UNIVERSITY OF THE WESTERN CAPE

The Influence of Contact Metasomatism and Fluid-Rock Interaction, on the Nature and Style of Platinum-Group Element Mineralisation in the Platreef, Northern Limb, South Africa: A Case Study from the Moordkopje Farm.

by

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DECLARATION

I declare that "**The influence of contact metasomatism and fluid-rock interaction, on the nature and style of Platinum- Group Element mineralisation in the Platreef, Northern Limb, South Africa: A case study from the Moordkopje Farm**." is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or cited have been indicated and acknowledged by complete references.

Senzangakhona Ndumo

November 2017

Signed: …………………………

ABSTRACT

The complexity of the Platreef stratigraphy and the generic position of the Ni-Cu-PGE mineralisation is a challenge to prospecting and mining companies in the Northern Limb of the Bushveld Complex, partially, as a result of various floor rock interactions with the reef. Therefore, this study evaluated the effects of contact metasomatic fluids on the nature and style of PGE mineralisation as the main event leading to the complexity of the Platreef stratigraphy from the contact zone near the floor rock.

Fifty samples from boreholes MO009 and MO019 drilled at Moordkopje 813 LR farm for Akanani Project by Lonmin Plc were used for this study. The mineralogy and geochemistry of the Platreef samples were studied and associated with their mineralisation occurrences. Major, minor and trace element contents were analysed by XRF analysis using fused beads, and PGE contents (Pt, Pd) in 11 samples were determined by Fire Assay.

The results of petrography showed that harzburgites and feldspathic pyroxenites are primary lithologies of Platreef located in the Middle zone of Platreef. Harzburgites have modal mineralogy of 60-70% orthopyroxene, 5-15% olivine, 0-5% clinopyroxene, and irregularly have very minor plagioclase grains, and 5% opaque minerals. Feldspathic pyroxenites are characterised by 85% orthopyroxenes, and <10% interstitial plagioclase, <5% clinopyroxene and minor opaque minerals. Pegmatoidal feldspathic pyroxenites and parapyroxenites are secondary lithologies which are products of siliceous metasomatic fluid action from the granite floor rock and contact metamorphism with calc-silicate xenoliths, respectively, and located at the Lower Platreef that is resting directly on the Archaean granite footwall. Pegmatoidal feldspathic pyroxenites are characterised by 60% orthopyroxene and <5% clinopyroxene, 15% intercumulus plagioclase, 15% of quartz and <5% accessory phlogopite and biotite; and parapyroxenites are characterised by <60% clinopyroxenes, <25% orthopyroxenes, and <15% ruptured olivine. These rock compositions are the effects of fluid-rock interaction at the contact between the footwall and the reef.

In terms of geochemistry, the harzburgites and feldspathic pyroxenites are characterised by high values of MgO (>20 wt%) and Fe_2O_3 (>10 wt%) as an indication of high orthopyroxene content, while the plagioclase content is characterised by high values of CaO and Al_2O_3 in feldspathic pyroxenites. The pegmatoidal feldspathic pyroxenites have significantly high values of SiO_2 (>50 wt%), Na_2O (~1.50 wt%), K_2O (>0.40 wt%), P_2O_5 (>0.05 wt%) and TiO_2 (0.11 – 0.64 wt%) to indicate the presence of quartz, albite, K-feldspar, phlogopite and apatite.

The high values in CaO, MgO and LOI is the characterisation of parapyroxenites as these contain high clinopyroxene and serpentine.

The presence of metasomatic fluids in Platreef lithologies is indicated mineralogically by substantial presence of quartz, and geochemically by high values of yttrium and zirconium. Geochemistry evaluated the effects of granite floor rock and calc-silicate xenoliths, respectively, by formulated ratios K_2O/TiO_2 and CaO/Al_2O_3 and were correlated with mineralisation as Cu/Zr using downhole plots. These correlation results showed no significant floor rock effects to the Ni-Cu-PGE mineralisation under the granite floor rock, in contrast to dolomite floor rock. The effects of contact metasomatism from the Archaean granite had only varied the lithological units of Platreef to subsequently complicate the primary lithological sequence which remain unresolved in this study. The shortfalls that remain unresolved are the stratigraphy of Platreef, and the position of the mineralisation that is related with the contact zones. This may be resolved by the study of isotope geochemistry.

KEYWORDS

Contact metasomatism

Fluid-rock interaction

Platreef

PGE mineralisation

Stratigraphy

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DEDICATION

This work is dedicated to my parents

Mr. ***Bhekisisa Abednego Ndumo*** *and Mrs.* ***Lydia Thokozile Ndumo***

and also to my brothers,

and to the rest of my family.

ABBREVIATIONS AND ACRONYMS

RLS	Rustenburg Layered Suite
MgZ	Marginal Zone
LZ	Lower Zone
CZ	Critical Zone
MZ	Main Zone
UZ	Upper Zone
XRF	X-ray fluorescence
LOI	Loss on ignition
wt.%	weight percent
ppm	parts per million
ppb	parts per billion
DA	Discriminant Analysis
LILE	Large-Ion Lithophile Elements
HFSE	High Field Strength Elements
PGE	Platinum Group Elements
BMS	Base metal sulphides

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CHAPTER 1

INTRODUCTION

1.1. Background

The Platreef is a 10 - 400 m thick layered mafic-ultramafic intrusion comprising of predominantly pyroxenitic lithologies, which hosts platinum group element (PGE) and base-metal sulphides (BMS) mineralisation. It is one of the world's largest deposits of PGEs, located in the Northern Limb of the Bushveld Complex in South Africa. Continually, the resources in the Platreef are largely contributing to the growth of South African economy as it is the most intensively prospected area for PGE mineralisation.

In contrast to the Western and Eastern Limbs, the Northern Limb PGE-bearing reef assigned to Platreef forms the lower part of the mafic-ultramafic sequence termed the Rustenburg Layered Suite (RLS), and rests directly on the footwall rocks. The RLS of the Bushveld Complex is universally divided into Marginal Zone, Lower Zone, Critical Zone, Main Zone, and Upper Zone. This universal division of RLS is strongly conformed in the Western and Eastern Limbs of the Bushveld Complex, while in the Northern Limb the basal parts of the division up to Lower Zone and some lower parts of the Critical Zone did not develop (White, 1994; Lee, 1996). This occurrence explains how Platreef had formed the lower part of the entire RLS sequence in the Northern Limb.

The RLS is a strongly layered sequence of ultramafic peridotites to pyroxenites which are associated with chromitites towards the base, with mafic norites, gabbronorites and anorthosites towards the top of the suite. The individual cumulate layers of RLS are mineralogically rich in pyroxenes, calcium-rich plagioclase and/or chromite. The Critical Zone (CZ) of the RLS carries one of the world's largest PGE- and BMS-mineralised horizons, which in the Western and Eastern Limbs are the famous chromitite group layers (e.g. LG, MG, UG2) and Merensky reef. In the Northern Limb, the mineralised horizon is the Platreef and is successively overlain by Main Zone (norites and gabbronorites). The successive relationship of Platreef to Main Zone in the Northern Limb and the key features of Platreef similar to features of Merensky Reef had made Wagner (1929) to correlate Platreef with Critical Zone elsewhere in the Bushveld Complex, with some authors accepting his suggestion (e.g. Gain and Monstert, 1982; White, 1994; Vermaak, 1995; Barnes and Maier, 2002). However, Wagner's long standing suggestion of correlating Platreef and Merensky Reef has been controversial in recent years. McDonald *et al*. (2005) did a study to critically review the geology of Platreef and Merensky Reef, and they demonstrated that these reefs are not linked, they formed from different magmas. Many recent authours seem to have been avoiding to correlate Platreef and Critical Zone, and rather refer it as the base of the Main Zone (originally from van der Merwe, 1976).

Therefore, the stratigraphy and thickness of the RLS differs in the Northern Limb from that of elsewhere in the Bushveld Complex (i.e. in the Western and Eastern Limbs). The Lower Zone is poorly developed in the Northern Limb; as a result, the PGE mineralised Platreef rests directly on the Transvaal Supergroup (i.e. the Penge banded iron formation; the Malmani dolomite) in the southern parts of the limb and rests on the Archaean granite-gneiss in the northern parts of the limb. This kind of occurrence in the Northern Limb brings complexity and uncertainties with regards to the nature of PGE mineralisation, as opposed to the Western and Eastern Limbs.

1.2. Problem statement

The main problem which has always been encountered by the prospecting and mining companies in the Platreef is the complexity of the Platreef stratigraphy and the generic position of the mineralisation (Kinnaird and McDonald, 2005). In contrast to the Eastern and Western Limbs, in these limbs, the stratigraphy of the reefs and the position of the PGE mineralisation are associated and follow distinguished patterns (Lee, 1996). As a result, mining activities in the Eastern and Western Limbs are not as complicated as the in the Northern Limb. McDonald *et al.* (2005) mentioned that the mining in the Eastern and Western Limbs had been done from tabular horizons within the layered intrusions.

As a result of the Platreef complexity, many questions and uncertainties had been drawn regarding the origin of the complexity. These questions are a way of attempting to find the core responsible process to form the stratigraphy of Platreef. Amongst all the imposed questions and resulting uncertainties, the most prevailing question is with regards to the effects of post-magmatic fluids on the origin of PGE mineralisation and Platreef stratigraphy. Such questions are as follows:

- Were the post-magmatic fluids the responsible process for the PGE mineralisation in the Platreef?

- Whether the hydrothermal fluids (especially the magmatic/metasomatic fluids) had significant effects on the PGE mineralisation and their position in the stratigraphy?

- Did the fluids enhance or attenuate the grade of the PGE mineralisation?

- Can these fluids differentiate the type of PGEs in terms of their mineralogical and geochemical affinity within the Platreef stratigraphy?

- Do these effects of fluid-rock interaction bring about the productive/economic effect on the PGE mineralisation?

These questions have not been fully addressed in literature especially in the northern parts of the Platreef where the floor rock is the Archaean granite.

The problem arise from the uncertainty of the origin of the layered Platreef intrusion and the relationship of the mineralisation with the stratigraphic framework. The origin and occurrence of the Platreef layers with its PGE mineralisation has been central problem that involved many authors (e.g. van der Merwe, 1976; Lee, 1996; Holwell and McDonald, 2005; Holwell *et al.*, 2005; Maier *et al.*, 2007; Pronost *et al.*, 2008; Maier and Barnes, 2010; Yudovskaya and Kinnaird, 2010). There are two basic theories that are currently proposed which are explaining the occurrence and evolution of the layered intrusions and mineralisation in the Platreef. First theory (i) is that there were at least four major influxes of fresh, undifferentiated magma responsible for the formation of these layered intrusions as well as mineralisation (van der Merwe, 1976). The second theory (ii) is that the 'phenomenon of turbulence' occurred which overturned the sequence of these semi-consolidated intrusions and triggered the concentration of the mineralisation horizon through mechanical unmixing (Maier and Barnes, 2010). The great variation of Platreef rocks with respect to their composition is the root of these theories, because the complexity cannot be accounted only on floor rock contamination. These theories have remained a big question in literature, with no clear conventional suggestion on the occurrence of the layered intrusions with the mineralisation.

Another closely related study to the current study was by Yudovskaya and Kinnaird (2010) who worked with the occurrence and evolution of chromite chemical composition in the Platreef. Using the conventional consideration that chromitite layers are markers revealing the structure of the layered sequence of Bushveld Complex which subsequently allows the correlation of units along tens of kilometres, Yudovskaya and Kinnaird (2010) aimed at clarifying the relationship between the successions of intrusive sills in the Platreef. They described the regional occurrence and chemical composition of the massive and disseminated chromite so that the origin of the chromitite mineralisation is understood. Ultimately, their aim was to recognise a sequence of processes which affected chromitite primary features of the Platreef and to determine whether any correlation could be made with chromitite of the main body of the Bushveld Complex, consequentially correlating Platreef intrusions with the other limbs. Their conclusions were that the cumulus and post-cumulus chromite in the Platreef was modified during crystallisation, cooling, development of fluid-rich phases and interaction with xenolith material. Furthermore, they concluded that the chemical compositions of chromite, orthopyroxene and olivine are consistent with the Platreef as the equivalent of the CZ in the Northern Limb. Therefore, some similar approach is used in the current study in a way that the study will understand the occurrence of PGE mineralisation and their position in order to establish the relationship of the layered sequence within the Platreef. And eventually attempt to correlate the occurrence of intrusions and mineralisation between the boreholes.

In particular, the result of fluid-related-interaction of Platreef and the footwall rocks significantly varied the 'primary' stratigraphic succession of the Platreef. Holwell *et al.* (2005) and Holwell and McDonald (2005) mentioned that the post-emplacement fluid activity is also an effect on the variations in the style of distribution of mineralisation regionally in the Platreef along the strike. A similar study was done by Mathez (1995) in the Merensky Reef. He featured in his article the work by Kelemen and colleagues (reference therein) who recognised that the Merensky Reef was modelled accordingly by magmatic metasomatism which was represented as the combined processes of assimilation and fractional crystallisation. Harris and Chaumba (2001) concluded that the rocks within and just above the Platreef were affected by fluid-rock interaction and the involvement of some external fluids. Another work by Pronost *et al.* (2008) interprets that the lack of documented correlation between PGE and sulphides content is probably from the post-crystallisation fluid-rock interaction.

1.3. Aims and objectives

The aim of this study is to evaluate if there are any effects that were caused on the nature and/or style of the PGE-mineralisation of the Platreef at Moordkopje after the emplacement of Platreef intrusion on the country rock at the Moordkopje local area which is the Archaean granite-gneiss.

The objectives of the study will be carried through with the use of corelogs from two boreholes from the Moordkopje farm in the Akanani Area where the floor rock is the Archaean granite. The objectives were aligned with the focus of relating the mineralisation to the stratigraphic sequence of Platreef, and determine the influence of post-magmatic activities on mineralisation and on stratigraphic sequence itself.

Therefore this study is objective to:

- understand the position of PGE mineralisation and the sequence of the layered intrusions in the Platreef, and understand the relationship between them. This objective will be achieved by petrographic analysis of borehole samples in two boreholes along the lithological succession, accounting on the textural and compositional changes within the package.

- identify different types of rocks within the Platreef of the study area in order to understand the occurrence of magmatic and metasomatic rocks, and also mineralised and non-mineralised lithologies. The classification of samples to similar rock types from the two boreholes will be used through both petrography and whole rock geochemistry. Ore petrography will be incorporated in order to identify mineralised lithologies and types of mineralisation, and the locality of mineralisation within the stratigraphy.

- identify the occurrence and effects of footwall signatures within the Platreef lithologies and quantify the occurrence and the extent of signatures. This will be formulated by studying the petrographic alteration patterns, alteration geochemistry (i.e. mass transfer) and spider diagrams in order to characterise and quantify the effects of mobility of major and trace elements (e.g. LILE).

- investigate the origin, evolution and setting of magma intrusions within the Platreef package, in order to detect the number of magma influxes in the package, and assimilation from country rocks, in a way to correlate the occurrence of influxes and assimilation with mineralisation occurrence. This will be achieved by identifying diametric and similar element patterns and associations using statistical element correlation and bivariate diagrams, and subsequently use specific element ratios.

CHAPTER 2

GEOLOGY

2.1. Regional geology

2.1.1. Bushveld Igneous Complex

The Bushveld Igneous Complex (BIC) is the world's largest layered mafic complex and with its major chromium, PGE and vanadium deposits (Eriksson *et al.*, 1995). Kruger (2005) said that BIC is the largest mafic magma chamber in which the products of intrusion and crystallisation can be directly observed. The BIC is situated in the northeastern part of South Africa to the north of Johannesburg (Figure 2.1). It was emplaced on the northern margin of the Kaapvaal Craton between 2060 - 2050 Ma (Walraven *et al.*, 1990; Kruger, 2005), and overlays the rocks of Transvaal Supergroup and Archaean granitoids and greenstones. The outcrop and sub-outcrop of the Bushveld Complex cover the area of approximately 65 000 km^2 (Eriksson *et al.*, 1995), and is made up of a succession of mafic and ultramafic cumulates 7-8 km thick (Kinnaird *et al.*, 2005; Holwell, 2006).

There are three major plutonic suites that stratigraphically form the BIC, namely, the layered mafic to ultramafic rocks of the Rustenburg Layered Suite (RLS), and the felsic rocks in the Rashoop Granophyre Suite (RGS) and Lebowa Granite Suite (LGS). The BIC is covered by the volcanic cover referred to as the Rooiberg Group. The layered mafic to ultramafic series, the RLS, forms the floor of the complex, and is made up of dark-coloured, heavy, igneous rocks interleaved with lighter, feldspar-rich layers (Eales, 2014). The succession of layered units of the RLS is subdivided, from the bottom, into Marginal Zone, Lower Zone, Lower Critical Zone, Upper Critical Zone, Main Zone and Upper Zone. The lithologies of the RLS in each zone are (e.g. according to Eales, 2014); orthopyroxenite, harzburgite and norites of Marginal Zone, dunite, harzburgites and orthopyroxenites of Lower Zone (LZ), orthopyroxenites, harzburgites and chromitite of Lower Critical Zone (C_LZ), orthopyroxenites, norite, anorthosite, chromitite and harzburgite of Upper Critical Zone (C_UZ), gabbronorites, gabbro and anorthosite of Main Zone (MZ), and various gabbro, anorthosite, magnetites and diorites of Upper Zone (UZ).These zones generally complete the stratigraphy of the two well-studied major limbs, the Western and Eastern Limbs. Whereas in the Northern Limb, the succession of these zones is incomplete and complicated.

There are five main limbs which contain the layered rocks of RLS, with much of their full extent still being covered by rocks that are either old or younger (Eales, 2014). From Kinnaird *et al.* (2005) these lobes are the:

- Eastern Limb,
- Western Limb,
- Far Western Limb, and
- Northern Limb,
- the southeastern Bethal Limb

However, the mafic and ultramafic rocks of the RLS crop out in Eastern, Western and Northern Limb. While in the Bethal occurrence of the complex refers to that portion of the eastern Complex concealed under a relatively thin cover of younger sediments of Karoo rocks (Eales and Cawthorn, 1996; SACS, 1980; Kinnaird *et al.*, 2005). The current study is restricted in the Northern Limb of the BIC. Much of the attention of the recent geological research in the Bushveld has been fixed onto the Northern Limb and its major PGE-mineralised pyroxenitic horizon called the Platreef.

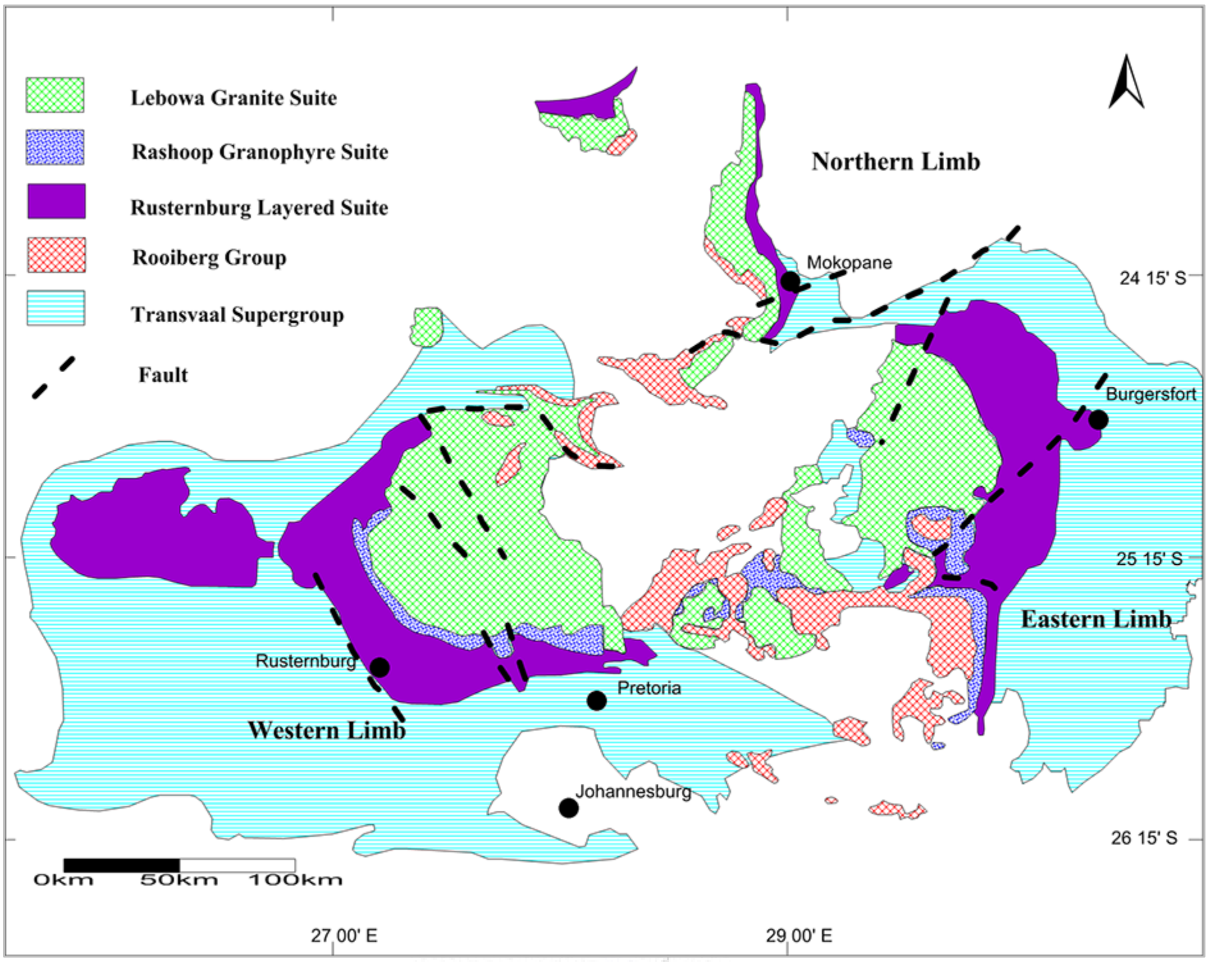


Figure 2.1. The geological map of the Bushveld Complex of South Africa. The outline of the Akanani prospect area is shown on the map encircled in red on the Northern Limb part where the study area is located.

