of KwaMhlanga (see folder). It is hosted in granophyric rock of the Rashoop Granophyre Suite underlain directly by Bobbejaankop granite. Its main commodities are tin, copper, lead, zinc, molybdenum, silver and gold (see Table 6.1). The deposit was mined from 1952 to 1954 before mining operations ceased.

6.2.1.1 Host rock petrography

The host rock is a fine to medium-grained dark pink granophyre containing quartz, K-feldspar and minor hornblende. This granophyre is extensively sheared, and the shear zones are infilled with quartz-hematite veining trending 168° with an inner zone of quartz surrounded by hematite. Hematite veining and gossanous ridges are found in the vicinity of the mine and to the north on Enkeldoorn 217 JR. Quartz veining is also found crosscutting the deep red granophyre. The main quartz-hematite veining can be followed directly to the shaft. There are also a number of lesser hematite-quartz ridges developed to the west of the major shear zone.

At the old mine plant a stockwork of quartz veins is found within the actual plant workings. The rock is now highly altered and weathered but may have been host to low-grade sulphide mineralisation. An extensive shear zone at the plant, trending 012° and dipping at approximately 12° to the south, is found associated with the extensive stockwork of veins (see Plate V - A). At the plant the granophyre is extensively chloritised, sericitised and hematised (see Plate V - B). Miarolitic cavities in the granophyre are infilled with quartz and hematite. Bobbejaank granite was found amidst the waste material at the plant, suggesting its presence directly beneath the granophyre, and a possible source of the mineralising fluids. To the west of the plant near the granophyre contact, a dark coloured coarse-grained K-feldspar rich granite is found, which is enriched in iron, possibly by fluid action probably related to the mineralisation at the mine.

Microscopically the host granophyre is fine to medium-grained, with intergrowth grains varying in size from 2 to 5 mm. The K-feldspar grains have been extensively sericitised and hematised, as well as being chloritised to a lesser extent (see Plate V - B). It is occasionally stained red by the hematite.

Chlorite clusters, consisting of radiating fibres 0,25 mm in size, are found associated with quartz veining cutting across the rock. Extensive goethite is found associated with these veins. K-feldspar nuclei grains and phenocrysts, which can reach 5 mm in size, are totally sericitised. The 2 mm quartz grains found scattered throughout the rock and between the altered K-feldspar grains may have been recrystallised to some extent.

6.2.1.2 Ore Petrography

Cassiterite occurs as subhedral grains, 0,25 mm in size, near the centre of quartz veins located at the centre of the shear zone. The cassiterite is found in association with rust red goethite and sericite, and is overgrown by pyrite. The cassiterite in the centre of the veining can reach sizes of 0,5 mm, and is found in fine-grained quartz of only 0,03 mm in size, along with fine chlorite grains (0,06 mm in size) and goethite (see Plate V - C).

Away from the centre of the vein, the vein quartz becomes coarser, being 0,5 mm in size on average, whereas the cassiterite grains become smaller, typically 0,125 mm in size and smaller. Subhedral to anhedral pyrite grains, ranging in size from 0,125 mm to 1,5 mm are found in association with the cassiterite. Chlorite fibres are associated with the pyrite. Chalcopyrite is found further away, as massive masses that have been brecciated and infilled by sphalerite. Small grains of cassiterite 0,125 to 0,06 mm in size are found within the chalcopyrite mass (see Plate V - D). Sericite fibres 0,06 mm in size are found associated with the sulphides.

Still further out from the vein centre, grains of pyrite, varying in size from 0,25 to 0,75 mm, have been overgrown by sphalerite (see Plate V - E). These are found in vein quartz, varying in size from 0,125 to 2 mm. On the margins of the vein massive hematite extensively overgrows and brecciates pyrite grains 0,125 to 0,75 mm in size, and small cassiterite grains 0,125 to 0,25 mm in size. The later hematite is found in large abundance away from the centre of the veining (see Plate V - F).

The paragenetic sequence would thus appear to be cassiterite - pyrite - chalcopyrite - sphalerite - hematite. Cassiterite precipitated early and is found near the centre of the veining in association with pyrite. The pyrite is extensively brecciated and infilled by sphalerite. Chalcopyrite precipitated next, away from the centre of the vein, and was also brecciated and infilled by sphalerite. The hydrothermal fluids deposited the metals in order of increasing solubility, with early precipitation of tin, proceeded by copper,

PLATE V

A: Photograph of stockwork of veins associated with a main vein in highly altered and weathered granophyre. Old mine plant, Zustershoek 246 JR.

B: Photomicrograph of sericitisation and minor hematisation of the feldspars in the granophyric texture of the host granophyre. Zustershoek Tin Mine, Zustershoek 246 JR. Uncrossed nicols; field of view is 2,2 mm wide.

C: Photomicrograph of cassiterite crystals (centre) and pyrite (lower left) surrounded by goethite near the centre of the shear zone quartz veining. Zustershoek Tin Mine, Zustershoek 246 JR. Uncrossed nicols; field of view is 1,89 mm wide.

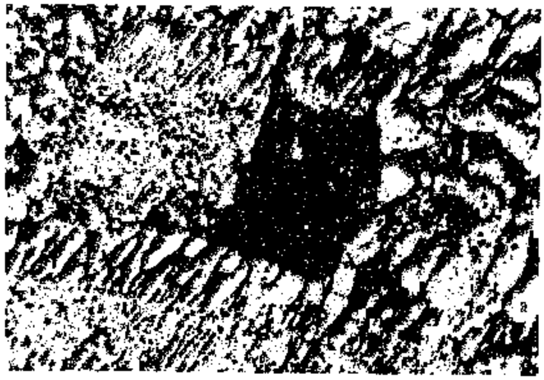
D: Photomicrograph of cassiterite (centre) overgrown by chalcopyrite (dark). Zustershoek Tin Mine, Zustershoek 246 JR. Uncrossed nicols; field of view is 3,55 mm wide.

E: Photomicrograph of brecciated pyrite crystals infilled by sphalerite (lower left) and overgrown and infilled by hematite (upper margin). The hematite has overgrown the sphalerite (upper centre margin). Zustershoek Tin Mine, Zustershoek 246 JR. Reflected light; field of view is 3,55 mm wide.

F: Photomicrograph of brecciated pyrite crystal (centre) and cassiterite (off centre lower left) overgrown by hematite. Zustershoek Tin Mine, Zustershoek 246 JR. Reflected light; field of view is 3,55 mm wide.

PLATE V

A



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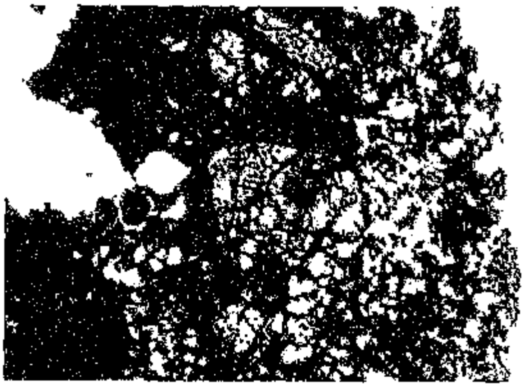

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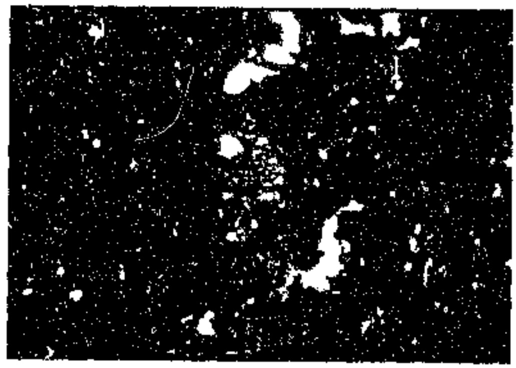
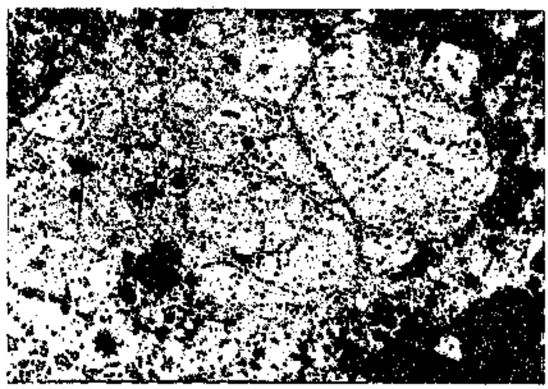


D

E



F

lead and zinc, as the temperature of the fluid decreased. This order follows the natural solubilities of these elements.

Hematite extensively brecciates and overgrows the cassiterite and pyrite away from the centre of the vein. Thus there is an early base-metal rich assemblage followed by a later oxidised iron-rich assemblage. A later assemblage consisting of malachite, azurite and other copper oxides and hydroxides is also present, found within the hematite and often associated with pyrite grains. This indicates the oxidation of chalcopyrite in the fresh ore to give rise to the malachite-rich oxidised assemblage.

6.2.1.3 Ore Geochemistry

The concentration of base and precious metals found in the ore at the mine is given in Table 6.1. The mine is very rich in copper (> 3500 ppm Cu, Table 6.1). The copper that is present in chalcopyrite, and in the oxidised assemblages of malachite and azurite, was introduced late in the paragenetic sequence, where it overgrew and replaced earlier cassiterite and pyrite, and thus accounts for its high concentration.

Tin hosted in cassiterite is the other major commodity found at the mine. Silver is present in large quantities, and is possibly hosted in tetrahedrite, although none was found in the samples taken. The other base metals such as zinc and lead are found in lesser amounts. The ore is rich in arsenic (around 1200 ppm), possibly hosted in arsenopyrite, although none was found in the dump samples taken. Its large abundance would suggest that it too was deposited late in the paragenesis, possibly along with or succeeding chalcopyrite. Galena and molybdenite have also been reported from the ore suite.

6.2.2 Enkeldoorn Tin Field

The Enkeldoorn tin field consists of several minor mineral occurrences all on the farm Enkeldoorn 217 JR (see folder). The mineralisation is hosted in shear zones, filled by quartz veining, trending 340° to 020° and dipping from 72° W to vertical, and containing minor sulphides. Of these occurrences two are host to base metal mineralisation. The northernmost occurrence is named the pipes and consists of an area of three cylindrical pipes found to the north of the Tweefontein - Moloto road (see folder). These cylindrical bodies have now been flooded. The second occurrence is named the eastern lode and is developed to the east of the pipes (see folder). The eastern lode is host to tin, copper, lead, zinc, silver and gold mineralisation.

Other minor localities such as the western lode, blue lode and intermediate lode are marked by quartz veining on the surface and occasional disseminated sulphides. The area was mined from 1904 to 1910, as well as in the early 1950s, and then intermittently until 1968, but has not been worked since. It was the first tin deposit to be found in the Bushveld granites, as reported by Merensky (1908). As it is also hosted in shear zones infilled with quartz, and showing a similar orientation to the Zustershoek Tin Mine shear zones, it does show similar characteristics to this deposit which is 4 km away.

6.2.2.1 Host Rock Petrography

Deep red K-feldspar rich Bobbejaankop granite is the host to the mineralisation in the Enkeldoorn tin field. The host granite contains anhedral, ferrohydroxide stained, sericitised and chloritised, 3 mm sized K-feldspar grains, and subhedral to anhedral quartz reaching sizes of 0,016 mm to 0,25 mm. Euhedral quartz grains 0,5 to 2 mm in size are also found, and often exhibit triple junction boundaries with each other, indicating some degree of recrystallisation in the host rock. There is a large abundance of chlorite, as very fine-grained dark green grains, found to be extensively replacing the K-feldspar grains, or in clusters growing as euhedral grains 0,06 to 0,25 mm in size.

Within the confines of the sheared granite, an abundance of light green sericite is found developed preferentially in the vicinity of the shear zone and intimately associated with mineralisation (see Plate VI - A). Within the shear zone, light green sericite is associated with mineralisation, along with 0,125 mm sized grains of epidote and 0,125 mm sized grains of quartz in the quartz veining. Abundant dark green chlorite is found concentrated along the shear zone, as well as around the sulphides (see Plate VI - B). Unlike the Zustershoek Tin Mine, hematite is not extensively developed, although the K-feldspars are extensively hematite stained, an incipient feature of deuteric alteration associated with the Bobbejaankop granite.

Away from the shear zones, the granite is typical of the Bobbejaankop granite with deep red K-feldspars, coalesced quartz and minor amounts of mafic minerals. Nearing the shear zone, sulphidic minerals, particularly pyrite and chalcopyrite become more abundant and the granite is extensively sericitised. In one instance, stringers of chalcopyrite cut through the rock, associated with blebs of pyrite 5 mm in size.

Entering the shear zone, the rock becomes chloritised to a large extent and becomes darker in colour. K-feldspar grains are extensively altered and replaced by chlorite, and quartz becomes less abundant. Sulphides are found as disseminated blebs throughout the rock. Within the shear zone, the rock is dark grey to black in colour, and is highly chloritised and sericitised, containing quartz grains 5 to 10 mm in size, either as recrystallised grains or as veining, within the shear zone.

6.2.2.2 Ore Petrography

The eastern lode, and to a lesser extent the western lode, are characterised by shear zones, infilled by quartz veining and disseminated sulphide mineralisation. Within a minor shear zone 15 mm wide, sulphides are intimately associated with chlorite and some minor epidote (see Plate VI - B).

Within the sheared granite the K-feldspar is a dark pinkish red colour caused by iron hydroxide staining, particularly along cleavage planes in the feldspar. There is minor chloritisation, as represented by dark green grains 0,06 mm in size, forming clusters

PLATE VI

A: Photomicrograph of chlorite crystals in association with sulphides in a chloritised and sericitised groundmass. Enkeldoorn tin field, east lode, Enkeldoorn 217 JR. Uncrossed nicols; field of view is 3,55 mm wide.

B: Photomicrograph of extensive chloritisation along a minor shear zone in sericitised Bobbejaankop granite. Abundant sulphides are found associated with the chlorite along this shear zone and decrease in abundance away from it. Enkeldoorn tin east lode, Enkeldoorn 217 JR. Uncrossed nicols; field of view is 3,55 mm wide.

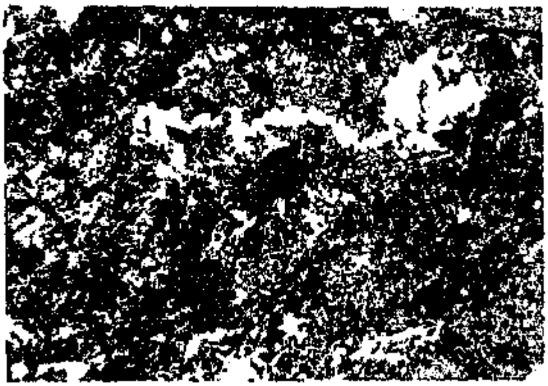
C: Photomicrograph of euhedral cassiterite crystal (centre) surrounded by and overgrown by chalcopyrite (dark) in chloritic groundmass. Enkeldoorn tin field east lode, Enkeldoorn 217 JR. Uncrossed nicols; field of view is 3,55 mm wide.

D: Photomicrograph of sphalerite (dark grey low relief) overgrown by arsenopyrite (white). The sphalerite has overgrown cassiterite (centre, dark grey, higher relief). Enkeldoorn tin field, east lode, Enkeldoorn 217 JR. Reflected light; field of view is 1,89 mm wide.

E: Photomicrograph of arsenopyrite (bright white) overgrowth of cassiterite (centre, dark grey) and chalcopyrite (bright yellow). The chalcopyrite has also overgrown the cassiterite. Enkeldoorn tin field, east lode, Enkeldoorn 217 JR. Reflected light; field of view is 2,2 mm wide.

F: Photomicrograph of sphalerite (centre, dark grey), exhibiting exsolution of chalcopyrite (yellow), having overgrown pyrite (bottom, whitish yellow). Enkeldoorn tin field, east lode, Enkeldoorn 217 JR. Reflected light; field of view is 1,89 mm wide.

PLATE VI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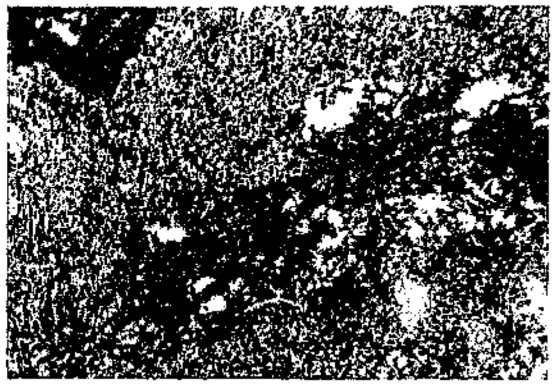
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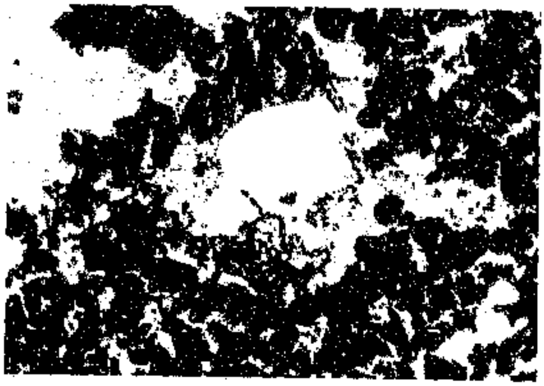
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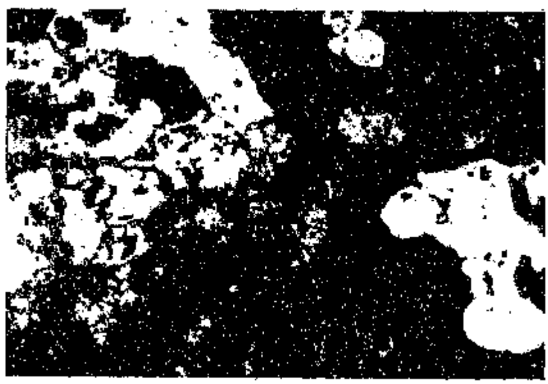
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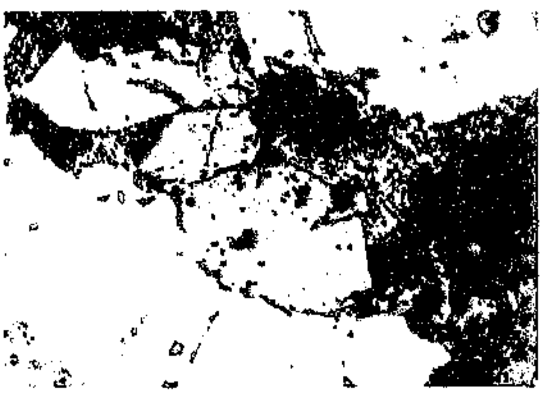
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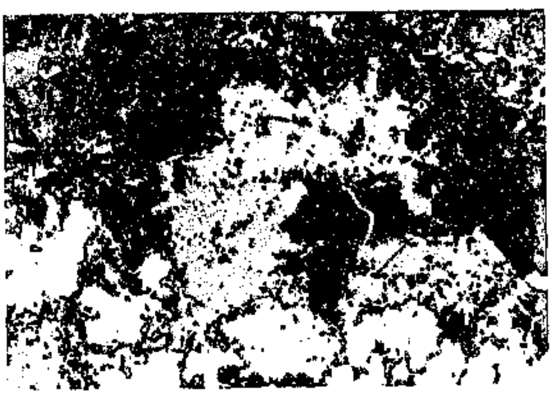

F

0,25 mm in size. Nearing the shear zone, the feldspars are highly chloritised, causing grain boundaries to be indistinct. Magnetite grains 0,125 mm in size, are found as part of the alteration of the feldspars. Anhedral quartz is present in minor amounts, often associated with 0,25 mm sized chalcopyrite grains.

A few centimetres away from the shear zone, in the chloritic groundmass, anhedral quartz 0,125 to 0,25 mm in size is found. Light yellow green epidote is found as amorphous clusters, varying in size from 1,25 to 0,25 mm and is part of the alteration of the feldspars, as well as being associated with the sulphides, particularly chalcopyrite (see Plate VI - A).

Along the shear zone, fine-grained recrystallised quartz with chlorite is found, along with small, hackly chalcopyrite grains surrounded by dark green chlorite. Chalcopyrite is often found in quartz-rich pockets, along with muscovite and epidote grains 0,25 mm in size, with quartz reaching 0,25 to 0,5 mm in size within these pockets. Sericite, in places where it has altered feldspar, is now overgrown by chlorite and epidote, which reach sizes of 0,03 to 0,25 mm.

There is an abundance of chalcopyrite within the shear zone, where there is also an abundance of light green epidote, quartz and radiating muscovite fibres, overgrown by epidote in areas (see Plate VI - B). Cassiterite is found as zoned reddish brown euhedral crystals, 0,25 to 0,75 mm in size, within the shear zone. Here it is surrounded by chalcopyrite (see Plate VI - C). Chalcopyrite is found as subhedral to anhedral grains 0,125 to 0,75 mm in size and often in clusters.

The amount and size of the sulphides falls sharply away from the shear zone. Cassiterite grains only 0,125 mm in size are found a few millimetres away from the shear zone, whereas few are found a few centimetres away. In other areas, a few millimetres from the main shear zone, subhedral to anhedral cassiterite grains 0,25 to 0,75 mm in size are surrounded by and occasionally overgrown by pyrite. Pyrite occurs as anhedral grains 0,25 to 1 mm in size. Chalcopyrite, mostly hackly and anhedral, reaching sizes from 0,25 mm to 1,5 mm but typically 0,5 mm, overgrows both the pyrite and cassiterite.

Away from the shear zone fine cassiterite clusters 0,5 mm in size are overgrown by chalcopyrite. The sulphides are more disseminated away from the shear zone. Sphalerite, showing exsolution of chalcopyrite (see Plate VI - F), occurs as 1 to 1,5 mm sized grains overgrowing cassiterite, chalcopyrite and 0,125 to 0.5 mm sized pyrite grains. Chalcopyrite veinlets, 0,03 mm in size, cut across the rock. Arsenopyrite, found as subhedral grains 1 to 1,5 mm in size, overgrows both cassiterite and chalcopyrite (see Plate VI - E), as well as sphalerite (see Plate VI - D).

The paragenetic sequence would thus appear to cassiterite - pyrite - chalcopyrite - sphalerite - arsenopyrite. Galena and bornite have also been reported from the eastern lode.

The pipes to the east of the eastern lode are also hosted in Bobbejaankop granite. The ore is hosted in a group of simple cylindrical pipes 2 km^2 in area. Microscopically the margins of the pipes are marked by euhedral vein quartz, 2 to 3 mm in size, exhibiting growth zones, growing from areas of fine-grained anhedral quartz grains 0,03 to 0,125 mm in size. Grains of clear fluorite 0,125 to 0,25 mm in size are found within the vein quartz. Small sericitic areas are found interstitially to the equigranular grains. Fine radiating muscovite grains occur near the fine-grained area.

The excavations are infilled with water and hence no ore could be found, and very few samples of vein quartz are available. The host granite is silicified and sericitised to a limited extent around the orebody.

6.2.2.3 Ore Geochemistry

The ore is rich in copper, zinc, lead, silver and gold (see Table 6.1), with the first three commodities hosted in chalcopyrite, sphalerite and galena respectively. The silver may possibly be hosted in galena. The primary commodity, tin, is present in relatively small amounts (202 ppm), but this may simply be a function of sampling, as the pipes are reported to contain 1,2 % tin, and the eastern lode 0,1 % tin (Geol. Survey Mineral reports, 1982). The Enkeldoorn tin field, unlike the Zustershoek Tin Mine, has no significant amounts of hematite associated with it. The paragenetic sequence is similar to Zustershoek, except for the absence of the later oxidised assemblage.

6.2.3 The Prins Anna Structure

This structure extends for approximately 10 km in an approximate north-south direction from Prins Anna 234 JR through Sybrandskraal 244 JR and south into Van Dykspruit 431 JR, where it terminates beneath sediments of the Waterberg Group (see folder).

It is not extensively mineralised, but is rather marked by hematite veining along the entire length, where it cuts through different lithologies. It shows its greatest base metal content on Prins Anna 234 JR just north of the Moloto - Sybrandskraal road (see folder). It is host to zinc and lead as well as lesser silver. The deposit represents 10 000 tons of mineable lead ore, but is a very low grade occurrence. It may, however, represent the oxidised surface expression of a large sulphidic ore body at depth.

6.2.3.1 Host rocks and morphology of structure

The structure cuts across many different lithologies, including granophyre, Sekhukhuni granite, and sediments and volcanics of the Loskop formation. On Prins Anna 234 JR, the structure cuts pinkish-red medium-grained granophyre, and is marked by quartz veining. At this locality the quartz veining, often exhibiting a cockscomb texture, has been brecciated and infilled with later quartz, itself having been brecciated a number of times and infilled by later quartz veining. To the south the brecciated quartz veining is infilled by hematite (see Plate VII - A). The fragments vary in size from 0,75 mm at the smallest to 2 and 4 mm and up to 20 mm at the largest.

Passing into the Sekhukhuni granite the structure is not easily traced and disappears. To the north of the Moloto - Sybrandskraal road, however, it reappears, and is marked by a hematite-limonite "gossanous" ridge trending 189° and approximately 11 m wide, but narrowing toward the road and north into the granite (see folder). The ridge is made up of euhedral to subhedral hematite crystals 0,25 to 1 mm in size and 2 mm at the largest, along with goethite which imparts a red colour to the rock. Small boxwork structures 2 to 3 mm in size and infilled with limonite are found within the hematite suggesting possible oxidation of sulphides. Minor quartz veining, made up of anhedral quartz 0,125 mm in size, is found in the gossanous ridge, as well as occasional vugs infilled with amorphous silica, leached from the quartz veining. In some areas, the ridge is particularly limonite rich, and this area is host to the greatest zinc and lead content.

To the south of the road the structure once again disappears, but re-emerges on Sybrandskraal 244 JR, where it cuts across the north-south trending Tweefontein - Cullinan road (see folder). Here the structure splits into two, one limb running near the Cullinan road, where it cuts through black rhyolite, and the other further to the east where it occurs within a quartzitic horizon within rhyolitic layers of the Loskop Formation.

Within the eastern arm of the structure fine hematite veining 3 - 5 mm in size cuts across a quartzite horizon in the Loskop Formation (see Plate VII - B). The overall hematitic quartzite ridge, approximately 20 m in width, shows an orientation of 350°, but the ridge is made up of hematite veining of various sizes and abundances, the majority of which have a strike of 074° and dip at 84° to the north. The second major vein orientation is 005° and dip at 75° to the west. These two vein orientations are the most dominant in the stockwork of veining in the quartzite ridge. It is worth noting that the first vein orientation is sub-parallel to a major crustal lineament, called the

Steelpoort fault lineament, which is a major structural feature in the eastern lobe of the Bushveld Complex. The second vein orientation is parallel to the north - south faulting and shearing dominant in the eastern margin of the Moloto pluton. This quartzite horizon continues onto Van Dykspruit 431 JR.

The hematite veining occurs within quartzite consisting of equigranular euhedral to subhedral, angular quartz 0,5 to 0,75 mm in size, but typically 0,5 mm. Hematite and goethite are found as large clusters within the quartzitic groundmass, and hematitic veins 2 to 5 mm in size, cut across the rock. In places, boytroidal hematite is found infilling open cavities in the hematite veining. A dark red granophyric rhyolite is found to the east of the quartzite horizon.

Further south, on Van Dykspruit 431 JR, a second parallel vein is found to the west of the quartzite-hosted veining, where it cuts through fine-grained black rhyolite. Moving south, the structure passes through an agglomerate whose fragments consist of a very fine grained, black, spherulitic textured rhyolite, with fibres 0,25 to 0,5 mm in size. Fragments within this agglomerate vary in size from 2 mm to 40 mm.

Under the microscope the fragments of rhyolite are surrounded by hematite crystals 0,25 mm in size, with sericite clusters 0,5 mm in size. Hematite crystals 0,5 to 0,75 mm in size are also found within the fragments. Hematitic clusters 0,125 to 0,25 mm in size are also occasionally found in the fragments. The hematite is often associated with rust red goethite. It would seem that the structure is making use of the agglomerate as a conduit rather than having created it by hydrothermal fracturing.

Still further south the structure passes into a sericitised yellow green granophyric rhyolite. Within the hematite veining, or near their margins, 0,5 mm sized, hackly, limonitic material is found. Here the structure clearly exhibits two generations of hematite veining, which was not as inherently apparent elsewhere. The first generation brecciates and alters the rhyolite. The second generation infills the first and occurs due to extension and brecciation along the previous veins. Renewed growth of hematite accompanies the second generation of veining. Southwards the structure diminishes in size and could not be traced into the Waterberg sediments at the southern end of Van Dykspruit 431 JR.

6.2.3.2 Geochemistry of the Prins Anna structure

Table 6.1 shows the base and precious metal geochemistry of the Prins Anna structure, at its most mineralised locality on Prins Anna 234 JR, 100 m north of the Moloto - Sybrandskraal road (see folder).

In moving from the northern, granophyre-hosted quartz-hematite breccia to the granite-hosted hematite-limonite ridge, Cu, Zn, Ni, Pb, As, and W contents increase, whilst Sn, Bi, and Sb contents remain low and constant. The hematite-limonite ridge, just north of the Moloto - Sybrandskraal road, is the site of the greatest concentration of metals, albeit at low grades, and has been prospected in the 1970's by Shell Minerals. Moving south onto Sybrandskraal 244 JR it is found that all the aforementioned elements decrease in content, whilst Sn, Bi, and Sb are still present in small amounts.

The structure has its greatest mineralisation potential in the southern region of Prins Anna 234 JR, north of the Hartbeesspruit river, and decreases in metal content to the north and south. Whether the site of greatest mineralisation was the site of predominant fluid flow or supergene enrichment by the stream is not known, but the metal contents suggest greatest deposition of metals at this locality.

6.2.3.3 General Comments

The Prins Anna structure also has a north-south trend, being parallel to the Zustershoek and Enkeldoorn shear zone trends. The structure is dominated by hematite, and has no fresh sulphides. Limonite is developed along the structure in certain areas, particularly in the most mineralised portion of the structure. This possibly points to the existence of original sulphides in the structure, which have now been oxidised. There is a strong possibility of a deep seated massive sulphide body beneath the Prins Anna structure, as also suggested for the Albert Silver Mine (Robb *et al*, 1994).

6.2.4 Other occurrences in the area

The Moloto pluton area is host to a number of smaller deposits and occurrences that are found hosted either in the granite or in the overlying roof rocks. They are the Hartebeestspruit gold deposit on Hartebeestspruit 434 JR, the Enkeldoorn and Rietfontein barite occurrences and a small copper occurrence on Sybrandskraal 244 JR.

6.2.4.1 Hartebeestspruit gold deposit

The Hartebeestspruit gold deposit consists of two separate occurrences situated 60 m from each other on the farm Hartebeestspruit 434 JR. The deposit is hosted in a thin extension of granophyre, found between the Sekhukhuni granite of the Moloto pluton and the overlying rhyolite to the east (see folder and Fig. 6.1) and is apparently mineralised with up to 20 g/ t of gold (Geol. Surv. S. Afr. Hbk. 7). The deposit was prospected and mined in the early 1930's before mining ceased. The occurrence to the west is marked by a small prospecting pit, with chloritised and sericitised granophyre and limonite within quartz veins, whereas the mine is situated directly east of the prospect pit, and is marked by a trench, dump and quartz veining 7 mm in size, oriented at between 165° and 151° within the granophyre.

6.2.4.1.1 *Host Rock Petrography*

The deposit is hosted in a fine-grained granophyre that has been extensively chloritised, and sericitised to a lesser extent in the most mineralised portions. The prospect pit to the west is hosted in granophyre that is slightly chloritised and sericitised to a large extent, but the granophyre at the mine shows predominantly propyllitic alteration with minor hematisation.

The granophyre consists of an intergrowth of sericitised K-feldspar and quartz to form intergrown textures 1,5 to 2 mm in size. The feldspars are a deep pinkish red due to being iron hydroxide stained. The feldspars are also chloritised by dark green chlorite to a lesser extent. Quartz grains, which are typically anhedral are found as distinct grains 0,25 mm and less in size. Separate, distinct quartz grains are found to be in greater abundance than separate K-feldspar grains and tend to be euhedral, approximately 0,5 mm in size, nearer quartz veins, which are 2 to 7 mm in size. Quartz within the quartz vein is found to be euhedral to subhedral and typically 1,5 mm in size. Quartz-rich pockets 1,5 to 2 mm in size consisting of anhedral quartz grains 0,06 to 0,125 mm in size, are also found scattered throughout the rock.

Minor amounts of highly chloritised plagioclase, with a composition of An_{25}, are also present. Magnetite, 0,125 mm in size, occurs as subhedral grains, and is found in association with chloritisation of the feldspars, as well as with epidote. Epidote fibres 0,25 to 0,5 mm in size are associated with the quartz veins. In the vicinity of the quartz veins the rock is highly sericitised. Muscovite fibres and epidote, 0,25 mm in size, are found on the boundaries of the veins. The sericite is often associated with epidote where the two are associated with quartz veining. This association is found particularly where small euhedral sulphide grains are found within or near the quartz veining.

Pyrite occurs as grains which are typically 0,25 mm to 3 mm in size and euhedral within or near quartz veins (typically 3 mm from the vein), and anhedral when disseminated throughout the rock. Pyrite is often found associated with sericite and epidote (see plate VII - C). Chalcopyrite, found as anhedral grains 0,125 to 0,25 mm in size, and anhedral arsenopyrite 0,125 to 0,5 mm in size, is also found, associated particularly with quartz veining, and widely disseminated throughout the rock. Gold is found associated with arsenopyrite, particularly near the quartz veining.

6.2.4.1.2 *Ore Geochemistry*

Table 6.1 gives the ore composition of the ore-bearing granophyre at the mine. The gold prospect to the west of the mine is rich in lead and arsenic, as well as lesser quantities of copper, zinc, tin, bismuth and antinomy, although this site is marked by quartz veining, limonite and sericitised granophyre and no sulphides. The mine, to the east, is rich in copper, lead, arsenic, yttrium, cobalt and gold. Sulphides present at the mine include pyrite, chalcopyrite and arsenopyrite with minor amounts of molybdenite. The gold is hosted in quartz veins occupying a shear zone having a similar orientation to the shear zones at Enkeldoorn and Zustershoek and to the Prins Anna structure, so that a major control on mineralisation orientation is evident in the Moloto granite pluton.

6.2.4.2 Sybrandskraal copper occurrence

This occurrence occurs to the south of Moloto on Sybrandskraal 244 JR, and is hosted in sandstone of the Rayton formation of the upper Pretoria Group (see Fig. 6.1). The occurrence is hosted in a shear zone trending 145°. The granophyre to the north is sericitised, is dark pink to red in colour when unaltered, and is brecciated in places with hematite veining cutting across it. The occurrence shows a similar type of morphology and orientation to the other occurrences in the Moloto pluton area.

6.2.4.3 Rietfontein and Enkeldoorn barite occurrences

Yellow barite is found associated with quartz, which is amethyst in places, in a 15 m long quartz vein trending 030° in Bobbejaankop granite on Rietfontein 214 JR, to the north of the Enkeldoorn tin field (see Fig. 6.1). Immediately to the southeast, a barite occurrence is found on Enkeldoorn 217 JR. On Enkeldoorn 217 JR a prospect pit marks the locality, but there is no clear indication as to the actual morphology of the occurrence. The Rietfontein occurrence appears to have developed from a low-temperature hydrothermal fluid. Even though they are hosted in Bushveld granite the

PLATE VII

A: Photomicrograph of vein quartz breccia infilled by hematite. Prins Anna structure - granophyre hosted, Prins Anna 234 JR. Uncrossed nicols; field of view is 3,55 mm wide.

B: Photograph of hematite veining in quartzite. Prins Anna structure, Van Dykspruit 431 JR.

C: Photomicrograph of euhedral cubic pyrite crystal associated with epidote, chlorite and quartz in a sericitised granophyric groundmass. Hartebeestspruit gold mine, Hartebeestspruit 434 JR. Crossed nicols; field of view is 3,55 mm wide.

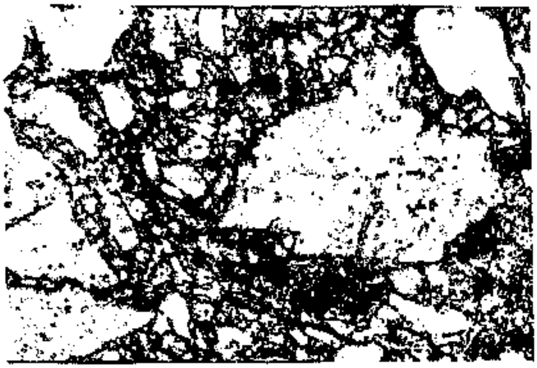
D: Photomicrograph of sericitised coarse-grained Verena granite. Rooipoort tin prospect, Hartbeestfontein 441 JR. The K-feldspars have been extensively sericitised. Crossed nicols; field of view is 2,2 mm wide.

E: Photomicrograph of growth zoned cassiterite crystal. Rooipoort tin prospect, Rooipoort 440 JR. Uncrossed nicols; field of view is 3,55 mm wide.

F: Photomicrograph of arsenopyrite (white) overgrowth of cassiterite (dark grey). Rooipoort tin prospect, Rooipoort 440 JR. Reflected light; field of view is 1,89 mm wide.

G: Photomicrograph of intergrowth of arsenopyrite (white) and cassiterite (dark grey). Rooipoort tin prospect, Rooipoort 440 JR. Reflected light; field of view is 1,89 mm wide.

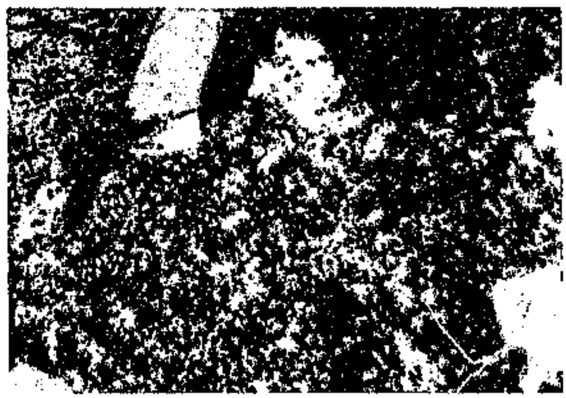
PLATE VII



A

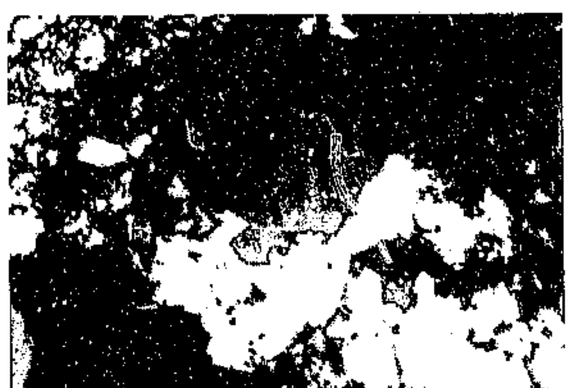
B

C

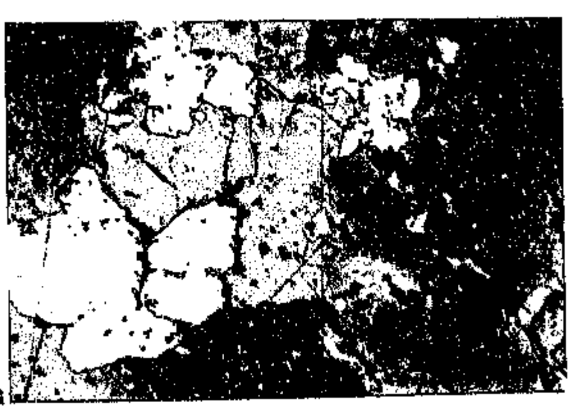


D

E



F



G

exact ages of these occurrences are not known; they may be post-Waterberg or even post-Karoo in age (Martini and Vorster, 1994).

6.2.5 General Comments on the Moloto Pluton area

The Moloto pluton area is characterised by tin, copper, gold and silver with lesser amounts of zinc and lead. The granite has a relatively low TEDI value (see Chapter 5), and the pluton is domed with higher level granites exposed in the margins and lower level granites exposed in the pluton centre (see Figure 6.2). Thus mineralisation would tend to be concentrated near the granophyre / rhyolite contact, as this preserves higher level, more fractionated granites than granites further in toward the centre of the pluton, where erosion has exposed lower level, relatively unfractionated granites. On the eastern margin of the pluton, Bobbejaankop granite is preserved, which indicates a high level in the granite sheet at this locality, and it is in or adjacent to this granite that all the mineral occurrences are found. Even the Prins Anna structure has its greatest metal potential near the granite - granophyre contact.

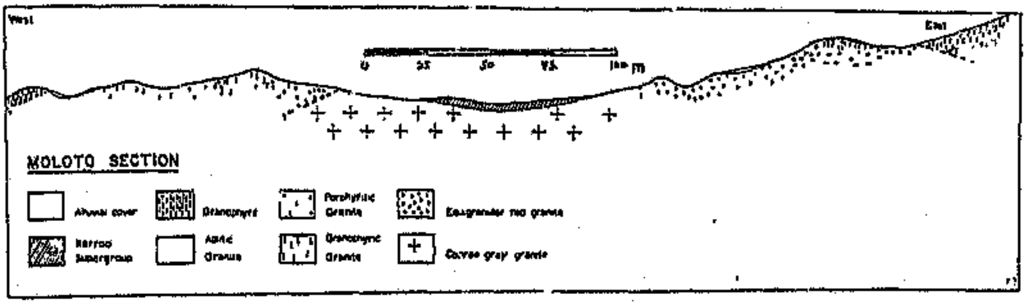


Figure 6.2 Section across the Moloto pluton, showing low level granites in the centre and high level granites at the margins (after Lenthall, 1975)

The north - south trend of the shear zones appears to be a dominant orientation along the eastern margin of the Moloto pluton, where north - south shear zones and faults are host to the Enkeldoorn tin field, the Zustershoek Tin Mine, the Prins Anna structure and the Hartebeestspruit gold occurrence. Two crustal antiforms parallel to two major crustal lineaments, one oriented NE - SW called the Wonderkop fault lineament and the other SE - NW called the Laersdrif fault lineament, intersect in the Moloto pluton causing doming of this pluton.

Doming may have influenced the fracture pattern, giving rise to a north - south fracture pattern, which would have influenced the subsequent passage of mineralising fluids. The lineaments may have been active from pre-Bushveld to syn- or even post-Bushveld times (Hartzer, 1994)(Cameron, 1971), and hence have influenced granite emplacement as well as localisation and passage of fluids and volatiles.

The granite pluton is approximately circular in shape, but is more elongated northeast - southwest, parallel to the Wonderkop fault, than southeast - northwest, parallel to the Laersdrif lineament, indicating the dominance of the former lineament in this part of the Complex. The stress field caused by doming of the pluton influenced the local structure of the pluton. In addition possible stresses caused by emplacement of the pluton, may have had a major influence on the orientation of shearing and faulting in the pluton. The presence of shear zones along the eastern contact, as compared to stockwork veining in the centre of the pluton, suggests that there was a greater development of stress along the eastern margin than anywhere else in the pluton, and hence no faults or mineralisation are found in the western central portions of the pluton.

6.3 Northwest Verena Granite Pluton Area

The Verena granite forms a pluton in the south central portion of the study area (see Fig. 6.1). It is a coarse-grained pinkish white granite with abundant K-feldspar phenocrysts 30 mm in size. A fine-grained chill phase is developed in the centre of the pluton on the farms Roodepoortje 250 JR and Zwartkopje 444 JR. The granite in this region is host to two occurrences of potential economic interest, namely the Albert

Silver Mine, and the Rooipoort tin occurrence. The granite is also host to minor occurrences near Rhenosterkop, which will be discussed in section 6.4. A copper occurrence occurs near the Moses River in rhyolites adjacent to the Verena granite on Roodepoort 439 JR. The base and precious metal contents of the mineral occurrences of the Verena pluton are given in Table 6.2 with some values taken from Scogings (1991).

Table 6.2 Base and precious metal contents for mineral occurrences within the Verena granite pluton

occur.	ppm Sn	ppm Mo	ppm Cu	ppm Pb	ppm Zn	ppm As	ppm Sb	ppm Ag	ppm Au	ppm F
Rietfontein										
sample 1	686	-	11	52	43	< 15	<10	< 1.0	0.03	28
sample 2	129	-	-	279	-	-	-	-	-	-
Rooipoort										
sample 1	29100	95	0.78%	0.21%	199	> 20 %	69	7.3	1.35	29920
sample 2	1.23%	84	0.52%	0.17%	32	3.80%	-	2.9	0.22	-
sample 3	0.79%	-	827	1336	19	3.64%	-	-	-	-
Leeuwfontein	34	-	250	811	15	1437	1218	27.6	0.01	119
Albert N	26	-	140	1691	860	1499	340	-	-	-
Albert Ag										
sample 1	5	15	5.52%	27800	2900	0.47%	9400	0.14%	0.5	11
sample 2	36	27	1.49%	839	206	348	0.24%	565.9	-	-
sample 3	-	-	813	789	102	174	0.17%	-	-	-
Zusterstroom	10	-	<5	22	459	<15	<10	< 1.0	0.01	28
avg. con.	5023	-	8515	3402	484	36570	2525	401	0.35	6021

6.3.1 Rooipoort tin occurrence

This occurrence is hosted in a shear zone trending 265° in coarse-grained dark red Verena granite that has been extensively chloritised and sericitised. The mineralisation is marked by a number of prospect pits straddling the Rooipoort 440 JR and the Hartbeestfontein 441 JR boundary. The deposit contains approximately 10 000 tons of tin ore, and is the biggest tin occurrence in the study area. To date the occurrence has not been thoroughly investigated by any mining company, although the Geological Survey of South Africa has studied this occurrence.

6.3.1.1 Host rock petrography

The Verena granite near the prospect pits is a deep pink to red, coarse-grained, K-feldspar and quartz-rich granite with dark red K-feldspar phenocrysts 20 to 30 mm in size, which stand out prominently on the weathered surface. The granite is very similar to the Bobbejaankop granite in appearance with coalesced, interconnected quartz grains 5 to 10 mm in size. However, there is a greater abundance of hornblende and biotite present than would be expected in typical Bobbejaankop granite.

Microscopically the groundmass K-feldspars, which are 2,5 to 7,5 mm in size, are subhedral to anhedral, and hematite stained, imparting a red colour to the rock. The feldspars are sericitised to a minor extent. Subhedral magnetite grains, 0,06 to 0,03 mm and less in size, are associated with the sericite. Anhedral orthoclase grains 3 mm in size are also found. Quartz grains occur as anhedral grains 2 to 5 mm in size, along with accessory, subhedral plagioclase, 0,75 mm in size, and with a composition of An_{27-31}.

Biotite, mostly highly chloritised, occurs as skeletal, subhedral pleochroic yellow green brown / dark green grains, 1 to 2,25 mm in size, along with pleochroic yellow green / orange green to dark green, anhedral to subhedral chloritised hornblende grains 0,75 mm in size. Magnetite occurs interstitially as grains 0,06 mm in size, and as subhedral grains 0,03 to 0,06 mm in size forming clusters 0,25 mm in size associated with chloritisation of the mafic minerals. Accessory minerals include subhedral grains of 0,25 mm sized zircon, fluorite and apatite, typically associated with or near the femic minerals.

The coarse-grained granite is cut by fine-grained dyke-like intrusions that are parallel to the two jointing directions of 247° to 265° and 328° to 344°. Field relations indicate that the fine-grained granite intruded the coarse-grained granite, as fragments of coarse-grained granite are found within the fine-grained granite. This relationship differs from elsewhere, such as near the Albert Silver Mine, where the opposite situation is predominant.

The fine-grained granite has a similar mineralogy to the coarse-grained granite, but is obviously finer-grained with pink, subhedral to anhedral, K-feldspar grains, 0,5 to 1,5 mm in size, which are often perthitic. Quartz is found as anhedral grains 0,5 to 2 mm in size. The granite exhibits granophyric texture in places, with K-feldspar grains acting as nuclei for the development of the texture. Biotite, which is the dominant femic mineral, is pleochroic dark brown / black to yellow brown / green in colour, often highly chloritised, and occurs as subhedral grains 1 to 2,5 mm in size. Hornblende, which is often associated with magnetite, is found as chloritised, subhedral to anhedral grains 0,5 mm in size. Chlorite is found as discrete, subhedral grains 0,25 mm in size, and often as an alteration product of biotite, hornblende and K-feldspar. Accessory fluorite is found as euhedral, purple grains 0,06 to 0,25 mm in size.

Pegmatoidal vugs 100 mm in size are found within the fine-grained granite, and contain quartz 25 mm in size and K-feldspar, 38 mm in size. The fine-grained phase has many characteristics of Klipkloof granite, and may in fact represent dykes of this late-stage granite intruding the Verena granite.

Nearing the prospect pits the coarse-grained granite becomes pink in colour with sericitisation, along with minor chlorite alteration. Microscopically the K-feldspars are highly sericitised, subhedral to anhedral grains 3 mm in size, although in most cases the boundaries between individual grains are not clear. Quartz is found as anhedral grains 2 to 3 mm in size (see Plate VII - D). The K-feldspar and quartz are occasionally intergrown. Vugs of euhedral quartz 1,75 to 4,25 mm in size are found within a fine-grained sericitic mass. Radiating muscovite fibres 0,125 mm in size are found near the vugs. Quartz-rich areas 1 to 1,5 mm in size, and occasional quartz grains 0,25 mm in size are found in sericitic areas immediately adjacent to quartz veins Muscovite fibres 0,25 to 0,5 mm in size are found in the rock, but are smaller in size near quartz vugs within the sericitic area.

At the prospect pits four different granite varieties are found in the dump site. They are:

- a fine-grained dark red Klipkloof-type granite with K-feldspar, quartz and hornblende,
- a coarse-grained dark pink to red Bobbejaankop-type granite with K-feldspar, coalesced quartz and hornblende,
- a light pink coarse-grained Bobbejaankop-type granite with K-feldspar, coalesced quartz, plagioclase, black biotite and chlorite, and
- a dark green to black coarse-grained chlorite-rich Bobbejaankop-type granite with disseminated sulphides and fluorite.

The three different coarse-grained granites represent an evolution from relatively unaltered granite through to chloritised, altered wall rock adjacent to the ore. The fine-grained granite could possibly represent a cap to the ore preventing fluid escape, and allowing a relatively high grade ore to be formed. The same situation is apparent at the Albert Silver Mine (see later).

Thus there is a transition, from light pink coarse grained K-feldspar and quartz-rich granites with an intermixed fine-grained phase, through a dark pink and light green sericitised coarse-grained granite, to a dark green highly chloritised coarse-grained granite cut by mineralised quartz veins. This alteration zone is no more than 10 m in width on either side of the mineralised veins. Alteration passes from phyllic 10 to 15 m away to propylitic within the shear zone hosting mineralisation.

6.3.1.2 Ore Petrography

The ore is hosted in quartz veins in an east-west trending shear zone, in chloritised dark green, coarse-grained granite. Within the shear zone quartz veins, which can be up to 30 mm wide, are found. The granite adjacent to these veins is highly chloritised, and is host to disseminated sulphide mineralisation and dark purple fluorite.

Immediately adjacent to the veins, the K-feldspars are sericitised to a limited extent. Muscovite fibres 0,25 mm in size are also found adjacent to the vein. Reddish brown and yellow zoned, anhedral cassiterite crystals, 0,375 to 0,75 mm in size, are found on the margins of the vein. In certain instances dark purple fluorite pseudomorphs replace the cassiterite, growing from the centre of the cassiterite crystal outwards (see Plate VIII - G). Small subhedral to anhedral arsenopyrite grains, 0,125 to 0,06 mm in size, are found on the vein margin.

Euhedral to subhedral quartz 0,25 to 0,5 mm in size is found at the vein margin giving way to large interlocking quartz grains 1 to 4 mm in size, typically 1,5 mm, toward the centre of the larger veins. Clear, anhedral fluorite 2 mm in size, is found along cracks perpendicular to the vein orientation. Near the centre of the vein, the quartz is euhedral reaching 4 mm in size. Clear fluorite is found in larger abundance near the vein centres.

Abundant cassiterite and arsenopyrite crystals, along with extensive sericite and ferrohydroxides associated with the metal-bearing minerals mark the centre of the vein. The outer portions of the vein centre contain highly brecciated reddish brown and yellow zoned cassiterite crystals 0,5 to 0,75 mm in size, with abundant associated sericite. The cassiterite is overgrown by subhedral to anhedral arsenopyrite 0,125 to 1 mm in size, which is also highly fragmented (see Plate VIII - C and D). In one instance adjacent to a small vein 1 mm in size cutting perpendicularly across the main veins, dark purple fluorite pseudomorphs replaces cassiterite (see Plate VIII - D).

In the centre of the vein there is a large abundance of highly brecciated cassiterite crystals 0,5 to 1,5 mm in size, cut by thin quartz veins 0,25 mm and less in size, in numerous orientations (see Plate VIII - B). The cassiterite crystals are zoned dark brown / yellow with some grains being blue to green in colour. Fine sericite is found associated with the cassiterite, which is overgrown and in places intergrown with angular, brecciated arsenopyrite 0,25 to 1 mm in size (see Plate VII - F and G).

The veined granite bears evidence of minor brecciation, not only in the sulphides and cassiterite but also on a small scale in the granite. A large vein, 30 mm in size, has an area of cassiterite mineralisation in the centre of the vein, cut by small perpendicular quartz veins 0,75 mm in size. The altered granite is brecciated and cuts into the main vein truncating against the central mineralised portions of the vein in many areas. Adjacent to one of the smaller perpendicular veins cutting across the main mineralised quartz vein, a small block of sericitised granite containing small disseminated subhedral cassiterite crystals 0,125 mm in size, abundant sericite and pyrophyllite fibres 0,125 mm in size, is found. This brecciated granite" blocklet" truncates abruptly against the main large vein. Associated with the smaller, perpendicular vein are anhedral dark purple fluorite pseudomorphs 0,75 to 1 mm in size (see Plate VIII - E), replacing cassiterite in certain areas and exhibiting the growth zonation of the cassiterite crystals.

Abundant secondary veins cutting perpendicularly across the main vein orientations pass into the host granite. In one instance a secondary vein varying from 1 mm to 0,5 mm in width, where it passed from the main vein into the host granite, contains angular fragments of cassiterite, quartz, arsenopyrite and clear primary fluorite (see Plate VIII - C and D). Along its margins vein quartz of the main vein is sheared and incorporated into the secondary vein. Hence possible later hydrofracturing may have been responsible for the secondary perpendicular veins brecciating the early sulphides. The timing of this later veining is unclear, but it is likely to have been relatively soon after the first mineralising episode, as chalcopyrite appears to be associated with this later veining and brecciation.

The granite away from the main veins is brecciated, sericitised and cut by small quartz veins 0,25 to 1 mm in size, oriented in all directions, hosting fine fragmented cassiterite and arsenopyrite, with larger ore-bearing mineral fragments in the veins. The K-feldspar grains in the granite are slightly sericitised, as well as being iron hydroxide stained. K-feldspar phenocrysts, 3,5 mm in size, are ferrohydroxide stained,

PLATE VIII

A: Photomicrograph of arsenopyrite (white) overgrowth of cassiterite (centre, dark grey), but itself having been overgrown by pyrite (yellow, off centre right). Rooipoort tin prospect, Rooipoort 440 JR. Reflected light; field of view is 1,89 mm wide.

B: Photomicrograph of arsenopyrite (dark) overgrowth of cassiterite (centre), and both being cut by later secondary quartz veins. Rooipoort tin prospect, Rooipoort 440 JR. Uncrossed nicols; field of view is 3,55 mm wide.

C: Photomicrograph of brecciated cassiterite and arsenopyrite cut by a secondary quartz vein perpendicular to the main mineralised vein. The secondary vein contains fragments of cassiterite, arsenopyrite and primary clear fluorite (left margin). Rooipoort tin prospect, Rooipoort 440 JR. Uncrossed nicols; field of view is 3,55 mm wide.

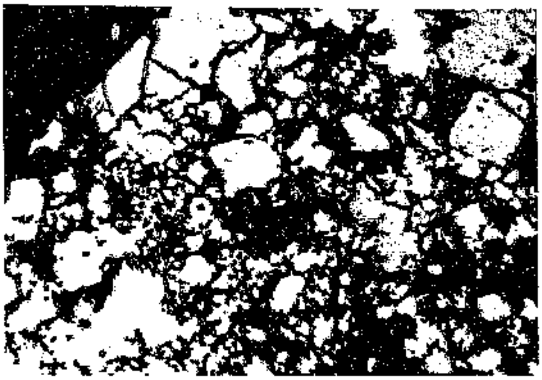
D: Photomicrograph of secondary quartz vein containing fragments of cassiterite, arsenopyrite and fluorite cutting perpendicularly to the main mineralised vein. In the centre region, adjacent to the secondary vein, secondary dark purple fluorite pseudomorphs replace cassiterite. Rooipoort tin prospect, Rooipoort 440 JR. Uncrossed nicols; field of view is 3,55 mm wide.

E: Photomicrograph of cassiterite and arsenopyrite mineralisation in the centre of the main vein cut by a secondary quartz vein (right margin), containing a secondary dark purple fluorite crystal. Rooipoort tin prospect, Rooipoort 440 JR. Uncrossed nicols; field of view is 3,55 mm wide.

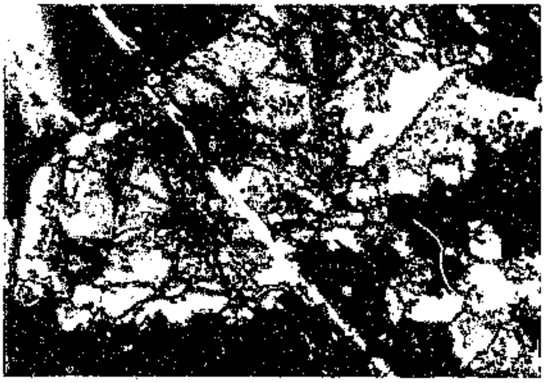
F: Photomicrograph of chalcopyrite (bright yellow) overgrowth of arsenopyrite (white, right margin). Rooipoort tin prospect, Rooipoort 440 JR. Reflected light; field of view is 1,89 mm wide.

G: Photomicrograph of dark purple fluorite pseudomorphs replacing earlier cassiterite grains. Rooipoort tin prospect, Rooipoort 440 JR. Uncrossed nicols; field of view is 3,55 mm wide.

PLATE VIII

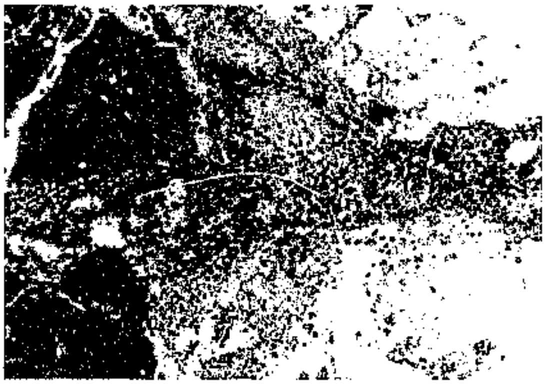


A



B

C



D

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slightly sericitised and are rimmed by small cassiterite and arsenopyrite crystals, 0,06 to 0,125 mm in size. Quartz is found as subhedral to anhedral grains 0,5 to 0,125 mm in size.

Within this granite, cassiterite crystals are associated with sericite fibres. Large growth zoned euhedral to subhedral cassiterite (see Plate VII - E), and arsenopyrite crystals, 0,25 to 0,5 mm in size, are associated with fine quartz veining, 0,5 to 1 mm in size, cutting across the rock. Chloritic veins 0,25 mm in size also cut across the granite.

The cassiterite in the sericitised granite is zoned dark brown / yellow, and is euhedral to subhedral, reaching sizes of 0,5 to 1mm up to 2 mm, particularly near quartz veins (see Plate VII - E). The cassiterite is found to be overgrown and intergrown with arsenopyrite, which shows similar size ranges as the cassiterite. The arsenopyrite is found to be extensively brecciated, but can reach sizes of 3 to 4,5 mm, and in some cases is intimately intergrown with minor chlorite clusters 0,25 mm in size. Fine sericitic veins 0,125 mm in size cut across the rock in places.

Chalcopyrite is found as irregular grains 0,25 to 2 mm in size associated with small, disseminated anhedral grains of arsenopyrite, 0,125 to 0,25 mm in size. Arsenopyrite is overgrown by chalcopyrite (see Plate VIII - F). Subhedral pyrite grains 0,125 to 0,25 mm to 1 mm in size at the largest overgrow arsenopyrite and cassiterite (see Plate VIII - A).

The paragenetic sequence is thus cassiterite - primary clear fluorite - arsenopyrite - pyrite. Brecciation of this early assemblage then followed with later or concomitant precipitation of chalcopyrite, and late-stage secondary purple fluorite pseudomorphs replacing the early cassiterite.

Galena and sphalerite are also reported from this locality, although none was seen in the samples taken. Martini and Vorster (1994) reported that the primary, high-temperature association of cassiterite - arsenopyrite - fluorite has been brecciated and cemented by chalcopyrite - bornite - galena of a lower temperature mineralisation event.

6.3.1.3 Ore Geochemistry

Table 6.2 gives the ore composition of the Rooipoort tin occurrence. The occurrence is rich in tin, copper, arsenic and lead hosted in cassiterite, chalcopyrite, arsenopyrite and galena respectively. There is a large amount of arsenic (> 3,5 %) as reflected by the large amounts of arsenopyrite.

6.3.1.4 General Comments

The host granite has a very low TEDI value (see chapter 5), and thus is highly fractionated and volatile-rich, explaining its Bobbejaankop-like appearance. The mineralising fluid made use of a shear zone trending 085° for its propagation, and which acts as a host to the mineralisation.

The early cassiterite - arsenopyrite - pyrite assemblage is brecciated and overgrown by chalcopyrite and later fluorite pseudomorphs replacing the early cassiterite. This bears evidence to a later fluid influx, possibly caused by reactivation of the faults and shear zones in the area and hosting the occurrence.

The nature of emplacement and possible basin development of this region of the Verena granite pluton could possibly influence the east-west direction of the host shear zone.

6.3.2 The Albert Silver Mine

The Albert Silver Mine on Roodepoortje 250 JR (see folder) is the most significant mineral occurrence in the study area, being a source of both base and precious metals.

The deposit, on the banks of the Moses River, is situated on the largest and most highly mineralised of a set of east - west trending hematite - quartz veins (see Plate IX - A). The deposit was discovered in 1885, and was mined continuously for approximately 14 years, and then intermittently until about 1910 (Robb *et al*, 1994). Various mining companies have held the mineral rights to the mine, most recently Anglo American Corporation, and the deposit has been re-examined a number of times. Present ore reserves to a depth of 150 m are estimated to be 1,2 million tons at 73 $g.ton^{-1}$ Ag, 0,42% Cu, 0,27 % Pb and 100 ppm U_3O_8 (Robb *et al*, 1994). At the present time the deposit is considered uneconomic. During its productive years the mine was high-graded, producing an estimated 20 000 tons of ore grading 1,14 $kg.ton^{-1}$ Ag and 10% Cu (Voet, 1981). Recent assays of dump material also reported isolated samples up to 400 $g.ton^{-1}$ Au and 0,48% Sb (Robb *et al*, 1994).

The deposit is hosted in fine-grained, pinkish grey granite, which becomes dark pink to red nearing the gossanous veins, but is found to be grey in the immediate vicinity of the mine, possibly due to later silicification and sericitisation of the feldspars. A coarse-grained, light pink porphyritic granite intrudes this fine-grained chill phase. The granite forms low, undulating topography with the Moses River forming a broad, shallow river valley. The Albert Silver Mine is situated on the southernmost of three major veins running east - west across Roodepoortje 250 JR. A north-south oriented post-mineralisation diabase dyke cuts across the Albert lode, dividing and dislocating the body into eastern and western sectors (Champion, 1970).

To the northeast of the mine is the north-east vein, and to the north-west of the mine the north vein (see folder and Fig. 6.1). On the boundary between Leeuwfontein 248 JR and Welverdiend 249 JR, a gossanous hematite - limonite vein is developed that has similar characteristics to the north vein (see folder and Fig. 6.1), and appears to be a continuation of the same vein system developed on Roodepoortje 250 JR. Considering that this vein is approximately 4 km away from the mine, this vein system could represent a large, mineable ore deposit.

6.3.2.1 Host rock petrography

The coarse-grained granite, which is found to the north of the Bronkhorstspruit road (see folder), and within a small area immediately to the south of the Albert Mine shaft, where it terminates the diabase dyke, intrudes the fine-grained apical phase of the Verena granite, which is host to the mineralisation at the mine. The coarse-grained granite is whitish pink in colour, with K-feldspar phenocrysts 30 mm in size, and a coarse matrix of K-feldspar, quartz, plagioclase, biotite and hornblende. Xenoliths of fine-grained granite, varying in size from 15 cm to 50 cm are found within the coarse-grained granite.

Microscopically the granite consists of sericitised, cloudy, subhedral to anhedral K-feldspar grains 0,5 to 2 mm in size, along with anhedral quartz 0,5 to 5 mm in size, but typically 2 mm. Perthite is found as anhedral grains 3 to 5 mm in size and forms a major proportion of the K-feldspars. Plagioclase occurs as subhedral, partly sericitised grains 0,5 mm to 1 mm up to 2,5 mm in size, and with a composition of An_{30-32}. Subhedral albite grains, 1,5 mm in size, are also found. Biotite is the main femic mineral, occurring as pleochroic dark yellow brown / dark green brown, subhedral grains 0,125 to 2 mm in size, and is often highly chloritised.