2.1.2. The geological background of the Northern Limb of Bushveld Complex

The Northern Limb of the Bushveld Complex, which forms focus of this study, extends from the Zebediela Fault, which is part of the Thabazimbi Murchison Lineament (TML), south of Mokopane, northwards for about 110 km until it is covered by younger Waterberg sediments (White, 1994; Kinnaird *et al*., 2005) (Figure 2.1). The layered mafic-ultramafic suite in the Northern Limb dips to the west (Eales, 2014), and strikes north-south direction with a sinuous outcrop (Kinnaird *et al*., 2005; Holwell and Jordaan, 2006; Van der Merwe, 2008).

The succession of the layered mafic series of the Northern Limb differs significantly from the sequences in the Eastern and Western limbs of the BIC such that no units of the LZ up to the lower parts of the Critical Zone are recorded for RLS (White, 1994; Lee, 1996). This deviation is owing to the poor development of these *zones* to a certain extent along the limb especially towards the north. Kinnaird *et al.* (2005) mentioned that it is not clear whether the Northern Limb was connected to the main BIC during emplacement. The stratigraphy of the layered mafic series in the Northern Limb is very complicated in a way that the PGE-mineralised horizon (i.e. the Platreef), which can be equated to the Merensky Reef of the Eastern and Western limbs (White, 1994; Kruger, 2005), rests directly on the country rocks of the Transvaal Sequence in the southern parts, and on the Archaean granite towards the north of the limb. The Platreef of the Northern Limb, as of this effect, developed a unique type of mineralisation (Schouwstra *et al.*, 2000). The Main Zone forms the hangingwall contact of the Platreef package (Kruger, 2005; and references therein), and the magnetite-bearing rocks of Upper Zone overlying the Main Zone gabbronorites especially in the northern parts of the limb (Van der Merwe, 2008).

2.1.3. The Platreef

A brief explanation on Platreef has been discussed in the introduction in Chapter one. The Platreef is a 10 - 400 m thick layered mafic-ultramafic intrusion comprising of predominantly pyroxenitic lithologies, and hosts platinum group element (PGE) and base-metal sulphides (BMS) mineralisation.

It forms the base of the Main Zone in the Northern Limb (Van der Merwe, 1976), and rests directly on the country rocks of Transvaal Supergroup and Archaean granite basement. The mafic rocks of Platreef were previously considered as part of the Critical Zone similar to that of the Western and Eastern Limbs of the Bushveld Complex (Wagner, 1929) with some authors accepting his suggestion (e.g. Gain and Monstert, 1982; White, 1994; Vermaak, 1995; Barnes and Maier, 2002). McDonald *et al.* (2005) provided a review that suggests that Platreef cannot be regarded as part of Critical Zone in any geological and geochemical aspect. Kruger (2005) interpreted both the Platreef and the Merensky Reef to form the base of the Main Zone of the Rustenburg Layered Series. Platreef strikes north-south and dips almost at 40^{o} south-west (Lee, 1996).

The Platreef sequence varies in thickness and has an irregular, varied footwall contact with the floor rocks from south to north of the limb. In the south, it rests on the Magaliesberg quartzite of the Daspoort Formation, and towards the north, it locally transgressed to banded ironstone of the Penge Formation and dolomite sequence of Malmani Subgroup, until to the Archaean granite-gneiss far north end of the limb (Eales and Cawthorn, 1996).

The lithologies of the Platreef are pyroxenites, feldspathic pyroxenites, gabbronorites, norites, harzburgites, peridotites, serpentinites and a variety of hybrid lithologies (Kinnaird *et al.*, 2005; Holwell and Jordaan, 2006; Holwell and McDonald, 2006).

The variety of hybrid lithologies at the lowermost Platreef is a result of the varied floor rocks in contact with them locally. That is, the hybridised lithologies by dolomite floor rock (generally referred to as parapyroxenites) are significantly varied from the ones by granite-gneiss ("quartzo-feldspathic pyroxenite"). McDonald *et al*. (2005) described Platreef as a contaminated, frequently xenolith-rich, unit that is geologically more complex than any of the PGE reefs in the Eastern and Western limbs.

The host rocks of the Platreef are predominantly coarse-grained feldspathic pyroxenite that consists of cumulus orthopyroxene (30–70 vol. %), intercumulus plagioclase (10–30 vol. %), post-cumulus clinopyroxene (up to 20 vol. %), subordinate phlogopite, quartz and accessory phases (Kinnaird *et al.*, 2005; Yudovskaya and Kinnaird, 2010). Other host rocks (e.g. olivine pyroxenites and feldspathic harzburgites) contain variable amounts of olivine (5–70 vol. %), and their plagioclase content may reach up to 10–15 vol. % (Yudovskaya and Kinnaird, 2010)

The varied floor rocks that underlain the Platreef has made this reef to develop a very unique type of mineralisation relative to other mineralised PGE-bearing reefs in the Eastern and Western limbs (i.e. Merensky Reef, UG2 Reef). Yudovskaya and Kinnaird (2010) said that the Platreef is characterised by a more widespread and richer sulphides mineralisation compared with the relatively restricted, sulphides-poor mineralisation of the Merensky and UG2 Reefs. The Platreef is a magmatic Ni, Cu and PGE deposit with the lower PGE grade, the Pt: Pd ratio of approximately 1, and higher Ni content than the Merensky and UG2 Reefs (Kinnaird *et al.*, 2005). Different styles of mineralisation occur within different sectors of the Platreef (Kinnaird *et al.*, 2005).

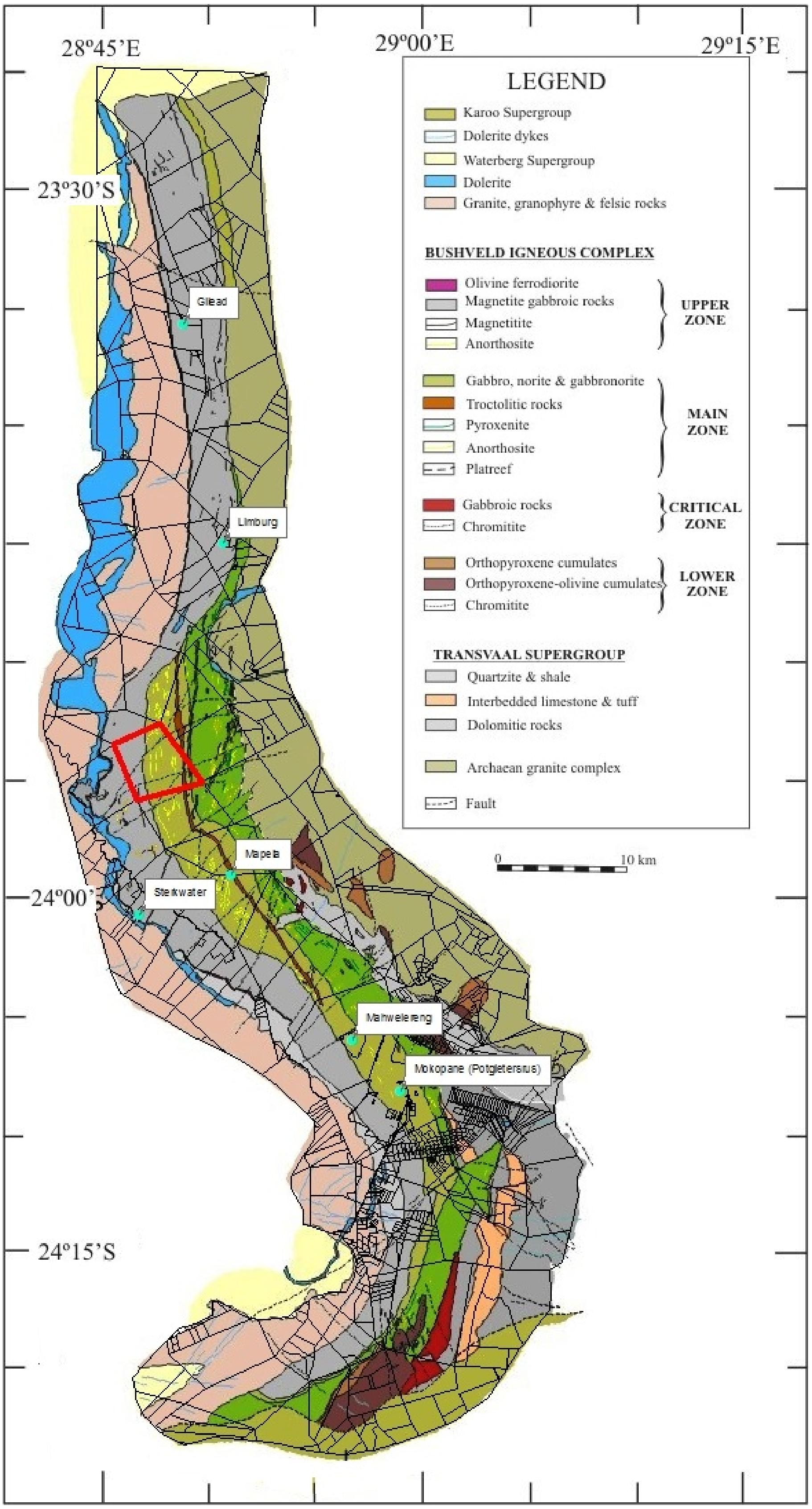


Figure 2.2. The geological map of the Northern Limb of the Bushveld Complex. The study area the Moordkopje Farm boxed in red. The map was modified by Ashwal *et al.* (2005) which is originally from Van der Merwe (1978).

2.2. Local geology

This section describes the local geology of Moordkopje 813 LR farm using the borehole information from published literatures (Cawthorn *et al.*, 1985; Holwell, 2006; Holwell and McDonald, 2006; Mitchell and Scoon, 2012). However, most of these authors have researched on the geology of Overysel farm and not Moordkopje farm, and their work was used here because these two farms have the same Archaean granite-gneiss footwall and adjacent to each other. Although, Platreef is a very complex reef with great variety of rock types, therefore this approach does not suggest similarities of geology, whatsoever, between these two farms. There is a lack of detailed petrography for much of the Platreef rocks at Moordkopje, such that, there is very little of the published geological description of the Moordkopje 813 LR farm apart from Roelofse *et al*. (2009), Roelofse and Ashwal (2008); Roelofse (2010), Roelofse and Ashwal (2012). Although these authors researched much only on the Main Zone at Moordkopje.

Furthermore, Moordkopje 813 LR and Zwartfontein 814 LR adjoining farms are designated as the Akanani Prospect Project that was initiated by Lonmin Plc (Figure 2.3). Geological descriptions of rocks at Zwartfontein 814 LR has been done by Van der Merwe (2011) and Mitchell and Scoon (2012), and this has also been used to relate and describe the local geology of Moordkopje 813 LR.

The local geology of Moordkopje will be described stratigraphically from the footwall of Archaean granite-gneiss, to varied Platreef lithologies, up to the hangingwall of Main Zone gabbronorites.

2.2.1. Moordkopje 813 LR

The Moordkopje 813 LR has Archaean granite-gneiss as the floor of the area. The granite and gneiss in the Overysel area (includes Moordkopje) were identified as the Utrecht Granite and as the Hout River Gneiss, respectively, by Geological Survey of South Africa (cited in Holwell and McDonald, 2006). Cawthorn *et al.* (1985) described the granite as a medium-grained white, granular rock that contains small flakes of biotite and occasional garnets. Holwell (2006) described the granite as a pink, fine- to medium-grained granite consisting of mesoperthitic alkali feldspar, quartz, minor muscovite and accessory monazite and kobeite.

The gneisses (normally referred to as granofels) are a set of banded gneisses comprising pale, quartzo-feldspathic bands and darker, more mafic orthopyroxene-rich bands (Holwell and McDonald, 2006). The gneisses has base metal sulphides present sporadically, that occur as small blebs along grain boundaries with no preferred association with either the pyroxenitic or felsic bands (Holwell and McDonald, 2006).

The gneisses were intruded by granitic dykes, and these dykes are composed of coarse-grained quartz and K-feldspar, which commonly display a myrmekitic intergrowth (Holwell, 2006). Cawthorn *et al.* (1985) had described this occurrence as the dike-like pegmatitic veins which trends east-west and have developed close to the contact with the Platreef. Moreover, the xenoliths of dolomite are not a significant component of the Platreef at Akanani (Mitchell and Scoon, 2012).

The Platreef has a relatively planar contact with the gneisses (Cawthorn *et al.*, 1985). The rocks of Platreef are typical orthocumulates with orthopyroxene and infrequent chromite as the only texturally cumulus phases, with plagioclase as the main intercumulus phase and clinopyroxene, mica and infrequent quartz (Cawthorn *et al.*, 1985). Platreef rocks in general as described above includes pyroxenites, feldspathic pyroxenites, gabbronorites, norites, harzburgites, peridotites, serpentinites and a variety of hybrid lithologies (Kinnaird *et al.*, 2005).

Holwell and McDonald (2006) described the pyroxenites as typically coarse-grained and made up of cumulus orthopyroxene of $En_{75–80}$, with 5–20% inter-cumulus plagioclase up to 5% clinopyroxene and a little quartz, with some accessory phlogopite, chromite and ilmenite. The involvement of quartz and other felsic phases within the Platreef rocks was explained by Barton *et al.* (1986) by proposing that the underlying granite was partially melted at the time of Platreef intrusion which led to contamination of lower Platreef.

Although pyroxenites are considered as the key and dominant rock type in Platreef (including Akanani area Platreef), Mitchell and Scoon (2012) believed that the most significant lithology in the mineralised sequence at Akanani is harzburgite. The description of this rock by Mitchell and Scoon (2012) was given as having irregular orthopyroxene oikocrysts of 5 cm or more in diameter that occurs in a matrix dominated by black serpentinite that contains relict unaltered olivine. According to Mitchell and Scoon (2012), harzburgite layers are typically well mineralised, in particular, with respect to base metal sulphides.

Lonmin divided the Platreef at Akanani into four lithological units, P1 to P4, respectively from the bottom to top. Van der Merwe (2011) summarised the description of these units as follows:

- The **P1 unit** consists predominantly of medium-grained feldspathic pyroxenite, with subordinate norite, gabbronorite, melanorite, pyroxenite and also harzburgite.
- The **P2 unit** is well-mineralised, and varies from medium to coarse-grained feldspathic pyroxenite with intervening layers of harzburgite.
- The **P3 unit** is mostly barren and consists of medium-grained pyroxenite with poikilitic clinopyroxene.
- The **P4 unit** varies from fine to medium grained melanorite to feldspathic pyroxenite, and contain no PGMs, except in association with mineralised harzburgites that transgressed through the upper P2, P3 and P4 units (even into the Main Zone).

The hangingwall to the Platreef consists of mottled anorthosite and leuconorite of the Main Zone, which is then overlain by Main Zone gabbro and norite (Van der Merwe, 2011). The similar in a broader description by Holwell and McDonald (2005) was that from Zwartfontein to Overysel, the Platreef is overlain by Main Zone norites and gabbronorites characterised by the presence of cumulus plagioclase.

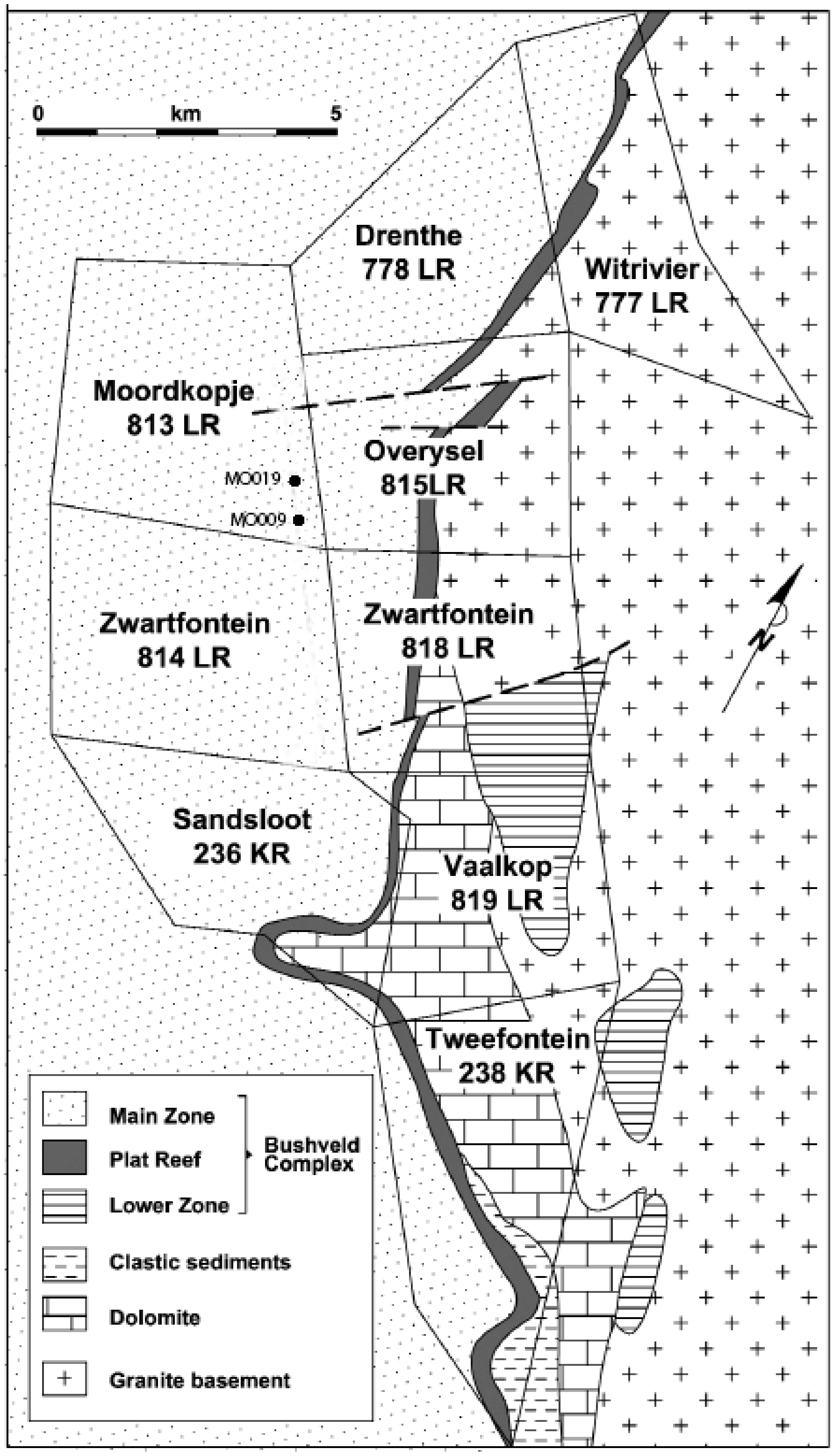


Figure 2.3. The geological map of the Northern Sector showing all the farms that form part of the sector. The map also shows the location of the boreholes of the project. The map was taken from Mitchell and Scoon (2012).

CHAPTER 3

METHODOLOGY

Methodology chapter will deal with the approach used in the current project. It details the relevance of each technique towards the aims and objectives of the work. The outline of the samples and the sampling methods form part of this chapter. The main geological analytical methods used are petrography and whole-rock geochemistry. Petrographic descriptions of the rocks precede geochemical analysis. The core focus and objective of the project is to understand rock succession and rock variation with depth, therefore, petrographic analysis plays a major role towards the objectives of the project. The whole rock geochemistry and the methods therein will be applied as a tool to characterised the rock in terms of elemental composition (i.e. major and trace elements), and to identify the occurrence and effects of footwall signatures within the Platreef lithologies as well.

3.1. Sampling and samples

The samples used for the project were taken from two boreholes from the Akanani Project at Moordkopje 813LR Farm. Access to cores was granted by Lonmin and the students did the sampling. The sampling method was based on lithological changes, rock alterations and mineralisation. Two boreholes were sampled and logged, namely, MO009 and MO019. Fifty two samples were collected in borehole MO009, and fifty eight samples from borehole MO019. The scope of sampling covered from the Main Zone, through Platreef and into the granite floor rock. In this project, however, only Platreef samples were studied for geological and geochemical characterisation and mineralisation occurrence, with some of the floor rock samples as reference samples to original Platreef samples.

3.2. Petrography

Thin-sections were prepared at University of the Western Cape Geochemistry Labs. Petrographic descriptions of the samples was done at the University of the Western Cape Microscopy Lab. The samples for thin sections were selected in a way to cover all the lithologies within the Platreef. Some of the Main Zone and floor granite-granofels samples were included to reference the hangingwall and footwall to the Platreef, respectively.