Chlorite, often totally replacing biotite, is also found as separate, distinct subhedral grains 0,25 mm to 0,75 mm in size, and is often associated with goethite. Magnetite occurs as subhedral grains 0,06 mm to 0,5 mm in size, with the largest been anhedral and 2 mm in size. It is also found as grains 0,03 to 0,06 mm in size forming clusters 0,125 mm in size, associated with chloritisation of the femic minerals. Accessory minerals include fluorite as anhedral grains 1 mm in size, and subhedral zircon 0,25 mm in size.

The fine-grained apical phase of the Verena granite, which is found at the Albert Silver Mine, is a pinkish grey rock with K-feldspar phenocrysts 10 to 30 mm in size, set in a fine-grained matrix of K-feldspar, quartz, plagioclase, biotite and hornblende. The granite is intruded by the coarse-grained phase of the Verena granite, as is seen in a number of sharp contacts between the two, such as to the north of the Albert Silver Mine, at the north-east vein, and at the southern boundary of Roodepoortje 250 JR (see Plate III - B and C).

Microscopically the granite consists of euhedral to subhedral, cloudy, ferrohydroxide-stained, sericitised K-feldspar grains typically 1 mm in size. K-feldspar phenocrysts, which reach up to 30 mm in size, often have rapakivi-like textures, with a rim of albite around the phenocrysts. Quartz is also found as phenocrysts, reaching sizes of 10 to 20 mm. Quartz in the groundmass occurs as subhedral to anhedral grains, 0,125 to 1 mm in size. Plagioclase, with a composition of An_{34-35}, occurs as euhedral, sericitised grains 0,25 to 0,75 mm in size.

Biotite, which is often highly chloritised, is the dominant femic mineral, occurring as pleochroic yellow green brown / dark green, subhedral to euhedral grains 0,125 to 1 mm in size, with some grains reaching 2 mm. The biotite is sometimes associated with magnetite, which is associated with chlorite, both being alteration products of the biotite. Hornblende occurs as an accessory mineral, and is also chloritised. It is found as subhedral grains, which are dark green in colour, and reaches sizes of 0,5 to 0,75 mm. Magnetite is found, mostly interstitially, as euhedral to subhedral grains 0,0625 mm in size. Accessory minerals include zircon, as subhedral to euhedral grains 0,06 to 0,5 mm in size, fluorite and apatite.

Nearing the quartz-hematite veins the fine-grained granite becomes progressively more altered. At the mine, this alteration zone is extensively developed on the northern side of the quartz-hematite "gossanous" ridge, but is not extensively developed on the southern flank of the Albert lode. Champion (1970) attributes this to the lode abutting against an east-west fault on its southern flank, which resulted in the erosion of part of the alteration zone during and after displacement. These same faults within the granite would appear to be responsible for the emplacement of the lodes in the granite.

The alteration zone associated with the Albert lode extends from between 10 to 20 m away from the lode, and is more extensively developed in the western sector of the lode. This may be attributable to the presence of the Moses River cutting across the lode in this area, which has caused a greater amount of alteration, associated with supergene enrichment, there. The alteration zone shows a number of different stages proceeding toward the lode. The various stages include incipient alteration, a quartz-sericite stage, a quartz-rich stage, the introduction of quartz, hematite and chlorite, and a chlorite-hematite stage, before intense hematisation in the immediate vicinity of the lode. The alteration shows different stages in different sectors of the lode as reported intensively by Champion (1970).

In moving toward the lode an incipient alteration is seen. The granite is sericitised to a limited extent with K-feldspar grains ferrohydroxide stained by incipient deuteric alteration, and kaolinised to a limited extent. The plagioclase grains are sericitised to a limited extent, and biotite has undergone partial pseudomorphous replacement by chlorite.

In the western portion of the lode, the granite undergoes alteration by sericitisation of the feldspars, introduction of coarse-grained quartz, and total chloritisation of biotite. Nearer the lode, coarse-grained quartz-rich bands are found and this is followed by hematite introduction; first as fine, disseminated particles and then as dense clusters nearer the lode.

In the central sector of the lode, the granite becomes chloritised first, along with intense kaolinisation of the K-feldspars (Champion, 1970). Abundant subhedral to anhedral quartz, 0,25 mm in size is found, along with abundant chlorite, replacing the feldspars. The chlorite occurs as clusters or as veins 0,125 mm in size. Chlorite is often associated with epidote and small clusters of magnetite. The biotite is completely chloritised, and the plagioclase highly sericitised. Nearer the lode in this sector, hematite is introduced, along with a greater amount of chloritisation of the rock. The hematite extensively replaces the feldspar grains, preserving the outline of laths in relict form (Champion, 1970). In the immediate vicinity of the lode, the rock is completely sericitised, and extensively replaced by large blebs of hematite.

In the eastern sector, feldspars are totally replaced by sericite, with no grain boundaries being evident 10 m from the vein (see Plate IX - B). Clusters of magnetite, up to 0,25 mm in size, consisting of anhedral grains 0,03 mm in size, are found associated with the sericitisation, particularly where K-feldspar phenocrysts, 2 mm in size, have been totally replaced. Minor chlorite veins, 0,125 to 0,25 mm in size, cut across the rock.

The granite in this region of the lode contains kaolinised orthoclase and chloritised and sericitised plagioclase near the lode, with intense chloritisation and introduction of fine-grained quartz and quartz veining 0,25 to 0,5 mm in size in the immediate proximity of the lode (see Plate IX - C). Minor amounts of hematite with associated ferrohydroxides are found in the chloritic groundmass, being part of the alteration. Found disseminated throughout the rock in this alteration stage are fine-grained disseminated sulphides, particularly chalcopyrite, along with vugs of purple fluorite 7 cm in size. Thin veinlets of chalcopyrite 0,25 mm thick are found sporadically in the rock, and pass over short distances of only 10 mm, suggesting some remobilization of the sulphides.

6.3.2.2 Ore Petrography

The ore at the mine is hosted in the largest of a number of sub-parallel quartz-hematite veins occupying east-west trending shear zones. The mine is found on the banks of the Moses River, and is in fine-grained granite. The quartz-hematite vein occurs as a ferruginous gossanous ridge, approximately 5 m wide, with an alteration envelope from 10 to 15 m away from the vein. The ore extends down to a depth of 120 m at least (Champion, 1970), and ore reserves are given to a depth of 150 m.
The old workings took the form of two development drives along the strike of the lode, at the 23 m and 47 m levels below surface, along with a number of raises and winzes which passed into the alteration zone (Champion, 1970). The mine is, however, now

PLATE IX

A: Photograph of Albert Silver Mine, from north of the Moses River. Note the prominent ferruginous gossanous ridges. Roodepoortje 250 JR.

B: Photomicrograph of sericitised granite, with minor chloritisation, approximately 10 m away from the main vein, Albert Silver Mine, Roodepoortje 250 JR. Uncrossed nicols; field of view is 2,2 mm wide.

C: Photomicrograph of chloritised granite, approximately 2 m away from the main vein, Albert Silver Mine, Roodepoortje 250 JR. Uncrossed nicols; field of view is 3,55 mm wide.

D: Photomicrograph of bornite (dark brown) overgrowth of pyrite (whitish yellow). Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 1,89 mm wide.

E: Photomicrograph of bornite (now altered to digenite)(blue - purple) having been overgrown by chalcopyrite (bright yellow) and galena (white with triangular pits). The chalcopyrite is also overgrown by the galena, the latter has also overgrown pyrite (off centre - whitish yellow). Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 1,89 mm wide.

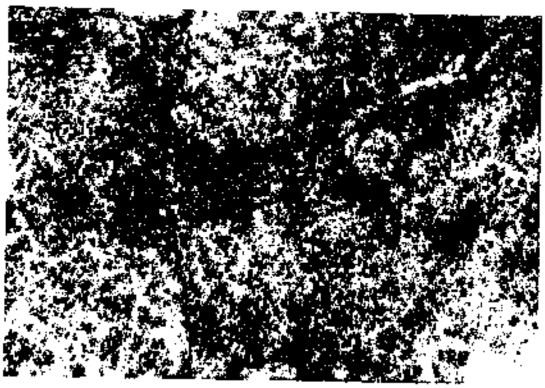
F: Photomicrograph of pyrite grains (yellow) overgrown by galena (white with triangular pits). Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 1,89 mm wide.

G: Photomicrograph of galena (white with triangular pits) overgrowth of rounded pyrite grains. In the upper right hand corner dark grey crystals of hematite have overgrown galena. Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 1,89 mm wide.

PLATE IX

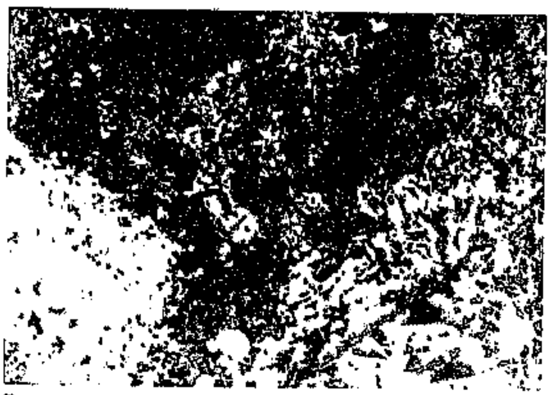
A

B



C

D



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G

completely flooded and thus the ore at depth could not be viewed. Ore samples were taken from the ore dump directly in front of the main shaft, where the lode is cut by the Moses River, as well as from a smaller dump to the west of this.

The ore shows a large number of sulphidic phases, and hence a number of interesting relationships (see Plates IX and X). The major sulphide minerals are pyrite, chalcopyrite, sphalerite, galena, arsenopyrite, argentiferous tetrahedrite, and bornite, with digenite occurring as an alteration of bornite, and to a lesser extent chalcopyrite. Champion (1970) also reported the presence of minor argentite, molybdenite and an unspecified Pb-Bi-Sb sulphosalt.

From borehole intersections, tne ore is found to be predominantly hosted in quartz veins and quartz-rich areas at a depth of between 100 to 175 m, occurring approximately at the contact between fine and coarse-grained Verena granite (Robb *et al*, 1994). In places the coarse-grained granite takes on the appearance of Bobbejaankop granite. The quartz-rich areas hosting sulphide mineralisation, consist of interlocking anhedral quartz grains 0,06 to 0,25 mm in size, with occasional large grains reaching 1,75 mm. Ferrohydroxides are found interstitially to the quartz grains along with minor amounts of sericite.

Three generations of quartz veining can be identified, with the first hosting the mineralisation and the others, crosscutting the first, being barren. Fluid inclusion data suggests no substantial temperature difference between the three generations of quartz veining (L. Robb, pers. comm, 1997). Within the veining and quartz-rich areas, tetrahedrite is found as anhedral grains 0,125 mm in size. Chalcopyrite is found as irregular, hackly grains, reaching sizes of 0,06 to 0,25 mm in size, when disseminated in the quartz-rich area. It is overgrown by sphalerite. The chalcopyrite can reach sizes of up to 3,375 mm, and is also found as veinlets 0,375 mm in size. On occasion, chalcopyrite blebs, up to 2 mm in size, are found adjacent to secondary quartz veins, crosscutting the earlier quartz-rich area. Tetrahedrite is often found near chalcopyrite, as small rounded grains 0,125 mm in size.

Within the granite, away from the quartz-rich areas and veining, the rock is extensively sericitised and contains abundant recrystallised quartz. Minor amounts of dark green chlorite, 0,125 to 0,25 mm in size, is associated with the sericite, along with hematite 0,06 to 0,125 mm in size. The feldspars have been totally sericitised, whereas elsewhere sericite and chlorite are intimately associated. Radiating clusters of chlorite are found associated with the sulphides. Goethite is also found, often associated with the sulphides, but more particularly with hematite.

Chalcopyrite is found as disseminated blebs 0,25 to 0,75 mm in size. Arsenopyrite, found as irregular, anhedral grains 0,125 to 0,375 mm in size, is found associated with chalcopyrite, as well as overgrowing it. Tetrahedrite, often found as anhedral grains 0,5 mm in size, overgrows pyrite, chalcopyrite, galena and arsenopyrite (see Plate X - B, C and D). Anhedral, rounded pyrite grains reaching sizes of 0,125 to 0,5 mm, are overgrown by arsenopyrite.

Elsewhere within the sericitised granite, cubic pyrite, 0,5 mm in size, is overgrown by chalcopyrite. Pyrite grains are also found as anhedral, broken up, rounded grains 1 and 2 mm in size down to 0,25 mm. Galena is found as subhedral grains 0,5 mm in size, and as large amorphous masses 3 mm and more in size, totally overgrowing rounded pyrite grains (see Plate IX - F and G and Plate X - E and F), as well as chalcopyrite and bornite, but is itself overgrown by arsenopyrite and tetrahedrite (see Plate X - C). Bornite is found as anhedral grains 0,125 to 2 mm in size at most, which have been extensively oxidised to digenite, disseminated throughout the rock. It overgrows pyrite (see Plate IX - D), but is overgrown by chalcopyrite and galena (see Plate IX - E). Champion (1970) recorded the presence of magnetite in the deeper levels of the boreholes he studied, and suggested that it may have been one of the first minerals to precipitate.

Hematite crystals, euhedral in shape, forming long fibrous thin grains 0,25 mm to 0,5 mm in length, to more stubby crystals 1 mm in size, overgrow pyrite, galena, sphalerite, chalcopyrite, in places oxidised to genite, bornite and tetrahedrite (e.g. see Plate X - E → G).

Robb *et al* (1994) reported observing cassiterite along the margins of a quartz vein. They also reported that some assayed veins yielded enhanced tin (200 ppm to 3000 ppm), and so they considered that sulphide precipitation may have been preceded by minor deposition of Sn ores, in the form of cassiterite.

Native silver is found as minute blebs, disseminated throughout the hematite, but alone cannot be responsible for the high silver content of the mine. Silver, however, is predominantly associated with tennantite, tetrahedrite-bearing galena and possibly the lead-bismuth sulphides.

From the above, a paragenetic sequence of pyrite - bornite - chalcopyrite - galena - sphalerite - arsenopyrite and finally tennantite-tetrahedrite is observed. Robb *et al* (1994) believe that cassiterite may have been deposited early before the sulphidic ore. Thus tin and possibly tungsten could have been deposited early, followed by sulphidic minerals, which passed from copper through lead and zinc, and onto deposition of fahlores, rich in arsenic and antinomy.

The sulphide minerals are extensively overgrown by a paragenetically later, high fO_2 assemblage of fluorite, chlorite, hematite (often the variety specularite) and pitchblende (Robb *et al*, 1994). These assemblages are generally found as open space fillings toward the centre of veins, or in miarolitic cavities (Robb *et al*, 1994). Fluorite occurs as vugs, 5 cm in size within the hematite, which overgrows the previous ore minerals. Pitchblende, which is the major uraniferous phase, occurs in association with the hematite, and as veinlets which cross-cut the sulphide mineralisation (Robb *et al*, 1994). Pitchblende is intimately intergrown with the hematite, and appears to be deposited contemporaneously (L. Robb, pers. comm, 1997).

The hematitic ore is highly radioactive, with assay values up to 15 kg.ton^{-1} U_3O_8 (Robb *et al*, 1994), whereas the sulphidic veins can reach values of 170 ppm to 300 ppm U_3O_8, but typically have values of 10 ppm to 50 ppm (Robb *et al*, 1994).

Robb *et al* (1994) reported on vugs in the hematite, wherein Fe-rich chlorite grew on the margins of the vug, with dark purple fluorite at the centre, suggesting secondary purple fluorite is the last mineral to be deposited in the oxidised assemblage of hematite - pitchblende - fluorite. Late-stage hydrofracturing may have possibly occurred due to brecciation, in places, of the fine-grained host phase associated with hematite in borehole cores (L. Robb, pers. comm., 1997).

The ore minerals show a distinct zonation in passing from west to east (Champion, 1970), as shown in Figure 6.3. Champion (1970) described in detail the abundance of each of the ore minerals in passing from west to east, by detailed examination of borehole core. The major ore minerals are present in different abundances in different portions of the lode. The other ore minerals, namely bornite, tennantite-tetrahedrite, argentite, magnetite and the bismuth sulphides, are only in abundance in portions of the lode. Native silver is found as very fine disseminated grains less than 0,001 mm in size (Champion, 1970). Hematite is in greater abundance than any other mineral. Pitchblende shows a similar trend to the hematite, with which it is associated.

This ore zonation probably has a direct correlation with the variation in the nature of the alteration zone, with hematisation more predominant in the western sectors and chloritisation more predominant in the east, corresponding with the ore minerals found in the different sectors. This may give clues as to the sequence of ore deposition as well as pointing to supergene enrichment, initiated by the Moses River, which affected the western portion of the lode preferentially.

The ore has undergone extensive supergene enrichment, particularly in the area drained by the Moses River (Champion, 1970). Due to periods of shearing and the presence of shear zones in and around the vicinity of the mine, the ore is susceptible to

PLATE X

A: Photomicrograph of tetrahedrite (dark grey) overgrowth of chalcopyrite (bright yellow) and bornite (dark brown). The bornite may be due to supergene enrichment of the chalcopyrite (centre). Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 2,2 mm wide.

B: Photomicrograph of tetrahedrite (dark grey) overgrowth of arsenopyrite (bright white - left), chalcopyrite (bright yellow) and pyrite (rounded white - right). Chalcopyrite has overgrown pyrite. Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 1,89 mm wide.

C: Photomicrograph of tetrahedrite (dark grey) overgrowth of chalcopyrite (bright yellow), galena (white with triangular pits) and arsenopyrite (white), from the centre outwards and along fractures. The galena has overgrown chalcopyrite. Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 3,55 mm wide.

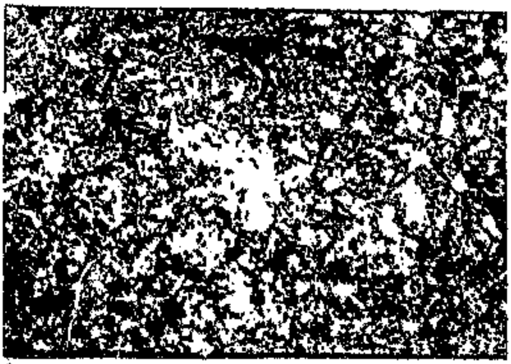
D: Photomicrograph of tetrahedrite (dark grey) overgrowth of arsenopyrite (white) and chalcopyrite (bright yellow). Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 2,2 mm wide.

E: Photomicrograph of chalcopyrite (bright yellow) overgrowth of pyrite (yellow white) and itself having been overgrown by galena (white with triangular pits). The galena has also overgrown pyrite. The galena and pyrite are overgrown by hematite crystals (dark grey - right margin). Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 1,89 mm wide.

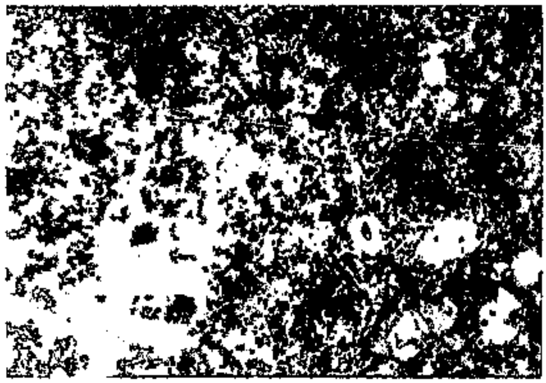
F: Photomicrograph of galena (white with triangular pits) overgrowth of pyrite (yellow) and both having been overgrown by hematite crystals (dark grey - upper margin). Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 3,55 mm wide.

G: Photomicrograph of galena (white with triangular pits) overgrown by hematite crystals (grey). Albert Silver Mine, Roodepoortje 250 JR. Reflected light; field of view is 1,89 mm wide.

PLATE X



A



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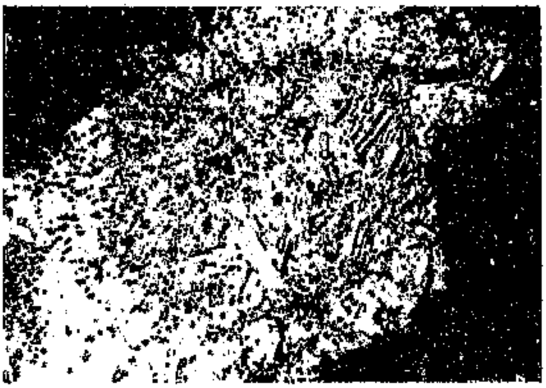

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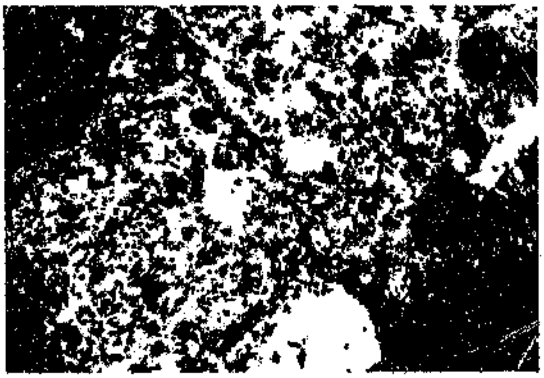

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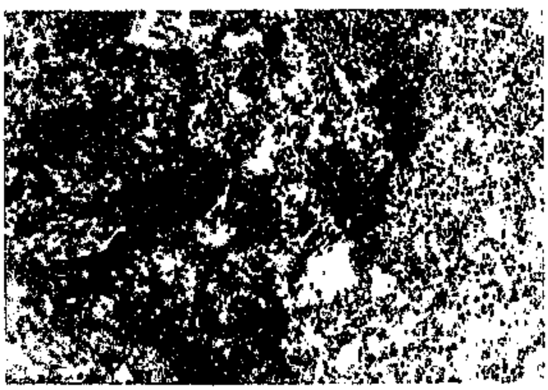


E

F

G

supergene enrichment. The presence of the Moses River, which cuts across the lode to the west of the main shaft, provides the necessary fluid for supergene enrichment in addition to a very minor component from rain water. In the supergene oxide zone at surface limonite, complex Bi, As, Sb, Pb oxides, a Lindackerite-type mineral ($Cu_5As_4O_{15}.9H_2O$), malachite, azurite, copper sulphate pentahydrate ($CuSO_4.5H_2O$) and the rare Cu - U - As mineral metazeunerite ($Cu(UO_2)_2(AsO_4)_2.8H_2O$) are found (Champion, 1970).

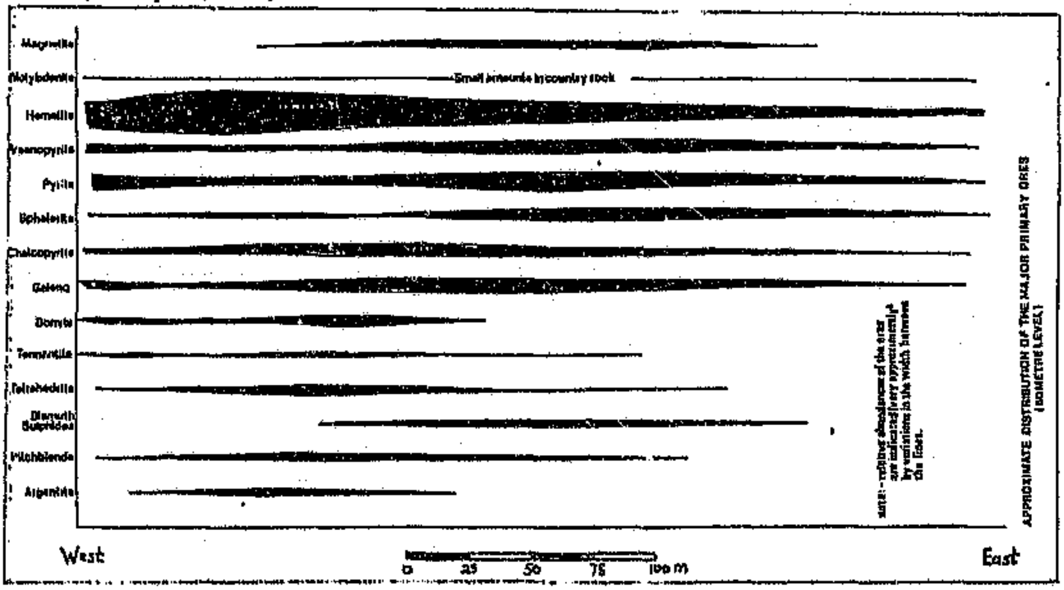


Figure 6.3 Concentration of ore minerals in the Albert Silver Mine lode (from Champion, 1970)

In the supergene sulphide zone at depth, minor amounts of covellite, chalcocite and bornite, which all replace chalcopyrite, are also found. Native silver, found as disseminated blebs in massive hematite, is found in the supergene sulphide zone, and probably originated from the percolation of superger fluids. The greater presence of both massive hematite, as well as native silver in the western sector at and in the vicinity of the Moses River, indicates the role of the river in the percolation and origin of the fluids responsible for supergene enrichment of the ore.

6.3.2.3 Ore Geochemistry

The composition of the ore at the Albert Silver Mine is given in Table 6.2. The ore shows high values of copper, zinc, lead, arsenic, bismuth, antinomy and silver, hosted in chalcopyrite, sphalerite, galena, arsenopyrite, Bi-Sb sulphosalts and argentiferous tetrahedrite respectively.

Antinomy shows surprisingly high concentrations (> 1700 ppm) compared to the other metals even though its host, tennantite and tetrahedrite are present in only a portion of the lode, and in relatively small amounts compared to the other ore minerals.

6.3.2.4 Other hematite-quartz veins in the area related to the Albert vein

Other hematite-quartz veins, trending east-west, are found on Roodepoortje 250 JR, and form part of the mineralising system (see folder and Figure 6.1). The north vein on Roodepoortje 250 JR shows an alteration zonation in going from unaltered granite toward the vein. Incipient alteration involves introduction of sericite replacing plagioclase, kaolinisation of at least 40% of the feldspars (Champion, 1970) and chloritisation of the biotite. Nearer the vein, the granite is extensively sericitised, making the rock light green in colour. This gives way to a lighter coloured granite, cut by occasional fine hematite veins travelling along fractures in the wallrock. In the proximity of the vein the sericitised portion of the rock gives way to large-scale introduction of quartz and hematite replacing the feldspars and micas.

The vein, approximately 10 m wide, is made up of interlocking, recrystallised quartz grains, 0,125 to 0,06 mm and less in size, associated with radiating chlorite clusters. Goethite and ferrohydroxides are associated with the hematite and stain the rock red. The hematite is often found as fibrous radiating clusters with grains 0,125 mm in size. The hematite is associated with extensive sericitisation in certain portions of the rock.

On the boundary between Leeuwfontein 248 JR and Welverdiend 249 JR, a hematite-limonite gossanous ridge is found, that also trends east-west (see folder and Fig. 6.1)and shows similar base metal contents as those found at Albert (see Table 6.2). This gossanous ridge would appear to be related to mineralisation at Albert, even though it is 3,5 km away from the Albert Silver Mine. The Leeuwfontein vein, approximately 2 m wide, occurs directly east of the north vein and the Albert vein, and protrudes from loamy soil with no other outcrop. It consists of quartz veining with euhedral to subhedral crystals 0,25 to 0,75 mm in size and 2 mm at the largest. These are surrounded by and intergrown with euhedral hematite crystals 0,125 to 0,25 mm in size. The hematite is associated with minor amounts of goethite and limonitic vugs in places. The vein here is more quartz-rich, and contains less hematite than those on Roodepoortje 250 JR.

Table 6.2 shows the base and precious metal contents of the north vein and Leeuwfontein vein. In passing from east to west, from the Albert Silver Mine through the north vein and to the Leeuwfontein vein, there is an overall decrease in Pb, As, Co, Au, and Ag, but an overall increase in Sn and W. If Sn and W are deposited first from a hydrothermal fluid, followed later by Pb and Cu and finally As, Sb, Au and Ag, then it can be considered that the Leeuwfontein vein was deposited first, followed by the lodes on Roodepoortje 250 JR, as Sn and W decrease in content in passing from the Leeuwfontein vein to the Roodepoortje veins. Zonation of the ore minerals at the Albert lode also tends to suggest this deposition from west to east.

6.3.2.5 General Comments

The Albert Silver Mine is the largest deposit in the area, and shows the widest range of commodities of any deposit in the study area. Supergene enrichment has led to the occurrence having larger amounts of silver and copper than it would otherwise have had, and is the main reason why this occurrence was mined for a period.

The presence of a fine-grained phase, which has been shown to be a chill phase of the coarse-grained phase (see Chapter 5), suggests that the ore-bearing fluids may have welled up beneath this fine-grained chill phase to form a stratiform high-grade massive sulphide body at depth (Robb *et al*, 1994). The veins seen at surface may just be sub-vertical quartz-sulphide veins caused by hydrofracturing of the fine-grained phase.

The east - west orientation of the Roodepoortje veins, as well as the Leeuwfontein vein, show a similar trend to the Rooipoort tin-bearing quartz vein trends, and may be caused by stress conditions inherent during emplacement of the Verena granite pluton.

The paragenetic sequence found at Albert is a fairly extensive one, and may be an almost complete paragenetic sequence for mineralisation in the granites of the Bushveld Complex. The paragenetic sequence, however, does not exhibit extensive early tin mineralisation, but does show an extensive development of a later more oxidised assemblage.

6.3.3 Other occurrences in the area

A minor copper occurrence, hosted in a shear zone trending 060°, occurs on Roodepoort 439 JR within the rhyolites of the Schrikkloof Formation of the Rooiberg Group, on the banks of the Moses River. Minor disseminated chalcopyrite is found within quartz veining within the shear zone.

6.3.3.1 Rooipoort copper occurrence

The Rooipoort copper occurrence on Rooipoort 440 JR occurs almost directly to the east of the Rooipoort tin occurrence. The occurrence is hosted in veins that trend 090°, parallel to the trend of the mineralisation at the tin occurrence. The small occurrence is marked by small amounts of massive hematite. It is hosted in Verena granite near the contact with overlying Rooiberg volcanics.

6.3.4 General Comments on the northwest Verena granite pluton area

The northwestern portion of the Verena granite area has a prominent east-west mineralisation direction, compared to the north-south direction of the Moloto granite pluton. An east-west stress field may have been caused by basin development in this portion of the pluton due to the intersection and interaction of two crustal synforms, parallel to the Wonderkop fault and Laersdrif fault lineaments respectively. This basining may have preserved the fine-grained apical phase at the Albert Silver Mine.

The Albert Silver Mine, high up in the granite pluton (low TEDI values - see Chapter 5), has little tin, but has metals characteristic of later fluid deposition, as well as large quantities of hematite. It is also worth noting that at Leeuwfontein no fine-grained phase is present, there is less hematite and there is a greater abundance of metals typically deposited early by a hydrothermal fluid. This would suggest that the mineralisation at Leeuwfontein is situated in lower level granites of the granite pluton than the granites at the Albert Ag Mine. This concurs with the notion that basin development has occurred in the immediate vicinity of the Albert Silver Mine, with high level granites preserved beneath the fine-grained chill phase, and with the surrounding granites been lower level granites.

Away from the Albert Ag Mine, lower level granites are exposed, such as the granites at Rooipoort tin, and the granites hosting the tin mineralisation on Leeuwfontein. Near the granophyre margin, higher level granites are preserved, hosting mineralisation, such as the Rooipoort copper occurrence and the nearby Hartebeestspruit Cu occurrence, both marked by hematite. Continued displacement along the shear zones and faults could have allowed fluid flow for extended periods of time, possibly even a few hundred thousand years (cf. Cathles *et al*, 1997).

6.4 Rhenosterkop area

The area around the solitary hill of Rhenosterkop contains a number of minor occurrences. The occurrences have no economic significance, but their position close to a possible volcanic vent, and the nature of the host rock, predominantly Bobbejaankop granite intermixed with Klipkloof granite, make the area worth investigating. There are three occurrences in the area, the Rietfontein tin occurrence and the Zusterstroom zinc and fluorite occurrences. The base and precious metal contents of the first two are given in Table 6.3.

Table 6.3 Base and precious metal contents of the mineral occurrences in the vicinity of Rhenosterkop

occur.	ppm Sn	ppm Mo	ppm Cu	ppm Pb	ppm Zn	ppm As	ppm Sb	ppm Ag	ppm Au	ppm F
Rietfontein										
sample 1	686	25	11	52	43	< 15	<10	< 1.0	0.03	28
sample 2	129	37	-	279	-	-	-	-	-	-
Zusterstroom	10	<5	<5	22	459	<15	<10	< 1.0	0.01	28

6.4.1 The Rietfontein tin occurrence

The Rietfontein tin occurrence is found to the east of the Zusterstroom - Bronkhorstspruit road, and to the north of the Zusterstroom 447 JR boundary (see folder and Fig. 6.1). The occurrence is hosted in Bobbejaankop granite with interdigitated Klipkloof granite to the north and south (see folder). Immediately to the east of the excavation pits is an extensive area of brecciation.