The petrography section was categorised into macroscopic and microscopic analyses in order to reflect the key features of the rock on hand-specimen and under the microscope. The key features of the rock observed herein are modal composition (i.e. major and minor constituents and accessory mineral content), textures, grain size variation, alteration and mineralisation with regards to the microscopic analysis. In terms of macroscopic analysis the descriptions were based on the colour of the rock and the texture of the rocks. The aim of this analysis was to present the rock succession in each core log. This analysis included the relationship in the boreholes in terms of lithological similarities.

The rock composition was expressed as modal percentages of mineral content obtained through visual estimation. The texture of the minerals was expressed in terms of grain shape (i.e. euhedral, subhedral and anhedral) and grain-size (i.e. fine-grained, medium-grained, coarse-grained and also pegmatoidal size). Grain-size was also expressed in terms of millimetres by visual estimation.

3.3. Geochemical data

Fifty samples from two drill cores were analysed for geochemistry. The geochemical data analysis was done on two different batches. The first batch of forty samples were analysed in 2011 at Acme Labs in Vancouver, Canada. The other ten additional samples were analysed in 2014 at C.A.F., Environmental Analysis Laboratory of Stellenbosch University in Stellenbosch, South Africa. The additional ten samples were added to improve the data in terms of being representative of the other lithologies in the core log. The geochemical analysis from Acme Labs in Canada included Fire Assay analysis of PGEs (Pt and Pd) for selected samples.

The sample preparation for all the samples was done at the University of the Western Cape before they were sent out for laboratory analysis. The rock samples from cores were initially washed with distilled water prior to crushing and milling. A representative sample of about 50 g was cut from a 15 cm sampled core (Plate 3.1), and was crushed and milled into powder using the Dickie and Stockler TS-250 mill.

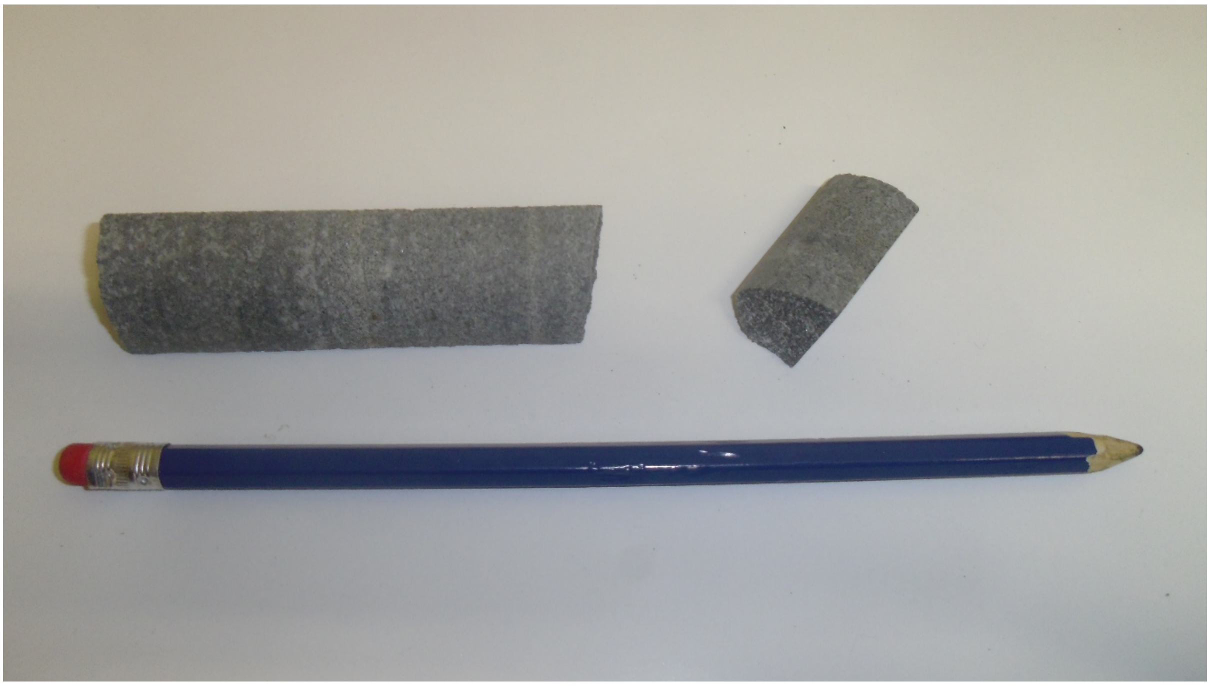


Plate 3.1. A representation of a 50 g cut sample that was crushed and pulverised during sample preparation for XRF laboratory analysis.

3.3.1. Major, minor and trace elements

The geochemical data was produced by XRF analysis using fused beads. The data was made up of major, minor and trace elements. The major and minor elements analysed as oxides were SiO_2, Al_2O_3, Fe_2O_3, MgO, CaO, Na_2O, K_2O, MnO, TiO_2, P_2O_5 and LOI determination in weight percentage (wt.%), and the trace elements were Ba, Ce, Co, Cr, Cu, Nb, Ni, Pb, Rb, Sr, Th, U, V, Y, Zn, and Zr in parts per million (ppm). The LOI (loss on ignition) which is weight loss (or gain) due to volatiles content of the rock (including the water combined to the lattice of silicate minerals) was done at 1 000 ºC, while the gain on ignition was related to the oxidation of the rock.

3.3.2. Platinum Group Elements (Pt and Pd)

The PGEs analysis was done on selected samples which are only Platreef samples. The table which shows the selected samples analysed is presented in Appendix I-C. The PGE analysis were used in reviewing the location and occurrence of mineralisation within the stratigraphy by looking at the high and low contents within the rocks. The PGEs were analysed by Fire Assay in Acme Labs as mentioned above. A total of 11 samples was analysed for platinum (Pt) and palladium (Pd) using a Thermofischer X-Series 2. The quality of analysis was controlled using the reference PGE internal standard solution as Specpure® Alfa Aeasar Precious metal, Plasma standard 21 solutions: Au, Ir, Os, Pd, Pt, Re, Rh, Ru at 10g/ml with matrix 20% HCl.

3.4. Whole rock geochemistry

The whole rock geochemistry was done to ascertain the fractionation trends of major and trace elements in the rock groups based on the classification done in petrography. This was achieved by using the statistical classification methods (i.e. Discriminant Analysis) in terms of major elements, and by using Spider diagrams in terms of trace elements. Furthermore, the whole rock geochemistry was used for alteration geochemistry in order to identify the occurrence and effects of footwall signatures within the Platreef lithologies by applying the method of Mass Transfer.

In sequence, the geochemistry section started by:

- Descriptive statistics which explains the distribution and interrelationships of the data and can be expressed in summary table. This technique is a useful tool to determine the structure of the data in order to work with a very reliable data and avoid incongruence in the data.

- Then, the geochemical characterisation of rocks using Discriminant Analysis, which ascertains the fractionation trends of major and trace elements in rock groups obtained by petrography.

- And lastly the geochemical exploratory methods (i.e. bivariate plots, element ratios and patterns) which deals with basic geochemical modelling that evaluates and models the differences amongst the rock groups, and identifies evolution and fractionation within the rock groups. This part is further useful in understanding the rock groups when incorporated with the mineralisation and the types of lithological alterations that were involved.

3.4.1. Descriptive statistics

The descriptive statistics is a preliminary review of the geochemical data set which includes data summary parameters (normally the range, minimum value, mean and/or geometric mean, and standard deviation), and also includes element interrelationship which is known as correlation analysis. Data summary table detects if the data is normally distributed (i.e. outliers and background values) which is the concern at the early stages of the geochemistry data analysis. Histograms were used to complement the data summary as a graphical representation of the distribution of data.

Element interrelationship (correlation analysis) was used to quantify the strength of associations between two geochemical elements. The correlation analysis was expressed using the correlation coefficient (r) which describes the quality of relationship between the geochemical elements at a scale between -1 and 1 (i.e. $-1 \leq r \leq 1$). Where -1 explains a very strong relationship of elements inversely, while 1 also explains a very strong but direct relationship between the elements.

3.4.2. Discriminant Analysis

Discriminant analysis (DA) is a statistical method of supervised classification (Filzmoser *et al.*, 2009). The supervised classification involves assigning geochemical elements into the pre-existing rock types or rock groups which were established from petrography. The objective of using DA was to geochemically characterise the rock groups and link them with the descriptions in petrography.

Discriminant Analysis has been widely used in exploration geology. Peh *et al.* (1998) applied DA as a tool to distinguish Quaternary sediments. In geochemistry, Discriminant Analysis is used to identify variables that exactly discriminate between different groups (e.g. rock types, chemo-stratigraphic layers).

3.4.3. Spidergrams

These are multi-element diagrams which are based on incompatible elements normalised using their estimated primitive mantle composition. In the current project, the estimated primitive mantle composition used was that by Sun and McDonough (1989) and McDonough and Sun (1995), as this is the most common method applied to the data of igneous rocks analysed through XRF. Spidergrams were used to characterised and quantify the effects of mobility of major and trace elements (e.g. LILE), and additionally to understand the compatibility and affinity of trace elements in each rock group. Furthermore, the spider diagrams provide assistance in evaluating trace element fractionation between the magmatic rock types and the metasomatic rock types.

3.4.4. Exploratory and modelling analysis

Exploratory and modelling analysis essentially is referring to the basic geochemistry analysis methods that evaluate and model the differences between the rock types in terms of element concentration. These methods, for example, include bivariate diagrams where two major and two trace elements are plotted on a scatter plot concerning the rock types so as to show variation in the composition of these rocks types. These analyses are further explained as follows:

3.4.4.1. Bivariate diagrams

Bivariate diagrams or scatter plots are diagrams that depict variation in element composition in rock types. These type of diagrams were applied in the current project so that the geochemical processes can be predicted based on how the elements behave relative to each other. Furthermore, the method also aided in identifying relationships among the rock types in a simplified approach.

3.4.4.2. Element ratios

The element ratios and patterns were used to investigate the evolution and setting of magma intrusions within the Platreef package by identifying diametric and similar element patterns and associations. The ratios used include transition elements and some the major elements e.g. CaO/Al_2O_3, K_2O/TiO_2 and Cu/Zr and Ni/Cr. The use of these ratios was to facilitate how the Platreef rocks originated in terms of their source and their evolution. Moreover, the element ratios were compared with mineral alterations and mineralisation occurrence of the area by downhole plots to assess the relationships between them. These ratios were also used to evaluate whether there was progressive influxes of different magmas, or whether it was only one magma that produced the Platreef package. The ratios Cu/Zr and Ni/Cr were mainly used for mineralisation assessment in the Platreef. The element ratios that were used in this study are similar to those by Cawthorn and Lee (2005) and Stevens (2007).

3.4.4.3. Alteration geochemistry and Mass transfer

The alterations and mass transfer are the guidelines in understanding the assimilation units that had occurred between two or more lithologies during and after the emplacement of one layer on the other. Mass balance was aimed at assessing the nature of the interaction between the granite-gneiss floor rock and the Platreef intrusion. The use of isocons of major and trace element transfer was applied to quantify the mass transfer in the rocks of Moordkopje. The study used the Microsoft Excel software (EASYGRESGRANT®) from López-Moro (2012) and Geochemical Data Toolkit® (GCDkit) from Janousek *et al.* (2006). These software apply the principles of the isocons with basis of equations by Gresens (1967), Grant (1986) and a review of the latter by Grant (2005).

$$C_i^A = M^O/M^A(C_i^O + \Delta C_i) \qquad eq.\ (1)$$

Where C_i is the concentration of species "*i*", and *O* and *A* refers to original and altered rocks respectively. MO and MA are equivalent masses before and after alteration, and ΔCi is the change in concentration in species "*i*".

3.4.4.4. Mineralisation

It was a necessity and important to understand the distribution of the platinum (Pt) and palladium (Pd), and also the base metals (Ni-Cu) in the Platreef at Moordkopje. However, gold (Au) and chromium (Cr) were also included in the analysis of the mineralisation of the study area. The box-plots and bivariate diagrams were used to depict the distribution of these metals within the Platreef.

CHAPTER 4

RESULTS

4.1. Introduction

Chapter four contains the outcomes of the petrography and the geochemistry of the project. Thin sections were studied under the microscope to determine the petrography of the rocks. Geochemical data are used to spatially define the compositional variation of the host rocks and associated mineralisation. This work was started with petrography in order to determine the spatial mineralogical variation patterns in the host rock and associated mineralisation. The former will be complemented with the spatial variation patterns of trace elements and oxides.

The purpose was to understand the sequence of the layered intrusions in the Platreef and the position of the associated PGE mineralisation. Then identify different types of rocks within the Platreef of the study area through petrographic analysis in order to understand the occurrence of magmatic and metasomatic rocks, and also mineralised and non-mineralised lithologies. The whole rock geochemistry was then done to ascertain the fractionation trends of major and trace elements in the rock groups based on the classification done in petrography.

These objectives were achieved by petrographic analysis of borehole samples in two boreholes (MO009 and MO019) along the lithological succession, accounting on the textural and compositional changes within the package. The classification of samples to similar rock types from the two boreholes was done through petrography and complemented through whole rock geochemistry. Ore petrography was incorporated in order to identify mineralised lithologies and types of mineralisation, and the locality of mineralisation within the stratigraphy.

4.2. Petrography

4.2.1. Introduction

Platreef consists of a series of pyroxenites and intercalating gabbronorites that show compositional variation and form discontinuous layers that are not easily correlated spatially. Hence, it has been an underlying problem to correlate the sequence of intrusive events amongst each other or to understand the stratigraphy of the rocks in Platreef. The comprehensible stratigraphy will assist and contribute to the mining companies to have a definite understanding of the subsurface when they are drilling in the Platreef.

The objectives in petrography are to provide at least a comprehensible schematic lithostratigraphy of the Platreef rocks. Ultimately, the intention is to develop a spatial correlation between two boreholes of Moordkopje farm.

In this study, petrography of the rocks of the Platreef (feldspathic pyroxenites and harzburgites, and some gabbronorites) was substantially studied in terms of spatial textural and mineralogical variations in the rocks. The aim was determine if there are any significant differences and similarities in rocks with respect to grain size, grain sorting, grain shape and primary mineralogical composition and the alteration in the rock successions. The former can provide useful information for inferring the systematic stratigraphic sequence of the Platreef rocks.

Numerous studies have been conducted on the petrography of the Platreef rocks (e.g. Harris and Chaumba (2001), Kinnaird *et al*. (2005), Roelofse and Ashwal (2012), Mitchell and Scoon (2012)), none have covered the petrography of Platreef at Moordkopje. Roelofse and Ashwal (2012) did petrography of lower Main Zone at Moordkopje, while Mitchell and Scoon (2012) did petrography at Akanani area in Zwartfontein. The petrography of Platreef rocks at Moordkopje has not been done before. This work is looking into closing this gap, with the aim of establishing a relative stratigraphy of Platreef at Moordkopje underlain by the granite floor rock.

The description of rocks was carried in two ways. First, by describing the rocks macroscopically through corelogging. The cores were logged from the footwall rocks to the Main Zone in each borehole. The aim is to identify the rock succession and correlate the lithologies in the boreholes. The other way of describing the rocks was by an optical microscope. The objectives of microscopic descriptions are to evaluate the mineralogical and textural trends stratigraphically from the footwall rocks to the base of the Main Zone.

The evaluation of the results for macroscopic descriptions was based on the mineralogical dominance (i.e. colour) and the textural attributes of the rocks. The colour of rocks was evaluated with respect to mafic-to-felsic appearance from the rock (dull and grey to pale and white). The leuconorites are more pale and whitish than the norites as a result of enrichment of plagioclase in the former. The pyroxenites are duller and grey than the feldspathic pyroxenites, where the latter has pale spots of plagioclase. In other words, the colour of these rocks is simply determined by the dominance of pyroxenes to feldspars. This information makes it possible to identify the relationship between the rocks of similar nature. The macroscopic textures were evaluated in terms of the visible grain sizes from one rock to another e.g. there are feldspathic pyroxenites which are pegmatoidal and those, which are medium-grained to fine-grained. The norites are mostly coarse-grained to medium-grained texture. The granite-gneiss floor is fine grained.

In terms of the microscopy results, these gave the mineral composition using the count method, thus an estimate the modal percentages of the mineral grains in the rock section. The microscopy results also gave the texture of the rocks, as to whether the rock has a very coarse or very fine texture. The textural terms were also used to characterise the rocks, e.g. ophitic texture when the cumulus plagioclase grains are enclosed by a pyroxene grains as prevalent in the Main Zone norites. The grain size of minerals were classified as measured in the field of view of the microscope e.g. 5 mm grain size of orthopyroxene. The grain shape was assigned in terms of a crystal face of the cumulus grains using the terms like euhedral, subhedral, anhedral, and 'elongated' for the plagioclase grains (and to some extent the biotite and amphibole grains as well).

4.2.2. Macroscopic descriptions of rock types

4.2.2.1. Rocks succession in boreholes

The lithological logs of MO009 and MO019 drill-cores, based on LONMIN Plc nomenclature for Akanani Project, are presented at the end of this section in Figure 4.2 and Figure 4.3. The rocks will be described successively from the footwall in each of the two boreholes to the top, Main Zone. The samples were not collected according to a regular interval from the cores. Rather, the samples were taken according to the change in major rock type, for example, a change from a feldspathic pyroxenite to a harzburgite would mean one sample taken for each, without considering the thickness of each rock type. A detailed description of sample collection is given in Chapter 3: Methodology.

A major aim of the work was to investigate the fluid-rock interaction. It was therefore important to take the floor rock into due consideration. Therefore, these two boreholes were selected intentionally to discern granitic floor effects on the Platreef rock sequence (or stratigraphy). Both boreholes are underlain by the same floor rock, which is a pink Archaean granite. This is the same granite which was mentioned by Harris and Chaumba (2001) and also Holwell and McDonald (2006) of Kaapval Craton. Therefore, in other words, selecting the granitic floor rock was to assess the fluid rock interaction effects, if any, on the Platreef stratigraphy and mineralisation during its emplacement.

The boreholes, MO009 and MO019 respectively, are geographically located at (X: -2651502.768; Y: -13445.906) and (X: -2650279.590; Y: -14339.890) towards the eastern boundary of the Moordkopje 813 LR Farm. They are about 1.5 km apart on the same drill traverse northwards, or along the same strike-line striking NW (Figure 4.1).

The following describes rock succession at Moordkopje in reference to the macroscopic appearance of the rock samples that were obtained from these two drill cores (MO009 and MO019). The descriptions of the common major rock types and other rocks under the microscope are in section 4.2.3.

The rock types of Platreef unit were studied in greater detail than the Footwall and Main Zone lithologies as the former and associated mineralisation is the focus of the study.

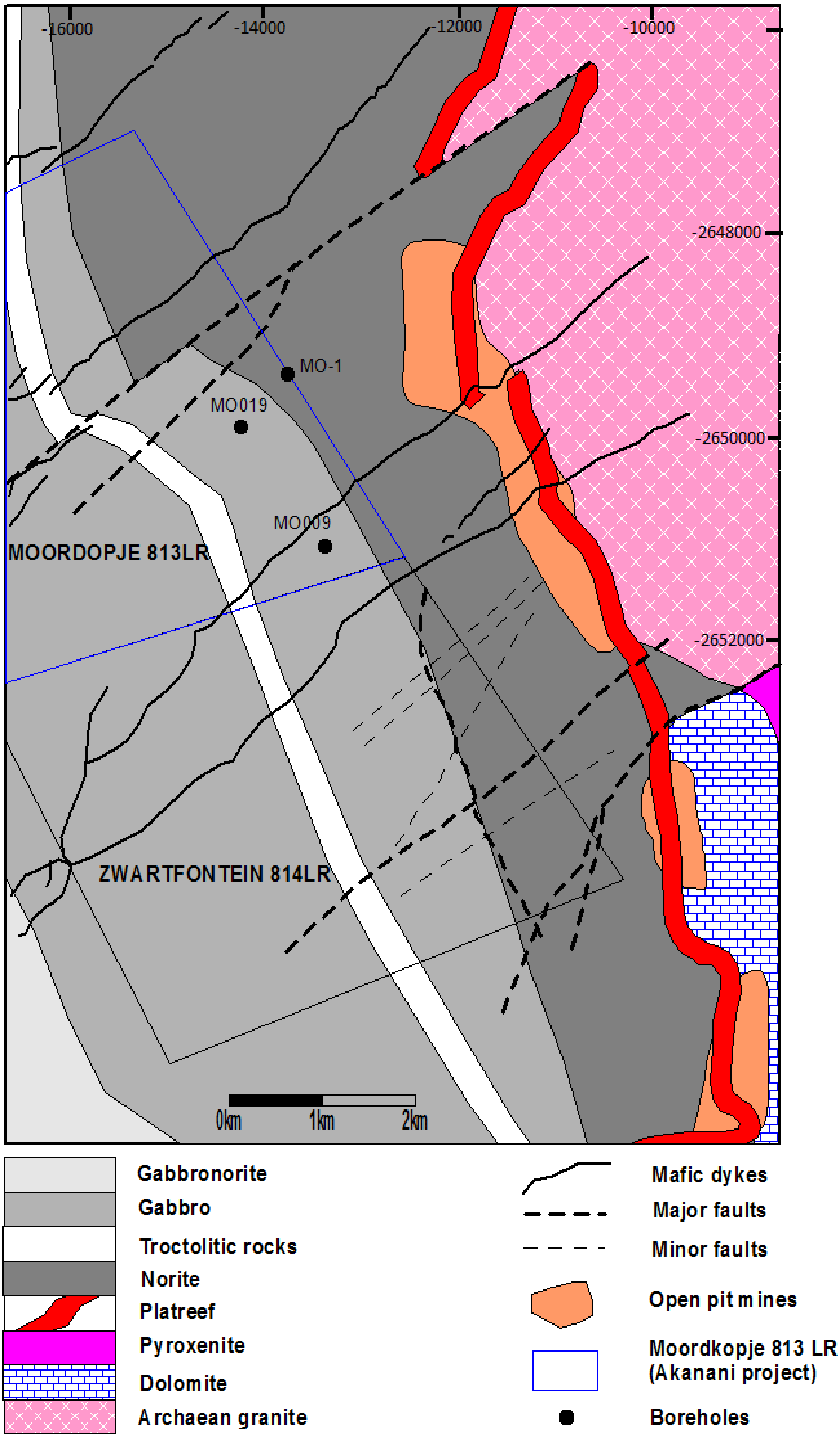


Figure 4.1. The regional map showing the allocations of the boreholes of this study (MO009 and MO019). Borehole MO-1 was studied by Roloefse and Ashwal (2012). The geological map was taken from van der Merwe (2011).