The host Bobbejaankop granite within 5 m of the mineralised shear zone on Rietfontein 446 JR (see folder) contains K-feldspar phenocrysts set in a matrix of K-feldspar, quartz, hematite, sericite and muscovite. K-feldspar phenocrysts, which are extensively ferrohydroxide stained, sericitised to varying degrees, as well as hematised, are subhedral in shape. The larger grains (16 mm or more) are hematised to a large extent along cleavage and twin planes. Smaller feldspar phenocrysts (4 mm in size) are euhedral to subhedral in shape, and are totally replaced by sericite. K-feldspar in the groundmass has been totally replaced by sericite and hematite (formerly magnetite?).

Quartz is found as subhedral phenocrysts 3,75 mm in size. Quartz in the groundmass occurs as anhedral grains 0,25 to 0,5 mm in size with 1,5 mm the largest seen. Muscovite grains 0,25 to 0,375 mm in size are found as anhedral grains in the groundmass. Ferrohydroxides are found associated with the hematite alteration. Muscovite clusters 2 mm in size comprising grains 0,25 mm in size are associated in places with sericitic alteration of the feldspars.

On the margins of the mineralised shear zone the rock has extensive quartz, radiating fibres of muscovite and small disseminated cassiterite crystals (see Plate XI - A). Quartz occurs as anhedral interlocking grains 1 to 2 mm in size. Extensive masses of radiating muscovite clusters 0,75 to 1 mm in size are found as veinlets cutting across the quartz mass. The centre of the muscovite veinlets are marked by deep brown ferrohydroxides. Muscovite fibres are also found separately, scattered throughout the rock with individual fibres reaching 0,125 to 0,25 mm in size. Grains of clear fluorite reaching sizes of 0,125 to 0,5 mm are found in the quartz groundmass, and are occasionally associated with the muscovite fibres. Euhedral to subhedral cassiterite occurs as crystals 0,125 mm in size within the quartz groundmass, and are often associated with the muscovite fibres. Away from the muscovite fibres and in more quartz-rich areas the cassiterite crystals can reach 0,5 mm in size.

At the centre of the vein, the cassiterite crystals become larger, and are found as subhedral, zoned reddish brown to pink and green grains 0,25 to 2 mm in size, but typically being 1 mm. The cassiterite crystals are sometimes found to form clusters 3 to 4 mm in size set in the muscovite-quartz rock (see Plate XI - B). Muscovite fibres form clusters 0,125 to 0,25 mm in size, consisting of radiating fibres 0,06 to 0,125 mm in size. These fibres, along with the cassiterite crystals, dominate the centre of the shear zone set in coarse, anhedral vein quartz 0,25 to 1 mm in size.

Muscovite is also found as skeletal grains 2 mm in size, which in parts has been replaced by sericite. Hematite / goethite clusters 1 mm in size are occasionally found associated with the muscovite clusters and the cassiterite crystals. Clear, anhedral fluorite 0,25 mm in size is also found associated with the radiating muscovite clusters. Vein quartz found with the radiating muscovite clusters is 0,125 to 0,0€ mm in size, and is finer grained than elsewhere in the vein. Martin and Vorster (1994) have reported minor sulphide mineralisation within the nearby breccia.

The presence of muscovite indicates the presence of relatively high temperature hydrothermal fluids having passed through the rock, and obviously been responsible for the mineralisation. The mineralisation is hosted in a shear zone trending 350°. The granites in the area are highly brecciated, and in many places extensively sericitised.

In a small prospect pit to the west of the Zusterstroom - Bronkhorstspruit road and 3,5 km from the summit of Rhenosterkop, the host Bobbejaankop granite to a small tin occurrence is a purply red colour, and is cut by quartz-hematite veining. The feldspars are sericitised and extensively replaced by fine hematite.

The base and precious metal geochemistry of the main tir urrence to the east of the Bronkhorstspruit - Zusterstroom road and Rhenosterkop on Rietfontein 446 JR is given in Table 6.3. The granites do not appear to be highly mineralised, although the results shown are not of the cassiterite-rich central zone. Molybdenum values are apparently as high as 120 ppm. The tin prospect to the west of the Zusterstroom - Bronkhorstspruit road contains enhanced tin values and some lead, but is not enriched in the other metals.

6.4.2 Zusterstroom zinc and fluorite occurrences

The granites on Zusterstroom 447 JR, immediately to the south of Rietfontein 446 JR, are also brecciated and highly altered in places. Approximately 2 km northeast of the Bronkhorstspruit - Zusterstroom road, sericitised and brecciated granite, cut by quartz-hematite veining, is found (see folder). The hematite colours the rock deep red. Veining has an orientation of 231°. This granite is found to contain enhanced zinc values.

The coarse-grained Bobbejaankop granite immediately to the north is also sericitised, with minor chloritisation and hematisation, being cut by quartz-hematite veining, and containing secondary muscovite. It is here that a borehole was sunk and fluorite was intersected in a sheared and broken up quartz body (Martini, 1982). To the south-southeast, near the Wilge River, quartz veining with small euhedral hematite and goethite crystals 0,125 mm to 0,25 mm in size are found. The base and precious metal concentrations of the zinc-hosting altered granite on Zusterstroom 447 JR is given in Table 6.3. The altered granites are not rich in metals, except for this quartz breccia, approximately 2 km northeast of the Bronkhorstspruit - Zusterstroom road.

6.4.3 General comments on the Rhenosterkop area

A plug of Bobbejaankop granite interdigitated with Klipkloof granite occurs in the vicinity of Rhenosterkop, extending in a southeast direction from near the Bronkhorstspruit - Groblersdal road to an area just north of the Wilge River (see folder). The granite in the area of Rhenosterkop is highly altered and brecciated in places, with brecciation occurring over a distance of 4 km near the contact of the Bobbejaankop and Klipkloof granites.

The presence of a breccia at this location may be due to the presence of an extension of the Steelpoort fault trending northeast - southwest and truncating in the granites of Leeuwfontein 228 JS to the northeast of Rietfontein 446 JR. If this fault is extrapolated in a southwest direction it would pass through the area of mineralisation on Rietfontein 446 JR and Zusterstroom 447 JR, as well as Rhenosterkop.

Whether this fault may have been used by the Klipkloof granite for its emplacement, or for preferential fluid flow causing subsolidus crystallisation of the Bobbejaankop-like granite is not clear, but it is worth noting that the trend of the brecciation in the granites is parallel to the Steelpoort fault orientation. Alteration and brecciation of the granites may also be related to renewed activity along the fault structure. Rhenosterkop, which appears to be a volcanic vent within the Rooiberg group, may have used this fault for its emplacement. Whether the mineralisation in this area is related to Rhenosterkop is also not clear.

6.5 Southern Dennilton Pluton Area

The Klipdrift / Boekenhouthoek molybdenum / gold occurrences occur to the west of the study area on the farms Klipdrift 62 JS and Boekenhouthoek 61 JS (see folder and Fig. 6.1). They occur within a nature reserve, but were studied due to their mineral associations not found elsewhere in the study area. Base and precious metal contents for the southern marginal area of the Dennilton granite pluton are given in Table 6.4, with certain values having been obtained from Scogings (1991).

Table 6.4 Base and precious metal contents of the mineral occurrences on the southern margin of the Dennilton granite pluton

occur.	ppm Sn	ppm Mo	ppm Cu	ppm Pb	ppm Zn	ppm As	ppm Sb	ppm Ag	ppm Au	ppm F
Klipdrift Mo sample 1	15	750	0.01%	990	121	12.20%	61	1.9	7.6	1198
sample 2	-	568	840	72	26	2.80%	-	1	6.9	-
sample 3	-	551	25	65	11	-	-	-	2.2	-
Klipdrift Au	10	20	<5	194	54	138	<10	<1.0	0.02	321
Boeken' Au	<10	<5	22	92	60	> 5 %	-	0.3	0.57	-
avg. con.	-	-	247	283	-	52535	-	1.07	3.46	760

6.5.1 Klipdrift Mo / Au occurrence

The Klipdrift molybdenum / gold occurrence on Klipdrift 62 JS, is hosted in jointing oriented at 110°, and is rich in molybdenum, arsenic and gold (Table 6.4), but has never been mined. Prospect pits and borehole collars exist at the site, indicating some degree of investigation in the past. The occurrence, along with the nearby gold occurrences on the same farm, were investigated due to their different ore assemblages and associations not found elsewhere in the study area.

6.5.1.1 Host Rock and Ore Petrography

The occurrence is hosted in deep red, sericitised and chloritised Bobbejaankop granite interdigitated with fine-grained Klipkloof granite in places. Klipkloof granite is found developed to the south of the occurrence. The granite consists of deep red, ferrohydroxide stained K-feldspar grains 5 to 10 mm in size, surrounded by yellowish green sericite and dark green chlorite, with associated hematite and goethite preferentially altering the feldspars along fractures (see Plate XI - C). Minor amounts of perthite are also found. Microscopically the K-feldspar grains make up approximately 70% of the rock.

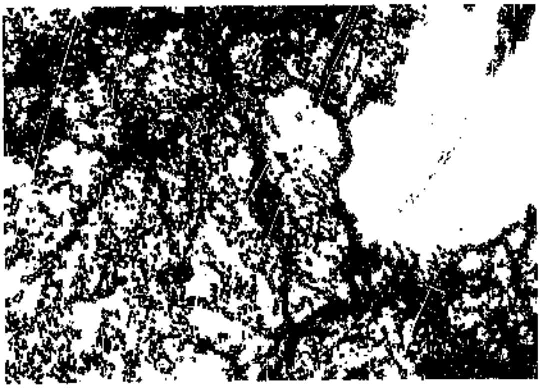
Rust red goethite and hematite, occasionally forming clusters 0,75 to 1 mm in size, are found in the chloritic - sericitic groundmass, as well as along fractures in the feldspars. Subhedral hematite crystals 0,5 mm in size are associated with anhedral quartz 0,25 to 1 mm in size. There is very little quartz in the rock, except for quartz veins cutting across the rock which contain vugs of purple fluorite within the centre of the veins. Clear, cubic crystals of fluorite 2 to 4 mm in size, are also found as vugs up to 30 mm in size in the granite.

Sericitic veinlets 0,125 mm in width, are found along major fractures across the rock, and replace the feldspars in places. Fibres of muscovite, 0,25 mm in size are occasionally found. Plagioclase, with composition An_{29-31} occurs as accessory, subhedral grains. Disseminated throughout the rock are grains of molybdenite varying in size from 3 to 5 mm. Molybdenite is also found as rosettes, 7 mm in diameter, disseminated throughout the rock. Grains of arsenopyrite 2 mm in size are also found disseminated throughout the rock.

PLATE XI

A

B

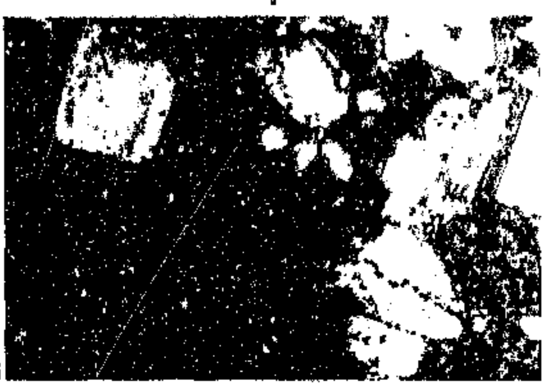


C

D

E

F



G

PLATE XI

A: Photomicrograph of radiating muscovite fibres set in a vein quartz groundmass. A small cassiterite crystal (dark brown -upper left near the margin) can be seen in the vein quartz. Rietfontein tin prospect, Rietfontein 446 JR. Crossed nicols; field of view is 3,55 mm wide.

B: Photomicrograph of cassiterite crystals in centre of the quartz vein shear zone along with radiating muscovite fibres. Rietfontein tin prospect, Rietfontein 446 JR. Crossed nicols; field of view is 2,2 mm wide.

C: Photomicrograph of hematised K-feldspar in Bobbejaankop-like granite. Klipdrift molybdenum prospect, Klipdrift 62 JS. Uncrossed nicols; field of view is 2,2 mm wide.

D: Photomicrograph of molybdenite (dark grey) overgrown by arsenopyrite (white). Klipdrift Mo occurrence, Klipdrift 62 JS. Reflected light; field of view is 2,2 mm wide.

E: Photomicrograph of molybdenite (dark grey) overgrown by arsenopyrite (white). Klipdrift Mo occurrence, Klipdrift 62 JS. Reflected light; field of view is 3,55 mm wide.

F: Photomicrograph of molybdenite (medium grey) overgrown by sphalerite (dark grey - lower left). The sphalerite has also overgrown arsenopyrite (white). Klipdrift Mo occurrence, Klipdrift 62 JS. Reflected light; field of view is 2,2 mm wide.

G: Photomicrograph of arsenopyrite (white) overgrowths of pyrite (yellow). Klipdrift Mo occurrence, Klipdrift 62 JS. Reflected light; field of view is 3,55 mm wide.

Molybdenite occurs along with arsenopyrite as subhedral grains 0,25 mm in size in a highly chloritised area, but are also found as disseminated grains 3 to 5 mm in size throughout the granite. Arsenopyrite, anhedral in shape and reaching sizes of 2,5 to 4 mm and up to 15 mm in large masses, overgrows molybdenite (see Plate XI - D and E). Quartz veins 9 mm in size cut across the rock, and consist of interlocking quartz grains 0,25 to 0,75 mm in size, along with ore minerals. The ore minerals occur in the greatest abundance near or adjacent to quartz veins.

Sphalerite appears to be later in the sequence, found as subhedral, cubic to elongate grains 0,125 to 0,25 mm in size when sub-cubic, to 0,5 mm in size when elongate. The sphalerite overgrows both molybdenite and arsenopyrite (see Plate XI - F). Chalcopyrite occurs as anhedral blebs, 0,125 mm in size disseminated in the rock. Sphalerite overgrows chalcopyrite and arsenopyrite. Cubic, subhedral pyrite 0,25 to 0,375 mm in size is found associated with arsenopyrite, and appears to be overgrown by the latter (see Plate XI - G). Thus, although not all the relationships are present, it would appear that molybdenite was deposited first, followed by pyrite, chalcopyrite and then widespread deposition of arsenopyrite followed by later, less voluminous sphalerite. Clear fluorite would seem to have been introduced early along with the molybdenite and pyrite although this relationship is not clear, and two generations of fluorite may be present. Purple fluorite may have been introduced later.

6.5.1.2 Ore Geochemistry

The base and precious metal contents of the Klipdrift Mo occurrence are given in Table 6.4. The rock is particularly rich in arsenic (>2,8 %), hosted in arsenopyrite, and would tend to indicate its introduction into the rock at a late stage due to its large content. The rock is also rich in gold (2 - 8 ppm, Table 6.4), which is likely to be associated with the abundant arsenopyrite in the rock. Molybdenum is present in substantial amounts, as seen by the abundant molybdenite disseminated throughout the rock.

6.5.1.3 General Comments

The occurrence is found in the upper levels of the Dennilton granite, just below Klipkloof granite and granophyre to the south. The mineralisation is concentrated along fractures in the Bobbejaankop-like granite, and is especially abundant at the intersection of the joints. Here the volatiles associated with the fractionated granites made use of unloading of the granite sheet for its propagation. Hematite, however, is not found in large amounts here.

6.5.2 Klipdrift Au occurrence

This occurrence is found to the east of the molybdenum occurrence on Klipdrift 62 JS (see folder and Fig. 6.1). A shear zone oriented at 045° hosts the occurrence. The occurrence is minor, and not as highly mineralised as the molybdenum occurrence, but it is also relatively rich in gold (0,02 ppm) and arsenic (138 ppm, Table 6.4). Medium-grained deep red altered Sekhukhuni granite acts as the host to the occurrence.

6.5.2.1 Host Rock and Ore Petrography

The host granite is deep red in colour, and is medium grained, consisting of deep red feldspars and quartz, with disseminated pyrite scattered throughout the rock. The K-feldspars are ferrohydroxide stained deep red and are cloudy, being subhedral to anhedral in shape, with minor sericitisation and are 0,375 to 3 mm in size. Lesser amounts of microcline are present. Plagioclase, also cloudy and sericitised, but distinctly clearer than the K-feldspars, is found as subhedral to anhedral grains, 0,5 to 2 mm in size, and with a composition of An_{30-38} (determined microscopically, as for all the determinations).

Quartz, which is the predominant mineral in the rock, is found as anhedral grains 0,5 to 1,5 mm in size. K-feldspar and quartz are often intergrown in a granophyric texture, forming intergrown grains 2 to 4 mm in size, and having either a K-feldspar or a plagioclase grain at its nucleus. Fibres of epidote, 0,375 mm in size, are found associated with clusters of magnetite, with individual grains of magnetite 0,125 to 0,06 mm in size. Dark red goethite is found along fractures in the K-feldspars. Epidote is found in clusters associated with pyrite grains disseminated throughout the rock. Epidote is also found as euhedral grains 0,06 mm in size, along with chlorite and magnetite alteration, along with red goethite. Subhedral to anhedral pyrite grains, 1,5 mm in size are found widely disseminated throughout the rock, and are broken up and infilled by dark green chlorite.

6.5.2.2 Base and precious metal geochemistry

The base and precious metal contents at this occurrence are given in Table 6.4. The granite contains small amounts of Pb (194 ppm), As (138 ppm) and Au (0,02 ppm), which is associated with the disseminated pyrite. The fluorine value (321 ppm) is relatively high, but not much more than the inherent values of Klipkloof granite. This occurrence may represent a higher level equivalent of the molybdenum occurrence, where most of the mineralisation has been deposited at lower crustal levels at the Mo occurrence in the granite sheet below.

6.5.3 Boekenhouthoek Au occurrence

The Boekenhouthoek Au occurrence is hosted in dark red granophyre of the Rashoop Granophyre Suite on the farm Klipdrift 62 JS near the boundary of Boekenhouthoek 61 JS, with a number of small prospects marked by quartz - hematite veining in granophyre on Boekenhouthoek 61 JS (see folder and Fig. 6.1).

6.5.3.1 Host rock and ore petrography

The mineralisation is hosted in dark red K-feldspar-rich granophyre, with vugs of quartz 10 to 25 mm in size and abundant arsenopyrite. The K-feldspar is extensively ferrohydroxide stained giving the feldspars a dark pink-red colour. Sericitisation has occurred along fractures and cleavage planes in the feldspar. Minor amounts of anhedral quartz, 0,375 mm in size are found to be intergrown with the K-feldspar, possibly indicating the remnant granophyric texture.

Quartz vugs, 10 mm or more in size are composed of euhedral quartz. Subhedral grains of K-feldspar, 1,5 to 2,5 mm in size, are found within the quartz vugs on occasion. The edge of the quartz vugs consist of euhedral quartz 2,5 mm in size, growing in toward a fine-grained quartz centre made up of equigranular, subhedral quartz grains 0,125 mm in size. Euhedral zircon grains 0,25 mm in size are found on the edge of the quartz vugs.

The bulk of the rock hosting mineralisation consists of a K-feldspar rich area, with small vuggy quartz areas 4 mm in size within it. The K-feldspar areas appear to be made up of subhedral to anhedral K-feldspar grains 0,25 to 0,5 mm in size, closely intergrown and possibly recrystallised. Sericitic clusters, 0,25 mm in size, are found in the feldspar groundmass, along with euhedral zircon grains 0,125 mm in size within the sericitic clusters. Magnetite occurs as euhedral to subhedral grains 0,06 to 0,125 mm in size, scattered throughout the feldspar groundmass.

Arsenopyrite occurs as highly fractured subhedral grains 1 to 3 mm in size, within or on the margins of the quartz vugs. The fractures within the arsenopyrite are infilled by sericite, along with small quartz grains 0,125 mm in size.

6.5.3.2 Ore Geochemistry

The base and precious metal contents for the Boekenhouthoek Au occurrence are given in Table 6.4. The occurrence is rich in arsenic (> 5 %), gold (0,57 ppm) and silver (0,3 ppm), and appears also to be a high level mineral occurrence, exhibiting late-stage mineralisation, just like the Klipdrift Au occurrence. There is no hematite or pitchblende associated with this occurrence, and no visible fluorite. The granophyre appears to have been extensively recrystallised, with introduction of quartz, associated with arsenopyrite in the form of vugs, as well as the introduction of feldspar. The rock has no granophyric texture whatsoever. Gold is evidently hosted in the arsenopyrite.

6.5.4 General Comments on the Dennilton Granite area

The Dennilton granite has a high TEDI value, that decreases proceeding southwards towards the Klipkloof granite contact, where the TEDI values become very low. The mineral occurrences associated with the Dennilton granite are found along its margin, typically near or hosted within the overlying Klipkloof granite or granophyre. No mineral occurrences have been found further in toward the centre of the pluton owing to its low TEDI values and low metal specific character. This reaffirms, once again, that there appears to be a correlation between highly fractionated (low TEDI) granites and the occurrence of mineralisation.

The escarpment between the Springbok flats to the north and a plateau to the south (cf. De Bruiyn, 1980), found along the Klipkloof -Dennilton granite contact, indicates that there is a progression from lower level granites upwards to higher level granites southwards onto the plateau. This explains why there are more mineral occurrences to the south, compared to the northeast portion of the Bushveld granites in the area of Dennilton and in Sekhukhuniland to the east (cf. Kleeman and Twist, 1989).

The mineralisation along the edge of the Dennilton granite also shows a distinctly different paragenesis than elsewhere, being dominated by gold, arsenic and cobalt. Au and in particular Co are considered to be deposited at relatively low temperatures by a metal-bearing hydrothermal fluid. The mineralisation here would thus point to precipitation from a low-temperature hydrothermal fluid compared to the higher temperature magmatic-dominated type of mineralisation found within the Verena and Moloto granites. As the mineralisation on the margins of the Dennilton pluton is hosted in high level granites compared to the Sn and Cu-Pb mineralisation hosted in the lower level granites of the Verena and Moloto plutons, this suggests an evolution of the mineralising fluid with height in the granites.

6.6 Other occurrences in the study area

The study area also has minor mineral occurrences scattered outside of the four main regions described. These fall within the Kameelpoort pluton and the rhyolites surrounding the four plutons in the study area. A brief description of each from north to south and west to east follows.

6.6.1 Western portion

6.6.1.1 Kameelpoort Cu - F occurrence

The Kameelpoort Cu - F occurrence is found on Kameelpoort 202 JR, near its northern boundary with Zandspruit 189 JR (see folder and Fig. 6.1). The occurrence is hosted in a quartz vein with an orientation of 080°/ 10° N within Sekhukhuni granite, and is marked by copper staining on surface. The vein contains fluorite in chlorite pockets and pockets of chalcopyrite. Chlorite alteration is found around the vein.

6.6.1.2 Kameelpoort rare earth and thorium occurrence

A minor occurrence of monazite is found within Sekhukhuni granite on Kameelpoort 202 JR, to the southeast of Kameelpoort settlement near the Moloto - Siyabuswa road.

6.6.1.3 Enkeldoornspoort zinc occurrence

An excavation within rhyolites of the Schrikkloof Formation of the Rooiberg Group was found on the farm Enkeldoornspoort 207 JR (see Fig. 6.1). The excavation is marked by a breccia and minor copper staining. The occurrence is enriched in zinc and copper (see Table 6.5) and is located along a fault that extends to the northwest to intersect the Vergenoeg fluorite - hematite body (see Fig 6.1). Whether there is any relation to the Vergenoeg body, with fluids originating from there, is unclear.

6.6.1.4 Rietfontein iron occurrence

A minor hematite occurrence is found on Rietfontein 214 JR, within rhyolites of the Kwaggasnek Formation. The occurrence is near the granophyre contact, near the northeastern corner of Rietfontein 214 JR.

6.6.1.5 Graslaagte Cu - As - Au occurrence

On Graslaagte 232 JR within rhyolites of the Schrikkloof Formation of the Rooiberg Group (see folder and Fig. 6.1), hematite veining trending 240° is found within dark red brown chloritised and hematised rhyolite. Associated with the hematite veining are flakes of golden brown biotite, indicating hydrothermal fluid activity through the rock. The rock is enriched in copper, arsenic, zinc, lead and gold (see Table 6.5).

6.6.1.6 Hartebeestspruit Fe, Zn occurrence

Within the rhyolites of the Schrikkloof Formation, near the contact with the overlying Ecca Group of the Karoo Sequence, on Hartebeestspruit 434 JR a quartz-hematite breccia vein trending 115° is enriched in iron and zinc.

6.6.2 Eastern portion

6.6.2.1 Hartbeesfontein Mo - Co occurrence

On Hartbeesfontein 93 JS, just north of the Moses River, in rhyolites of the Schrikkloof Formation, and near the Verena granite contact (see folder and Fig. 6.1), granitic veins in a shear zone trending 355° are enriched in molybdenum, arsenic, cobalt, nickel, gold and silver. Ore minerals include arsenopyrite, molybdenite, erythrite and impure graphitic material (Geol. Surv. S. Afr. Hbk. 7).

6.6.2.2 Langkloof F occurrence

On Langkloof 229 JS, just north of an extension of the Steelpoort fault, and within rhyolites of the Kwaggasnek Formation, irregularly disseminated fluorite of a low grade is found. This occurrence is found near the mineralised agglomerate layer separating the Kwaggasnek and Schrikkloof Formations in this eastern portion of the study area.

6.6.2.3 Mineralised agglomerate layer

The volcanic agglomerate horizon, separating the lower Kwaggasnek Formation from the upper Schrikkloof Formation of the Rooiberg Group, is irregularly mineralised along a strike length of approximately 40 km, stretching from Leeuwfontein 228 JS (see folder) around to Doornnek 88 JS, and on to Rhenosterfontein 227 JR to the west. The agglomerate is often infilled with limonitic material and occasionally hematite. Elsewhere it is a deep pink, sericitised rock, infilled by quartz veining between the fragments. In other areas, such as on Engelschedoornboom 95 JS (see folder and Fig. 6.1), the mineralisation occurs as fine-grained sphalerite with pyrite, minor galena and occasional arsenopyrite. These sulphides form irregular impregnations, mainly in the agglomerate but, to a lesser extent, also in the lava (Martini and Vorster, 1994). The grade is always low, but may be due to upwelling solutions that may not have reached the surface, as no sinters have been found (Martini and Vorster, 1994).

6.6.3 Geochemistry of some of the minor mineral occurrences

The base and precious metal contents of some of the minor mineral occurrences within the study area listed in section 6.6 are given in Table 6.5.

Table 6.5 Base and precious metal contents of some of the minor mineral occurrences in the study area

sample	ppm Cu	ppm Zn	ppm Pb	ppm As	ppm Sn	ppm Bi	ppm Y	ppm W	ppm Co	ppm Au	ppm Ag	ppm F
207-26	284	460	91	<15	<10	<7	<5	7	9	<0.01	<1.0	<10
232-95	1527	177	152	2262	12	80	131	12	83	0.05	<1.0	10
90-138	19	34	<15	<15	<10	<7	63	23	<5	-	-	-

207-26: excavation in brecciated rhyolite, Enkeldoornspoort 207 JR

232-95: hematite veining in altered rhyolite, Graslaagte 232 JR

90-138: agglomerate layer, Rietfontein 90 JS

The Enkeldoornspoort excavation (section 6.6.1.3) has enhanced Cu and Zn values but is not of any economic significance. The site was prospected at some stage, but was abandoned. The Graslaagte occurrence (section 6.6.1.5) is enriched in Au, Cu, Zn, Pb and As but has never been prospected. Mineralising fluids would seem to have been derived from the underlying granites. The agglomerate layer separating the Kwaggasnek and Schrikkloof Formations is not significantly enriched in any particular element at the site sampled but is found to be enriched in Pb and Zn elsewhere, such as on Engelschedoornboom 95 JS.

6.7 General Discussion

The Moloto pluton is rich in Sn, Cu, Pb, As, Ag and Au, as seen by the average values from mineral occurrences in and around the pluton (see Table 6.1). Cu is the most abundant metal in the granites of the Moloto pluton, followed by As and Sn. Hence the Moloto pluton exhibits large concentrations of metals that are paragenetically relatively early in the mineralising event. The Verena granite is rich in Sn, Cu, As, Ag and F in some areas. Arsenic is the most abundant followed by Ag and Cu. Hence the Verena granite contains a greater abundance of metals deposited later in the mineralising episode. The southern, more fractionated margin of the Dennilton granite is rich in As, Au and Ag, in that order, and so is significantly enriched in late-stage metals.

In passing from the Moloto pluton to the Verena pluton, to the southern margin of the Dennilton pluton Sn, Cu, Pb and Zn decrease in abundance, whereas As and Au (in general) tend to increase in abundance. These observations agree with the average TEDI value of the plutons which are 79 (Moloto pluton), 55 (coarse-grained Verena granite) and 33 (Dennilton granite - southern margins), including Bobbejaankop and Klipkloof granite found within the pluton or its margins.

Hence the least fractionated pluton (the Moloto pluton) is rich in Sn and Cu, whereas the Verena pluton (which is more fractionated), is rich in Cu and Ag. The most highly fractionated portions of the granite sequence in the study area (the southern margin of the Dennilton pluton) is rich in Au and Ag. It is worth noting that the mineralisation in the Moloto pluton is intimately associated, in most cases, with Bobbejaankop granite, which is associated with or host to tin mineralisation, whereas the Au occurrences of the Klipdrift / Boekenhouthoek area are associated with Klipkloof granite, illustrating the changing nature of fluids and volatiles with an increasingly fractionating granitic magma.

6.8 Conclusions

The granites offer large potential for mineralisation, particularly the upper portions of the granite sheet with low TEDI values. As Bobbejaankop and Klipkloof granites are usually found near the top of the granites they are obviously prime targets in any exploration program. As the upper portions of the granites are preserved near the contacts with overlying rhyolite or granophyre, rather than near the centre of the pluton where erosion has exposed lower levels of the granite, the margins of a pluton offer larger potential for mineralisation targets than do the centres of the plutons. There are notable exceptions, such as the Albert Silver Mine, but in these cases other factors, such as the presence of a fine-grained chill phase, have affected the locality of the mineralisation.

The level within the pluton affects the ore assemblage, with tin being dominate lower down in the granites, giving way to copper and lead further up, and gold and arsenic at the very top of the granites. Height in the granites also determines the extent to which an oxidised assemblage of hematite-fluorite and possibly pitchblende, overgrows an earlier sulphidic assemblage, such as at the Albert Silver Mine. There are other criteria, however, that will also affect this, such as rate of erosion and unroofing of the granites. However, height in the granite is the predominant factor affecting the ore assemblage, as seen for the Zustershoek Tin Mine, the Enkeldoorn tin field and the Rooipoort tin and copper occurrences.

Ore-bearing fluids originate from a fractionating granite at depth, and pass upwards depositing metals, with tin deposited early. These fluids have a large magmatic component, and give rise to occurrences such as the Rooipoort tin occurrence and the Enkeldoorn tin field. Higher up in the granites the deposition from the ore-bearing fluids give rise to later metals, such as lead and copper being deposited and there is a larger meteoric component present, giving rise to a large quantity of hematite in the ore (Robb *et al*, 1994, Freeman and Robb, 1995, Freeman *et al*, 1997). In these type of deposits a cap rock is often found, which prevents the ore-bearing fluids from reaching the surface, as well as hosting the deposit. Such examples include the Albert Silver Mine and the Zustershoek Tin Mine.

Due to the high heat productive capacity of the granite (McNaughton *et al*, 1993), the mineralising fluids continued circulating for a long time, possibly a few hundred thousand to a few million years. Cathles *et al* (1997) investigated the duration of hydrothermal fluid flow set up by a shallow intrusion. For a large intrusion they estimated fluid circulation of up to a few hundred thousand years. Even though their model applies to mafic and ultramafic rocks, fluid flow in the granites would have been of a similar magnitude, or slightly longer due to their large radiogenic decay.

Various magmatic pulses may have been active over time and possibly have caused a long hydrothermal event.

With time the fluids mixed with a meteoric / connate fluid, which with time became increasingly dominant and gave rise to the precipitation of later assemblages. Where the mineralising episode continued for a long time, the fluids became predominantly meteoric / connate in nature, and oxidised assemblages such as hematite and possibly fluorite were deposited (Freeman and Robb, 1995).

The morphology and orientation of the mineralisation appears to be controlled by large-scale factors. These are associated with the predominant stress field present within a pluton during emplacement or subsequent uplift or deformation. Major crustal lineaments, such as the northeast-southwest trending Steelpoort and Wonderkop faults, and the southeast-northwest trending Laersdrif fault lineament, may also have affected granite emplacement and structure within the plutons, and hence mineralisation trends within the granites.

The granophyres offer no potential for mineralisation, being just a hypabyssal equivalent of the Rooiberg Group, but rather act as hosts to mineralising fluids derived from the underlying granites. The Rooiberg Group also acts as a repository for mineralisation derived from the underlying granites and possibly the Rustenburg Layered Suite (Schweitzer *et al*, 1995b). It could however act as a host to volcanogenic massive sulphide deposits, but no such occurrences have presently been found. The minor mineral occurrences in the Rooiberg Group, such as the Enkeldoornspoort and Graslaagte occurrences, and the mineralised agglomerate layer, seem to have been derived from fluids originating at depth, and making use of permeable conduits such as faults, agglomerates or breccias for its passage.