Plate 4.1. The layout of the samples from boreholes MO009 and MO019. The logging did not include the whole borehole length, however, only the selected samples are displayed.

A. Borehole MO009

The MO009 drill hole ended at intercepting the pink granite at a depth of 2018.66 m from the surface. The sampling of this drill core began at a depth of 120 m (where sample MO009-1 was taken), and the last sample (MO009-52) was taken at the end depth of 2018.66 m. The sampling programme was specifically based on mineralised zones. The section at a shallower depth from 120 m to the surface is part of Main Zone which is not of the study's interest.

The MO009 corelog from the bottom comprises of the pink granite, which was intercepted by the drillhole at the maximum depth of the core. The available thickness of the granite is of 3.57 m. It is light in colour, and fine grained. The feldspars are very creamy pinkish in colour (Plate 4.2).

Plate 4.2. The pink granite that forms the basement in the Northern Sector of the Platreef. The sample is at a depth of 2018.66 m (MO009-52)

There was a core-loss of 17.97 m of which there is no information known in terms of rock identity. However, at depths between 2001.32 m and 2008.71 m are calc-silicate xenoliths that were sampled as MO009-49 and MO009-50. The thicknesses of these calc-silicates are 20 cm and 16.7 cm respectively. They are very fine-grained and dark grey in colour (Plate 4.3).

Plate 4.3. The calc-silicate at a depth of 2001.32 m in core MO009. It is relatively a very fine rock.

The calc-silicates are overlain by a zone of thin interlayer between granofels of the footwall and the pyroxenites of the Platreef. This zone is 16.22 m thick, where there is alternating thin beds (or xenoliths) of granofels and pyroxenites (i.e. this type of granofels is later termed as hybrid rocks). Plate 4.4 shows the various types of hybrid rocks in this zone or within the zone.

The hybrid rocks show visible xenoliths of pyroxenites (augite-rich pyroxenites in particular) within a granite rock matrix (Plate 4.4), and the rock is relatively fine grained.

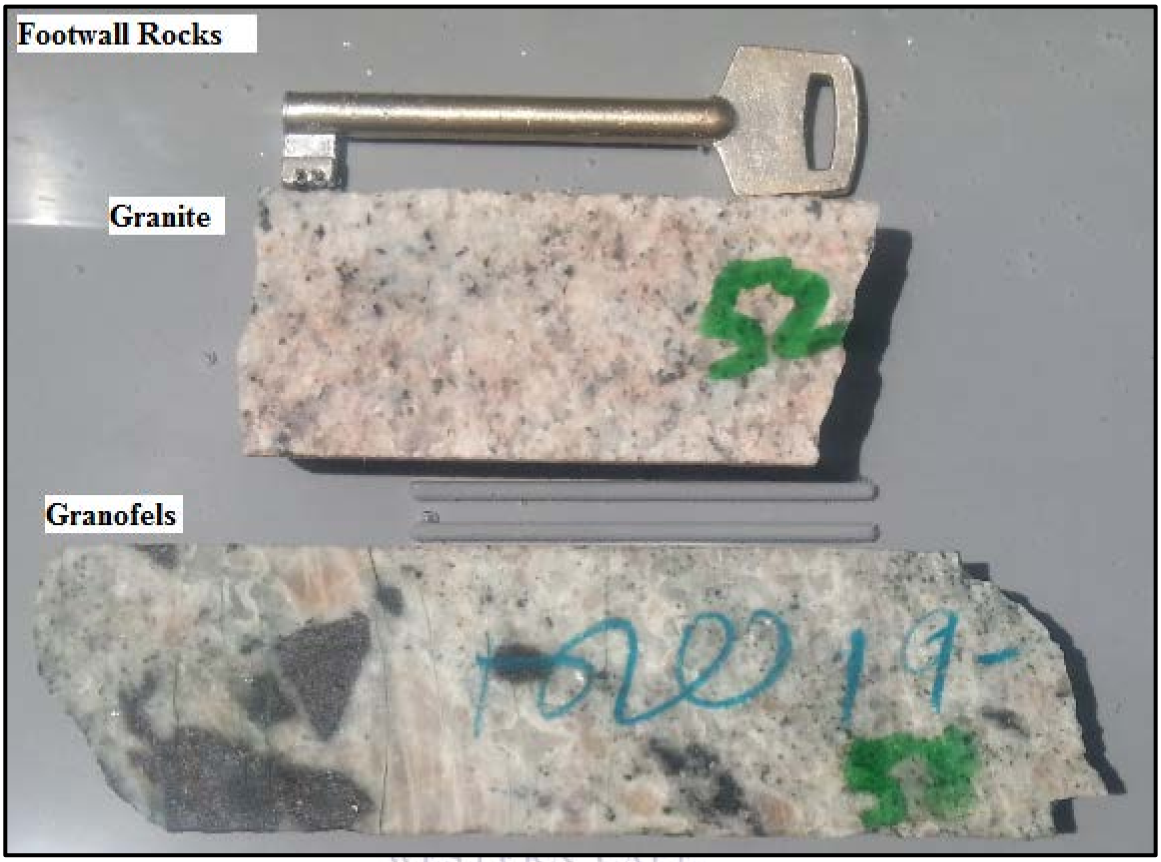


Plate 4.4. The granite and the granofels representing the footwall rocks at Moordkopje Farm. The granite was intercepted in MO009 at 2018 m, and MO019 did not intercept the granite but has granofels as the base rock which is mentioned in MO019 section.

On top of the 'interlayered zone of granofels and pyroxenite', is a layer of gabbronorite of 6.93 m thickness. The gabbronorite is intercalated by 64 cm thick harzburgite layers, which is also bound between or surrounded by granofels (xenoliths) at a depth of 1976 m.

A feldspathic pyroxenite of 4.21 m thickness follows on top of the gabbronorite at a depth of 1970 m. This rock is shown in Plate 4.5B is medium grained, light in colour relative to the typical pyroxenites.

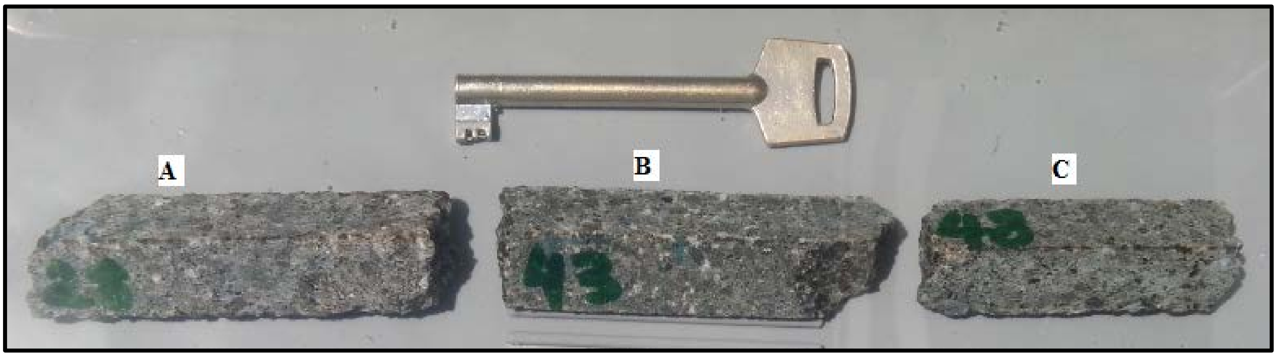


Plate 4.5. **A.** The feldspathic pyroxenite at a relatively shallower depth of 1,867.26 m (sample MO009-28). **B.** The feldspathic pyroxenite at relatively middle depth of 1971.03 m (sample MO009-43) white grains of plagioclase are visible. **C.** The feldspathic pyroxenite at a relatively deeper depth of 1,996.64 m (sample MO009-48).

Overlying the feldspathic pyroxenite is a thin layer (1.04 m) of leuconorite at depth of 1968.72 m. An 87.14 m thick norite layer up to 1878.70 m downhole overlays the leuconorite. This thick layer of norite is cross-cut by a quartz-feldspar vein of about 1 cm at 1937.72 m, and also intercalated by a 55 cm granofels xenolith at depth of 1930.13 m downhole. This norite is coarse grained as shown in (Plate 4.6A, MO009-42). Sample MO009-23 in shallower depths and this norite (sample MO009-42) appears similar and may support correlation.

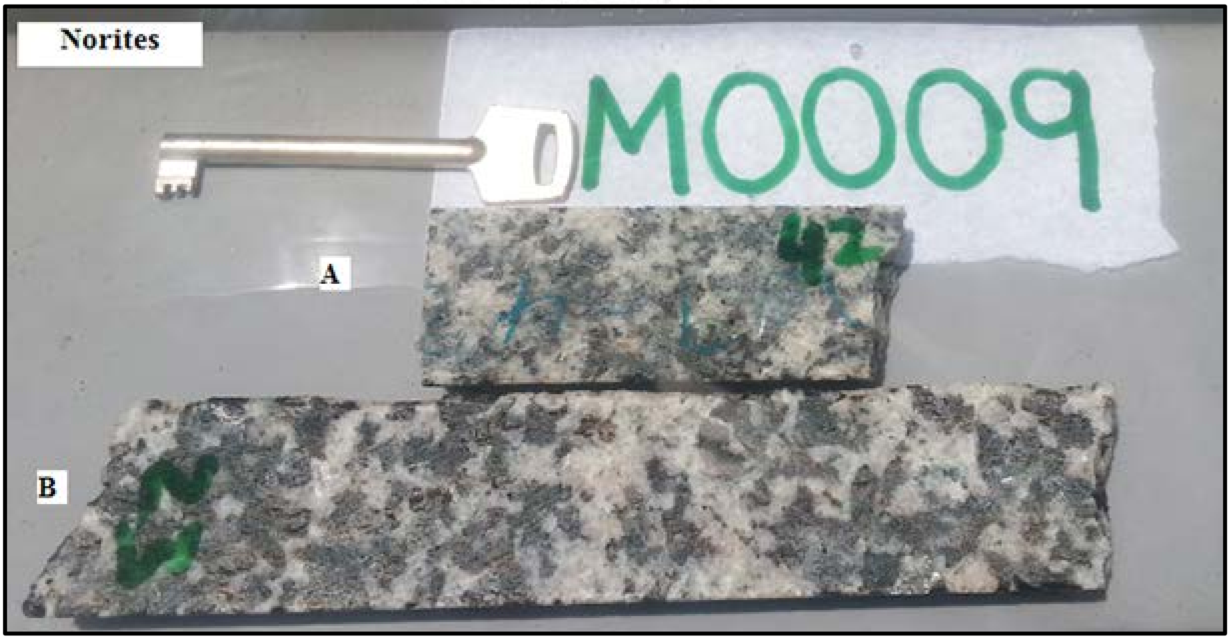


Plate 4.6. Similar lithology of coarse-grained norites found at different depths. Norite **A** is a sample at a depth of 1960.58 m, and norite **B** is a sample at a depth of 1846.37m.

Overlying the norite are two thin layers of leuconorites, which enclose gabbronorite layer. The thicknesses of the upper and lower leuconorites are 1.02 m and 1.25 m respectively, while the gabbronorite is 1.05 m.

Downhole, the norite layer is followed by the Platreef package lithologies, which include feldspathic pyroxenites, melanorite, and harzburgite, in their order of succession. The feldspathic pyroxenite (sample MO009-28, Plate 4.5A) is similar to those at greater depths (sample MO009-43, Plate 4.5B). The harzburgite layer is 3.6 m thick, thus thicker than those below at depth.

The melanorite layer is 9.66 m thick and overlies the feldspathic pyroxenite. The melanorite encloses a 10 cm thick, medium grained gabbronorite layer at a depth of 1858 m. Overlaying the melanorite layer is the norite layer, 68.15 m thick, sampled as MO009-23 (Plate 4.6B).

From this point of norite layer to the top of the drill-hole, is the lithologies of Main Zone only. The occurrence of mottled anorthosites has been used to mark the beginning of the Main Zone in the Northern Limb (e.g. Holwell and McDonald, 2005; Kekana, 2014). The dominant and abundant lithologies in the Main Zone are norites, gabbronorites, leuconorites and anorthosites. Nonetheless, the Main Zone was not of interest for this study.

Borehole: MO009

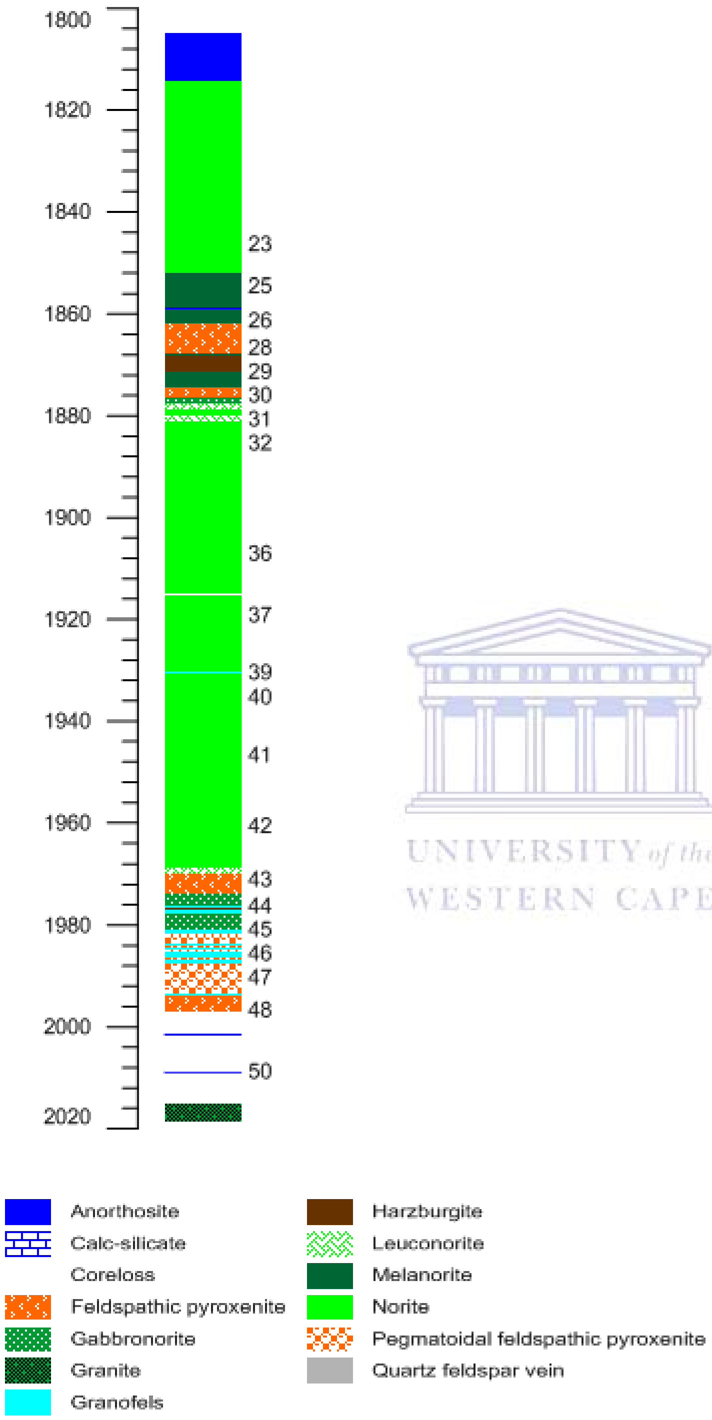


Figure 4.2. The log showing the lithological succession in borehole MO009. The logging includes part of the Main Zone, Platreef and floor rocks; from a depth of 1800 m to the borehole end-depth of 2018 m.

B. Borehole MO019

The MO019 drill hole ended on intercepting the granofels at a depth of 1869.39 m. The sampling of borehole MO019 began at a depth of 24 m with sample MO019-1, and ended with sample MO019-58 at a depth of 1869.39 m. The core is outlined in Figure 4.3 in terms of rock succession from the bottom to sample MO019-37 where Platreef zone comes to contact with Main Zone at this depth. Similarly, for borehole MO019, the section at a shallower depth to the surface is of Main Zone which is not of the study's interest.

The core at the bottom has a granofels footwall rock. A granofels of 96.88 m thickness was intercepted at a depth of 1772.51 m. Plate 4.7 shows a granofels sample (MO019-58). At this depth, the footwall rock consists of a mixture of Platreef feldspathic pyroxenites and granite footwall. A granofels in Plate 4.7 is coarse grained and has constituents of pink granite footwall and assimilated fine-grained feldspathic pyroxenites rock grains.

The granofels occurs in different mineralogy and different textures in different stratigraphic sections, however it is the same massive floor rock. A relatively very fine-grained granofels which is at the upper depth than the granofels in Plate 4.7 is shown in Plate 4.8. These two different types of granofels are the base rocks of MO019, however, they occur in different localities in the stratigraphy, and with the different interaction of assimilations. This is further discussed in Chapter 5: Discussion.

Plate 4.7. The granofels as a product rock of the constituents from feldspathic pyroxenites of Platreef and granite from the Footwall (sample MO019-58). These type of rocks are at the base of MO019 borehole.

Plate 4.8. A relatively very fine-grained granofels sample MO019-51. This is a different type of granofels product rock than the other granofels mentioned above.

Overlying the granofels floor rock is a 16.5 m thick feldspathic pyroxenite which is cross-cut by quartzo-feldspathic veins (Plate 4.10). The feldspathic pyroxenite grades from medium-grained (Plate 4.9B, sample MO019-49) to pegmatoidal grained in the upper depth (Plate 4.10, sample MO019-48).

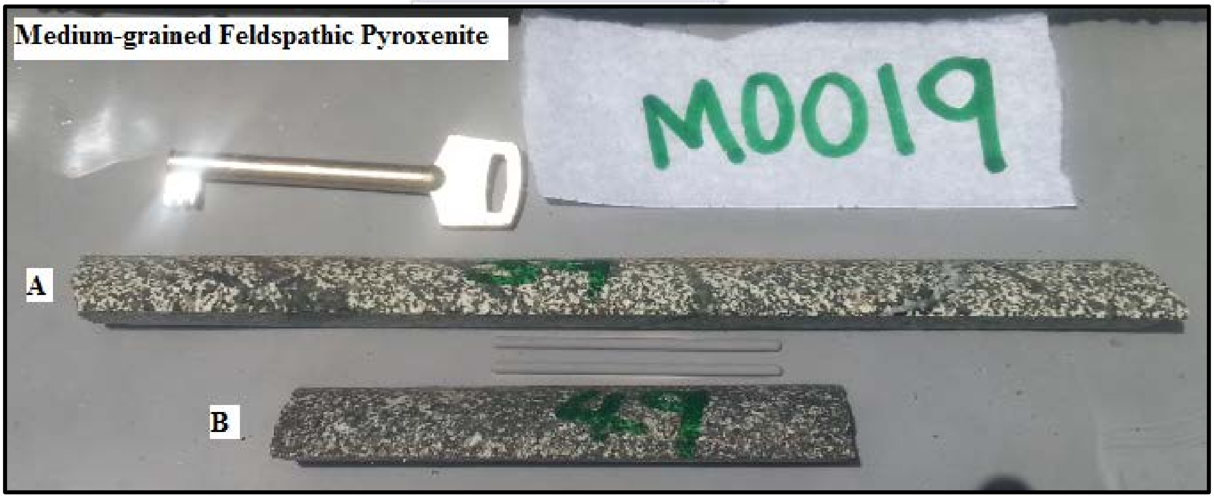


Plate 4.9. Medium-grained feldspathic pyroxenites at depths 1716.23 m (**A**) and 1764.68 m (**B**) samples MO019-39 and MO019-49 respectively.

The feldspathic pyroxenite has intercalations of pegmatoidal quartz veins, olivine-bearing pyroxenite, and chromitite in order of their succession at depths 1765.80 m, 1765.05 m, and 1763.74 m with thicknesses of 7 cm, 27 cm and 12 cm respectively (see Figure 4.3). The occurrence of quartz veins that cross-cut the feldspathic pyroxenite appears that it was relatively very intense in this zone/depth than anywhere else in the stratigraphy (Plate 4.10).

Plate 4.10. A pegmatoidal feldspathic pyroxenites which are cross-cut or filled with quartz veins, sample MO019-48.