CHAPTER 7

ALTERATION AND THE NATURE OF THE MINERALISING FLUIDS

7.1 Introduction

The mineral occurrences are derived from hydrothermal fluids, derived from magmatic fractionation of the granitic magma that gave rise to the Lebowa Granite Suite (Robb *et al*, 1994). These fluids mixed with a meteoric / connate fluid component, giving rise to the various mineral assemblages seen (Freeman and Robb, 1995, Freeman *et al*, 1997). Associated with this mineralisation are various alteration assemblages and gangue minerals that allow something of the nature of the ore-bearing fluids to be investigated. The source of the fluids, the degree of fluid mixing, and the inherent nature of the fluid can hereby be examined. To this end examination of the alteration assemblages associated with the mineral occurrences, as well as Fe determinations and petrographic fluid inclusion studies were undertaken.

7.2 Alteration assemblages

The mineral occurrences in the study area show zones of alteration related to the passage of hydrothermal fluids through the rock. As the occurrences are small the altered regions around them are typically a few meters in width. Another factor complicating interpretation is that some alteration assemblages have superimposed themselves on earlier assemblages, causing complex paragenetic sequences and alteration assemblages to be found at some occurrences. The Albert Silver Mine serves as an example, where prolonged fluid flow has given rise to alteration zonation from early incipient alteration to the Fe-rich alteration associated with the final paragenesis of hematite - pitchblende and fluorite.

7.2.1 Incipient alteration

Incipient deuteric alteration involves chloritisation of the mafic minerals, biotite and hornblende, as well as iron-oxyhydroxide staining of the feldspars, and minor replacement of the feldspars by sericite. Depending on the ore assemblage, as one moves closer to the mineralised zone, extensive sericite (in most cases), as well as chlorite totally replace the feldspars. Fine-grained recrystallised quartz is also found in some alteration assemblages.

7.2.2 Alteration associated with Sn-dominated systems

Occurrences which contain metals precipitated by early magmatic fluids, such as tin or molybdenum, have a predominantly propylitic alteration with minor sericitisation. The Enkeldoorn tin field, as an example, is dominated by chloritic alteration. Other occurrences, such as the Rooipoort and Rietfontein Sn occurrences, however, are dominated by sericite and muscovite respectively. Enkeldoorn is, however, seen to be enriched in Pb and Zn, and may indicate a later alteration assemblage associated with these metals.

For the tin occurrences, such as Rietfontein and Rooipoort, the initial stages of alteration in the granites is extensive sericitisation of the feldspars. Muscovite fibres are found on occasion. In the case of Rietfontein, radiating muscovite fibres are found in the sheared granite, and cassiterite crystals 1 to 2 mm in size are associated with these clusters. Minor kaolinisation of the granite, along with minor chloritisation, is also found.

7.2.3 Alteration associated with Cu-dominated systems

In copper dominated occurrences, such as the Albert Silver Mine, chloritisation is found to be less dominant than sericitisation. The Sybrandskraal Cu occurrence is dominated by sericitisation of the host granophyre. The Albert Silver Mine and related veins, however, exhibit a long-lived hydrothermal history, and their alteration assemblages are complex (e.g. Champion, 1970), varying from incipient alteration of the granites, from approximately 20 m from the vein, to sericitisation and intense chloritisation, giving way to hematisation immediately adjacent to and within the vein.

From descriptions of host rock and ore petrographies those occurrences that were exposed to some degree of meteoric / connate fluids, such as the Albert Silver Mine and the Zustershoek Tin Mine, have an extensive amount of hematitic alteration associated with them, often superimposing itself on the earlier assemblages.

7.2.4 Alteration associated with Pb-Zn-dominated systems

In Pb - Zn dominated systems, such as the Prins Anna structure and the Zusterstroom altered granites, sericitisation is dominant, with hematisation and associated goethite beginning to appear in the alteration assemblage, particularly in the case of the Prins Anna structure.

7.2.5 Alteration associated with late-stage metal deposition

The mineral occurrences typically found high up in the granite sheet, such as the Hartebeestspruit, Klipdrift and Boekenhouthoek Au occurrences, have alteration assemblages varying from phyllic into the phyllic - argillic boundary. Hartebeestspruit is found to be both sericitised and chloritised with minor hematisation. As this occurrence is rich in Pb and Cu this alteration assemblage would appear to be derived from earlier fluid flow, giving rise to the Cu and Pb mineralisation, than that which gave rise to the Au mineralisation. The hematisation may be associated with the later Au precipitation. The Klipdrift Mo occurrence has early molybdenum precipitation with associated chloritisation and sericitisation, and later Au precipitation with associated minor hematisation. The Klipdrift and Boekenhouthoek Au occurrences are dominated by intense iron-oxyhydroxide staining of the feldspars and minor hematisation. Introduction and recrystallisation of feldspar and quartz would appear to have taken place, particularly for the Boekenhouthoek occurrence where the mineralised granophyre is very coarse-grained and has no granophyric texture.

7.2.6 Alteration zonation

Zonation from propylitic to phyllic alteration, in moving away from the mineralised zone, was noted for a few of the occurrences, such as Enkeldoorn and Rooipoort. At Rooipoort an outer phyllic zone, approximately 20 m away gives way to a zone of intense chloritisation around the mineralised shear zone. At Enkeldoorn, where there is a greater Cu component, the shear zone hosting mineralisation is highly chloritised (where chalcopyrite has been deposited), whereas sericitisation is found 2 m from the mineralised shear zone. The granophyre-hosted Zustershoek Tin Mine, being also copper dominated, is dominated by later hematisation and iron oxyhydroxide staining of the feldspars, with extensive sericitic replacement of the feldspars and minor chloritisation. Here the later meteoric / connate component has dominated the alteration assemblage at this locality.

7.2.7 Alteration styles

Potassic alteration, where K-feldspar recrystallises or is introduced is rare, and propylitic alteration in its strictest form is secondary to phyllic alteration. In some cases an intermediate case between propylitic and phyllic alteration is found. Argillic alteration is rare but has been noted, possibly at the Boekenhouthoek Au occurrence, as well as the shear zone at the Rooipoort tin occurrence. The latter bears evidence of two episodes of ore deposition, one where early cassiterite and arsenopyrite are deposited, followed by later brecciation and infilling by chalcopyrite. The predominantly phyllic alteration appears to be associated with the early cassiterite, whereas the later, low-temperature argillic alteration may be associated with the chalcopyrite deposition.

A change from predominantly propylitic to phyllic and possibly argillic alteration, with a late superimposition by oxidising fluids to give the late hematitic assemblage points to a gradual decrease in fluid temperature with deposition, and an increasingly oxidising fluid dominating the ore fluids.

Hemley and Jones (1964) illustrated the temperature range versus expected log a_{K+}/a_{H+} that could be expected for different alteration assemblages. The range would be anywhere from 500° C for muscovite to be stable, as for example at the Rietfontein occurrence, down to temperatures of 300° C for argillic alteration assemblages, such as at Boekenhouthoek Au (see Figure 7.1).

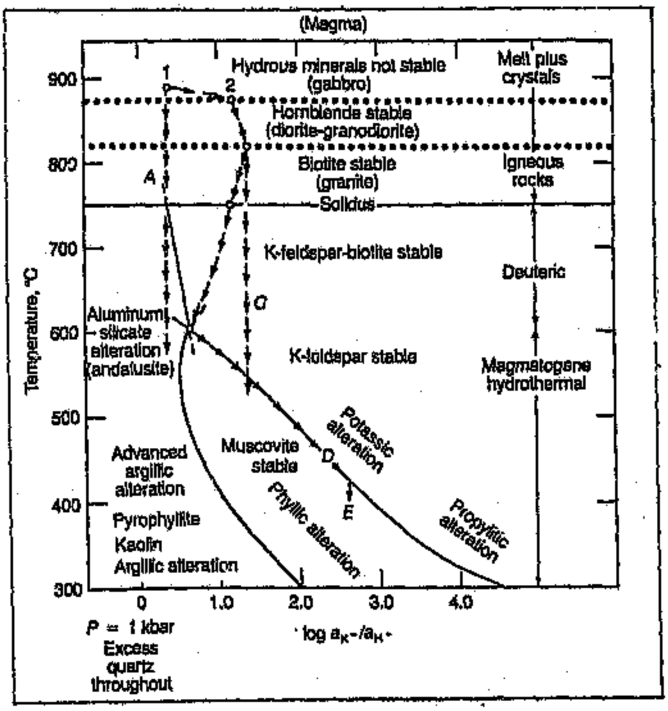


Figure 7.1 Plot of log a_{K+}/a_{H+} vs. temperature showing the temperature ranges of alteration assemblages associated with mineralisation (after Burnham and Ohmoto, 1980)

7.3 Fe^{2+}/ Fe^{3+} Ratios

A number of samples of granite, varying from fresh unaltered granite to altered granite associated with, or host to, mineralisation, were analysed for their Fe^{2+} and Fe^{3+} contents. The method used was that of Wilson (1960), described in Appendix B. Fe^{2+}/Fe^{3+} ratios were then determined to see whether they could be used as an exploration tool, similar to the TEDI index, and also to test the hypothesis of an increasingly greater meteoric / connate fluid component affecting mineralisation higher up in the granites.

Six samples of granite, from a variety of locations varying from the base to the top of the granites, were analysed. TEDI values, field relationships and petrographic and textural criteria determined the height of the samples in the granites. Seven samples of altered granite, either hosting or associated with mineralisation, were examined in the same way. The majority of the altered granite samples are from Sn-dominated systems. These samples were taken from the Rietfontein tin occurrence and altered granite in the vicinity. Samples of actual ore could not be analysed, as the high metal contents seriously affect the Fe^{2+}/Fe^{3+} determinations. The analyses are given in Table 7.1.

The samples have been listed according to TEDI values, from the lowest TEDI values, representing the most fractionated granites, to the highest TEDI values, representing the least fractionated. The altered granite samples have been ordered in a similar fashion.

Figure 7.2 plots the Fe^{2+}/ Fe^{3+} ratio against the TEDI value for both the unaltered and the altered granite samples. From Table 7.1 it is seen that, at least, for the samples taken from the Dennilton granite, i.e. 58-163, 63-159 and 63-161, the Fe^{2+} / Fe^{3+} ratio decreases with decreasing TEDI value, i.e. increasing amounts of fractionation. The

Table 7.1 Fe^{2+}/ Fe^{3+} determinations for selected granite samples

unaltered granites						
sample	ppm Sr	FeO_T %	Fe^{2+} %	Fe^{3+} %	Fe^{2+}/Fe^{3+}	TEDI
63-161	12	2.28	0.81	1.47	0.55	5
63-159	16	2.49	1.1	1.39	0.79	12
202-15	17	1.78	1.34	0.44	3.04	29
217-37	27	3.13	1.57	1.56	1.01	67
250-115	76	2.05	1.68	0.37	4.54	93
58-163	48	2.05	1.47	0.58	2.53	105
altered granites						
sample	ppm Sr	FeO_T %	Fe^{2+} %	Fe^{3+} %	Fe^{2+}/Fe^{3+}	TEDI
250-114	21	5.46	1.97	3.49	0.[illegible]	18
447-127	18	4.54	1.11	3.43	0.32	5
446-118	10	3.39	0.72	2.68	0.27	5
446-124	9	3.97	0.68	3.29	0.21	3
446-119	11	1.4[illegible]	0.16	1.25	0.13	2
447-126	14	5.23	0.51	4.72	0.11	3
446-123	14	4.29	0.23	4.07	0.06	5

58-163: grey Sekhukhuni granite, Maloek Zyn Kop 58 JS

250-115: fine-grained Verena granite, Roodepoortje 250 JR

217-37: Bobbejaankop granite, Enkeldoorn 217 JR

202-15: fine-grained red Sekhukhuni granite near Klipkloof dyke, northwestern margin, Kameelpoort pluton, Kameelpoort 202 JR

63-159: Bobbejaankop-like Sekhukhuni granite, Rhenosterkuil 63 JS

63-161: Klipkloof granite, Rhenosterkuil 63 JS

250-114: altered fine-grained Verena granite, Albert Silver Mine, Roodepoortje 250 JR

447-127: chloritised and sericitised coarse-grained Bobbejaankop granite, Zusterstroom 447 JR

446-118: chloritised and sericitised Bobbejaankop granite, Rietfontein 446 JR

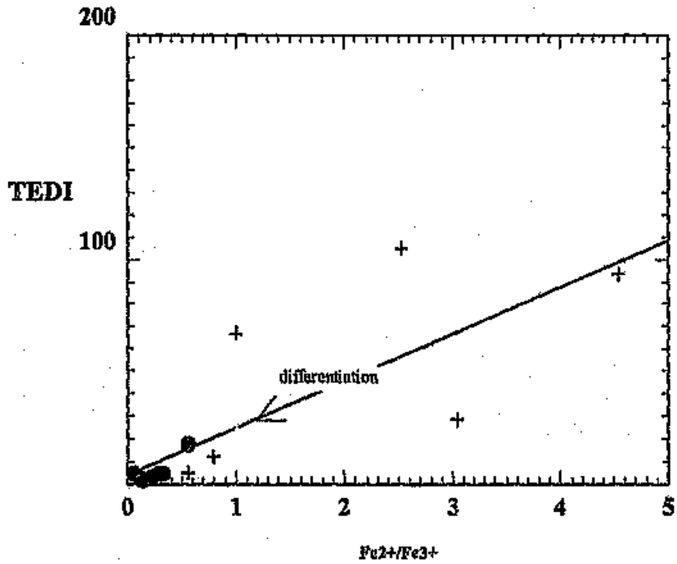
446-124: altered Bobbejaankop-like coarse-grained Verena granite, Rietfontein tin occurrence, Rietfontein 446 JR

446-119: ser[illegible]d, hematised Bobbejaankop granite, Rietfontein 446 JR

447-126: [illegible]-hematite breccia, Zusterstroom 447 JR

446-123: sericitised and chloritised Bobbejaankop granite, Rietfontein 446 JR

% Fe_2O_3 determined by XRF analysis, and % FeO determined by Wilson's (1960) method (see Appendix B).



Legend

● altered granite samples
+ unaltered granite samples

Figure 7.2 Plot of Fe^{2+}/ Fe^{3+} ratios versus TEDI values

Fe^{2+} decreases from 1,47 to 0,81, whereas the Fe^{3+} increases from 0,58 to 1,47, hence causing the Fe^{2+}/ Fe^{3+} ratio to decrease.

The decreasing Fe^{2+}/Fe^{3+} ratio correlates with the decreasing TEDI value with increasing height and degree of fractionation in the granites. High level granites have the greatest Fe^{3+} content reflecting the concentration of fluids and the progressive reddening of the granite (caused by microcrystalline hematitisation of feldspar) in the upper reaches of the granite. Hence the trend in Fe^{2+}/Fe^{3+} ratios mirrors that of the TEDI values, and so could be used in conjunction with or as an alternative to TEDI values in an exploration program.

The altered granite samples tend to cluster, and are characterised by very low TEDI values and low Fe^{2+}/Fe^{3+} ratios in Fig. 7.2. Sample 250-114 has a higher Fe^{2+}/Fe^{3+} ratio and higher TEDI value than those near Rhenosterkop, but is characterised by a chlorite dominated alteration assemblage. Mineralised samples, particularly those characterised by the late stage paragenetic sequence, are characterised by an association with high fO_2 fluids that are responsible for the intense hematisation which typify these deposits.

Figure 7.2 exhibits some important points:

- The TEDI value decreases upwards in the granites
- The Sr content decreases upwards
- The Fe^{2+} ion concentration decreases and the Fe^{3+} increases with increasing height in the granites
- The Fe^{2+} / Fe^{3+} ratio decreases with increasing height

With increased degrees of fractionation, Sr and Ba decrease in abundance whereas Rb increases in abundance causing the TEDI value of the higher level granites to decrease. With increasing degree of fractionation and height in the granites the granites crystallised from a more volatile-rich magma which caused intense deuteric alteration of the feldspars and chloritisation of the mafic minerals. Oxidation of magnetite results in the decrease of Fe^{2+}/Fe^{3+} in the granite and the precipitation of hematite in the crystal lattices of the feldspars. Hence with increasing degrees of fractionation in the granites, the Fe^{2+} is progressively oxidised to Fe^{3+} causing the Fe^{2+}/ Fe^{3+} ratio to decrease with height in the granites.

Trends in Fe^{2+}/Fe^{3+} ratios appear to be different in the various plutons studied, as witnessed by the widely separated sample points of the unaltered granites in Figure 7.2. The three samples from the Dennilton pluton are virtually colinear, whereas the other three unaltered granite samples, each from three separate plutons, show different Fe^{2+}/Fe^{3+} ratios and TEDI values from each other. This could suggest that each of the plutons in the study area were chemically isolated, and did not form part of a single laccolithic intrusion, as suggested by McCarthy and Hasty (1976), Groves and McCarthy (1978) and Kleeman and Twist (1989).

7.4 Fluid Inclusion Studies

Fluid inclusions provide valuable information on the fluids that were present. not only during formation of the rocks (primary inclusions), but also those which were present at later stages of the rock's evolution (secondary inclusions). Estimations of the temperature at which the fluids were trapped, as well as their basic composition, can be obtained from fluid inclusion studies. Thus they can serve as useful indicators of the fluids responsible for the various mineralisation styles present in the granites, as well as shedding light on the origin and evolution of those fluids.

A general petrographic study of fluid inclusions from some of the mineral occurrences in the study area was undertaken in order to compare the characteristics of these fluids with fluids from other occurrences and deposits, such as those recorded for the Zaaiplaats Tin Mine (Pollard *et ul*, 1991 and Ollila, 1981) and for the Rooiberg tin deposit (Ollila, 1981).

7.4.1 The Zaaiplaats Tin Mine

The mineralisation at the Zaaiplaats Tin Mine is hosted in coarse-grained Bobbejaankop Granite, overlain by a thin sheet of fine-grained granite called the Lease Granite. This granite is bound along its upper margin by a marginal pegmatite. The granites of the Lebowa Granite Suite intrude the granophyres of the Rashoop Granophyre Suite. The mineralisation at the Zaaiplaats Tin Mine is found in three forms:

- Low-grade orebodies: These form the most extensive ore type mined in the Lease Granite, which is a red- or grey-coloured granite, which contains cassiterite as a hydrothermal infill component in miarolitic cavities (Pollard *et al*, 1991). They generally occur in the uppermost portion of the Lease Granite, with the upper limit of the orebodies often coinciding with the base of the pegmatite zone. A second type of ore called lenticular orebodies, occurring in the Lease Granite, are composed of cassiterite, feldspar, sericite, fluorite, scheelite and sulphides, and have a more restricted distribution (Pollard *et al*, 1991).

- Zone of disseminated mineralisation in the Bobbejaankop Granite: This zone of disseminated mineralisation occurs approximately 50 m below the Lease Granite. Cassiterite is found as a hydrothermal infill mineral in interstitial miarolitic cavities in this zone, along with scheelite. Within these miarolitic cavities a general paragenetic sequence of quartz, perthitic alkali feldspar, and chlorite (originally biotite?) are the earliest infill minerals, followed by cassiterite, scheelite, synchysite (more rarely bastnaesite), arsenopyrite, and molybdenite. The final minerals precipitated are fluorite, calcite, quartz, sericite, hematite, chalcopyrite, pyrite and galena (Pollard *et al*, 1991).

- Pipe orebodies: The third type of mineralisation is that of a series of cassiterite-bearing pipe orebodies that occur in localised groups forming interlinked systems. The pipes exhibit large variations in plunge and azimuth and range from circular to highly irregular in cross section. The pipes are found in both the Bobbejaankop and Lease granites, but do not extend into the overlying granophyres. The pipes have an outer zone rich in quartz and tourmaline enclosing an inner zone rich in feldspar, sericite and / or chlorite. In some pipes fluorite, quartz, calcite and sulphides occupy the central portion. The majority of the pipes are not localised by fractures (Pollard *et al*, 1991).

The granites and all mineralisation styles are crosscut by subvertical veins of several orientations. They are composed mainly of quartz, fluorite and calcite with minor chlorite, hematite, chalcopyrite, galena and sphalerite. They are late-stage features not directly related to mineralisation.

Pollard *et al* (1991) recognised three types of inclusions at Zaaiplaats. These are:

- Type I inclusions: These are two- and three-phase inclusions that contain carbon dioxide. They have been observed in quartz from the Lease and Bobbejaankop granites, quartz from the marginal pegmatite, and early cavity-filling quartz from the disseminated mineralisation. In most cases they occupy healed fractures and thus appear to be secondary.

- Type II inclusions: These inclusions contain H_2O-rich liquid, a small vapour bubble, and up to six different solid phases. Several subtypes are recognised on the basis of the assemblage of solid phases. The three major phases are halite, sylvite, and Fe chloride. Other minor phases include tiny unidentified, opaque, birefringent and nonbirefringent solids. These inclusions have been observed in quartz from the Lease and Bobbejaankop granites, quartz from the marginal pegmatite, and early quartz from cavities in the granites.

- Type III inclusions: These inclusions contain liquid, a small vapour bubble (approximately 5 vol. %) and minor solid phases similar to those observed in type 2 inclusions. They have been observed as primary inclusions in quartz, fluorite and calcite from a cavity in the pegmatite, late quartz from cavities in the disseminated mineralisation zone, quartz and calcite infill from the central portion of one of the pipes, and quartz from late-stage veins.

Pollard *et al* (1991) report that the results from their study are similar to those obtained by Ollila (1981).

Pollard *et al* (1991) report that the dominant fluid type in early hydrothermal minerals at Zaaiplaats is a high-temperature, high salinity solution represented by type 2 inclusions. There is a progressive decrease in homogenisation temperature determined by dissolution of solid phases from a high of 596° C in granite and early cavity-filling quartz to a low of 160° C in later cavity-filling quartz and fluorite. At the same time, there is a change from inclusions containing several solid phases (e.g. Fe chloride, halite and sylvite) to inclusions containing halite solids (± the minor unidentified phases).

Inclusions which homogenise at less than 200° C are dominated by type 3 (liquid-vapour) inclusions, which occur in late infill quartz, fluorite, and calcite from cavities in granite, pegmatite, pipes and in vein quartz. Total salinities in NaCl equivalent weight percent range from 15 to 68 percent, and are considered as minimum estimates due to the presence of additional salts in solution. Type 2 and 3 inclusions form part of a continuous evolution from high-temperature, high salinity fluids to lower temperature, moderate salinity fluids occurring in later minerals.

At Zaaiplaats the Bobbejaankop granite intruded relatively impermeable granophyre, and the evolution of the magmatic fluid phase, which formed the miarolitic cavities, was not associated with extensive hydraulic fracturing, so that the hydrothermal fluids were largely confined within the pluton. Due to the disseminated nature of the mineralisation, its confinement within the granites, and the progressive decreases in temperature and salinity of the hydrothermal fluids, the hydrothermal system is a good approximation of the closed-system model, where fluids are continuously recycled within the pluton causing extensive alteration. Thermodynamic modelling of hydrothermal transport and deposition of tin indicates that in rock-buffered systems, such as Zaaiplaats, more than 99 % of the initial tin in solution will be precipitated above 400° C (Pollard *et al*, 1991).

Early fluid inclusions contain solid phases including halite, sylvite and Fe chloride and homogenise at temperatures up to 600° C. This fluid evolved to lower temperatures and salt concentrations during precipitation of cavity, pipe and vein filling minerals. An H_2O - NaCl - CO_2 fluid was trapped as primary inclusions in quartz from the Bobbejaankop pipe, and as rare secondary inclusions in granite quartz and early cavity-filling quartz. Homogenisation and compositional data for these inclusions are consistent with fluid immiscibility at temperatures around 350° C and lithostatic pressure of about 1250 bar. It is possible that the CO_2-bearing fluid played a role in the early stages of pipe formation. At the same time that the granites were undergoing pervasive alteration, the saline fluids precipitated ore and gangue minerals in cavities and pipes. A progressive decrease in temperature from around 600° to 200° C, accompanied by a decrease in salinity from 68 to 15 equiv. wt percent NaCl is observed from fluid inclusion studies.

7.4.2 The Rooiberg Tin Deposits

The Rooiberg Tin deposits are situated within the Rooiberg Fragment in the western lobe of the Bushveld Complex. The continental shallow marine sedimentary and volcanic rocks of the Transvaal Sequence, which constitute the Fragment, were deposited on the Archaean Kaapvaal Craton in an intra-cratonic, graben-controlled basin. The roughly triangular-shaped fragment is surrounded by granophyres of the Rashoop Granophyre Suite and by granites of the Lebowa Granite Suite, the latter being clearly intrusive (Rozendaal *et al*, 1986).

The Rooiberg tin deposits are stratabound and classified as conformable or unconformable according to their geometric relationship with the bedding. Conformable mineralisation includes pockets, bedding-plane mineralisation, bedded lodes, and bedding-plane related stringers. Pocket-type mineralisation refers to bedding-plane and fracture controlled, cassiterite-bearing, irregularly shaped nodules. Bedding-plane mineralisation is defined as disseminated cassiterite dispersed within sheet-like bodies that tend to lie parallel to the bedding.

Unconformable ore bodies tend to occur as steeply dipping lodes that strike parallel to the major fracture directions. The prevailing ore assemblage is: cassiterite, pyrite, chlorite, tourmaline and carbonates associated with varying amounts of magnetite, hematite, chalcopyrite, quartz and potassic feldspar. The close spatial association between bedded lodes and steep fractures is obvious in all the mines (Rozendaal *et al*, 1986).

Ollila (1981) performed number of heating and freezing runs on inclusions from the Leeuwpoort Mine, south of the Rooiberg Mine, in the Rooiberg area. He described the inclusions as moderately saline with liquid and vapour phases that homogenise to a liquid or a vapour phase. The inclusions were found in quartz of the cassiterite-bearing bedded lodes. In these lodes cassiterite is usually associated with magnetite, hematite, pyrite and chalcopyrite with quartz and ankerite being the common gangue minerals (Ollila, 1981). Ollila (1981) recognised two generations of quartz, namely a clear euhedral older generation enclosed in a younger, milky generation. The fluid inclusions were taken from the older, clear quartz. Ollila (1981) reported that all the inclusions studied were undersaturated with regard to NaCl and other daughter minerals were not usually observed in them. Ollila (1981) suggested an estimated pressure correction of 500 bars for the homogenisation temperatures. He reported homogenisation temperatures from 134° to 220° C, with a pressure correction, at 500 bars, varying between 45° and 48° C. He reported salinities ranging from 13.9 to 22.0 equiv. wt % NaCl.

The tin mineralisation is considered to be derived from the underlying granites of the Lebowa Granite Suite. Extensive subvertical fracturing, related to the intrusion of the acid phase of the Bushveld Complex, as well as volumetric shrinking of the crystallising granite, resulted in a tensional regime producing near-horizontal tension fracturing, and hence assisted the localisation of the ore bodies, particularly the conformable ore bodies (Rozendaal *et al*, 1986).

The Rooiberg Tin deposits represent an open system in which extensive faulting and fracturing of the sedimentary fragment allowed magmatic fluids from the underlying Lebowa Granite Suite to move up and make use of the prevailing fracture system in the movement of the mineralising fluid and the precipitation of ore. In this regard the

Zaaiplaats and Rooiberg tin occurrences represent two end members of a whole range of mineralisation styles and settings possible in the granites and associated roof rocks of the Bushveld Complex.

7.4.3 Evidence for Fluid mixing - The Spoedwel Copper Mine

Freeman and Robb (1995) have reported on fluid inclusion studies that have illustrated that there are at least three episodes of ore precipitation. The first episode of mineralisation, typified by the Zaaiplaats tin deposit, occurred at relatively high temperatures (> 600° C to 400° C (Pollard *et al*, 1991, McNaughton *et al*, 1993)), and resulted in the formation of orthomagmatic cassiterite and scheelite. Pollard *et al* (1991) recognised a progressive decrease in temperature from 600° C to 200° C, accompanied by a decrease in salinity from 68 to 15 equivalent weight percent NaCl and a decrease in $\delta^{18}O_{fluid}$ values from 6.4 to 1.4 per mil.

At lower temperatures (> 200° C), the mesothermal Cu - Pb - Zn assemblage was deposited e.g. the Albert Silver Mine and Spoedwel and Boschhoek Cu mines / occurrences to the northeast of the study area (Freeman and Robb, 1995). This later assemblage is associated with widespread secondary fluorite precipitation.
Robb *et al* (1994) recognised a third episode of mineralisation at the Albert Silver Mine post-dating the Cu - Pb - Zn assemblage, wherein a late assemblage of Fe - U - F was precipitated.

Freeman and Robb (1995) recognised a regional variation in the relative proportions of these three ore assemblages, with the northern and northwestern sectors of the Complex containing greater tin (e.g. the Zaaiplaats Tin Mine). The southeastern sectors, including the study area, however, are dominated by the mesothermal Cu - Pb - Zn assemblage (e.g. the Albert Silver Mine and the Spoedwel Cu deposit).

Freeman and Robb (1995) re-examined the Spoedwel copper mine in light of these new paragenetic assemblages. The Spoedwel Copper Mine is found to the northeast of the study area and to the west of Marble Hall. The mineralisation occurs in the upper portion of the Lebowa Granite Suite, and is hosted by de-silicified medium-grained brick-red granite, often referred to as an episyenite. The highest grade of mineralisation occurs at the contact between two granite varieties. Mineralisation and de-silicification occurred simultaneously, with excess silica expelled into the immediate hanging-wall, where it occurs as cryptocrystalline quartz veins (Freeman and Robb, 1995).

The first ore mineral to be deposited was cassiterite, forming the orthomagmatic suite. The main sulphide mineralisation occurred at a later stage and exhibits a paragenetic sequence of arsenopyrite, pyrite, galena, tennantite, sphalerite, chalcopyrite, bornite and chalcocite. The third and final episode of mineralisation resulted in covellite, hematite and fluorite precipitation (Freeman and Robb, 1995).

Freeman and Robb (1995) have classified the fluid inclusions according to the variation in phase proportions. Type 1 inclusions consist of two phases (liquid and vapour), and are subdivided according to the degree of fill by the vapour phase. Type 2 inclusions contain both liquid and vapour phases, as well as one or more solid phases. Type 3 and 4 inclusions are monophase liquid, and monophase vapour inclusions respectively.

Fluid inclusions containing any number of solid phases from a possible list of 11 minerals including halite, sylvite, $FeCl_2$, hematite, muscovite, 2 unidentified opaques and 4 other unidentified crystals, are associated with the more saline fluid populations, whereas fluid inclusions in fluorite rarely contain any solid phases (Freeman and Robb, 1995).

Homogenisation temperatures (T_h) for fluid inclusions in interstitial quartz and fluorite range from approximately 150° to 300° C. T_h values for vein quartz fall into two categories; 200 - 230° C for terminated quartz crystals lining fractures, and 160 - 193° C for secondary quartz overgrowth filling the remaining fracture space. The early quartz-hosted fluid inclusion populations have higher T_h values than the later populations hosted by fluorite (Freeman and Robb, 1995).

The early fluids are highly saline (27 wt.% eNaCl), and are hosted by interstitial quartz. This fluid population does not occur in fluorite, indicating that fluorite precipitation began at a later stage. The most saline fluids trapped in fluorite are moderately saline (14 wt% eNaCl). The fluids trapped in progressive crystal growth stages and in secondary trails are less saline, the Ca content decreases, and the presence of hematite and opaque daughter / trapped crystals becomes less common. The Ca-rich fluid inclusion populations have been associated with the second episode of mineralisation, whereas the inclusion populations with little or no Ca in solution have been related to the third pulse of mineralisation during which covellite, hematite and fluorite deposition occurred (Freeman and Robb, 1995).

Late stage quartz veins consisting of two generations of quartz have salinities of approximately 9 wt% eNaCl for the first generation, and salinities between 0.3 and 0.5 wt% eNaCl for the second generation (Freeman and Robb, 1995).

Using Raman spectroscopy, Freeman and Robb (1995) discovered the presence of nitrogen, methane, carbon dioxide, hydrogen sulphide and water in the fluids. The presence of nitrogen and methane in all fluid populations in interstitial quartz led Freeman and Robb (1995) to suggest the presence of a meteoric fluid component in the system.

The Spoedwel copper deposit has all three episodes of mineralisation preserved. Gangue minerals associated with each of the ore assemblages may give fluid inclusions, which could be used to determine the nature of the fluid during deposition of each episode.

Freeman and Robb (1995) proposed that due to the variable phase proportions in the fluid inclusions, the broad range of densities and salinities in single fluid populations, and the presence of methane and nitrogen in the fluids, th.. there may be a second fluid component in the system, namely of meteoric or connate origin, increasingly mixing with the changing magmatic fluid over time, and giving rise to the three different mineral assemblages observed.

In summary the early magmatic fluids have a high temperature (600° C or more) and a high salinity (68 wt % eNaCl). Cassiterite is precipitated at temperatures of above 400° C. At lower temperatures the fluid is less saline, and in open systems where meteoric / connate fluids c[illegible]cessed, fluid mixing begins, and precipitation of a Cu - Pb - Zn assemblage occurs at temperatures above 200° C. With time and progressive domination by meteoric / connate fluids a late Fe - U - F assemblage is deposited on the preceding assemblages. At this stage the hydrothermal fluids have a very low salinity, are nitrogen rich and are low temperature (< 200° C).