Overlying the feldspathic pyroxenite is parapyroxenite that is 26 m thick (Plate 4.11). The parapyroxenite is very fine grained relative to the feldspathic pyroxenites, and has no feldspars (i.e. no visible creamy white grains). A feldspar-quartz vein sampled as MO019-44 cross-cuts this parapyroxenite at depth 1750.67 m.

Plate 4.11. A parapyroxenites at a depth from 1729 m to 1755 m in borehole MO019, sampled as MO019-42, MO019-43 and MO019-45.

A norite of 10.41 m thick overlays the parapyroxenite. This norite is also cross-cut by quartz-feldspar veins successively at depths 1727.70 m and 1721.36 m.

Overlying the norite at depth 1718.39 m is the feldspathic pyroxenite that is 3.84 m thick (Plate 4.12). The feldspathic pyroxenite is medium to coarse grained, with a cumulative texture of intercumulus plagioclase cementing the orthopyroxenes (Plate 4.12).

Plate 4.12. A medium- to coarse-grained feldspathic pyroxenite at depth 1717.19 m, sample MO019-38, with visible plagioclase feldspar as white grains.

A 9.12 m leuconorite (Plate 4.13) overlies the feldspathic pyroxenite at a depth of 1714.5 m. The leuconorite is coarse grained and mostly composed of plagioclase in a form of white patches (Plate 4.13). This rock was intercalated by a 38 cm gabbronorite and very thin layers of pegmatoidal pyroxenites.

Plate 4.13. A leuconorite at depth 1706.55 m, sample MO019-37, with a coarse grain texture.

The leuconorite in sample 37 (Plate 4.13) introduces the beginning of Main Zone. The rocks that overlay from this point are Main Zone until to the beginning of the drill hole. The descriptions and layout of those rocks are not given here. The borehole description of the two boreholes was focused on floor rocks and Platreef rocks.

Borehole: MO019

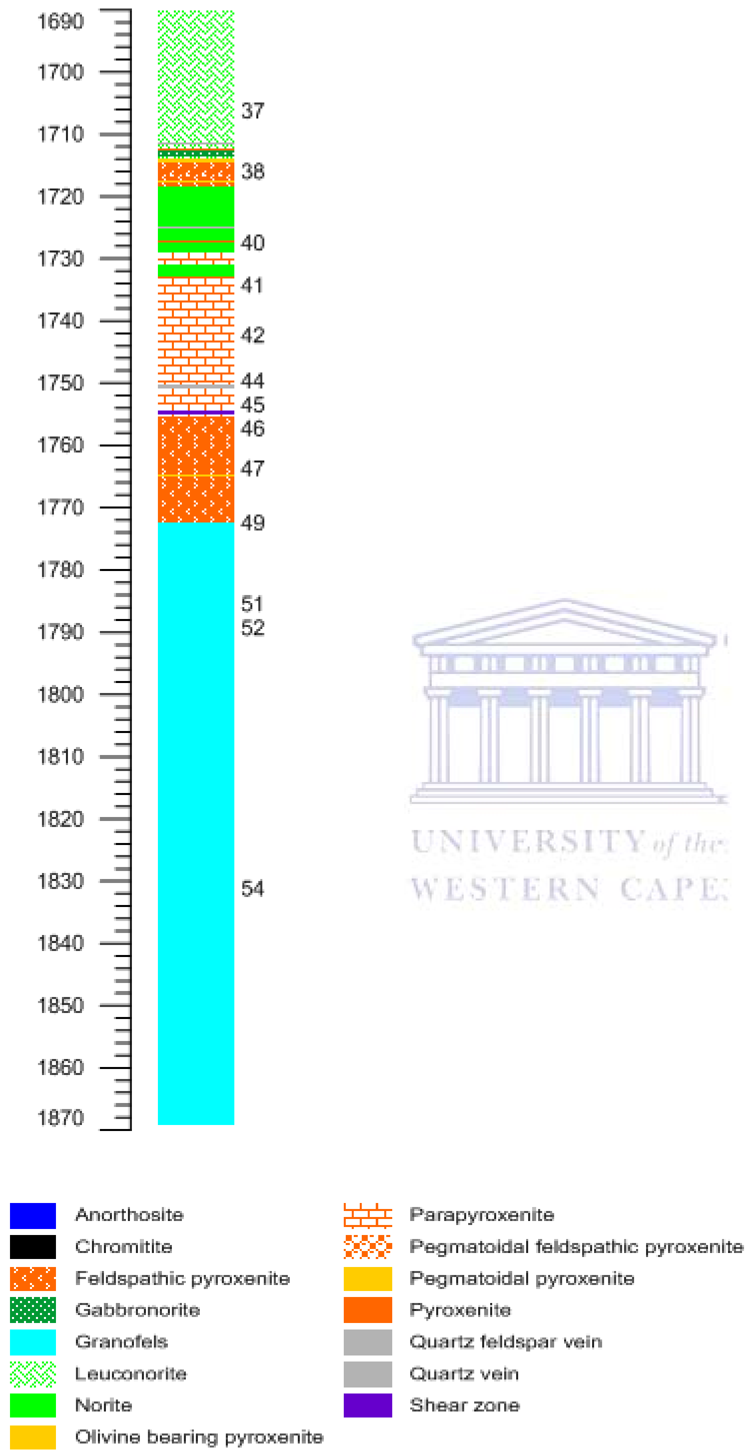


Figure 4.3. The log showing the lithological succession in borehole MO019. The log also includes Main Zone, Platreef and floor rocks; from a depth of 1690 m to the borehole end-depth of 1869 m.

4.2.2.2. Relationship in boreholes (MO009 and MO019)

The description and correlation of rocks from both the boreholes was done in order to establish the similarities and differences between the lithologies and the spatial correlation of the rock succession. The rocks that are similar are discussed first which typically include Main Zone rocks; and the distinctly different rocks types are discussed later, especially the Platreef lithologies.

The footwall in both boreholes is essentially comprised of granite rocks. The fresh unaltered Archaean granite was intercepted in MO009, and in MO019 granofels (gneiss) was intercepted which is the altered granite. Nonetheless, Archaean granite is the main floor body in the area.

The irregular and sporadic occurrence of calc-silicate xenoliths at the base of the Platreef (Armitage *et al*., 2002) may not be ignored in this area as they are discontinuous bodies. As a result, the calc-silicate xenoliths were intercepted in borehole MO009 and not in MO019. Therefore, calc-silicates cannot be considered for correlation as these are remote and discontinuous bodies that are foreign to the reef.

There is similarities in some rock types in these boreholes especially the Main Zone rocks (leuconorites, norites and anorthosites). However, the Main Zone is out of the scope of this current project. Inconsiderable similarities are seen in the Platreef rocks between the two boreholes, e.g. similar feldspathic pyroxenites with different textures, which cannot be considered for correlation purpose.

The first example of similar rocks, the Main Zone norites in MO009 (samples MO009-2 and MO009-4) are similar to the norites in MO019 (sample MO019-2) i.e. the texture and colour are similar (Plate 4.14). These norites occur at shallow depths of about 300 m and less. The similarities are also seen in the leuconorites from the boreholes; an example is shown in Plate 4.13.

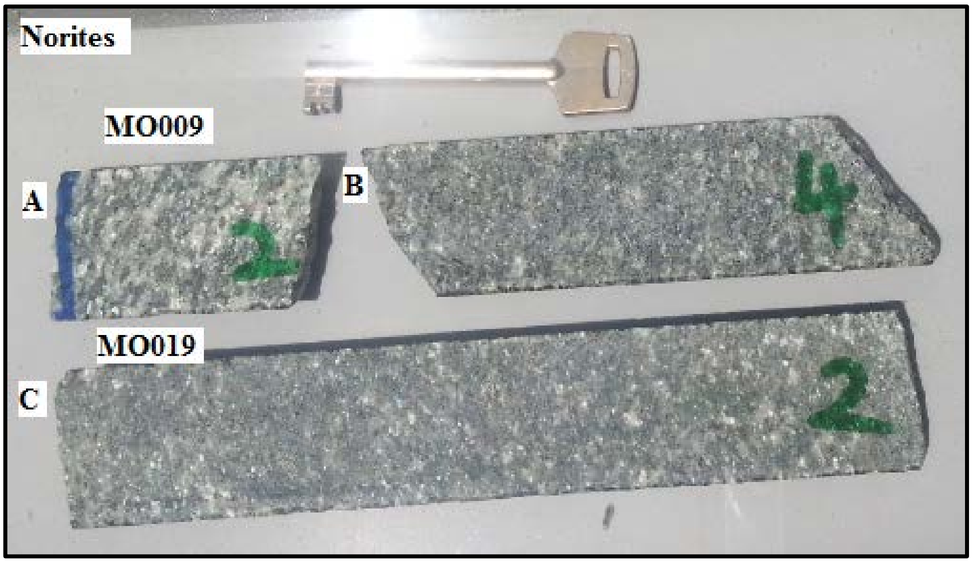


Plate 4.14. A demonstration which shows how the Main Zone norites well correlate to each other in both the boreholes. Norite **A** and norite **B** are samples from MO009 at a different depth; they are very similar to norite **C** which is from MO019.

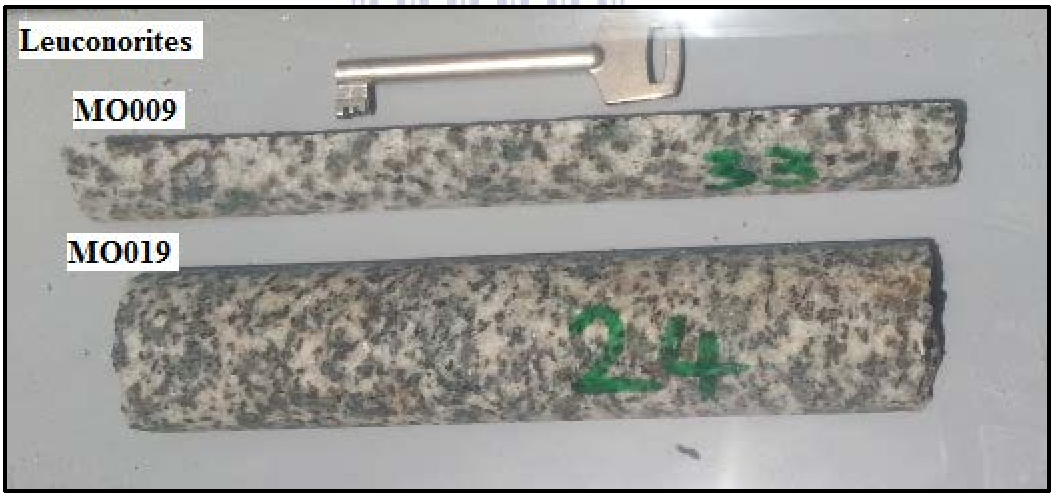


Plate 4.15. The similarities displayed in leuconorites from both boreholes (MO009 and MO019) which also form part of the Main Zone. The texture and the colour are very closely related which may suggest a correlation.

Another Main Zone example of similar rocks is the mottled anorthosites shown in Plate 4.16. These mottled anorthosites are mostly at the base of the Main Zone near the top contact of Platreef with Main Zone. Generally, Main Zone is very much correlated between the lithologies, and correlation can be established.

Plate 4.16. The similar lithologies in both boreholes which is the mottled anorthosites and which forms part of the Main Zone.

The main focus of the current project is essentially on Platreef major rocks. The Platreef is a complex zone of different lithologies which, according to Armitage *et al*. (2002), was subjected to different processes during the course of its development. There are no traceable correlations of the similar major rock types between the boreholes. The examples are given below of the variation of Platreef rocks from the two boreholes.

The most common rock found in both MO009 and MO019 is the feldspathic pyroxenite. Nevertheless, it varies much in terms of grain size which is due mainly to relative locality, within the Platreef, to the floor rock (Plate 4.17). Feldspathic pyroxenites within the Platreef can be located (1) proximal to the floor rock; (2) in the middle of the Platreef zone near the harzburgites (i.e. relatively further from the floor rock); and (3) proximal to the norites and anorthosites of the Main Zone (i.e. far from the floor rock). This concept is further discussed in the next chapter.

Plate 4.17 below depicts the variation of feldspathic pyroxenites in the boreholes in terms of grain size. The medium grained feldspathic pyroxenites, which is common in the middle of the Platreef (Plate 4.17A), has less visible interstitial plagioclase (white grains) than the coarse-grained feldspathic pyroxenites (which is common proximal to the floor rock). The fine-grained feldspathic pyroxenite has very fine pyroxene grains relative to the medium grained feldspathic pyroxenite (Plate 4.17B). However, the plagioclase grains are still visible in fine-grained feldspathic pyroxenites.

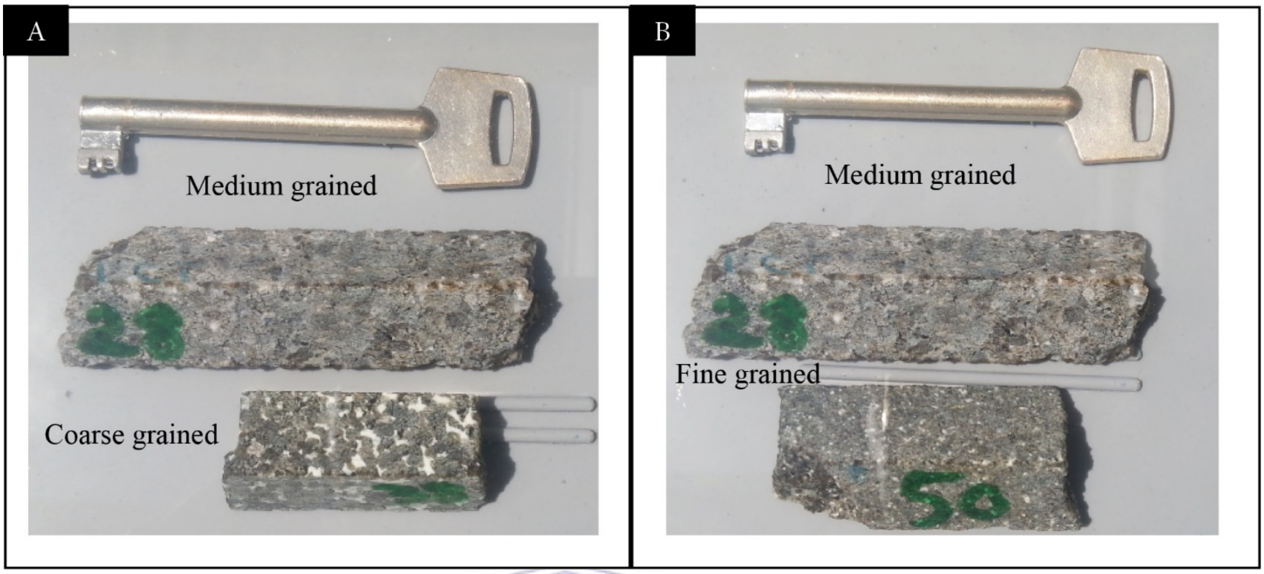


Plate 4.17. The variation of feldspathic pyroxenites with respect to texture (i.e. grain size) which occurs in Moordkopje Farm. **A.** Medium grained feldspathic pyroxenite as compared to a coarse-grained feldspathic pyroxenite. **B**. Medium grained feldspathic pyroxenite as compared to a fine-grained feldspathic pyroxenites.

The occurrence of parapyroxenites in the Platreef zone is dependent on the presence of calc-silicates, which is the reason they were intercepted only by borehole MO009. Borehole MO019 did not intercept the parapyroxenite, as a result, this rock cannot be correlated between the boreholes. In exclusion of calc-silicates in this area, there possibly may be definite correlations of pyroxenites that could have been established between the boreholes. In Plate 4.18 the parapyroxenites are compared to the feldspathic pyroxenites that generally occurs in both boreholes at Moordkopje, in order to demonstrate the dissimilarity of parapyroxenites to other pyroxenites in the Platreef.

Plate 4.18. The parapyroxenites only found in borehole MO019 and not in MO009, and are compared to the feldspathic pyroxenites which generally present in both the boreholes.

4.2.3. Microscopic descriptions of rock types

4.2.3.1. Introduction

The main purpose of petrographic descriptions is to provide an outline on mineralogical make-up of the major rocks of the Footwall, Platreef and Main Zone in boreholes MO009 and MO019, such that the rocks which have similar compositions are classified together, the rocks which are altered are identified and those rocks that are unaltered (if any) as well. The alterations should be very well understood as they contribute to understanding the mass transfer in the latter, the resultant of assimilation. In addition, the types of alterations should be known in relation to their source, whether they are from the footwall material in the process of footwall interaction or whether they are magmatic in the process of Platreef magma emplacement. In other words nonetheless, petrography is applied to classify rocks and describe their predicted origin and evolution.

In this section, the layout is that the Footwall rocks are described first, then Platreef rocks and the Main Zone rocks in the end. At the end of the petrographic descriptions, a table of summaries of all the descriptions is included.

FOOTWALL

Moordkopje is in the Northern Sector of the Northern Limb where the footwall is comprised of the Archaean granite (Kinnaird *et al.*, 2005). The granite floor rock extends northwards which includes other farms like Overysel and Drenthe. Other rocks in the footwall include the hybrid rock which was referred to as the granofels. Granofels is a resulted rock type due to the assimilation of portions of granite floor and the Platreef. The hybrid rocks occur at the contact units between the footwall (granite) and the Platreef (pyroxenites). They have the contents of both the granite footwall (e.g. quartz and K-feldspars) and the pyroxenites of Platreef (e.g. orthopyroxenes and clinopyroxene). In this study nonetheless, these rocks have been classified as part of the footwall rocks. Another type of rock that occurs erratically at the footwall vicinity is the calc-silicate which occurs as xenoliths in the southern parts of the Moordkopje farm.

The granite footwall was intercepted in MO009, and borehole MO019 ended without intercepting the footwall. The footwall of MO019 is predominantly granofels which is varied in two types (further descriptions in 'Granofels' section). Due to the emplacement of Platreef on top of the granite, the units of granite were then heated and altered to produce a unique suite of two types of 'hybrid rocks'. Therefore, the base of MO019 is predominantly the granofels (as seen in the layout of MO019 log in Figure 4.3).

A. Granite

The granite at Moordkopje has the mineralogical makeup (in modal percentages) of >60% of quartz and 35% alkali feldspars, and <5% accessory minerals like biotite and secondary minerals like sericite (essentially alterations products) (Plate 4.19). The grain size is very fine with <1 mm grains. The texture shows the intergrowth of quartz and feldspars (myrmekitic texture). The alteration of feldspars to materials of cloudy patches of sericite is prevalent (Plate 4.19B). There are no opaque minerals visible in the granite at Moordkopje; essentially the footwall rocks are non-mineralised in this area.

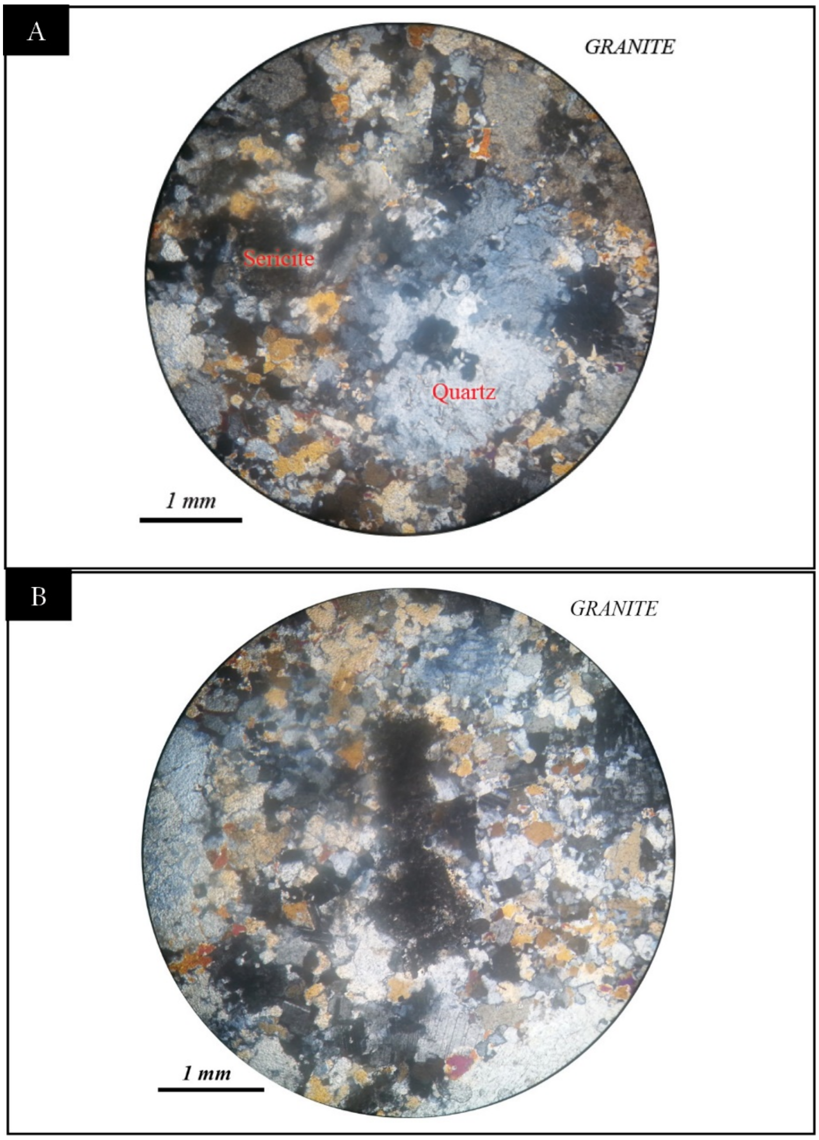


Plate 4.19. A photomicrograph of granite floor rock in MO009, with plates **A** and **B** showing a different microscopic views of the same granite sample. In plate **B**, the cloudy shaded region in the centre is the sericite alteration.

B. Granofels

Granofels, may be referred to as a hybrid rock, is typically a unique suite of rock type that resulted in syn- and post-magmatic placement of Platreef onto the Archaean granite as a result of assimilation of units of Platreef pyroxenites and granite floor rock. However, the nature of assimilations varies locally such that different hybrid rocks are resultant. In the current study, two compositionally different granofels were noted and termed as Granofels I and Granofels II. However, only borehole MO019 has both types of granofels; and borehole MO009 only has Granofels I.

Granofels I

The granofels I is basically a granite gneiss which Holwell and McDonald (2006) described it as banded gneisses. There is alternating light bands and dark bands (Plate 4.20), according to Holwell and McDonald (2006) the bands comprise pale, quartzo-feldspathic bands and darker, more mafic orthopyroxene-rich bands. Granofels are hybridised rocks (hybrid rock) which refers to that they composed of felsic contents of the granite and mafic silicates from the pyroxenites proximal to the granite footwall. This rock can also be occur as xenoliths (sample MO009-39, Plate 4.21) within the Platreef zone bound within the feldspathic pyroxenites.

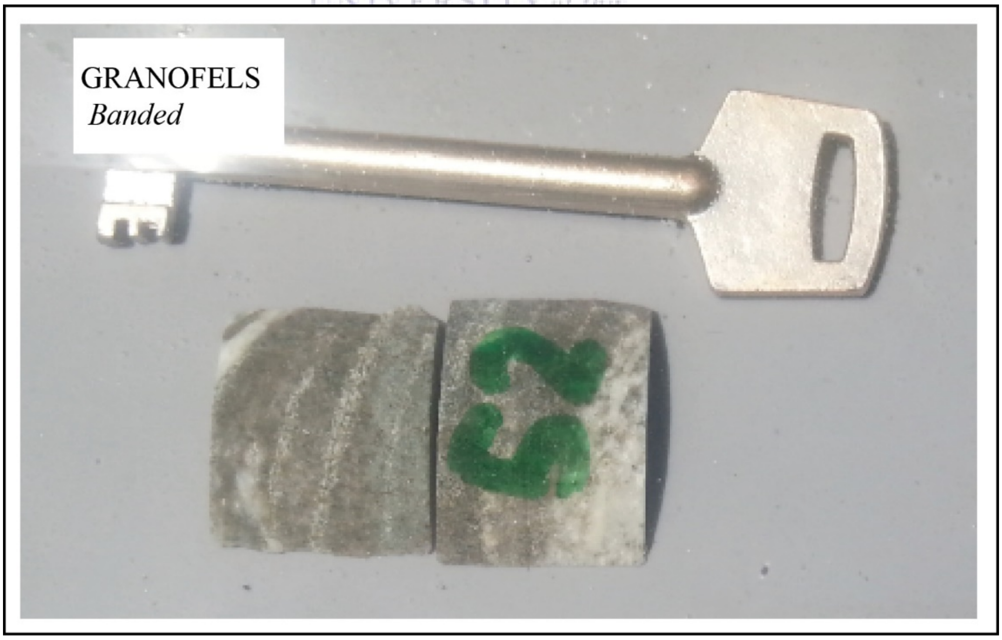


Plate 4.20. A representable granofels I displaying the banded gneisses where the light bands are quartz-feldspars (sericite) and the dark bands are orthopyroxenes. A sample from MO019 at 1788.20 m (MO019-52).

The mineralogical modal composition of granofels I in this area is >80% of plagioclase, K-feldspars and quartz; and <20% of pyroxenes (Plate 4.21). The grain size is the same as that of granite with very fine grains of less than 1 mm. However, the elongated pyroxenes of about 1.5 mm occurs within the rock. The elongated pyroxenes form the foliations that are mentioned above to make up the texture of the rock. Alterations are similar to granite, the plagioclase alters to sericite, and however, the presence of pyroxenes shows another alteration of granulated or fine pyroxenes (Plate 4.21).

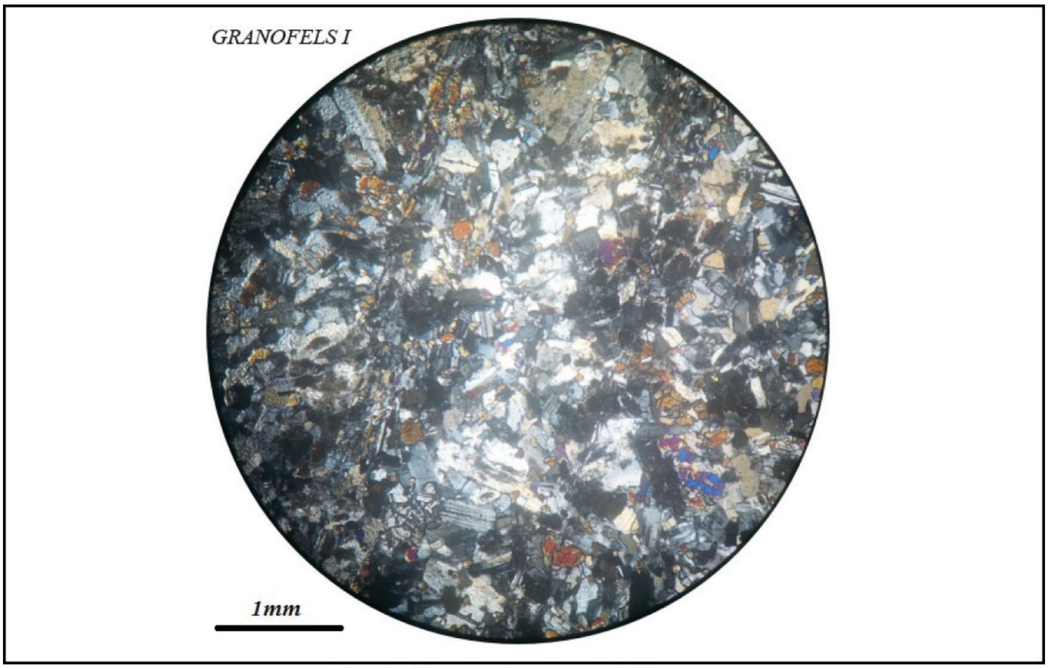


Plate 4.21. A photomicrograph of Granofels I in borehole MO009. The alternating bands are visible as described in the text. The colourful small grains are the remnants of pyroxenites.

Granofels II

Granofels II is another type of hybridised rock which essentially its origin is not very clear however is assumed as of pyroxenite origin (or feldspathic pyroxenite) of Platreef that is found at the contact between the footwall (floor rock) and the Platreef. These rocks are in the same class as the granofels I, however, they are dominantly composed of mafic silicates with the incorporation of granite contents. The mineralogy of this rock is ~50% of orthopyroxenes; <35% of quartz and plagioclase and 15% clinopyroxene (Plate 4.22B). These rocks are relatively coarse to medium grained. The alterations are very low intensity with pyroxenes to amphiboles. Granofels II in this zone show incorporation of sulphides minerals within them (Plate 4.22D).

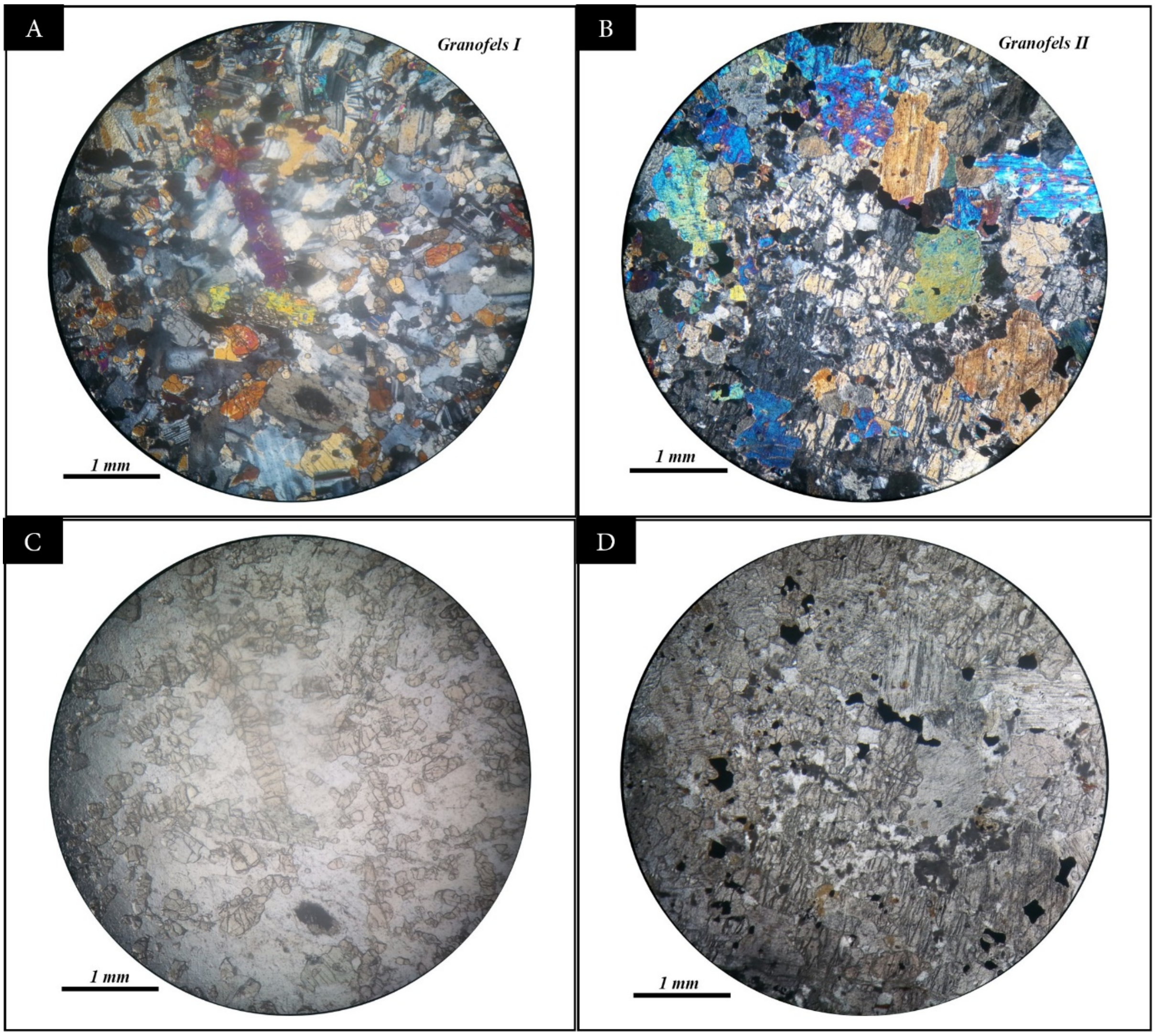


Plate 4.22. Photomicrographs of granofels in MO019 showing granofels I (**A**) and granofels II (**B**). **A-B** are in polarised light, and **C-D** are a representation of the same view of A and B in plane polarised light. **A.** The granofels I is relatively fine grained and has more floor rock components than granofels II. **B.** The granofels II shows more of Platreef components than granofels I with sulphide inclusions. These are granofels hybrid rocks at Moordkopje.

C. Calc-silicate xenoliths

The dolomite is the floor rock of the Platreef in the Central Sector of the Northern Limb (e.g. in Sandsloot farm) (Kinnaird *et al*., 2005). This rock is the Malmani Dolomite of Transvaal Supergroup. Armitage *et al.* (2002) noted that calc-silicates hornfels were produced through thermal metamorphism of siliceous dolomite with a variety of skarn assemblages. The occurrence of calc-silicate xenoliths within Akanani Platreef was described by Van der Merwe (2011) by the possible Platreef magma transport direction (southeast to northwest), over Transvaal sediments onto the granitic footwall. The mineralogy of calc-silicates in this area is

60% of plagioclase, with 40% of the altered dolomite grains and accessory minerals e.g. minor biotite (Plate 4.23).

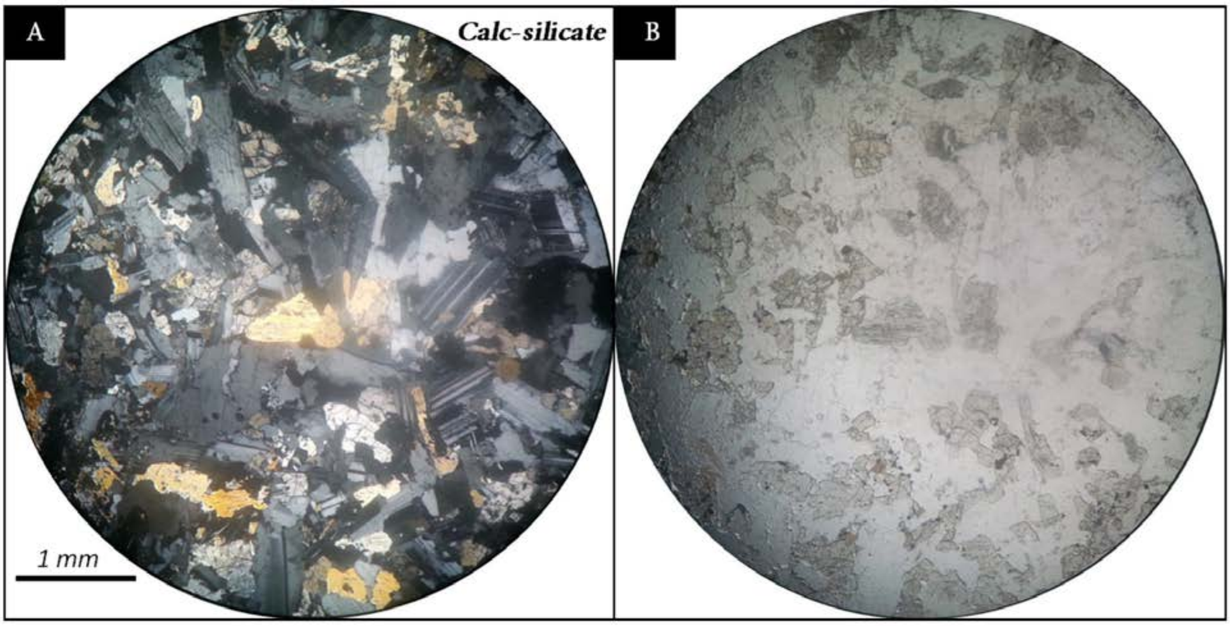


Plate 4.23. A photomicrograph of the calc-silicate in MO009 sample MO009-50 at a depth of 2008.71 m. **A** represents polarised light and **B** represents non-polarised light.

PLATREEF

The Platreef rocks are generally pyroxenites and feldspathic pyroxenites, with some other olivine lithologies (harzburgites and serpentinised pyroxenites) and erratic chromitite layers. As mentioned above, Kinnaird *et al.* (2005) noted that all the Platreef lithologies comprise orthopyroxene, clinopyroxene, olivine and plagioclase. Similar observations have been made on the rock samples of Moordkopje area under a microscope. The rocks of Platreef were not named according to any geochronological order (i.e. age, stratigraphic position); however, these rocks were outlined randomly into groups of Platreef rocks.

A. Pyroxenites

Serpentinised pyroxenites

The serpentinised pyroxenites are primarily the olivine-bearing pyroxenites that had undergone serpentinisation alteration. Due to magmatic alterations, the olivines are serpentinised and they are ruptured to a secondary mineral called serpentine (Plate 4.24A). The mineralogy of these serpentinised pyroxenites is <65% of orthopyroxenes, <15% of serpentine, <10% of plagioclase, <5% olivine; and <5% of clinopyroxenes and other accessory minerals (Plate 4.24). The serpentinised pyroxenites are medium to coarse grained, with a texture of interlocked grains of pyroxenes of 3-4 mm grain sizes. High alterations occurred in this part of Platreef near the olivine-bearing pyroxenites, high serpentinisation and very weak sericitisation, with some actinolite-tremolite secondary minerals from pyroxene alterations. The ore minerals (predominantly chromite) are only observed in serpentinised pyroxenite and harzburgite (Plate 4.24D).

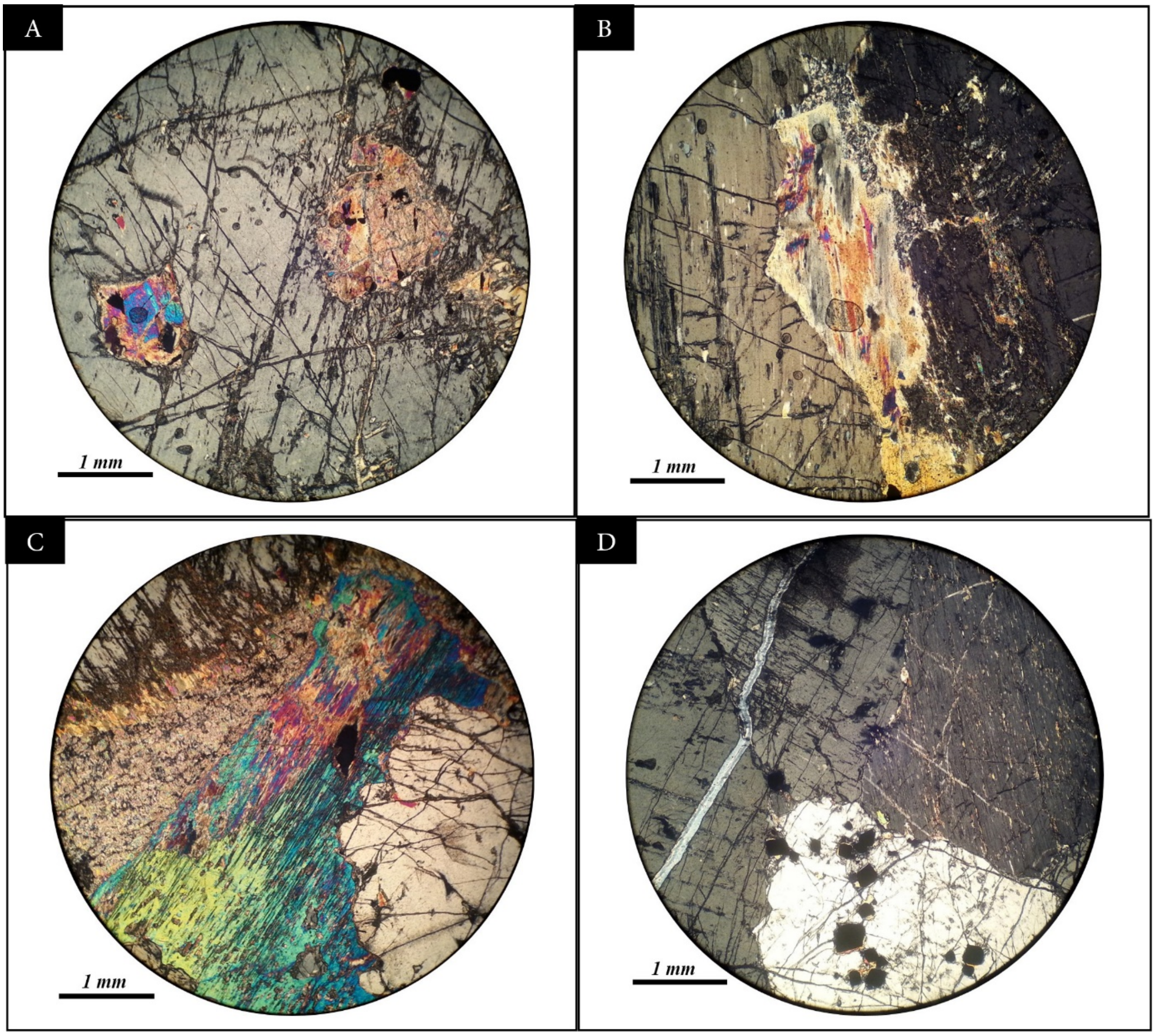


Plate 4.24. Photomicrographs of the serpentinised pyroxenite. Plates **A–D** represents the same sample (MO009-29) with a different view on the stage. **A.** The two grains of ruptured olivines which show some network of high serpentinised grains around them. **B.** The big grain in the middle is the alteration of pyroxenes to amphiboles (actinolite-tremolite). **C.** The representation of clinopyroxene within the serpentinised pyroxenite. **D.** The incorporation of ore minerals (chromite) within the serpentinised pyroxenites.

Parapyroxenites

The parapyroxenites are clinopyroxene-rich pyroxenites that are relatively at the base of the Platreef zone. They are fine grained and their mineralogy is <60% clinopyroxenes, <25%

orthopyroxenes, and <15% is remnants of olivine (Plate 4.25). The grain size is between 1 - 3 mm, with anhedral grains of pyroxenes and with the poikilitic texture. The alterations are intense in both the pyroxenes and olivines which are related to contact with calc-silicates. The pyroxenes alter to amphiboles (e.g. actinolite-tremolite), and olivines alter to serpentine.