The high U, Th and K_2O capacity, particularly of late stage fractionates such as the Bobbejaankop granite, imparts a high heat producing capacity to the granites, such that hydrothermal fluid circulation may have continued for a few million years after crystallisation of the granite (McNaughton *et al*, 1993). This long lived hydrothermal fluid circulation is reflected in the complex and often extensive alteration assemblages associated with the mineral occurrences and deposits, such as the alteration assemblages at the Albert Silver Mine (e.g. Champion, 1970).

7.4.4 Fluid inclusion studies from the study area

General fluid inclusion petrographic studies were undertaken for some mineral occurrences in the study area. It was found that despite careful sampling, the rocks did not contain suitable inclusions, being either too small (less than 1 μm) or that the quartz was too milky and hence not suitable for petrographic observation of fluid inclusions. It was hoped that comparison of the fluid temperatures and compositions could be compared with fluid inclusion studies from other occurrences, such as those described above and from elsewhere in the acid rocks. However, general petrographic observations did help illustrate a few points, despite no microthermometric work being carried out or salinity or density determinations being made. Further work in this regard is required if the nature of the mineralising fluids responsible for the polymetallic mineralisation in the felsic rocks of the Bushveld Complex is to be understood.

The general observations are as such:

- In Bobbejaankop granite, the quartz contains abundant inclusions, often imparting a cloudy appearance to the quartz in some samples. This testifies to the high volatile content associated with these granites. Primary inclusions are two-phase with a vapour bubble occupying 15 % of the volume of the inclusions. The inclusions are found to have inconsistent liquid : vapour (L:V) ratios, with some being single phase and are typically 2 μm or less in size. These inclusions imply entrapment at relatively high temperatures in order to have such large vapour bubbles at room temperature and are compositionally simple (absence of daughter crystals). Secondary inclusions are very small, being typically 0,5 μm or less in size and are typically one phase, with minor two-phase inclusions observed, indicating fracture healing by lower temperature fluids.

- Inclusions from early tin dominated mineralising systems, such as the Rietfontein tin occurrence, have large primary inclusions, 10 μm or more in size and often with a vapour bubble occupying between 10 to 15 % of the inclusion volume. Halite and sylvite daughter crystals are observed in some inclusions. Secondary inclusions are smaller, typically 2 μm in size, and are mostly one phase with a small percentage having vapour bubbles occupying 10 to 15 vol. %.

- Mineral occurrences that are dominated by the second phase of mineral precipitation, viz. the (Cu) - Pb - Zn assemblage (Freeman and Robb, 1995), such as the Prins Anna structure and the Enkeldoornspoort occurrence, typically have monophase, very small primary and secondary inclusions. The secondary inclusions are generally smaller than the primary inclusions. Inclusions with vapour bubbles were occasionally seen, but the quartz from these occurrences was found to be very milky and unclear and hence hindered petrographic observations.

- Samples from the Albert Silver Mine, known to exhibit a large degree of fluid mixing (see Freeman and Robb, 1995), exhibit small (generally 1μm or less), primary inclusions which are typically one phase. Some exhibit vapour bubbles and some monophase inclusions have daughter crystals (sylvite?). Secondary inclusions are generally one phase with some exhibiting a vapour bubble (generally 15 vol. %).

- Early mineralisation, such as tin, and possibly molybdenum, mineralisation have fluids which would have been precipitated at high temperatures (large vapour bubbles), be highly saline and have complex compositions (halite, sylvite and other daughter crystals). With time and precipitation of later Cu-Pb-Zn mineralisation the temperatures of the fluids, and hence temperature of entrapment, dropped, giving rise predominantly to inclusions with one phase present. Minor fracture healing and entrapment of secondary inclusions trapped this lower temperature fluid. Later inclusions record fluids that were lower temperature (mostly monophase), less saline and compositionally simpler (absence of daughter crystals).

Simple petrographic observations have qualitatively recorded the more accurate, quantitative observations of other workers working on different deposits and in different areas of the felsic rocks of the Bushveld Complex. The observations thus point to a complex, but universal, system of fluid flow, mixing and mineral precipitation across the entire area of the felsic rocks of the Bushveld Complex.

7.5 Conclusions

The granites show a marked decrease in their Fe^{2+} ion concentration, with an associated increase in Fe^{3+} ion concentration, with increasing height in the granites. This reflects the transition from relatively unfractionated granites at depth, where grey hornblende granites dominate, to high level red biotite granites at higher crustal levels. The altered granites associated with mineral occurrences show a slight rise in Fe^{2+} and a large increase in Fe^{3+} and therefore a decrease in the Fe^{2+}/Fe^{3+} ratio with increasing height in the granites, reflecting an increasing degree of fluid mixing and deposition of a late oxidised assemblage of hematite - pitchblende and fluorite.

The fluids passed from high temperature (> 600° C), high salinity fluids (68 equiv. wt % NaCl), associated with orthomagmatic cassiterite and scheelite precipitation, to lower temperature fluids (> 200° C) associated with deposition of Cu - Pb - Zn assemblages, where some degree of mixing of the magmatic fluids with meteoric / connate fluids had begun. Low temperature (< 200° C), low salinity (approximately 15 equiv. wt % NaCl) fluids are associated with late stage nitrogen-rich fluids giving rise to precipitation of an oxidised assemblage of hematite-pitchblende-fluorite, thought to have been derived from a predominantly meteoric / connate fluid.

The alteration assemblages associated with the mineral occurrences reflect the temperature of metal deposition, but are often complex due to long-lived fluid activity and possible deposition of metals ranging from magmatic fluid dominated to meteoric

/ connate fluid dominated, with a large degree of fluid mixing occurring. Early stanniferous mineralisation is typically associated with propylitic alteration with associated phyllic alteration on the margins, whereas phyllic alteration becomes more predominant with increasing height in the granites and increasing degree of fluid mixing. Hematisation is found to become predominant in high level mineral occurrences, or where a long lived hydrothermal system has eventually become dominated by predominantly meteoric / connate fluids (e.g. the Albert Silver Mine).

CHAPTER 8

CONTROLS ON THE NATURE AND LOCALISATION OF MINERALISATION

8.1 Introduction

Numerous small, polymetallic, mineralised localities are known throughout the granites and related roof rocks of the Bushveld Complex. Many authors have studied the styles of mineralisation and possible origin of the major deposits. Abundant literature exists on the endogranitic tin deposits at Zaaiplaats (e.g. Strauss (1955), Coetzee and Twist (1989), Crocker (1986), McNaughton *et al* (1993), and Pollard *et al* (1991)), as well as the exogranitic tin deposits at Rooiberg (e.g. Leube and Stumpfl (1963), Rozendaal *et al* (1986)), and other deposits such as the Vergenoeg fluorspar mine (Crocker (1979)).

Few authors, however, have described the smaller mineral occurrences, and there have only been a few authors (e.g. Robb *et al* (1994)) who have attempted a generalised model for mineralisation in the acidic rocks of the Bushveld Complex. Field mapping, geochemical and petrographic studies have revealed a number of related and interactive factors which would appear to have had a major influence on the localisation, morphology and nature of mineralisation in the acidic rocks of the Bushveld Complex. As such, this chapter deals with these controls which include in situ fractional crystallisation, structural controls and other factors, such as supergene enrichment. Much of the chapter is a reiteration and summary of some of the points raised in previous chapters.

8.2 In Situ crystal fractionation

Authors such as McCarthy and Hasty (1976) and Groves and McCarthy (1978) have illustrated that the Nebo granite has undergone pronounced, in situ, fractionation, a feature that is particularly noticeable with respect to the distribution of the trace elements, such as Rb, Ba and Sr. Kleeman and Twist (1989) confirmed the sheet like nature of the Nebo granite and documented the variations observed within the granite sheet in proceeding from its base to its upper levels. The variations in the granites are:

- a change in colour upwards, passing from a grey hornblende rich granite upwards to a dark red, biotite-dominated granite
- Hornblende and plagioclase decrease in abundance, whereas biotite and K-feldspar increase in abundance. Quartz increases in abundance marginally.
- SiO_2 increases from 69 to 76 %, K_2O from 4,6 to 5,7 %; FeO decreases from 6 to 2%, TiO_2 from 0,4 to 0,1%, and CaO from 1,7 to 0,4%; while Na remains fairly constant (Kleeman and Twist, 1989).
- Rb increases while Ba and Sr both decrease. As a function of this the trace element differentiation index (TEDI) decreases from values of 5000 in the lower levels of the granites down to values of 100 and less in the upper levels (Walraven, 1986)(see Chapter 5).
- The upper part of the Nebo granite frequently contains dykes and sills of light-pink aplitic granite that may contain lenses of pegmatoidal material. This aplite, called the Klipkloof granite by numerous authors, is more abundant near the top of the Nebo granite, where it exhibits TEDI values of less than 10.
- The deep red Bobbejaankop granite that is characterised by coalesced, linked chains of quartz along with deep red K-feldspar grains, occurs at the top of the Nebo granite. It is similar, compositionally, to the Klipkloof granite, and would appear to be a near end product of fractionation of the granitic magma that gave rise to the Nebo granite. This granite is often associated with mineralisation and is host to mineralisation at the Zaaiplaats tin mine.

Progressive fractionation gives rise to a magma which may force its way to higher crustal levels, and form a small plug of highly fractionated granite (Groves and McCarthy, 1978). This is the explanation for the origin of the Bobbejaankop granite, particularly at the type locality at Zaaiplaats.

The Klipkloof granite is derived from the very last magma remnants and would appear to have been filter pressed, and explains why it is often found as sills and dykes cutting across less fractionated, lower level granites. The Klipkloof granite would also carry a certain amount of exsolved H_2O fluid with it, and this would give rise to pegmatites which are often found associated with the Klipkloof granite, such as at Zaaiplaats (Strauss, 1955). Naturally, the Bobbejaankop granite would also carry some exsolved H_2O fluid with it too. For this reason, the Bobbejaankop and Klipkloof granites, in addition to the upper levels of the Nebo granite, are highly prospective for base metal mineralisation in any exploration program.

8.2.1 Degree of fractionation of the granite plutons

From a compilation of TEDI values and their distribution the degree of fractionation of a granite pluton may be determined and correlated with field observations. From this the mineralisation potential of a pluton can be determined, as well as areas of possible greater exploration potential demarcated.

8.2.1.1 Kameelpoort pluton

The pluton to the north of Kameelpoortnek 218 JR (see folder) is relatively unfractionated but does have higher level granites (with lower TEDI values) near the margins. The area contains Klipkloof granite sills near the contact between the granite and granophyre. This area joins onto the barren Springbok flats area to the north.

8.2.1.2 Moloto pluton

Further south, the Moloto pluton is a relatively highly fractionated granite due to:

1. its domical nature due to the interaction of crustal warping in the area. The domical nature of the pluton has given rise to lower level granites been exposed toward the centre of the pluton (see Fig. 6.2), as indicated by TEDI values ranging from 80 to 134 (see Table 5.1). Granites toward the pluton margins have lower TEDI values (80 to 60, Table 5.1).
2. the presence of Bobbejaankop-type granite on Enkeldoorn 217 JR (see folder) along the margins of the pluton and near the granophyre contact on Zustershoek 246 JR. Bobbejaankop granite was found in the dump at the old tin workings on Zustershoek 246 JR indicating its presence beneath the granophyre hosting the mineralisation there.
3. the presence of minor tin occurrences (Enkeldoorn 217 JR and Zustershoek 246 JR)(see folder), indicating an inherent concentration of tin and incompatible elements in the pluton relative to the barren pluton to the north. However the tin concentrations are low compared to more economic tin areas such as Zaaiplaats (Lenthall, 1972a).

8.2.1.3 Verena granite pluton

The Verena Granite is also a relatively highly fractionated pluton. Many workers have considered the Verena granite to be a marginal facies of the Nebo Granite. This would seem to bear out due a number of factors:

1. its pink / red colour, indicative of deuteric alteration, as seen in granites near the top of the succession
2. its coarse porphyritic nature
3. the presence of a fine-grained apical phase in the centre of the pluton (on Roodepoortje 250 JR)(see folder and Fig. 4.1), and along the margins of the pluton, as well as the presence of both Klipkloof and Bobbejaankop type granite ear

Rhenosterkop on the farms Rietfontein 446 JR and Zusterstroom 447 JR (see folder and Fig. 4.1)

4. the presence of tin deposits (Rooipoort 441 JR and Rietfontein 446 JR), and base / precious metal mineralisation at the Albert Silver Mine (Roodepoortje 250 JR)(see folder and Fig. 6.1).

A TEDI contour diagram of the Verena granite pluton is given in Figure 8.1. The diagram indicates that the main coarse-grained portion of the pluton exhibits TEDI values in the 100s and less, with values decreasing toward a SE - NW trending area in the western portion of the pluton. In this area the fine-grained apical phase is found with values generally in the 100s. This confirms that the fine-grained phase is a lesser fractionated phase of the granite that cooled relatively quickly. Directly beneath it, the granite underwent advanced levels of fractionation. In the vicinity of the fine-grained cap a number of small prospects including Rooipoort Sn and the Albert Silver Mine are found (see folder, Figs. 6.1 and 8.1).

Mineralisation has occurred where the upper levels of the granite are preserved. To the SE, along the same trend the granite also exhibits low TEDI values where Bobbejaankop granite, interspersed with Klipkloof granite, outcrops adjacent to Rhenosterkop (see Fig. 8.1 and Figure 4.1). This granite hosts tin mineralisation at Rietfontein 446 JR (see folder and Fig. 6.1), as well as minor fluorite mineralisation nearby on Zusterstroom 447 JR. Along this SE - NW trend, the granite is downwarped preserving higher level granites, as well as the fine-grained cap, and is mineralised. To the east, lower levels of the pluton are exposed in a similar trend. Here the granite is barren.

Further to the east toward the rhyolite contact, higher level granites are found along with minor mineralisation, as seen by the molybdenum mineralisation near the rhyolite contact on Hartbeesfontein 93 JS (see folder). Thus, despite the pluton being at a topographically similar height throughout TEDI values indicate that the granite is exhibiting upwarping and downwarping, probably as a result of major crustal structural features (see later).

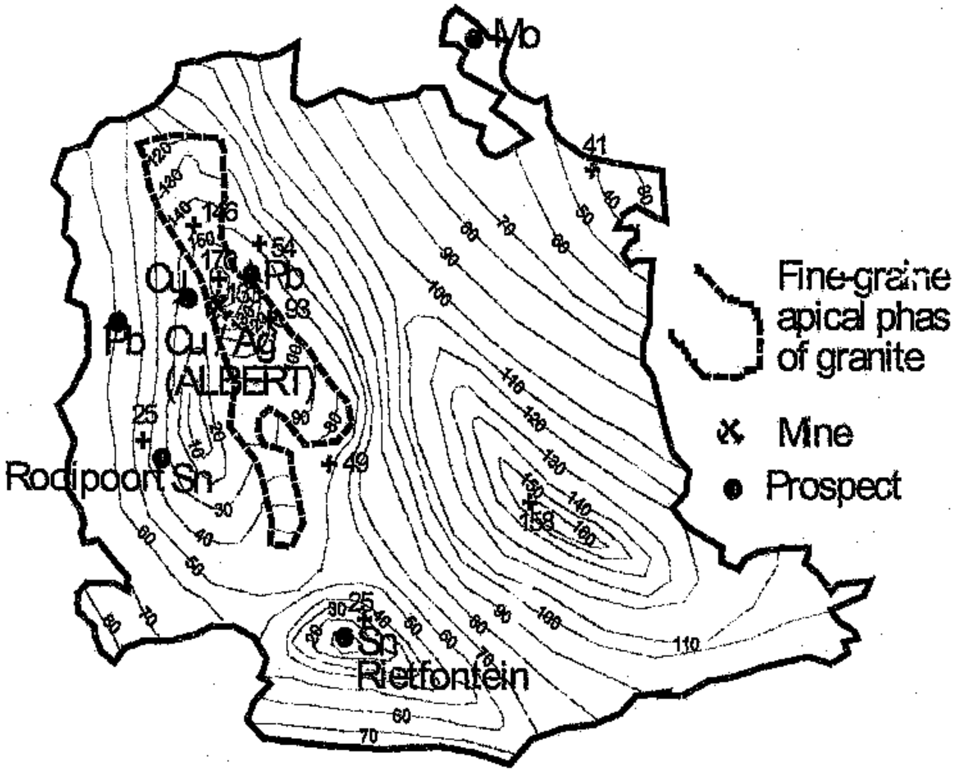


Figure 8.1 TEDI contours and mineral occurrences in the Verena pluton

8.2.1.4 Dennilton granite pluton

The Dennilton granite pluton stretching to the south of Dennilton is relatively unfractionated due to:

(a) its predominantly grey colour, compared to the deep red colour of higher level granites,

(b) Hornblende is also present along with biotite, particularly in the lower portions of the batholith. Plagioclase is found in greater abundance than in the other plutons.

(c) the scarcity of any base / precious metal deposits in the pluton. Moving further south, the granite takes on a redder appearance, and in some instances looks similar to the Bobbejaankop granite, particularly where it is in contact with or near the

Klipkloof granite. Hence, higher level granites are exposed further south at the pluton margins.

Clubley-Armstrong and Sharpe (1979) suggested that this region represents an upfaulted block falling between the Steelpoort and Wonderkop faults, which fits with the observations made above. The Moses River drains the Dennilton granite pluton creating a large peneplain to the north of the escarpment. It is worth noting that the granites north of the escarpment, such as in Sekhukuniland to the east, are barren. These granites are lower down in the granite sheet proposed by McCarthy and Hasty (1976) and so do not exhibit mineralisation.

8.2.1.5 Effect of erosion

Higher level granites are preserved along the margins of plutons by the surrounding granophyres and rhyolites that protect the margins from pervasive erosion. In the central regions of the plutons greater erosion occurs, as shown in Figure 8.2 (and Fig. 6.2).

The central portions of both the Kameelpoort and Moloto plutons are drained to the north by major perennial rivers causing the land to be flat and outcrop poor. The Kameelpoort pluton is drained by the Kameel River and its tributary the Sandspruit, and the Moloto pluton by the Enkeldoringspruit in the north, and the Hartebeestspruit draining west to the south (see folder, Figure 1.3 and Fig. 8.2). These rivers have affected the outcrop of the plutons, with the Kameelpoort pluton within a valley, with granophyre on either side forming higher country.

The Moloto pluton has been affected by the two rivers draining it. The Enkeldoringspruit has exposed lower levels in the north central region, leaving higher level Bobbejaankop granite to the east on the margins. To the south, the Hartebeestspruit flowing to the west has exposed lower level granites. Between the drainage basins of the two rivers lies a wedge of granophyre which stretches in towards the center of the pluton. To the south, away from the Hartebeestspruit, Pretoria Group sediments, Loskop Formation rocks and stratigraphically higher Waterberg and Karoo sediments are exposed.

Most of the major mineral occurrences in the area are situated near the margins of plutons where higher level granites are preserved after erosion by rivers have removed the higher level granites in the centers of the plutons. Thus the level of intrusion and erosion is important. The Moloto pluton, for example, has no major mineral occurrences near its center, except for the Prins Anna structure, but has a number of mineral occurrences along its margin. The Dennilton pluton has major mineral occurrences, such as Klipdrift, Boekenhouthoek and Houtenbek, along its margins at the escarpment.

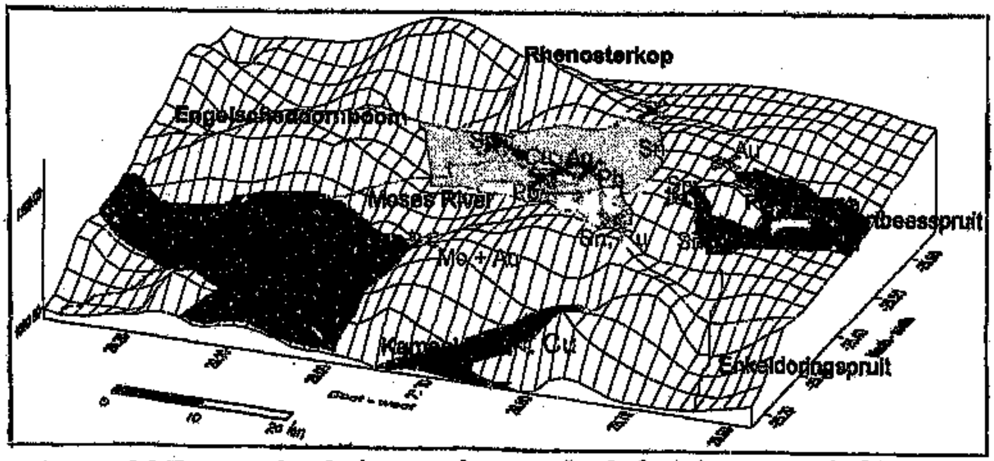


Figure 8.2 Topography, drainage and present level of erosion as a control to present-day localisation of mineralisation

The granites south of the escarpment are also at a higher level in the granite sheet than those to the north and east on the Springbok flats and Sekhukhuniland. Thus the present level of exposure of the pluton plays a major role in determining the economic potential of a granitic area and present-day localisation of mineralisation.

8.2.1.6 Mineralisation potential of the roof rocks

The Rashoop Granophyre Suite itself shows little to no potential of creating ore deposits from its own magmatism, and acts more as a repository for mineralisation derived from the underlying granitic suite (e.g. Zustershoek 246 JR). Granophyre overlying high-level highly fractionated granites may have mineralising fluids derived from these granites pass through it and give rise to mineralisation. This is the case at the Zustershoek Tin Mine, and the Hartebeestspruit and Boekenhouthoek Au occurrences.

The Rooiberg Group in the area also acts as a repository for mineralisation derived from the underlying granites. The possibility of massive volcanogenic sulphides in the Rooiberg Group does not seem feasible, probably owing to its anorogenic, within plate setting. Other likely ore forming processes in the Rooiberg Group could be related to the intrusion of the Rustenburg Layered Suite, which could have given rise to the introduction of ore bearing fluids into the Rooiberg Group (Schweitzer *et al*, 1995b).

8.3 Mineralisation in a vertical context

The various mineral occurrences and deposits within the granitic and associated roof rocks show a wide range of commodities and paragenetic sequences (see Chapter 6). Some occurrences are dominated by Sn, others by Cu and others by Pb and Zn and even Au. Different associations in the mineral occurrences come about due to the height of the mineralisation in the granites. In general terms the main commodities and parageneses found depend on where the mineralisation has occurred vertically and the extent to which fluid mixing has occurred. Thus Sn will dominate mineralisation lower down in the granites, whereas higher up Cu, followed by Pb and Zn will dominate, and Au and possibly Co will dominate in the very upper reaches and into the overlying roof rocks. An assemblage of Fe-U-F superimposes itself on the earlier assemblages with increasing degree of fluid mixing and height in the granites.

8.3.1 Height differences in mineralisation

TEDI values can be used to give an indication of the height in the granites of various mineral occurrences showing different metal associations and commodities. Mineralisation in each of the granite plutons may be examined with regard to TEDI values to examine if height in the granites influences metal associations. Mineralisation in the granophyres and rhyolites present a separate problem due to being derived from the underlying granites.

Four major mineralisation styles are recognised. They are:

1. Sn-dominated occurrences with lesser Cu, Pb and Zn. Mo may be important in certain occurrences. These occurrences are typically hosted in granites with a TEDI value of around 50. Propylitic alteration is the dominant alteration assemblage. This type is typically hosted in Bobbejaankop or Bobbejaankop-like granite.
2. Cu-dominated occurrences with subordinate Pb and Zn, but little Sn. The occurrences are hosted in granites typically having a TEDI value of around 40. Propylitic alteration is still predominant but there is a substantial amount of associated phyllic alteration.
3. Pb, Zn-dominated occurrences with lesser Cu. The precious metals may be present in substantial amounts. The host granite has TEDI values typically around 30. Phyllic alteration with minor hematisation occurs.
4. Au, Ag-dominated systems hosted in granites with TEDI values less than 20 or in the granophyric roof rocks. Hematisation is a dominant alteration assemblage. Co and Sb may be present in substantial amounts.

The mineral occurrences in the study area can generally be placed into one of these four categories as shown in Figure 8.3. The metals are ordered according to the accepted sequence of metal deposition from a hydrothermal fluid.

rock type or pluton	Type I	Type II	Type III	Type IV
	Sn - Mo - W - F - Cu - Pb - Zn - As - Sb - Bi - Ag - Au - Co			
Schrikkloof Formation		Graslaagte	Enkeldoornspoort	
Granophyre		Zustershoek		Hartebeestspruit Boekenhoutho
Moloto	Enkeldoorn		Prins Anna	
Verena	Rietfontein Rooipoort		Leeuwfontein north vein Albert	
Denilton (southern margins)	Klipdrift Mo			

Figure 8.3 The four types of mineralisation styles in the acidic rocks of the Bushveld Complex

The horizontal positions are just estimates, with the position determined by the abundance of the major commodities, as many of the mineral occurrences show a wide range of commodities. With increasing degree of fractionation and associated increase in height in the granites the mineralisation passes from type 1 to type 4 styles. This change in commodities is reflected by a change in the paragenetic sequence.

8.3.2 Paragenetic sequences

The paragenetic sequences at the individual deposits examined in the present study are:

- Rietfontein Sn: disseminated cassiterite
- Rooipoort Sn: cassiterite - fluorite (primary) - arsenopyrite (brecciated and broken up by later fluid) - chalcopyrite - fluorite (secondary)
- Enkeldoorn Sn: cassiterite - pyrite - chalcopyrite - sphalerite
- Zustershoek Sn: cassiterite - pyrite - sphalerite - siderite - hematite
- Klipdrift Mo - Au: molybdenite - pyrite - arsenopyrite - sphalerite
- Albert Ag: cassiterite? - pyrite - bornite - chalcopyrite - galena - sphalerite - arsenopyrite - tetrahedrite (argentiferous) - hematite / chlorite / fluorite
- Prins Anna: granophyre - quartz veining - brecciated - infilled by more quartz veining and massive hematite

- Hartebeestspruit Au: pyrite in quartz veins or assoc. with them, overgrown by chalcopyrite and later arsenopyrite
- Klipdrift Au: disseminated pyrite
- Boekenhouthoek Au: arsenopyrite
- possible overall paragenetic sequence in the granites: cassiterite - molybdenite - fluorite (primary) - pyrite - bornite - chalcopyrite - galena - sphalerite -arsenopyrite - tetrahedrite - hematite = pitchblende - fluorite (secondary)

Both spatial and temporal relationships have influenced the nature of the mineralisation, with at least three episodes of ore formation occurring. The first episode of mineralisation (typified by Rietfontein and Rooipoort Sn) occurred at relatively high temperatures (ca. 600° to 400° C)(Freeman *et al*, 1997), and resulted in the formation of orthomagmatic or magmatic fluid derived cassiterite and an early generation of fluorite. At lower temperatures (400°→ 200° C), where processes were essentially fluid dominated, a mesothermal Cu-Pb-Zn-As-Ag-Au assemblage was deposited (exemplified by the Albert Silver Mine). A third episode of mineralisation resulted in the formation of a Fe-U-F assemblage and is recognised at some of the deposits (e.g. Zustershoek Tin Mine and the Albert Silver Mine).

The extended nature of these three-stage paragenetic sequences are considered to reflect widespread mixing between an early fluid derived by H_2O - saturation of the granitic magma and a meteoric fluid, circulation of which was stimulated by the long-lived high heat-productive capacity of the Bushveld Complex, as well as exhumation of the metallotect.

Freeman *et al* (1997) provide further evidence to support this hypothesis. These include:

1. two major episodes of fluorite precipitation at certain deposits recognised by the use of cathodo-luminescence
2. the recognition of covellite overprinting of Cu-bearing sulphides along grain boundaries and microfractures. This overprinting is characteristic of retrograde

thermal processes and the imposition of an oxidising fluid, and not simply lower temperatures.

3. tourmaline veins and spheroids have been mapped, both in the study area and elsewhere in the granites, and are considered to form by the interaction of boron-rich, magmatically derived fluids with Fe-Mg-rich connate fluids.
4. the coexistence of hypersolvus (single feldspar) unmineralised and subsolvus (two feldspar) potentially mineralised granites are interpreted as being the products of meteoric water incursions.
5. fluid inclusion indicators and
6. stable isotope signatures of fluid inclusions which indicate at least two sources of carbon, and $\delta^{18}O$ and δD values which fall outside the range of purely magmatic fluids.

Thus in general the mineral associations change with height in the granites, or rather with increasing degree of interaction with meteoric or connate fluids. The early high temperature (ca 600° C) Sn - W assemblage was precipitated by orthomagmatic processes, as well as the circulation of magmatic fluids. With time, the granites cooled, and were subject to regional uplift and erosion. Fractures developed, or were reactivated, and acted as conduits for external fluids of meteoric and / or connate origin.

The late magmatic fluids, enriched in incompatible metals (and volatiles), interacted with the connate / meteoric fluid, of contrasting chemistry and possibly also metal-charged, resulting in the localised precipitation of a secondary, lower temperature (> 200° C) mineral assemblage (Cu-Pb-Zn-As-Ag-Au) in the zone of fluid mixing. As the external fluid component became progressively more dominant, the late Fe-U-F (>140° C) paragenesis formed. The extended paragenetic sequence in the acid rocks of the Bushveld Complex is adequately explained by a combination of orthomagmatic processes and sub-solidus fluid mixing as depicted in Figure 8.4.

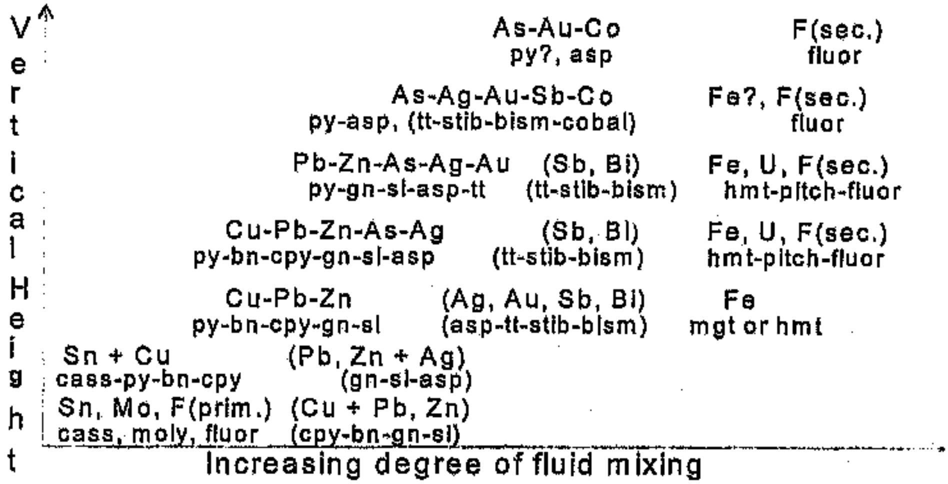


Figure 8.4 Metal associations and paragenetic sequences as related to height in the granites and degree of fluid mixing

8.4 Structural Controls

Mineralisation in the granitic rocks is greatly affected by structural controls. From large scale crustal lineaments that influence granite emplacement and form, to smaller scale structure such as faults, shear zones and jointing. The presence of permeable conduits and cap rocks will also influence mineralisation and its emplacement on the local scale.

8.4.1 Large scale structures

Two major crustal lineament orientations can be identified in and around the study area as shown in Figure 8.5. The first is the NE - SW trending Wonderkop fault with parallel trending Steelpoort fault to the southeast. This direction is itself semi-parallel to the Murchison lineament. The other is the SE - NW trending lineaments and faults parallel to the Laersdrif fault (see Lee and Sharpe,1986).

The Wonderkop / Steelpoort fault direction is predominant with the development of the Steelpoort fault in the southeast of the study area, and a major crustal lineament stretching from beyond Dennilton through the Makhutso granite and beyond Moloto to the southwest (see Fig. 8.5). The Laersdrif lineament expresses itself in a number of smaller faults and dykes. The two lineaments have influenced granite emplacement, local structure and localisation of mineralisation.

The Kameelpoort pluton intruded parallel to the Wonderkop fault lineament, and the Moloto pluton shows a slight elongation in its present-day shape in the same direction. The Verena and Makhutso plutons, however, show a SE - NW elongation, parallel to the Laersdrif fault lineament. The Verena and the Makhutso plutons were intruded at a later stage than the Kameelpoort and Moloto plutons, owing to the more fractionated nature of the Verena pluton and the younger age of the Makhutso granite. This may suggest that the Wonderkop fault lineament is older and deeper seated than the Laersdrif lineament. This would follow, as the Wonderkop fault lineament is parallel to the Murchison lineament, itself a long lived and deep-seated lineament (Cameron, 1971).