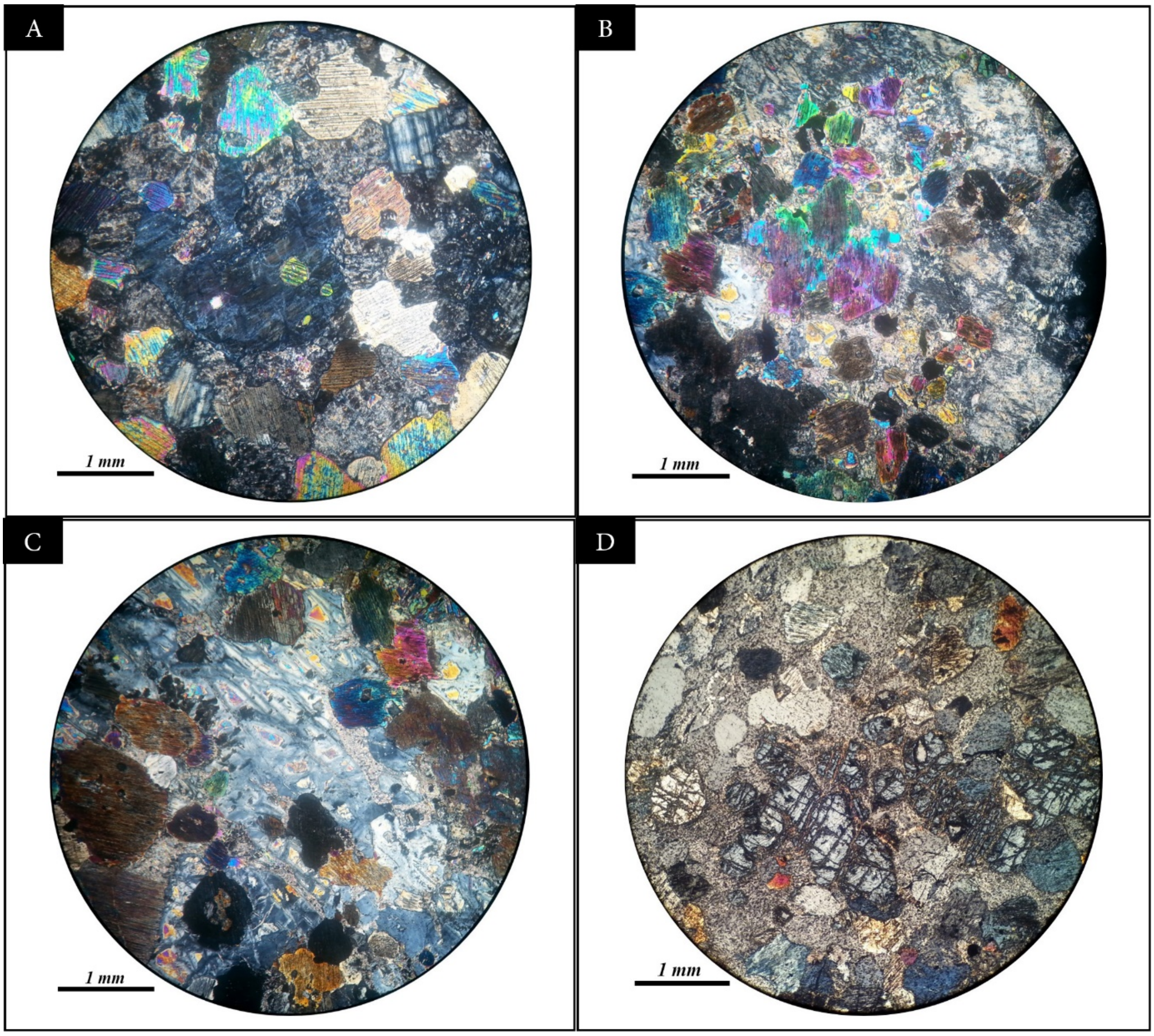


Plate 4.25. Photomicrographs of the parapyroxenites in MO019. **A-C**. The variation of the parapyroxenite with the domination of Cpx with broken olivine remnants in **C** and alterations of Cpx to actinolite-tremolite. **D**. The remnants of olivine which have altered to serpentine in the middle of the view.

B. Harzburgites

The harzburgites are associated with very weak mineralisation of this area, and they are mostly located proximal to the serpentinised pyroxenites. Harzburgite is very coarse grained (Plate 4.26), with the modal mineralogy of 60-70% of orthopyroxene, 5-15% of olivine, and 0-5% of clinopyroxene, and to some extent, some very minor grains (0-5%) plagioclase is present and other accessory minerals. Its texture is generally interlocked subhedral grains of orthopyroxenes with the grain size of >3.5 mm. The prevailing alteration products are serpentine; most of the olivines were serpentinised. Other low intense alterations is orthopyroxenes to greenish mineral (amphiboles). They have a network of veins on them, and these veins are filled with clinopyroxenes.

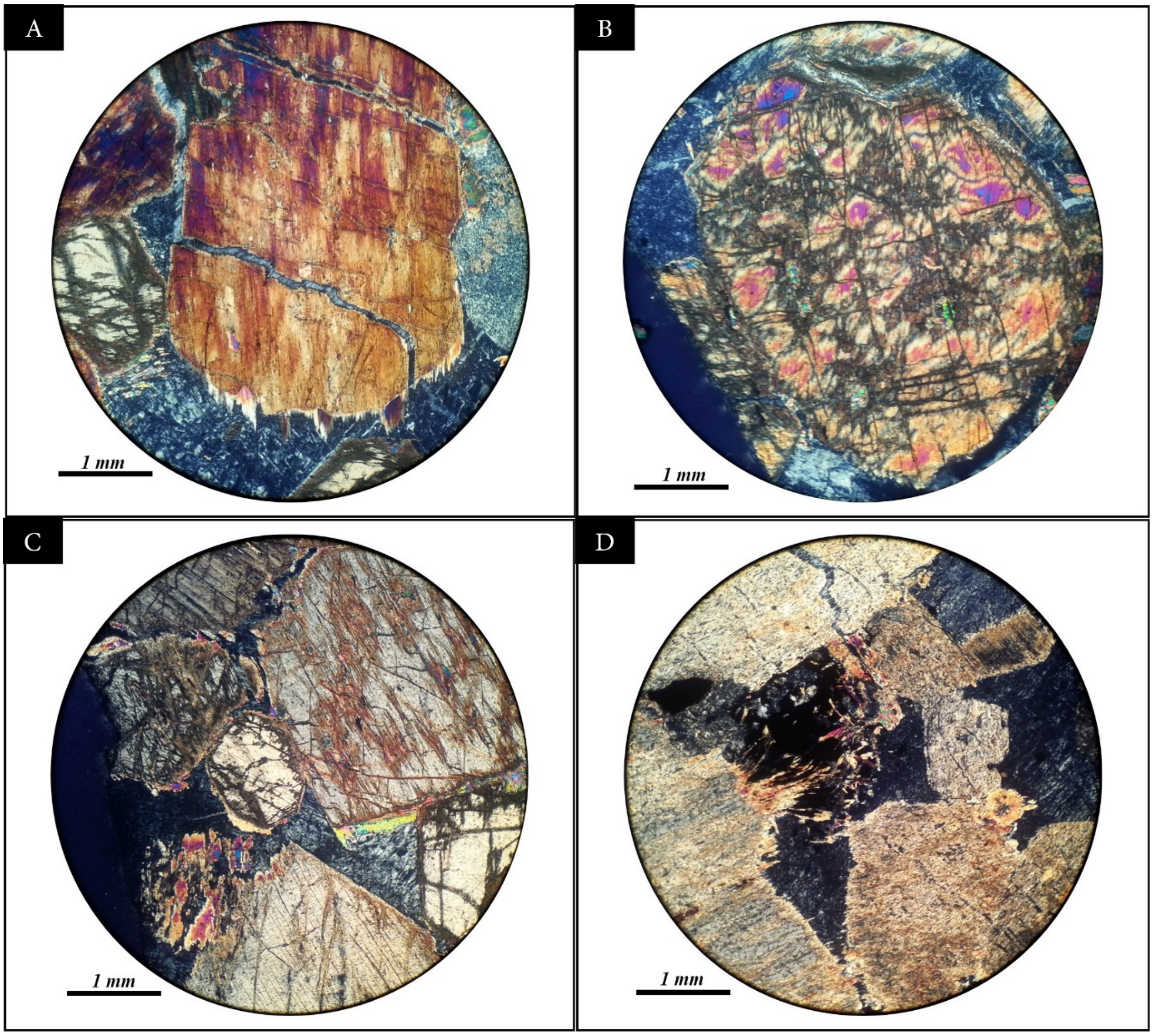


Plate 4.26. Photomicrographs of the harzburgite. **A.** An altered Opx with a big cross-cutting vein filled with siliceous material which is typical at Moordkopje. **B.** The 4.5 mm ruptured olivine grain which went through high alteration and fracturing. **C.** The occurrence of Cpx on the grain boundaries and sometimes Cpx is filled within the veins. **D.** The typical alteration of Opx to actinolite-tremolite which can be needle-shaped.

C. Feldspathic pyroxenites

Feldspathic pyroxenites

The feldspathic pyroxenites generally dominate the whole of the Platreef package, which makes them be situated in almost every stratigraphic level within the Platreef. The feldspathic pyroxenites proximal to the granite floor rocks normally have quartz (and phlogopite), as a result of the transported material from the granite floor rock during interaction. This type of feldspathic pyroxenite is generally termed pegmatoidal feldspathic pyroxenite (Plate 4.27 and Plate 4.30) as it is also relatively very coarse grained with quartz. Pegmatoidal feldspathic pyroxenite is normally regarded as another different rock type within the Platreef. Thus, the pegmatoidal feldspathic pyroxenite is further explained in the following sub-section.

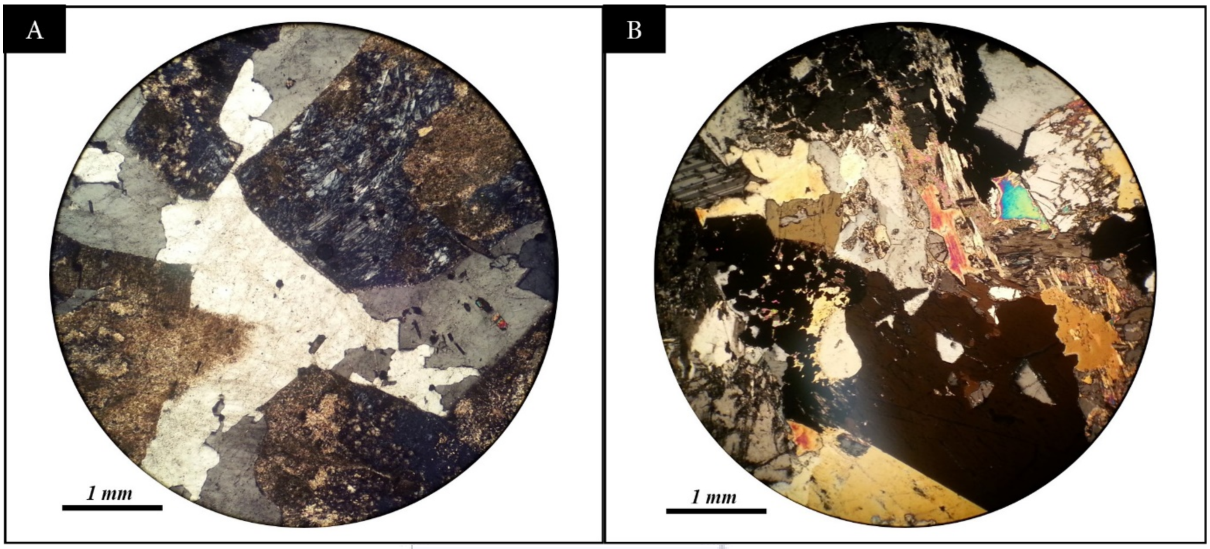


Plate 4.27. Photomicrographs of the pegmatoidal feldspathic pyroxenites. **A**. The Opx are intensely altered and granulated, with quartz and altered plagioclase surrounding the Opx. **B**. The view showed the occurrence of phlogopite in pegmatoidal feldspathic pyroxenites and altered Opx and plagioclase. Opx grains are relatively very coarse-grained in these rocks.

The feldspathic pyroxenites proximal to the olivine-bearing rock types (e.g. harzburgite, serpentinised pyroxenites) are essentially medium grained and with a low concentration of plagioclase relative to the other feldspathic pyroxenites (Plate 4.29A). It has no addition of quartz and biotite (or phlogopite) as contamination from the floor rock. The grain shapes of these feldspathic pyroxenites is generally anhedral to subhedral. However, it has the minor clinopyroxenes at the grain boundaries as postcumulus phase (Plate 4.28A), which may be the influence of the occurrence of parapyroxenites or rather a magmatic occurrence. The mineralogy of these feldspathic pyroxenites is 85% orthopyroxenes, and <10% interstitial plagioclase, <5% clinopyroxene and minor opaque minerals. The most common alteration at the zone is uralitisation and some low sericitisation.

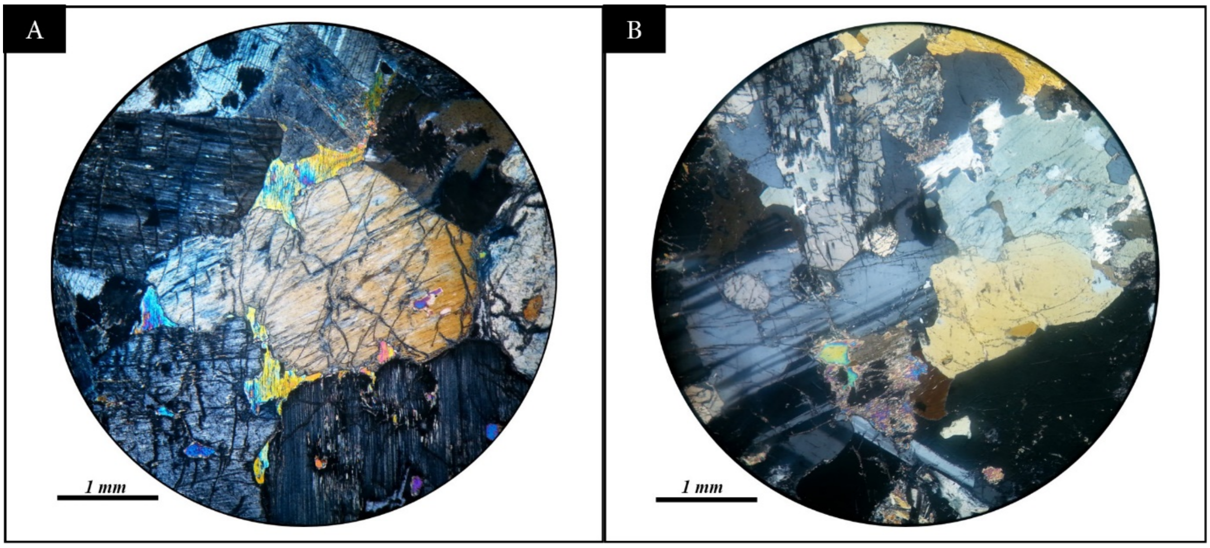


Plate 4.28. The variation of feldspathic pyroxenites in MO019 which has no significant difference in the variation of feldspathic pyroxenites of MO009. **A**. The feldspathic pyroxenite that is interlocked with Opx grains and a development of Cpx at the grain boundaries. **B**. The feldspathic pyroxenite that is proximal to the Main Zone which has euhedral Opx grains and significant plagioclase content relative to the others, and with a development of phlogopite.

The feldspathic pyroxenite proximal to the Main Zone is essentially very much related to the melanorites. These feldspathic pyroxenites have recrystallised as the orthopyroxene grains are very well euhedral and are textured poikilitically on plagioclase (Plate 4.29B). Mitchell and Scoon (2012) have referred to these type of rocks as recrystallised orthopyroxenite where they classify them as reconstituted lithologies. The mineralogy is relatively the same as the above mentioned feldspathic pyroxenite type, with an exception of higher concentration of plagioclase. Therefore, the relative mineralogy is 75% orthopyroxene, and 8–15% intercumulus plagioclase with <5% of alterations and accessory minerals. The sericitisation is more common and very low phlogopite.

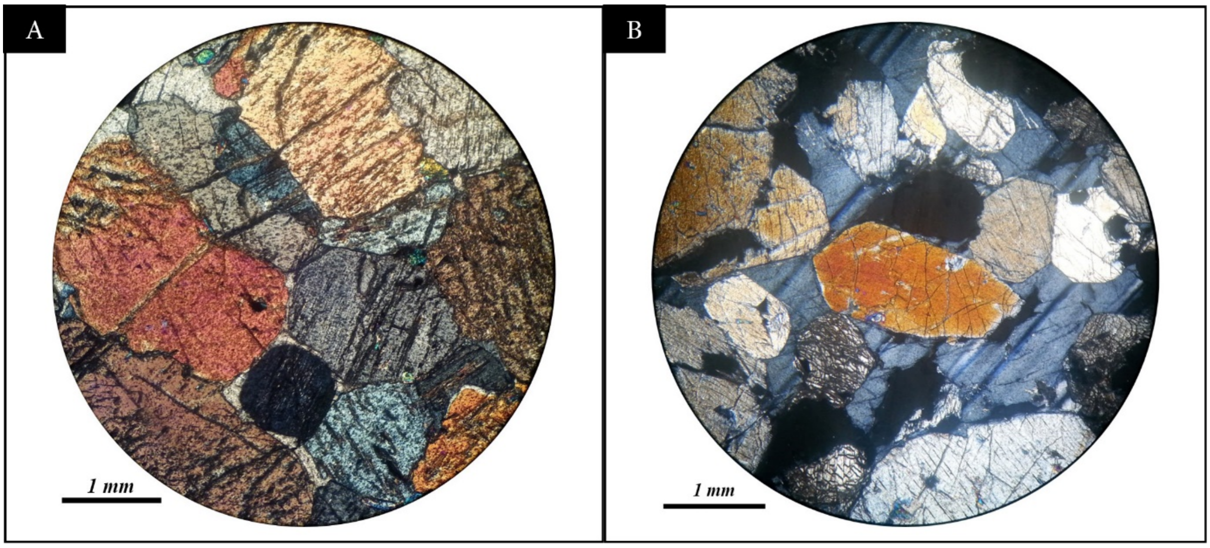


Plate 4.29. Photomicrographs of the feldspathic pyroxenites. **A**. The feldspathic pyroxenite proximal to the harzburgites, showing the very low concentration of interstitial plagioclase and interlocking Opx grains with an occurrence of Cpx on grain boundaries as intercumulus crystallisation. **B.** The feldspathic pyroxenite proximal to the Main Zone, showing very well euhedral Opx grains with a big poikilitic plagioclase around the Opx grains.

Pegmatoidal feldspathic pyroxenites

The pegmatoidal feldspathic pyroxenites are very much related to the granite floor rocks as they are quartz-bearing feldspathic pyroxenites of Platreef. They are a variety of feldspathic pyroxenite that was reworked and affected by the external components of the granite floor rock. The mineralogy is 60-65% orthopyroxene and <5% clinopyroxene, 15% of intercumulus plagioclase, and 10-15% of quartz and <5% some occurrence of phlogopite from biotite (i.e. biotite occurred as a postcumulus phase within the pegmatoidal feldspathic pyroxenites) (Plate 4.30B). The texture in these rocks is diverse where intercumulus plagioclase enclosing orthopyroxene poikilitically, and another texture which is a myrmekitic texture which explains the inclusions of quartz and k-feldspar grains within the rock (Plate 4.30A). These are very coarse to pegmatoidal rocks and anhedral to subhedral grains. The alterations in pegmatoidal feldspathic pyroxenites are essentially the occurrence of biotite-phlogopite series; very weak alterations on the orthopyroxene and weak sericitisation.

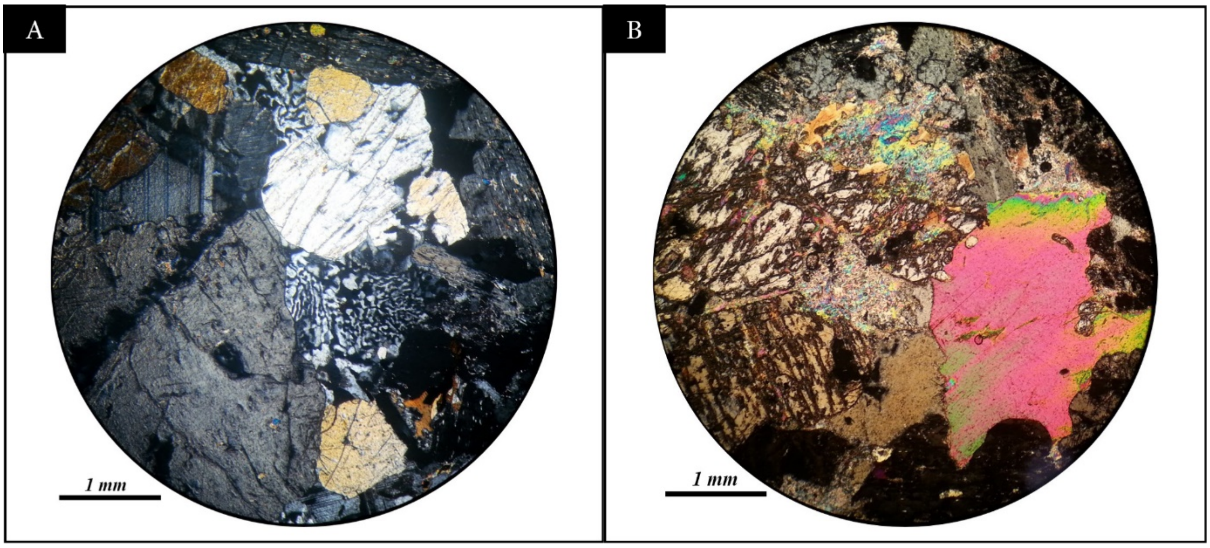


Plate 4.30. Photomicrographs of the pegmatoidal feldspathic pyroxenite. **A**. The myrmekitic texture in these rock types is showing the intergrowth of quartz. The Opx grains around the quartz are very coarse grained relative to the other feldspathic pyroxenites. **B.** The recrystallised biotite to phlogopite in pegmatoidal feldspathic pyroxenite and the intercumulus Cpx within fractures.