Large-scale crustal warping has occurred parallel to these lineaments (see Fig. 8.5). The Kameelpoort pluton is situated on an antiform parallel to the Wonderkop fault lineament (De Bruiyn, 1980). This antiform extends to the southwest, so that Kwaggasnek Formation rocks are exposed to the southwest of the pluton. The Moloto pluton lies at the intersection of the Wonderkop fault lineament antiform and a Laersdrif fault trending antiform, whose intersection gave rise to doming of this pluton (see Fig. 6.2).

The western half of the Verena pluton lies on a synform adjacent to Rhenosterkop, in a zone trending parallel to the Laersdrif lineament. Bobbejaankop granite on Rietfontein 446 JR and the fine-grained apical phase present on Roodepoortje 250 JR are preserved along this trend (see also Fig. 8.1). It is worth noting that the Bobbejaankop-like plug, with interdigitated Klipkloof granite to the east of Rhenosterkop, is along an extension of the Steelpoort fault which would pass directly through Rhenosterkop. This structure would have affected granite emplacement of these late stage differentiates, as well as fluid and volatile flow and hence mineralisation. A basin may possibly be developed in the vicinity of the Albert Silver Mine where the fine-grained apical phase has been preserved (see Fig. 8.5). Tensional fractures developed in an E - W direction in this portion of the pluton where it exhibits its greatest mineralisation. Directly adjacent to this trend is an antiform, around Wolvenkop 227 JS and Leeuwfontein 228 JS (see folder and Figures 8.5 and 8.1), where the Verena granite is domed preserving low-level granites which are barren.

The Makhutso granite falls along this antiform and could explain why the Makhutso granite, a relatively unfractionated granite with Sn-dominated mineralisation, is exposed in this area. Rhenosterkop itself lies at the intersection of an extension of the Steelpoort fault and a lineament parallel to the Laersdrif lineament (see Figure 8.5), and hence its emplacement as a volcanic vent at a structurally weak spot in the crust is reasonable (Twist, 1983).

The Rooiberg Group, to the northeast of Verena, on the farms Engelschedoornboom 95 JS and Rietfontein 90 JS outcrops at the intersection of two antiforms (see Fig. 8.5) creating a domical feature, reflected by the high flat topography in the area. The low grade mineralisation within the agglomerate layer comes about due to this doming and subsequent upwelling of fluids along this permeable conduit.

Doming has strong influences on mineralisation due to the stresses set up due to doming. Doming is conducive to hydrofracturing and the subsequent movement of mineralising fluids along the fractures and / or shear zones thereby generated.
As a direct consequence of doming the pluton fractures radially due to high tensional forces along the apical regions of the dome. The Moloto pluton underwent tension so as to give rise to the dominant N - S shear zones and faults present in the pluton, and which are host to mineralisation. This tensional stress propagated into the overlying roof rocks and surrounding country rocks, particularly along the eastern margin. It is

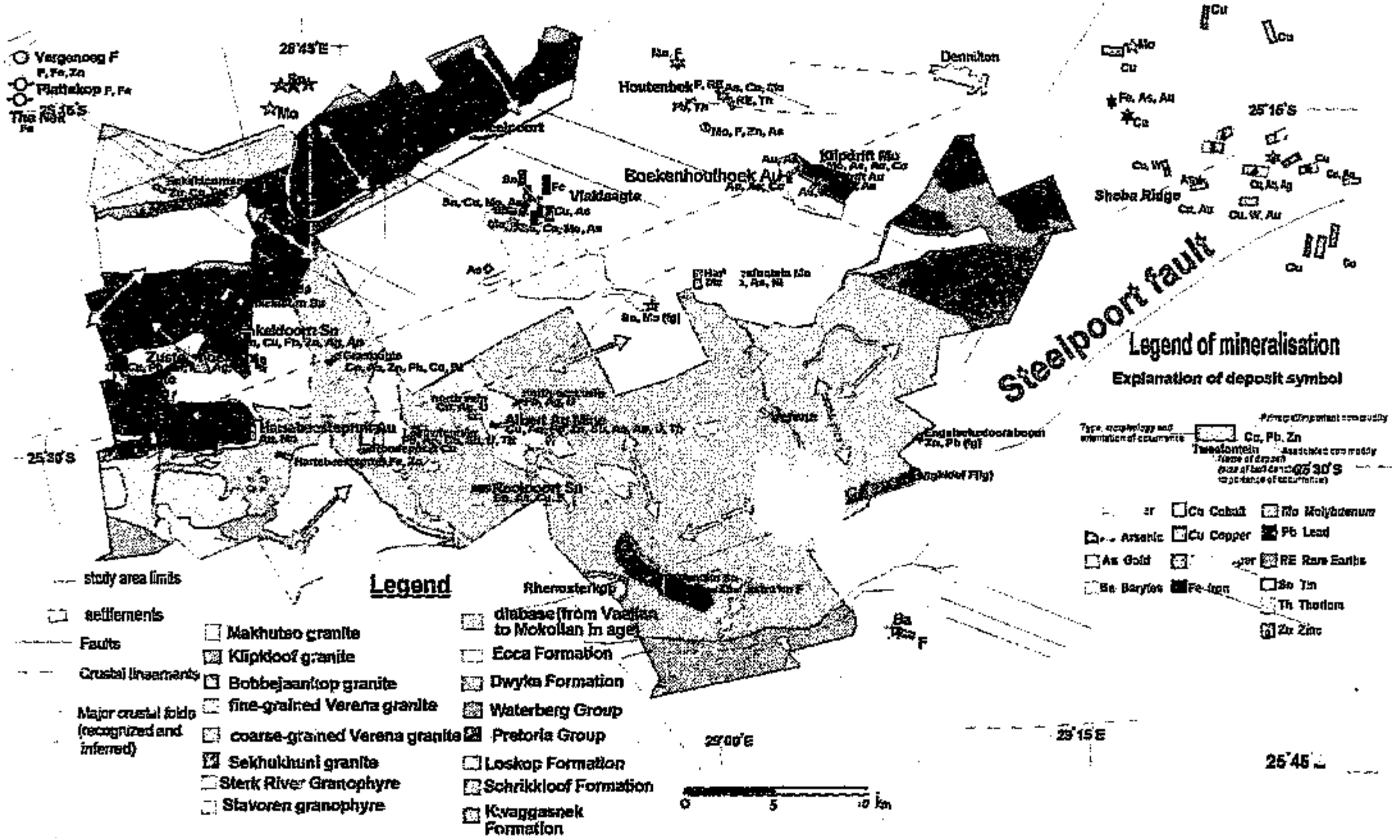


Figure 8.5 Large scale structure of the study area and its influence on mineralisation

significant that the Prins Anna structure lies almost directly in the centre of the pluton at the point of intersection and interaction of the two antiforms.

A point worth noting is that the Wonderkop lineament influences the western portion of the study area, whereas the Laersdrif lineament influences the eastern portion of the study area. This would appear to be purely a function of distance away from the major faults that cause the lineaments. The Laersdrif lineament would appear to have affected the position of the escarpment in the eastern to central portions of the study area, which runs in an approximately ESE - WNW direction, parallel to this trend. The escarpment to the west on Zandspruit 189 JR, Melkhoutfontein 183 JR and Zaagkuilfontein 204 JR is developed in a NE - SW direction, parallel to the Wonderkop fault.

In terms of mineralisation, the major structural features have influenced the localisation of mineralisation. In the Kameelpoort pluton, the Kameelpoort Cu - F occurrence has an orientation parallel to the Wonderkop lineament and the trend of the pluton (see Fig. 8.5). The Enkeldoornspoort Zn - Cu occurrence is found along a fault, parallel to the Laersdrif lineament, which extends northwestwards to the Vergenoeg F mine.

The Enkeldoorn Sn field, the Zustershoek Tin Mine, the Prins Anna structure and the Graslaagte Cu - Zn occurrence all fall along or near a major NE - SW trending lineament, parallel to the Steelpoort fault (see Fig. 8.5). The Hartebeestspruit Au occurrence falls on a smaller lineament parallel to the Steelpoort fault lineament, whereas the Hartebeestspruit Fe - Zn, the Roodepoort Cu and the Leeuwfontein Pb - Ag occurrences fall off, but still parallel to, it. The Au and Mo occurrences on Klipdrift 62 JS and Boekenhouthoek 61 JS fall along the intersection of the major NE - SW lineament running through the centre portion of the area, and a lineament parallel to the Laersdrif lineament (see Fig. 8.5). Even other mineral occurrences outside the study area exhibit the major influence of structural control. The predominantly copper mineralisation of Sheba Ridge (see Fig. 8.5) falls along the Steelpoort fault, whereas the Vergenoeg Fe-F mine to the northwest of the study area has been influenced by the Laersdrif lineament (see Fig. 8.5)

8.4.2 Minor structures

Quartz veining, faults, shear zones and jointing all give an indication of the tectonics subsequent to emplacement and / or extrusion of the felsic rocks. Due to lack of good exposure in many areas a detailed study of structural features was not possible, but some general observations about some of the granitic plutons, as well as overall trends, can be examined from the data collected. These minor structures also influence mineralisation, being either host to or created by the mineralising fluids, or affecting the orientation and morphology of the mineralisation. No distinction was made between systematic and non-systematic jointing, and so this will influence the interpretations to some extent.

A rose diagram for the Kameelpoort pluton, combining both veining and joint orientations is given in Figure 8.6 a). Three major orientations are present in the structural features of the pluton. Both jointing and veining have been influenced by the Pretoria- Zebediela anticlinal lineament oriented at 036° (Clubley-Armstrong and Sharpe, 1979). The main axis of the anticline, along which the pluton is developed, is along this orientation, indicating a major influence in this part of the study area.

Veining has been influenced by the Murchison lineament at 056° (Clubley-Armstrong and Sharpe, 1979). The Steelpoort fault orientation, oriented at 047° (Clubley-Armstrong and Sharpe, 1979) appears to have had little to no influence on the local structure in the pluton. The Laersdrif fault lineament (122°) has influenced veining, jointing and brecciation orientation in the pluton, and indicates its importance in influencing the structure of the eastern Bushveld Complex.

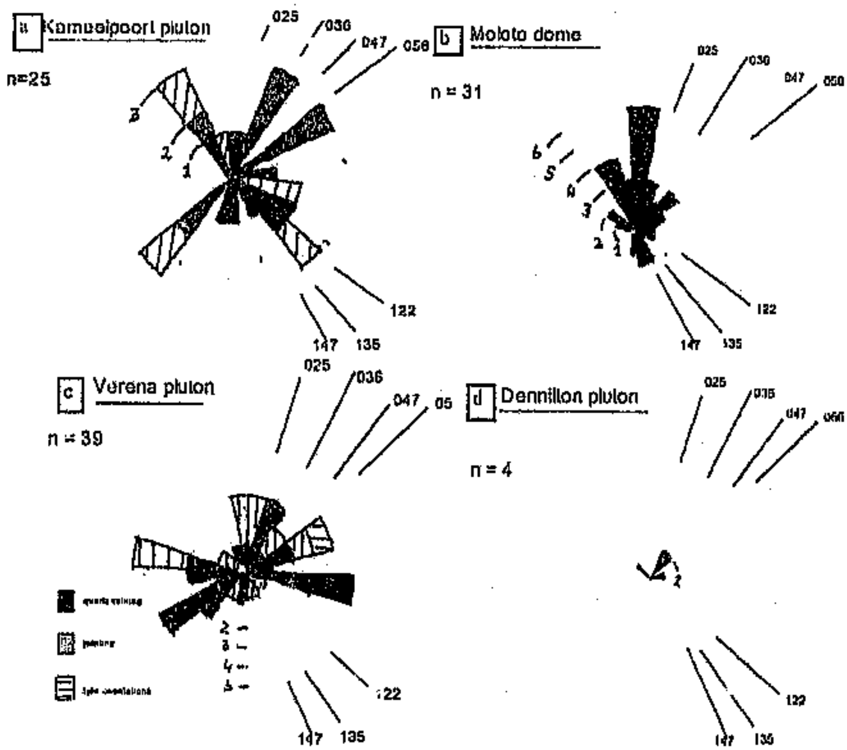
The Thabazimbi-Murchison lineament, and possibly the Steelpoort and Wonderkop faults, are long-lived deep seated structures which have undergone numerous periods of reactivation during the development of the Kaapvaal craton, so that these orientations, including, possibly, the Laersdrif fault were responsible for the shape, extent and deposition of the Transvaal Supergroup as well as for the Bushveld Complex (Hartzer, 1994).

The rose diagram for the Moloto pluton is given in Fig. 8.6 b. Here the dominant orientation is approximately 005° indicating the effect of the interaction of two antiformal structures giving rise to the domical nature of the pluton, and creating tensional fractures in the pluton. Most of the mineralisation in the pluton is hosted in shear zones or veins along this orientation. The Murchison / Steelpoort lineaments have influenced veining in the dome, along with minor vein orientation along the Laersdrif lineament orientation. Another orientation falling between 150° and 165° cannot be tied in to any major lineament, and may indicate some later tectonic influence on this pluton.

The Verena pluton, as shown in Figure 8.6 (c), has three major orientations of its local structural features. The dominant orientation affecting jointing, dyke orientation and veining is parallel to the Murchison trend, with the Steelpoort fault secondary to this trend. Veining and jointing falls in the 090° to 105° orientations, and indicates the effects of tensional forces set up due to basin development in the vicinity of the Albert Silver Mine. A minor orientation is also found developed in the interval 345° to 360°. Whether this is due to some influence from the updoming of the Moloto pluton or some secondary tectonic effect is unclear.

The Dennilton pluton, as shown in Figure 8.6 (d), has very few readings due to the small extent of this pluton in the study area. However orientations of veining in this pluton indicate that they have been strongly influenced by the Murchison / Steelpoort orientations, as well as the Laersdrif orientation to a lesser extent.

Hence major crustal lineaments and large scale crustal features have influenced the localised structure in the plutons. Scogings (1991) noted that north-east trending breccia veins, parallel to the Wonderkop / Steelpoort faults, tend to be barren.



025° = Great Dyke Trend
036° = Pretoria - Zebediela anticline
047° = Steelpoort fault
056° = Murchison trend
122° = Laersdrif fault
135° = Amsterdam lineament
147° = Kraaipan trend

Figure 8.6 Rose diagrams indicating the orientation of linear structure in each of the plutons of the study area.

It may be suggested that veins parallel or sub-parallel to the Laersdrif lineament tend to be more subject to mineralisation, but there is no real evidence to confirm this.

8.4.3 Structure as host to mineralisation

Structural features play an important role in the passage of mineralising fluids and in the deposition of metals. Pre-existing faults, shear zones, breccias and other features, such as agglomerate horizons are conducive areas to fluid flow and can act as conduits and often hosts to mineralisation. This is particularly the case in the roof rocks, which host mineralisation derived from the underlying granites. The Zustershoek Tin Mine and the Hartebeestspruit Au occurrence are hosted in shear zones in granophyre developed due to tensional forces created in updoming of the Moloto pluton and which propagated into the surrounding granophyre.

The Prins Anna structure, in its southern limb, makes use of an agglomerate horizon in its propagation, as it offer less resistance to fluid flow and is a permeable conduit. The Enkeldoornspoort Zn occurrence is found at a site of ' \ociation, along a major fault, and which acts as an ideal conduit to fluids derived from depth.

The Albert Silver Mine and its related veins owe their origin to shearing in the pluton, and the passage and interaction of magmatic and meteoric fluids along these conduits over an extended period. Mineralisation at the Albert Silver Mine is also influenced by the presence of a fine-grained cap rock that has caused welling of fluids beneath it to form a possible stratiform high-grade ore-body (Robb *et al*, 1994). Stratiform mineralisation was reported by Champion (1970), who also considered the possibility of fluid ponding beneath the fine-grained apical phase of the Verena granite.

The agglomerate layer in the western portion of the study area, which marks the boundary between the underlying Kwaggasnek and the overlying Schrikkloof Formation of the Rooiberg Group, contains low-grade mineralisation along a strike-length of 40 km (Martini and Vorster, 1994). Here upwelling of fluids along this permeable conduit seems likely, particularly in view of the fact of the presence of a domical feature underlying the Rooiberg Group in this area, which would allow upwelling of fluids from the underlying granite into the overlying lithologies. Mineralisation is low-grade, which confirms fluid flow from a generalised, not specific, source.

Permeable horizons are, therefore, an ideal conduit for mineralising fluids, and an important feature to be examined in any exploration program.

8.5 Other Controls

Other factors that have an influence on the nature and localisation of mineralisation include supergene enrichment, source of fluids, and timing and extent of mineralisation. Some of these factors are directly related to the previously mentioned factors, but in themselves they can be of significance.

8.5.1 Supergene enrichment

Supergene enrichment plays an important role in determining the grade and economic potential of any deposit \ occurrence. In the case of the Albert Silver Mine, supergene enrichment increased the silver content of the ore, and made the occurrence a profitable deposit worked at the turn of the century. Champion (1970) reported on the presence of numerous supergene minerals e.g. malachite, azurite and the rare Cu-As mineral metazeunerite, as well as secondary native silver.

The Albert Silver Mine has ideal conditions for supergene enrichment, namely:

- low rates of erosion, due to the slowly, eroding landscape of the resistant granitic terrain.
- the low, undulating terrain that allows a slow-flowing dendritic drainage pattern to be developed
- the area is situated in an area of relatively low rainfall, so that meteoric fluids have ample time to percolate downwards and interact with the ore body.
- the Moses River which flows directly through the gossanous vein, and hence over the fault which gave rise to propagation of the mineralising fluids.

Champion (1970) reported that supergene enrichment was greater in the western portions of the lode in the immediate vicinity of the Moses River. Thus supergene enrichment contributed to make the Albert Silver Mine the largest and most important deposit in the study area. Other occurrences with suitable factors could be affected by supergene enrichment making them economically important whereas they might not have been of major significance otherwise.

8.5.2 Other factors

8.5.2.1 Rate of erosion

Probably the most important factor is the rate of erosion and exhumation of the granitic rocks. Low erosion rates, along with extent and depth of faulting, will influence the extent of meteoric fluid interaction, and hence the nature and paragenesis of the mineralisation.

The Enkeldoorn tin field and the Zaaiplaats Tin Mine provide ideal examples of this factor. The Zaaiplaats Tin Mine, located at a higher crustal level is dominated by the oxidised, hematitic assemblage, whereas the nearby granite-hosted Enkeldoorn tin field, albeit similar, shows no late paragenesis, and contains less Cu mineralisation. Here erosion of the Moloto pluton exposed the Enkeldoorn tin field at a late stage in the mineralising event so that the oxidised meteoric derived assemblage is virtually absent, whereas the Zaaiplaats Tin Mine was subjected to a longer period of meteoric fluid influence.

8.5.2.2 Source of fluids

The anorogenic nature of the Bushveld granites influences the nature of the mineralisation associated with them, just as S-type granites are known hosts to Cu, Mo and Au mineralisation, and I-type granites host to Sn, W and U mineralisation.

8.6 Conclusions

A number of interrelated factors have played a part in influencing the nature and localisation of mineralisation in the felsic rocks of the Bushveld Complex.

Fractionation of the granitic magma from its base upwards, and possibly from its margins inwards, has led to more highly fractionated granites in the upper levels of the granites which are more subject to mineralisation. Within an individual pluton areas of greater fractionation and hence greater mineralisation potential can be demarcated.

The mineralisation style changes with height in the granites with Sn-dominated, predominantly magma-derived mineralisation occurring at lower levels and giving way to Cu- through to Pb, Zn-dominated mineralisation higher up. This change comes about not only due to the increased fractionation of the granitic magma and changes in the characteristics of the mineralising fluid but also due to an increasing degree of fluid mixing between the changing magmatic fluid and a meteoric / connate fluid (Freeman et al, 1997). Where the meteoric / connate assemblage predominates a late-stage oxidised assemblage is found superimposing itself on the earlier assemblages.

Major crustal structure has influenced granite emplacement, local small-scale structure and the passage of mineralising fluids. Faulting, and crustal warping has occurred parallel to two major crustal lineaments which have greatly influenced the eastern lobe of the Bushveld Complex.

Other factors, such as supergene enrichment and the rate of erosion have lesser effects on the nature of the mineralisation.

CHAPTER NINE: CONCLUSIONS

9.1.1 The Rooiberg Group

Partial melting of the lower crust occurred during late Pretoria Group times and generated an acidic magma which gave rise to the felsic rocks of the Bushveld Complex. The oldest felsic rocks in the study area are those of the upper Rooiberg Group subdivided into a lower, more massive, Kwaggasnek Formation, which was extruded under quiet, passive conditions, overlain by the flow-banded, agglomeratic and tuffaceous horizons of the upper Schrikkloof Formation.

The prominent Union Tin Member agglomerate horizon, separating the two formations, represents a change in the style of volcanism from more passive, for the Kwaggasnek Formation, to more explosive and active for the Schrikkloof Formation. Subaerial volcanism with periods of subaqueous sedimentation are represented by the agglomeratic horizons with occasional sedimentary intercalations. Sedimentation began to be more dominant during Loskop Formation times giving way to the sandstones, shales and conglomerates of the overlying Waterberg Group.

9.1.2 The Rashoop Granophyre Suite

The Rashoop Granophyre Suite was formed hypabyssally to the volcanics of the Rooiberg Group to which it is related. The bulk of the granophyres formed by hypabyssal crystallisation of the felsic magma beneath the rhyolitic cover, with metasomatism and recrystallisation of volcanics and roof sediments being locally important elsewhere.

9.1.3 The Lebowa Granite Suite

Continued fractionation of the felsic magma gave rise to a granitic magma that intruded into roof rocks with which it is genetically related. Progressive fractionation of the granitic magma gave rise to the granites, passing from grey hornblende rich granites towards the base upwards into pinkish red biotite-rich granites in the upper levels, which are likely to be mineralised, having a greater concentration of the incompatible base metals. If there was incremental emplacement of successive sheets or dykes of granite, as may be the case (see Section 7.3), each pluton, possibly differentiated to varying degrees, underwent its own differentiation from more primitive rocks at its base to more evolved granites near the top and centre of each pluton. The Bobbejaankop granite, a deep red, coarse-grained K-feldspar rich granite, which is often host to or associated with mineralisation, particularly tin, is thought to represent one of the last remnants of magma to crystallise.

The Klipkloof granite, a pinkish brown aplitic granite, is considered to represent the very last remnants of magma to crystallise, and is found as dykes or sills cutting across the main Nebo granite sheet, as well as being associated with the Bobbejaankop granite.

The Makhutso granite, a grey biotite rich granite in the central portion of the study area, represents the last pulse of felsic magmatism of the Bushveld Complex, and was derived from renewed partial melting of the lower crust and intrusion of this less fractionated granitic magma into the older, more fractionated Nebo granites.

9.1.4 Geochemistry as an aid to exploration

Trace elements such as Rb, Ba and Sr are useful indicators of the amount of fractionation a granitic magma has undergone. Walraven (1986) defined the trace element differentiation index (TEDI) as Ba × (Sr / Rb), with which he determined the amount of fractionation various granites had undergone. Ba and Sr, being compatible elements, decrease in concentration with increasing degrees of fractionation whereas Rb, being incompatible, increases in concentration with increasing degrees of fractionation.

As such the granites show high TEDI values toward their base, decreasing in value upward, to the most fractionated Bobbejaankop and Klipkloof granites, exhibiting low TEDI values of less than 50. Hence the most highly fractionated granites, and those most likely to be mineralised could be demarcated. TEDI values of altered rocks which differ substantially from the surrounding rocks may indicate the passage of mineralising fluids through the rock, which would affect the Sr / Rb ratio, and hence the TEDI value. Hence TEDI values can be useful exploration tools for mineralisation.

Granites with an average TEDI value of 50 or less are more likely to be mineralised. The granite plutons in the study area are all relatively highly fractionated (TEDI generally less than 100), with the highest level granites being preserved along the margins of the plutons at its contact with overlying granophyre or volcanics. Mineralisation is preferentially found at or near the margins of the plutons, or where high level granites have been preserved, for e.g. at the Albert Silver Mine.

9.1.5 Controls on mineralisation

There are a number of controls on mineralisation in the acid rocks of the Bushveld Complex. Localisation and the nature and morphology of the mineralisation are a combination or interaction of some, if not all, of these factors.

9.1.5.1 In situ crystal fractionation

Crystallisation proceeded from the outer periphery of the sheets, causing a more highly fractionated granite and a volatile-rich phase of the magma, rich in metals and other incompatible elements, to collect at the more central cupolas or roof highs in the centre of the lobes of the Complex (Crocker, 1979). These volatile-rich phases, which streamed upwards from the neck or point of origin of the intrusive sheets, and the highly fractionated magmas are in evidence in the central portion of all three lobes of the Bushveld Complex. As the study area is located near the south central portion of the eastern lobe of the Bushveld Complex, with that to the south hidden under younger cover, this may explain the numerous small polymetallic mineral occurrences in the area.

The volatiles suppress the crystallisation temperature of the granite close to the roof zone, causing a change in the predominant mafic mineral, perthitisation of the feldspars, chloritisation of biotite and release of iron as magnetite from the K-feldspar lattices, which upon oxidation to hematite gives rise to the red colouration of the granites associated with mineralisation. Centripetal crystallisation also initiates, in some instances, radial hydrofracturing along which the metal-rich volatiles move. Thus crystal fractionation would give rise to the concentration of a metal-rich volatile phase near the roof of the granites, or associated with the last remnants of crystallisation, and thus the concentration of mineralisation in the upper preserved portions of the granites.

9.1.5.2 Height of mineralisation and the effects of fluid mixing

Owing to the high K, Th, and U content of the granites they had a long-lived high heat producing capacity caused by prolonged radiogenic decay of these elements. Circulation of fluids, set up by this high heat producing capacity, could have continued for millions of years, allowing a long time for mineralisation to occur and mineralising fluids to circulate. Mineral assemblages are found to differ with height in the granites, as indicated by TEDI values. Mineralisation associated with granites with TEDI values in the order of 50 to 60 are Sn, W, F (primary) ± Mo dominated with an assemblage deposited as cassiterite, wolframite, fluorite and molybdenite respectively with early pyrite often accompanying the early minerals. The Bobbejaankop granite is found to be the predominant host of this type of mineralisation. These metals are deposited by orthomagmatic processes or from early magmatic fluids.

With increasing fractionation (and hence decreasing TEDI values) and time, Cu, Pb, and Zn in the form of chalcopyrite (with possibly bornite), galena and sphalerite become dominant, and tin is found in lesser quantities. It is found that the changing magmatic fluid or pulses are increasingly mixing with a meteoric / connate fluid, giving rise to this second paragenesis. With time As, Ag and Au begin to become predominant, along with lesser Sb and Bi, with the deposition of arsenopyrite, stibnite and tennantite-tetrahedrite in the very upper portions of the granite sheet. In the overlying roof rocks Au, with possibly Co, is found to be a dominant commodity, such as at the Hartebeestspruit and Boekenhouthoek Au occurrences, both of which are hosted in granophyre.

Higher up in the granites and / or into the overlying roof rocks, particularly the granophyres, an oxidised assemblage of Fe, U and late F in the form of hematite, pitchblende and fluorite is found to superimpose itself on the earlier sulphide assemblages, with Fe-rich chlorite and fluorite deposited in vugs. This late paragenetic sequence is particularly well exhibited at the Albert Silver Mine, but is also evident at other occurrences. This late paragenesis is derived from a predominantly meteoric / connate fluid which had deposited these late minerals after the mineralising event had proceeded to a late stage (Freeman and Robb, 1995, Freeman *et al*, 1997).

Fluid mixing is a dominant factor determining the nature of the ore assemblage. Lower down in the granites, and / or where the mineralising episode was not preferentially accessed by meteoric / connate fluids, mineralisation is predominantly magmatic with precipitation of early sulphides. With time and higher up in the granites, and with a greater meteoric / connate fluid influence later assemblages precipitated. If the mineralising event advances to a stage where there is a predominantly meteoric / connate influence then there could possibly be an oxidised assemblage of hematite superimposing itself on the earlier sulphide assemblage.

9.1.5.3 Structural controls

Mineralisation is mostly directly influenced by major structure, being either bound by it or found along faults, etc. parallel to these structures. Pre-existing structural features, such as breccias, shear zones or minor faults, amongst others, will also aid the passage of fluids as well as host the deposit.

9.1.5.3.1 *Major crustal lineaments*

Major crustal lineaments, such as the Steelpoort / Wonderkop faults trending NE - SW and the Laersdrif fault trending SE - NW, have influenced overall structure in the area (see Fig. 8.5). These lineaments, which may have been active from pre-, syn- to even post-Bushveld times, may have influenced Bushveld Complex formation and shape (Hartzer, 1994), granite emplacement as well as, certainly, the passage of mineralising fluids, whether they be magmatic or meteoric / connate and hence the nature and morphology of the mineralisation. These orientations, which themselves are parallel to other major lineaments, such as the Murchison lineament, appear to have influenced the Kaapvaal Craton structure to a large extent (Hartzer, 1994)(Cameron, 1971).

9.1.5.3.2 *Crustal warping*

Major crustal warping occurred parallel to these lineaments This warping has directly influenced the shape and outcrop pattern of the plutons. Intersection of crustal antiforms and synforms have given rise to dome and basin development, such as in the Moloto pluton or the "basin" around the Albert Silver Mine, which preserved a fine-grained chilled phase of the Verena granite there.

Doming produces tensional fracturing, along which volatiles may move, as well as exposing high level rocks in its core. Interaction of crustal warps will influence doming, and the subsequent trend of fracturing or shear zoning that is often host to mineralisation.

9.1.5.4 Other controls on mineralisation

A geochemical or physical barrier such as the shale horizons at Rooiberg, or the fine-grained chilled margin at the Albert Silver Mine, may cause the fluid to preferentially precipitate its load of metals, and possibly give rise to a high grade mineralised occurrence.

Other factors influencing mineralisation are supergene enrichment, which has influenced the ore at the Albert Silver Mine, as well as the rate of erosion and fracturing of the roof rocks. These are dependent on a number of factors, such as drainage, topography and climate, but may influence the ore, enriching it further in certain elements and metals.

9.1.5.5 Mineralisation in the felsic roof rocks

The roof rocks to the granites act more as repositories to mineralisation derived from the granites, rather than as sources of mineralisation. Factors which influence mineralisation in the granites also influence mineralisation in the roof rocks, such as structure, proximity to high level granites, and accessibility of fluids into the roof rocks, as well as interaction of the magmatic and meteoric components. It is generally found that roof rock hosted occurrences do not contain early predominantly magmatic dominated assemblages, but show assemblages indicating a fair degree of fluid mixing, as well as having an oxidised assemblage of hematite associated with them.

9.1.6 Generalised model for mineralisation in the felsic rocks of the Bushveld Complex

Figure 9.1 combines the effects of structure and present level of erosion and topography, to indicate how the interaction of a number of factors has influenced the localisation of mineralisation. Diagrams using geographic information systems (GIS) should be used to combine all the available data, be it geological, geochemical,

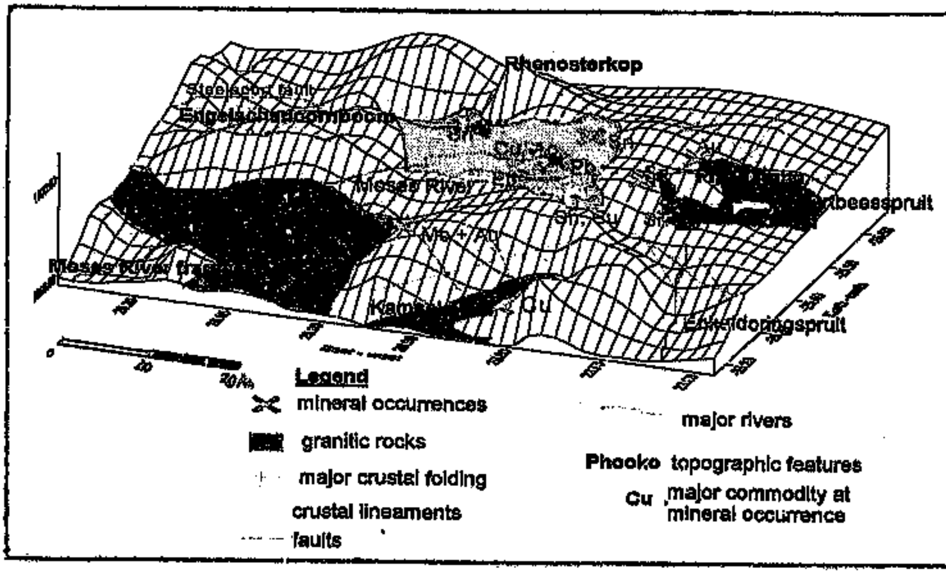


Figure 9.1 Diagram showing effects of topography, drainage and major crustal features on granite emplacement and present day localisation of mineralisation

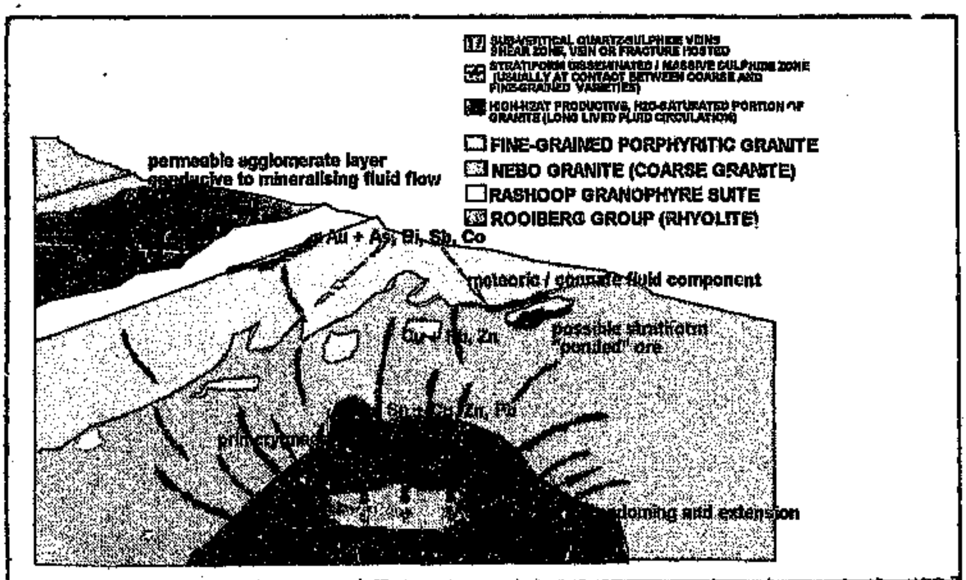


Figure 9.2 Diagram showing the source of fluids and the effect of fluid mixing in controlling the nature of the ore assemblage (after Robb *et al*, 1994)

structural, or other factors, to target areas of exploration potential. Figure 9.2 shows how fluid mixing as well as structure has influenced the localisation as well as the nature of mineralisation.

Interaction of all of the above factors has given rise to the localisation, morphology and nature of mineralisation in the acid rocks. Thus in an exploration program, features such as height in the granites, structure and geochemistry should all be incorporated to delineate areas of greater exploration potential.

GEOCHEMISTRY OF THE FELSIC ROCKS

Table A1 Geochemistry of the Lebowa Granite Suite in the study area

sample	58-163	63-159	63-161	65-151	93-136	189-23	189-24	202-16	202-19	218-37	218-39
$\%SiO_2$	76.751	76.970	77.303	77.330	75.695	77.098	78.843	77.184	76.101	75.602	77.027
$\%TiO_2$	0.136	0.104	0.132	0.076	0.167	0.098	0.134	0.086	0.093	0.175	0.104
$\%Al_2O_3$	11.763	10.869	11.192	11.444	12.300	11.670	11.190	11.807	11.468	11.969	11.477
$\%Fe_2O_3$	2.050	2.485	2.276	1.763	2.142	1.632	0.984	1.781	1.069	3.131	2.536
%MnO	0.048	0.032	0.032	0.011	0.014	0.004	n.d	0.021	0.002	0.039	n.d
%MgO	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
%CaO	0.543	0.030	0.024	0.052	0.451	0.150	0.018	0.136	1.162	0.136	0.042
$\%Na_2O$	3.776	3.380	2.891	4.007	3.890	4.014	3.757	3.878	4.256	3.409	3.502
$\%K_2O$	4.976	5.302	6.118	4.869	5.270	5.155	5.264	5.106	5.074	5.257	5.241
$\%P_2O_5$	0.015	0.023	0.006	0.004	0.025	0.007	0.007	0.010	0.013	0.005	n.d
%L.O.I.	0.430	1.728	1.593	0.730	0.950	0.822	0.809	0.547	1.088	0.986	0.933
%Total	100.509	100.924	100.568	100.286	100.903	100.650	100.924	100.656	100.326	100.710	100.862
ppm Sb	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
ppm Sn	<10	12	<10	<10	<10	<10	<10	<10	<10	<10	<10
ppm Nb	19	44	39	32	32	39	26	17	23	28	36
ppm Zr	198	283	323	203	175	225	269	187	272	236	236
ppm Y	68	87	88	80	76	97	44	120	100	97	119
ppm Sr	48	16	12	15	56	17	19	17	29	27	12
ppm Rb	211	259	309	290	392	260	212	173	242	275	299
ppm Pb	21	15	17	<15	34	<15	<15	<15	<15	<15	<15
ppm As	<15	<15	<15	<15	<15	<15	21	<15	<15	<15	<15
ppm Bi	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7
ppm Zn	52	37	55	47	48	17	16	16	17	46	29
ppm W	9	<7	<7	<7	14	<7	14	<7	7	8	<7
ppm Cu	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
ppm Ni	<5	5	7	7	8	5	6	<5	<5	<5	5
ppm Co	5	5	6	5	8	6	<5	6	6	<5	<5
ppm V	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15
ppm Cr	9	14	13	<9	17	9	20	<9	23	<9	14
ppm Ba	461	201	116	198	285	168	215	293	351	678	249
ppm Au	-	-	-	-	-	-	-	<0.01	-	<0.01	<0.01
ppm Ag	-	-	-	-	-	-	-	<1.0	-	<1.0	<1.0
ppm F	-	-	-	-	-	-	-	472	-	627	213

Table A1 (cont.)

Sample	217-43	217-49	227-117	246-75	246-76	250-108	260-109	250-110	250-113	250-115
%SiO_2	75.386	73.496	72.432	74.342	75.554	74.048	76.278	73.644	73.642	74.799
%TiO_2	0.242	0.211	0.291	0.239	0.115	0.246	0.184	0.286	0.297	0.168
%Al_2O_3	11.928	11.437	12.695	11.477	11.574	13.327	12.217	13.026	13.112	13.403
%Fe_2O_3	2.540	5.604	2.853	4.043	2.864	2.533	2.156	2.588	2.823	2.050
%MnO	0.009	0.125	0.025	0.107	0.059	0.030	0.032	0.036	0.066	0.027
%MgO	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	0.289	n.d
%CaO	0.172	0.424	0.991	0.536	0.492	0.535	0.437	1.077	0.422	0.930
%Na_2O	3.584	2.209	3.704	3.953	2.951	3.565	3.979	4.122	3.722	4.123
%K_2O	5.401	5.174	4.800	5.261	5.433	4.899	4.797	4.650	4.683	4.696
%P_2O_5	0.016	0.025	0.053	0.016	n.d	0.152	0.041	0.054	0.071	0.020
%L.O.I.	0.618	1.556	0.686	0.516	0.887	1.248	0.990	0.908	1.158	0.605
Total(%)	100.095	100.261	98.530	100.488	99.930	100.583	101.111	100.392	100.286	100.821
ppm Sb	<10	11	<10	<10	<10	<10	<10	<10	<10	<10
ppm Sn	12	22	10	<10	10	11	<10	10	22	<10
ppm Nb	30	29	24	21	38	36	33	37	36	36
ppm Zr	294	283	222	422	260	236	186	253	263	182
ppm Y	219	96	63	79	119	65	62	78	72	79
ppm Sr	36	24	95	52	17	90	60	99	75	76
ppm Rb	222	238	273	221	300	352	354	299	285	358
ppm Pb	<15	<15	19	42	22	21	17	19	32	22
ppm As	<15	<15	<16	<15	<15	<15	<15	<15	<15	<15
ppm Bi	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7
ppm Zn	37	50	42	179	99	25	24	42	72	27
ppm W	<7	<7	<7	10	<7	7	10	8	8	9
ppm Cu	<5	<5	<5	7	<5	<5	<5	<5	5	<5
ppm Ni	<5	<5	6	8	<5	<5	6	7	7	6
ppm Co	5	<5	8	6	5	6	5	6	8	7
ppm V	<15	<15	15	<15	<15	<15	<15	15	18	<15
ppm Cr	<9	<9	<9	13	<9	10	16	16	14	17
ppm Ba	698	771	455	1161	131	572	316	512	507	437
ppm Au	-	-	-	-	-	-	-	<0.01	<0.01	-
ppm Ag	-	-	-	-	-	-	-	<1.0	<1.0	-
ppm F	-	-	-	-	-	-	-	952	717	-

Table A1 (cont.)

sample	441-102	441-103	444-116	447-130	MAK-1
$\%SiO_2$	76.862	76.804	74.069	76.827	73.123
$\%TiO_2$	0.174	0.106	0.203	0.111	0.167
$\%Al_2O_3$	11.658	11.865	12.139	11.696	12.645
$\%Fe_2O_3$	2.358	1.732	2.262	1.995	1.697
%MnO	0.042	0.026	0.028	0.021	0.029
%MgO	n.d	n.d	n.d	n.d	n.d
%CaO	0.521	0.399	0.732	0.324	1.099
$\%Na_2O$	3.384	3.756	4.056	3.956	4.811
$\%K_2O$	4.798	5.005	4.921	5.200	4.701
$\%P_2O_5$	0.015	0.002	0.035	0.009	0.034
%L.O.I.	0.870	0.644	0.921	0.632	0.395
Total(%)	100.683	100.341	99.356	100.769	98.602
ppm Sb	<10	<10	<10	<10	<10
ppm Sn	<10	14	<10	11	<10
ppm Nb	35	37	35	27	43
ppm Zr	213	100	203	190	198
ppm Y	97	88	61	74	95
ppm Sr	33	24	61	23	89
ppm Rb	307	335	357	332	191
ppm Pb	18	28	24	22	<15
ppm As	<15	<15	<15	<15	<15
ppm Bi	<7	<7	<7	<7	<7
ppm Zn	45	35	30	30	17
ppm W	11	9	<7	7	<7
ppm Cu	<5	<5	<5	<5	<5
ppm Ni	<5	<5	<5	6	8
ppm Co	8	6	7	5	8
ppm V	<15	<15	<15	<15	<15
ppm Cr	<9	10	17	17	22
ppm Ba	229	245	265	47	492
ppm Au	-	-	-	-	-
ppm Ag	-	-	-	-	-
ppm F	-	-	-	-	-

n.d. not detected

Table A2 Granite sample positions

sample no.	lat.	long.	sample no.	Lat.	long.
58-163	25° 18' 46" S	29° 08' 56" E	227-117	25° 31' 48" S	28° 59' 12" E
63-159	25° 21' 14"S	29° 07' 17" E	246-75	25° 26' 52" S	28° 43' 13" E
63-161	26° 22' 16"S	29° 07' 35" E	246-76	25° 26' 53" S	28° 43' 03" E
65-151	25° 20' 36" S	29° 13' 37" E	250-108	25° 28' 26" S	28° 51' 26" E
93-136	25° 25' 50" S	29° 00' 45" E	250-109	25° 28' 05" S	28° 51' 37" E
189-23	25° 13' 17" S	28° 49' 20" E	250-110	25° 28' 35" S	28° 52' 29" E
189-24	25° 13' 30" S	28° 49' 38" E	250-113	25° 28' 43" S	28° 53' 03" E
202-15	25° 15' 53" S	28° 46' 54" E	250-116	26° 29' 31" S	28° 54' 40" E
202-19	25° 15' 26" S	28° 46' 42" E	441-102	25° 31' 32" S	28° 52' 26" E
218-37	26° 22' 25" S	28° 42' 50" E	441-103	25° 31' 34" S	28° 52' 28" E
218-39	25° 22' 21" S	28° 42' 55" E	444-116	26° 30' 42" S	28° 56' 19" E
217-43	25° 24' 17" S	28° 42' 08" E	447-130	25° 35' 24" S	29° 01' 44" E
217-49	25° 24' 52" S	28° 43' 26" E	MAK-1	25° 23' 16" S	28° 55' 26" E

58-163: coarse-grained grey Sekhukhuni granite, Maloek Zyn Kop 58 JS

63-159: medium grained dark red Sekhukhuni granite, Rhenosterkuil 63 JS

63-161: fine-grained golden brown Klipkloof granite. Rhenosterkuil 63 JS

65-151: coarse-grained dark red Sekhukhuni granite, Vreemdeling 65 JS

93-136: coarse-grained dark pink Verena granite, Hartbeesfontein 93 JS

189-23: fine-grained light pink Klipkloof granite, Zandspruit 189 JR

189-24: coarse-grained dark red Bobbejaankop-like Sekhukhuni granite, Zandspruit 189 JR

202-15: fine-grained red Sekhukhuni granite, Kameelpoort 202 JR

202-19: fine-grained dark pink Sekhukhuni granite, Kameelpoort 202 JR

217-37: coarse-grained dark red Bobbejaankop granite, Enkeldoorn 217 JR

217-39: fine-grained dark pink Klipkloof granite, Enkeldoorn 217 JR

217-43: coarse-grained dark red Bobbejaankop granite, Enkeldoorn 217 JR

217-49: coarse-grained black Bobbejaankop granite, Enkeldoorn 217 JR

227-117: coarse-grained light pink Verena granite, Wolvenkop 227 JS

246-75: medium-grained, grey granophyric Sekhukhuni granite, Zustershoek 246 JR

246-76: medium-grained dark red Bobbejaankop granite, Zustershoek 246 JR

250-108: fine-grained pink-grey Verena granite, Roodepoortje 250 JR

250-109: coarse-grained pinkish white Verena granite, Roodepoortje 250 JR

250-110: fine-grained pinkish grey Verena granite, Roodepoortje 250 JR

250-113: fine-grained, dark pink Verena granite, host to mineralisation at Albert Silver Mine, Roodepoortje 250 JR

250-115: fine-grained light pink Verena granite, Roodepoortje 250 JR

441-102: coarse-grained dark red Verena granite, Hartbeesfontein 441 JR

441-103: fine-grained dark red Verena granite, Hartbeesfontein 441 JR

444-116: coarse-grained whitish pink Verena granite, Zwartkopje 444 JR

447-130: fine-grained dark pink Klipkloof granite, Zusterstroom 447 JR

MAK-1: medium-grained grey Makhutso granite, Hartbeesfontein 224 JR

Table A3 Geochemistry of the roof rocks

sample	63-162	89-140	90-138	95-134	205-22	205-27	214-32	228-132	228-133	248-94	434-89
%SiO_2	76.393	73.243	73.555	74.586	73.063	73.956	74.469	70.07	71.651	74.603	74.975
%TiO_2	0.195	0.24	0.295	0.243	0.259	0.253	0.24	0.339	0.333	0.24	0.228
%Al_2O_3	11.502	10.998	9.628	10.92	10.982	12.597	11.242	11.397	10.799	11.393	11.51
%Fe_2O_3	2.755	4.251	8.248	4.265	4.991	3.836	3.61	6.904	6.923	3.878	3.513
%MnO	0.052	0.046	0.053	0.085	0.057	0.042	0.033	0.033	0.021	0.06	0.124
%MgO	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d
%CaO	0.349	1.09	0.005	0.784	0.705	0.483	0.239	0.629	0.572	0.395	0.894
%Na_2O	3.334	2.209	n.d	2.727	3.159	3.831	2.97	2.741	2.785	3.466	2.104
%K_2O	[illegible].275	5.954	7.18	4.987	4.726	5.46	5.496	6.471	5.897	5.439	6.298
%P_2O_5	[illegible].004	0.014	0.042	0.021	0.012	n.d	0.031	0.039	0.028	0.015	0.005
%L.O.I.	1.067	1.068	0.654	1.542	1.266	0.671	1.792	0.581	0.49	0.854	0.434
Total(%)	99.927	99.113	99.659	100.16	99.219	101.03	100.12	99.204	99.5	100.36	100.08
ppm Sb	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10
ppm Sn	<10	<10	<10	<10	<10	<10	<10	<10	<10	10	<10
ppm Nb	24	19	16	22	21	22	23	20	19	23	23
ppm Zr	377	407	337	428	406	412	449	396	382	481	474
ppm Y	91	62	63	68	67	70	69	62	56	78	81
ppm Sr	20	61	22	29	42	57	45	48	48	37	119
ppm Rb	194	207	336	176	166	170	222	250	301	201	291
ppm Pb	<15	26	<15	17	<15	<15	28	<15	<15	25	106
ppm As	<15	<15	<15	<15	<15	<15	<15	20	16	<15	<15
ppm Bi	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7	<7
ppm Zn	53	122	34	99	61	55	103	71	80	85	214
ppm W	7	<7	23	11	<7	9	7	<7	<7	<7	8
ppm Cu	<5	<5	19	<5	<5	<5	<5	<5	18	<5	6
ppm Ni	<5	<5	<5	5	<5	<5	<5	<5	<5	6	<5
ppm Co	6	6	<5	<5	<5	<5	<5	6	<5	<5	<5
ppm V	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15	<15
ppm Cr	15	13	<9	<9	10	9	<9	12	15	14	10
ppm Ba	739	1171	1845	1151	1058	1247	1205	1194	1295	1234	1550
ppm Au	-	-	-	-	-	<0.01	-	-	<0.01	-	-
ppm Ag	-	-	-	-	-	<1.0	-	-	<1.0	-	-
ppm F	-	-	-	-	-	1235	-	-	1367	-	-

Table A3 (cont.)

sample	434-90	439-98	440-100	440-101	446-121	446-122
$\%SiO_2$	73.27	71.282	73.735	78.966	73.117	72.339
$\%TiO_2$	0.243	0.336	0.515	0.226	0.42	0.36
$\%Al_2O_3$	11.062	11.55	12.672	9.932	12.781	13.393
$\%Fe_2O_3$	4.22	7.17	6.135	3.186	6.72	6.626
%MnO	0.059	0.154	0.034	0.019	0.089	0.051
%MgO	n.d	n.d	0.122	n.d	0.179	n.d
%CaO	0.669	0.217	n.d	n.d	n.d	n.d
$\%Na_2O$	3.74	4.248	n.d	n.d	n.d	n.d
$\%K_2O$	4.841	4.602	4.258	6.465	4.297	3.989
$\%P_2O_5$	0.021	0.065	0.133	0.035	0.03	0.024
%L.O.I.	0.75	0.821	2.358	1.241	2.005	2.362
Total(%)	98.974	100.45	99.863	100.07	99.637	99.145
ppm Sb	13	<10	<10	<10	10	15
ppm Sn	10	10	10	14	11	<10
ppm Nb	24	20	15	20	17	22
ppm Zr	375	406	227	433	405	474
ppm Y	67	72	45	67	48	48
ppm Sr	51	46	44	40	25	16
ppm Rb	227	191	323	244	290	278
ppm Pb	76	<15	<15	12	15	<15
ppm As	<15	<15	<15	<15	<15	16
ppm Bi	<7	7	<7	8	<7	<7
ppm Zn	205	101	31	42	209	156
ppm W	7	12	9	26	16	9
ppm Cu	28	<5	10	<5	<5	<5
ppm Ni	6	<5	15	8	13	9
ppm Co	6	6	5	7	<5	6
ppm V	<15	<15	106	<15	30	<15
ppm Cr	13	<9	79	19	32	18
ppm Ba	1011	1071	510	1782	950	413
ppm Au	-	-	-	-	-	-
ppm Ag	-	-	-	-	-	-
ppm F	-	-	-	-	-	-

n.d. not detected

Table A4 Roof rock sample positions

sample no.	lat.	long.	sample no.	lat.	long.
63-162	25° 22' 33" S	29° 07' 32" E	248-94	25° 28' 05" S	28° 47' 25" E
89-140	25° 24' 53" S	29° 09' 35" E	434-89	25° 30' 24" S	28° 42' 19" E
90-138	25° 24' 11" S	29° 06' 50" E	434-90	25° 30' 28" S	28° 42' 26" E
95-134	25° 29' 04" S	29° 08' 01" E	439-98	25° 30' 38" S	28° 49' 18" E
205-22	25° 20' 18" S	28° 45' 57" E	440-100	25° 33' 36" S	28° 51' 14" E
205-27	[illegible] 19' 45" S	28° 46' 57" E	440-101	25° 33' 21" S	28° 51' 18" E
214-32	[illegible] 20' 39" S	28° 38' 51" E	446-121	25° 35' 20" S	28° 56' 56" E
228-132	[illegible] 31' 20" S	29° 04' 00" E	446-122	25° 35' 29" S	28° 56' 47" E
228-133	25° 31' 16" S	29° 04' 01" E			

63-162: medium-grained dark purple granophyre, Rhenosterkuil 63 JS

89-140: dark brown, vesicular rhyolite, Schrikkloof Formation, Zwartfontein 89 JS

90-138: agglomerate layer, Union Tin Member, Schrikkloof Formation, Rietfontein 90 JS

95-134: dark brown vesicular rhyolite, Schrikkloof Formation, Engelschedoornboom 95 JS

205-22: black massive rhyolite, Kwaggasnek Formation, Klipfontein 205 JR

205-27: medium-grained dark red granophyre, Klipfontein 205 JR

214-32: medium-grained dark pink granophyre, Rietfontein 214 JR

228-132: black vesicular rhyolite, Kwaggasnek Formation, Leeuwfontein 228 JS

228-133: black vesicular flow banded rhyolite, Kwaggasnek Formation, Leeuwfontein 228 JS

248-94: medium-grained deep red granophyre, Leeuwfontein 248 JR

434-89: black vesicular porphyritic rhyolite, Kwaggasnek Formation, Hartebeestspruit 434 JR

434-90: medium-grained dark pink granitic granophyre, Hartebeestspruit 434 JR

439-98: dark purple red vesicular rhyolite, Schrikkloof Formation, Roodepoort 439 JR

440-100: grey / black massive rhyolite, Loskop Formation, Rooipoort 440 JR

440-101: dark brown / orange flow banded volcanic, Loskop Formation, Rooipoort 440 JR

446-121: dark brown, slumped sediment, Loskop Formation, Rhenosterkop, Rietfontein 446 JR

446-122: grey agglomerate, Loskop Formation, summit of Rhenosterkop,

Rietfontein 446 JR

Note: Data for Figure 5.1 was obtained from CIPW norm calculations carried out by the software program Minpet 2.0®. The Q, A and P ratios were calculated from these results. The R1 and R2 ratios for Figure 5.5 were calculated from the above geochemical data.

APPENDIX B

ANALYTICAL ERRORS OF THE MAJOR AND TRACE ELEMENT DATA OBTAINED USING THE PHILLIPS 1400 XRFS

Standards used for calibration of PW1400 XRFS for silicate analysis.

STANDARD	%Fe2O3	%MnO	%TiO2	%CaO	%K2O	%P2O5	%SiO2	%Al2O3
NIM-G	2.02	.02	.00	.79	5.03	.01	76.31	12.18
NIM-S	1.41	.01	.00	.68	15.40	.12	63.85	17.40
NIM-N	8.96	.18	.20	11.49	.25	.03	52.57	16.48
NIM-D	16.87	.22	.02	.28	.01	.01	38.66	.30
NIM-P	12.77	.22	.20	2.67	.09	.02	51.39	4.20
AN-G	3.39	.04	.22	16.03	.13	.01	46.67	30.04
AC-E	2.54	.06	.11	.34	4.51	.01	70.63	14.76
MA-N	.47	.04	.01	.59	3.19	1.40	66.86	17.69
AGV-1	6.79	.10	1.06	4.96	2.91	.48	59.48	17.22
FK-N	.09	.01	.02	.11	12.88	.02	65.37	18.71
BHVO-1	12.15	.17	2.69	11.33	.52	.27	49.61	13.71
MICA-FE	26.33	.36	2.57	.44	8.98	.46	35.31	20.01

STANDARD	%MgO	%Na2O	%LOI	%Total
NIM-G	.06	3.39	0.45	100.42
NIM-S	.46	.43	0.28	99.70
NIM-N	7.49	2.46	-0.40	99.83
NIM-D	43.18	.04	-0.93	99.42
NIM-P	25.47	.37	-0.84	96.03
AN-G	1.81	1.64	0.65	99.84
AC-E	.03	6.57	0.37	99.53
MA-N	.04	5.86	1.82	97.60
AGV-1	1.54	4.27	1.59	100.01
FK-N	.01	2.59	0.54	99.82
BHVO-1	7.18	2.25	-0.71	99.82
MICA-FE	4.67	.31	1.43	98.31

Analytical precision for major element analysis.
The analysis are based on 107 duplicate samples representing 6 calibrations. New fusion discs and powder pellets were prepared for each machine calibratio For this reason the statistics presented should represent the total analytica uncertainty in the procedure, including sample preparation.

Element	Standard deviation	Average % error
Fe2O3	0.24	-0.6
MnO	0.01	1.6
TiO2	0.02	0.4
CaO	0.23	0.6
K2O	0.07	-5.2
P2O5	0.01	0.4
SiO2	0.73	1.1
Al2O3	0.36	3.8
MgO	0.22	-3.1
Na2O	0.44	11.2
LOI	0.08	0.7
Total	1.16	0.9

Analytical precision for trace element analysis.
The analysis are based on 69 duplicate samples representing 5 calibrations.
New powder pellets were prepared for each machine calibration.
For this reason the statistics presented should represent the total analytica uncertainty in the procedure, including sample preparation.

Element	Standard deviation	Average % error
Rb	2	19.5
Sr	3	1.9
Y	1	4.5
Zr	1	1.1
Nb	1	22.1
V	5	4.9
Cr	11	9.9
Co	4	8.0
Ni	5	4.0
Cu	4	6.4
Zn	3	2.1
Ba	19	40.5

Standards used for calibration of PW1400 XRFS for trace element analysis.

STANDARD	ppm Rb	ppm Sr	ppm Y	ppm Zr	ppm Nb	ppm Co	ppm Ni
AGV-1	67.	662.	21.	225.	15.	15.	17.
GA	175.	310.	21.	150.	12.	5.	7.
GH	390.	10.	75.	150.	85.	1.	3.
G-2	170.	478.	11.	300.	13.	5.	5.
NIM-G	325.	10.	143.	300.	53.	0.	8.
NIM-S	530.	62.	1.	20.	0.	3.	7.
NIM-P	4.	32.	5.	15.	0.	110.	555.
NIM-N	5.	260.	7.	14.	0.	58.	120.
NIM-L	190.	4600.	22.	11000.	960.	2.	2.
NIM-D	0.	3.	0.	8.	0.	208.	2040.
PCC-1	0.	0.	0.	0.	1.	110.	2400.
BR	47.	1320.	30.	250.	98.	52.	260.
BHVO-1	11.	403.	28.	179.	19.	45.	121.
MAG-1	149.	146.	28.	126.	12.	20.	53.
SGR-1	83.	420.	13.	53.	5.	12.	29.
SCO-1	112.	174.	26.	160.	11.	11.	27.
QLO-1	74.	336.	24.	185.	10.	7.	6.
STM-1	118.	700.	46.	1210.	268.	1.	3.
RGM-1	149.	108.	25.	219.	9.	2.	4.
SDC-1	127.	183.	40.	290.	18.	18.	38.
DR-N	73.	400.	28.	125.	8.	35.	15.
GS-N	185.	570.	19.	235.	21.	65.	34.
MICA-FE	2200.	5.	50.	800.	270.	23.	35.
MICA-MG	1300.	27.	0.	20.	120.	24.	110.
FK-N	860.	39.	0.	13.	0.	16.	3.
BX-N	10.	110.	114.	520.	58.	35.	190.
DT-N	5.	27.	10.	370.	0.	12.	16.
UB-N	6.	10.	3.	8.	0.	100.	2000.
GXR-1	14.	259.	0.	38.	1.	8.	41.
GXR-2	78.	160.	17.	269.	11.	9.	21.
GXR-3	92.	950.	15.	63.	2.	43.	60.
GXR-4	160.	221.	14.	186.	10.	15.	42.
GXR-6	90.	35.	14.	110.	8.	14.	27.
GSP-1	254.	234.	29.	530.	26.	7.	10.
MA-N	3600.	84.	1.	27.	173.	1.	3.
AN-G	0.	76.	8.	15.	2.	25.	35.

STANDARD	ppm Cu	ppm Zn	% TIO2	ppm V	ppm Cr	ppm Ba
AGV-1	60.	88.	1.06	123.	12.	1221.
GA	16.	80.	0.38	38.	12.	840.
GH	14.	85.	0.08	5.	6.	20.
G-2	11.	85.	0.49	36.	9.	1680.
NIM-G	12.	50.	0.00	2.	12.	120.
NIM-S	19.	10.	0.00	10.	12.	2420.
NIM-P	18.	100.	0.20	230.	23950.	46.
NIM-N	14.	68.	0.20	220.	30.	102.
NIM-L	13.	395.	0.48	81.	10.	450.
NIM-D	10.	90.	0.02	40.	2870.	10.
PCC-1	10.	42.	0.01	30.	2730.	1.
BR	72.	160.	2.60	235.	380.	1050.
BHVO-1	136.	105.	2.71	317.	289.	139.
MAG-1	30.	130.	0.75	140.	97.	479.
SGR-1	66.	74.	0.26	128.	30.	290.
SCO-1	29.	103.	0.63	131.	68.	570.
QLO-1	29.	61.	0.62	54.	3.	1370.
STM-1	5.	235.	0.14	9.	4.	560.
RGM-1	12.	32.	0.27	13.	4.	807.
SDC-1	30.	103.	1.01	102.	64.	630.
DR-N	50.	145.	1.09	220.	42.	385.
GS-N	20.	48.	0.68	65.	55.	1400.
MICA-FE	5.	1300.	2.50	135.	90.	150.
MICA-MG	4.	290.	1.63	90.	100.	4000.
FK-N	2.	10.	0.02	3.	5.	200.
BX-N	18.	75.	2.37	310.	290.	34.
DT-N	9.	28.	1.40	150.	240.	130.
UB-N	28.	85.	0.11	75.	2300.	30.
GXR-1	1110.	765.	0.06	76.	13.	680.
GXR-2	76.	530.	0.50	52.	36.	2240.
GXR-3	15.	207.	0.17	42.	19.	5000.
GXR-4	6520.	73.	0.48	87.	64.	1640.
GXR-6	66.	118.	0.83	186.	96.	1300.
GSP-1	34.	103.	0.66	53.	13.	1310.
MA-N	140.	220.	0.01	5.	3.	42.
AN-G	19.	20.	0.22	70.	50.	34.

THE VOLUMETRIC DETERMINATION OF FERROUS IRON IN SILICATE MATERIAL

1. Outline

The sample is dissolved in hydrofluoric acid in the presence of quinquivalent vanadium that is reduced by the ferrous iron in the sample as it dissolves. The excess unreduced vanadium is titrated with a standard ferrous ammonium sulphate solution. Sodium diphenylamine sulphonate is used as the indicator.

2. Application

The method is applicable to silicate material containing more than 0.5 per cent ferrous oxide.

3. Reagents

Sulphuric acid 10N - Dilute 280 ml of sulphuric acid to 1000 ml with water.
Phosphoric acid 1:1 - Dilute 100 ml of phosphoric acid to 200 ml with water.
Ammonium metavanadate (NH_4VO_3) - A.R. Grade.
Boric acid saturated solution - Dissolve about 70 g of boric acid in 1000 ml water. Heat until dissolved, then cool and decant off the supernatant solution.
Sodium diphenylamine sulphonate solution 0,32% w/v - Dissolve 0,32 g of barium diphenylamine sulphonate in water. Add 0,5 g sodium sulphate, filter and dilute to 100 ml with water.
Ferrous ammonium sulphate solution 0,03N - Dissolve 11,7647 g of A.R. grade ferrous ammonium sulphate in 800 ml of water containing 28 ml of sulphuric acid. Cool and transfer to a litre volumetric flask and dilute to volume. Standardise, using two 25 ml aliquot portions. Add 3 ml of 10N sulphuric acid, 2 ml of 1:1 phosphoric acid, and about 10 ml of water. Add 5 drops of indicator

solution and titrate with a 0,0500N potassium dichromate solution. Subtract a blank of 0,05 ml from this titration as the indicator consumes this amount of potassium dichromate. Calculate the normality of the iron solution and the ferrous oxide equivalent as follows:

Normality of ferrous ammonium sulphate solution =

(Volume of potassium dichromate solution × 0,05) / 25

1 ml ferrous ammonium sulphate solution ≡ Normality of ferrous ammonium sulphate solution × 0,0719 g ferrous oxide. (A)

4. Amount of sample

Estimated FeO content %	Weight of sample g	Weight of Ammonium Metavanadate g
0,5 → 2	1,0	0,1000
2 → 10	0,5	0,1000
10 → 20	0,5	0,2000
20 → 30	0,5	0,3000

5. Procedure

a. Transfer the accurately weighed sample to a 100 ml polythene beaker and add exactly the required amount of ammonium metavanadate.

b. Add 10 ml of hydrofluoric acid, cover and set aside until the sample has decomposed. For most samples, 48 hours is sufficient, but some refractory samples will require up to 32 days digestion.

c. Add 30 ml of 10N sulphuric acid and wash the sample solution into an 800 or 1000 ml beaker containing 5 drops of indicator solution, using 250 ml of saturated boric acid solution. Stir the solution until any white curdy precipitate formed during decomposition has dissolved.

d. Add 15 ml of 1:1 phosphoric acid and titrate with the standard ferrous ammonium sulphate solution, while stirring with either a glass rod or a plastic covered magnetic stirrer. At the endpoint the solution changes from purple to pale green. (B)

e. un a standard with each sample, adding exactly the amount of ammonium metavanadate and the other reagents that were added to the sample, and allow to stand for the same time as the sample before titrating. (C)

f. Calculate the amount of ferrous oxide in the sample as follows:

$$\% FeO = ((C - B) \times A \times 100) / \text{weight of sample}$$

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