HANGING WALL

The hanging wall is referring to the Main Zone (MZ) of the Bushveld Complex in the Northern Limb. The Main Zone (according to van der Merwe, 1978; cited in Kinnaird *et al*., 2012) is up to 2200 m thick above the Platreef and is dominated by gabbronorites with norites, gabbro, anorthosites and some pyroxenites. Nevertheless, at Moordkopje the norites (including leuconorites and melanorites) and anorthosites are the dominant rocks that comprise this zone.

Melanorites have been recently regarded as the cap of the Platreef zone at Akanani. However, in the current study, that consideration has not been ignored as these rocks have been identified between Main Zone and Platreef. Nonetheless, in this study, melanorites have been classified under Main Zone. The Main Zone, in any way, is not significantly part of this study's scope; and very little attention has been given to this zone. Roelofse and Ashwal (2012) did the lower Main Zone in detail which may be one of the references for a detailed Main Zone description of this area.

A. Gabbronorites

The mineralogy of the gabbronorites in this area is predominantly 30 - 45% of cumulus plagioclase, >45% of both orthopyroxene and clinopyroxenes, <5% of accessory minerals, namely, biotite and alterations of pyroxenes and plagioclase to fine-grained materials (Plate 4.31). The gabbronorites exhibit a coarse intergranular texture with large poorly-sorted grains of anorthite with grains of orthopyroxenes in between them. In addition, a sub-ophitic to ophitic texture in the gabbronorites does occur to some extent, in cases where clinopyroxene is the oikocryst enclosing the cumulus plagioclase laths (Plate 4.31).

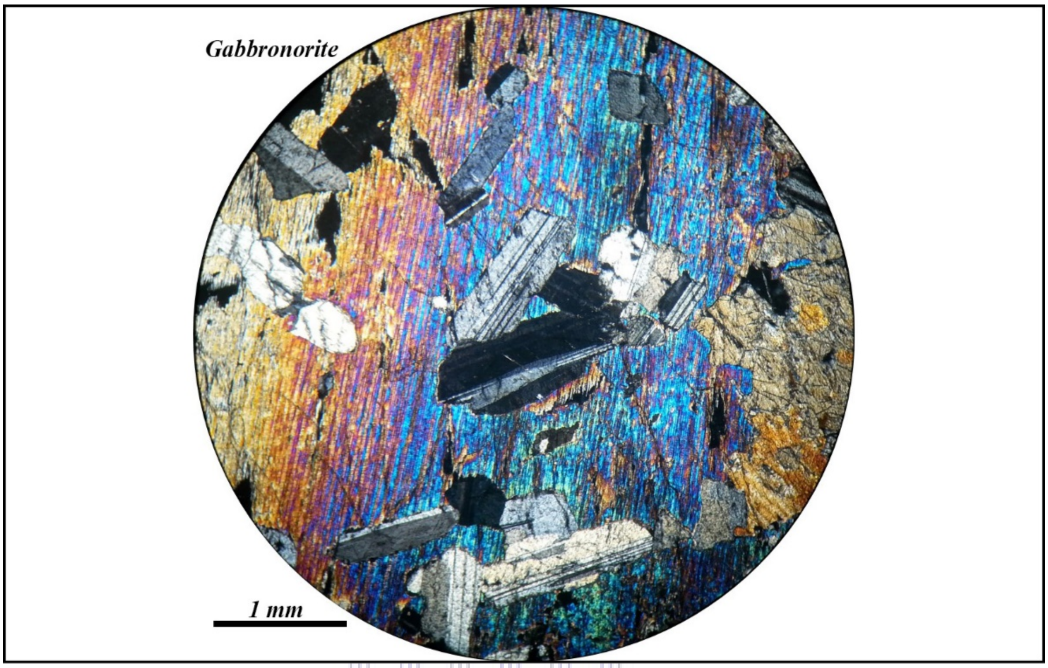


Plate 4.31. A photomicrograph of gabbronorite. The very poikilitic grain in the centre is the Cpx and the Opx on the right. The Cpx and Opx within these rocks can be distributed evenly in terms of modal percentage.

B. Melanorites

The melanorites are found at the contact between the Main Zone and the Platreef, and occasionally at the contact between the Platreef and the Floor. They have the lowest content of plagioclase compared to the other two gabbronorite varieties, and have higher content of pyroxenes as well. Melanorites can easily be confused with the feldspathic pyroxenites. The main difference between melanorite and feldspathic pyroxenite is the state of plagioclase. Melanorites have cumulus plagioclase, and the feldspathic pyroxenites have interstitial plagioclase. Both these rocks can have a reworked orthopyroxene to a euhedral grain of orthopyroxene (see Plate 4.29B and Plate 4.32A). The mineralogy of the melanorites is >65% orthopyroxenes, 20-30% of cumulus plagioclase, and <5% of biotite and phlogopite and other accessory minerals (Plate 4.32 C-D).

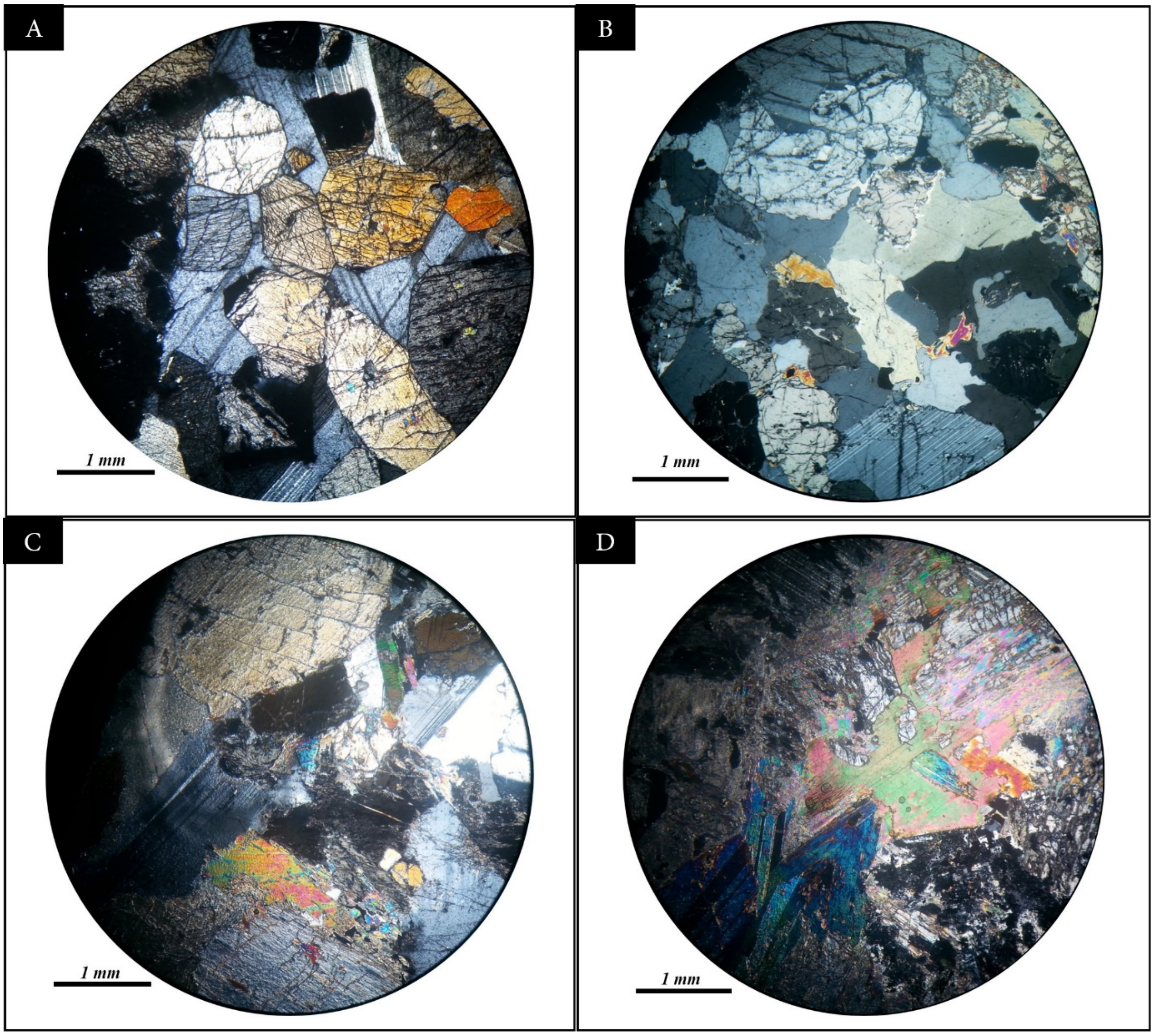


Plate 4.32. Photomicrographs of different melanorites of the Moordkopje farm. **A.** The Opx grains are very well euhedral and much related to feldspathic pyroxenites, but with a cumulus plagioclase. **B.** These rocks are very much comprised of quartz compared to the other rocks of Platreef and Main Zone. Quartz can make-up about 20% of the rock. **C-D**. The melanorites can also show the postcumulus biotite and phlogopite in them, as the grains of biotite and phlogopite are seen in **C** and **D.**

C. Norites

Norites are very similar to the gabbronorites. However, the difference is the significantly reduced clinopyroxene content in the norite. Norites more orthopyroxene than clinopyroxene. The mineralogy is 30 - 45% of cumulus plagioclase, >45% orthopyroxene and <5% postcumulus clinopyroxenes, <5% of accessory minerals including biotite. The main alterations in the Main Zone rocks are sericitisation and the occurrence of biotite as postcumulus (Plate 4.33).

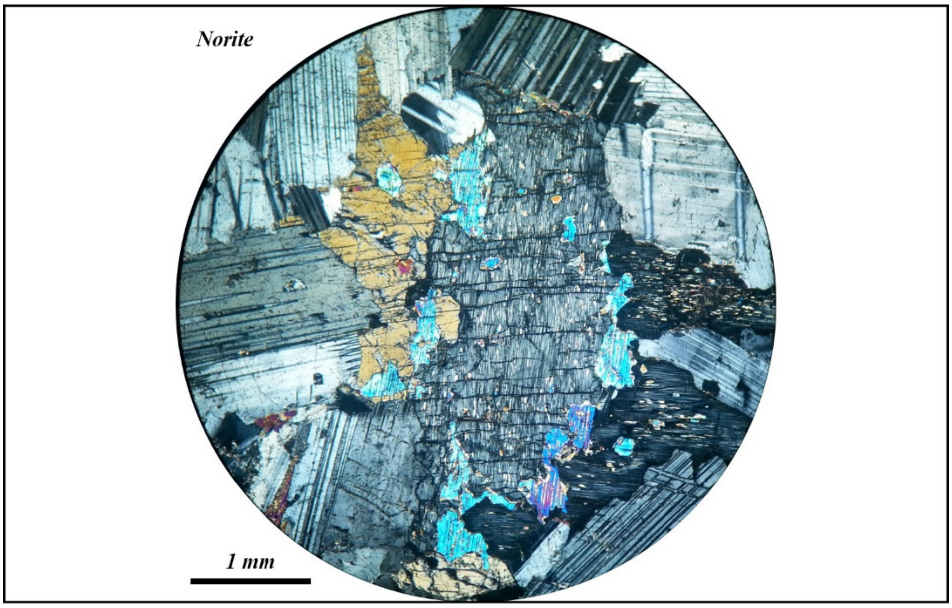


Plate 4.33. A photomicrograph of the norite. The rock is dominated by the Opx and cumulus plagioclase, and it shows some late-stage accumulation of biotite and Cpx at the grain boundaries.

D. Leuconorites

The leuconorites differ from the norites in their modal content of plagioclase and pyroxenes. The mineralogy of the leuconorites is 60 - 75% of plagioclase, >20% pyroxenes, and <5% of clinopyroxene and biotite as accessory minerals (Plate 4.34). The grain size is typically determined by the plagioclase laths; they are 3 – 4 mm long on average, and the grain sizes of the pyroxenes about 2 mm (generally smaller than the plagioclase grains). The texture of the leuconorite is ophitic with interstitial clinopyroxenes enclosing the plagioclase as the oikocryst (Plate 4.34). The alteration products are sericite from the plagioclase alteration, and some amphiboles with much subdued degree of alteration.

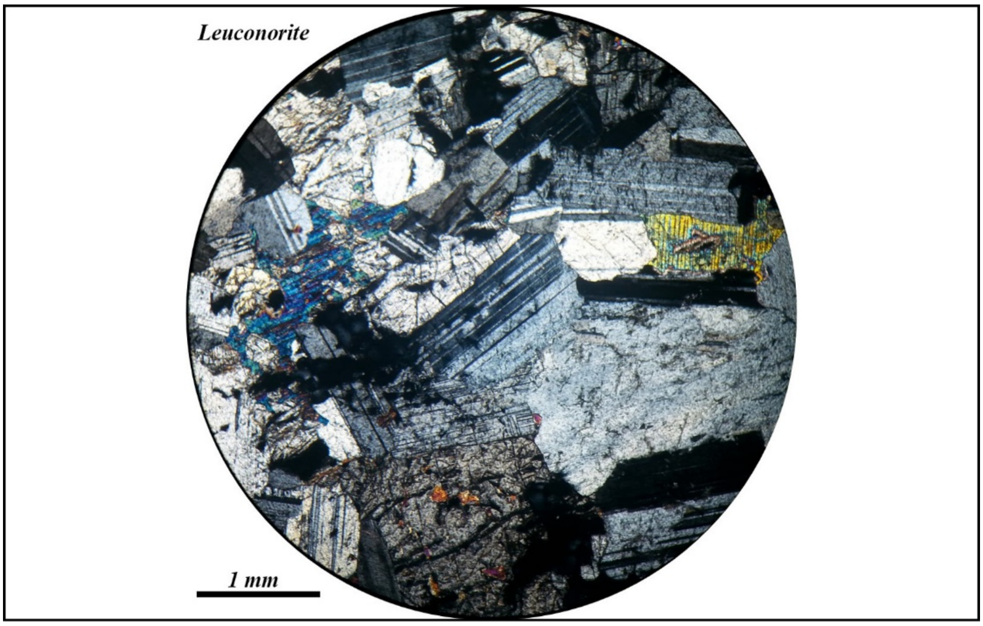


Plate 4.34. A photomicrograph of a typical leuconorite in the Main Zone of Moordkopje. The very low content of Opx and Cpx compared to the norites.

E. Anorthosites

The anorthosites, especially the mottled anorthosites, define the boundary between the Main Zone and the Platreef (Holwell and McDonald, 2005; Mitchell and Scoon, 2012). They have 95% of interlocked plagioclase and some patches of intercumulus orthopyroxenes of <5%. They show some intense alteration of the plagioclase to fine sericite.

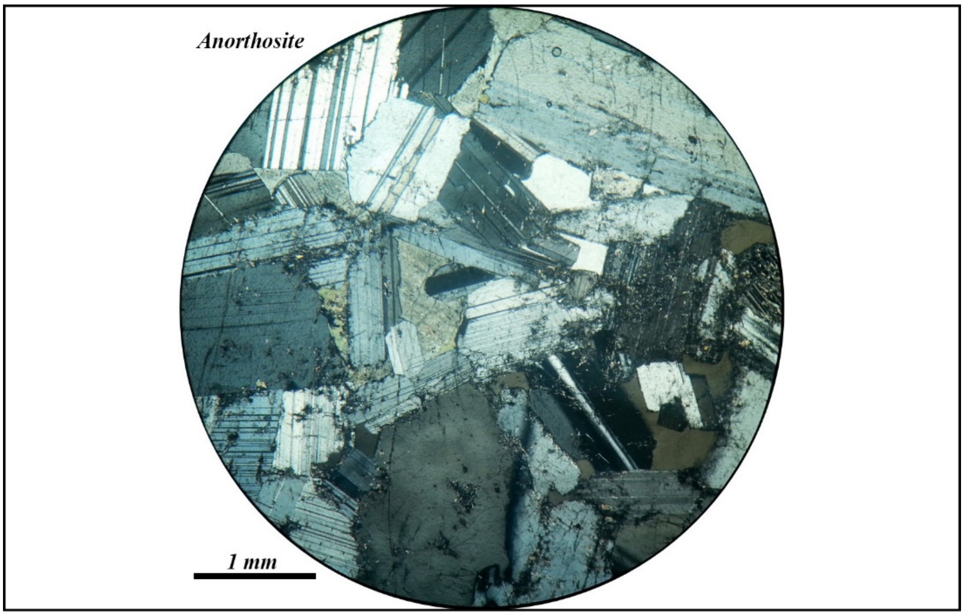


Plate 4.35. A photomicrograph of anorthosite. It is dominantly cumulus plagioclase and very little content of pyroxene. It is very much sericitised especially at the grain boundaries of plagioclase.

Table 4.1. Petrographic summary of the major rock types with respect to the systematic lithostratigraphy.

DEPTH LEVEL	ROCK TYPES	SUB-ROCK TYPES	PRIMARY MINERALOGY (MODAL VOL. %)	GRAIN SIZE & TEXTURE	ALTERATIONS & ACCESSORY MINERALS
HANGING WALL	Norites	Leuconorite	60 -70% Plag, >20% Pyx, and <5% Biot and other accessory minerals	2 – 3 mm medium grained Intergranular + subophitic texture	Sericitisation of plagioclase
		Norite	40 - 55% Plag, >45% Opx, <5% Biot and accessory minerals	2 – 3 mm medium grained Intergranular + subophitic texture	Clinopyroxene to fine-grained material of amphiboles (actinolite)
	Gabbronorites		40 - 50% Plag, 25% Opx, 20% Cpx and <5% Biot and accessory minerals	3 – 4 mm medium to coarse Cumulus plagioclase Ophitic texture	Weak sericitisation
	Anorthosites	Mottled anorthosite	95% Plag and some oikocryst of pyroxenes(Cpx and/or Opx) of <5%	3 – 4 mm Interlocking and Sub-ophitic texture	Intense sericitisation
	Melanorite		20 % Plag, >60% Opx, and 10% Quartz <5% phlogopite	3 – 4 mm (medium to coarse) Cumulus plagioclase Sub-ophitic texture	Alteration of orthopyroxenes to actinolite Postcumulus biotite - chloritisation Weak sulphides mineralisation (chalcopyrites)
PLATREEF	Feldspathic Pyroxenites	Pegmatoidal	65% Opx, 20% Plag, 15% Qtz, <5% biotite and phlogopite	>5 mm (coarse-to-pegmatoidal grained) Poikilitic texture Euhedral to subhedral	Medium alterations Uralitisation + sericitisation Weak chloritisation No visible ore minerals
		Feldspathic	60% Opx +25% Cpx +15% Plag	3 - 4 mm (medium-to-coarse grained) Intergranular + poikilitic texture Subhedral to anhedral	Weak serpentinisation Weak sericitisation No visible ore minerals
	Harzburgites		5-15% Oliv + 60-70% Opx + some other accessory minerals	3 – 4 mm (coarse grained) Interlocked + intergranular texture	Fibrous amphiboles within the olivine grains Intense serpentinisation Actinolite-tremolite Chromite (weak)
	Pyroxenites	Serpentinised pyroxenite	5-15% Oliv, 50-60% Opx, <5% Cpx, <10 Plag and other accessory minerals	3-4 mm (medium to coarse grained) Interlocked grains of pyroxenes	Intense serpentinisation + Sericitisation Chlorite + actinolite-tremolite Chromite (weak)
		Parapyroxenites	60% Cpx, 25% Opx, 15% fragments of Oliv	1 -3 mm (fine-to- medium grained) Poikilitic + interlocked texture Anhedral	Moderate alterations Granulation + serpentinisation Uralitisation
	Calc-silicate xenoliths		60% plagioclase, with 40% of the altered dolomite grains	1 - 2 mm (fine grained) Ophitic texture	Accessory biotite Altered dolomite
FOOTWALL	Granofels II		~50% of Opx+Cpx ; <35% of Quartz and Plagioclase and 15% Cpx.	Fine to medium grained Non-foliated interlocking grains	Very weak pyroxene alterations to amphiboles and chlorite Weak sericitisation
	Granofels I		>80% of plagioclase, K-feldspars and quartz; and <20% of pyroxenes	< 1 mm (very fine grained) Granular texture Foliated	Sericite
	Granite		>55% Qtz, 40% K-feldspars, and the other 5% accessory minerals e.g. biotite	< 1 mm (very fine grained) Myrmekitic texture	Sericitisation Biotite

4.2.4. Ore mineralogy

The Platreef itself at Moordkopje is primarily made up of feldspathic pyroxenites and harzburgites. These two types of rocks have been considered as the pristine lithologies of the Platreef in this study area. The considerable feature that makes them distinct from the other Platreef lithologies is that they are olivine-bearing rocks.

Ore mineralogy section is intended to provide a relative representation of mineralisation occurrence at Moordkopje from the two boreholes. Even though, the mineralisation occurrence at Moordkopje is very weak.

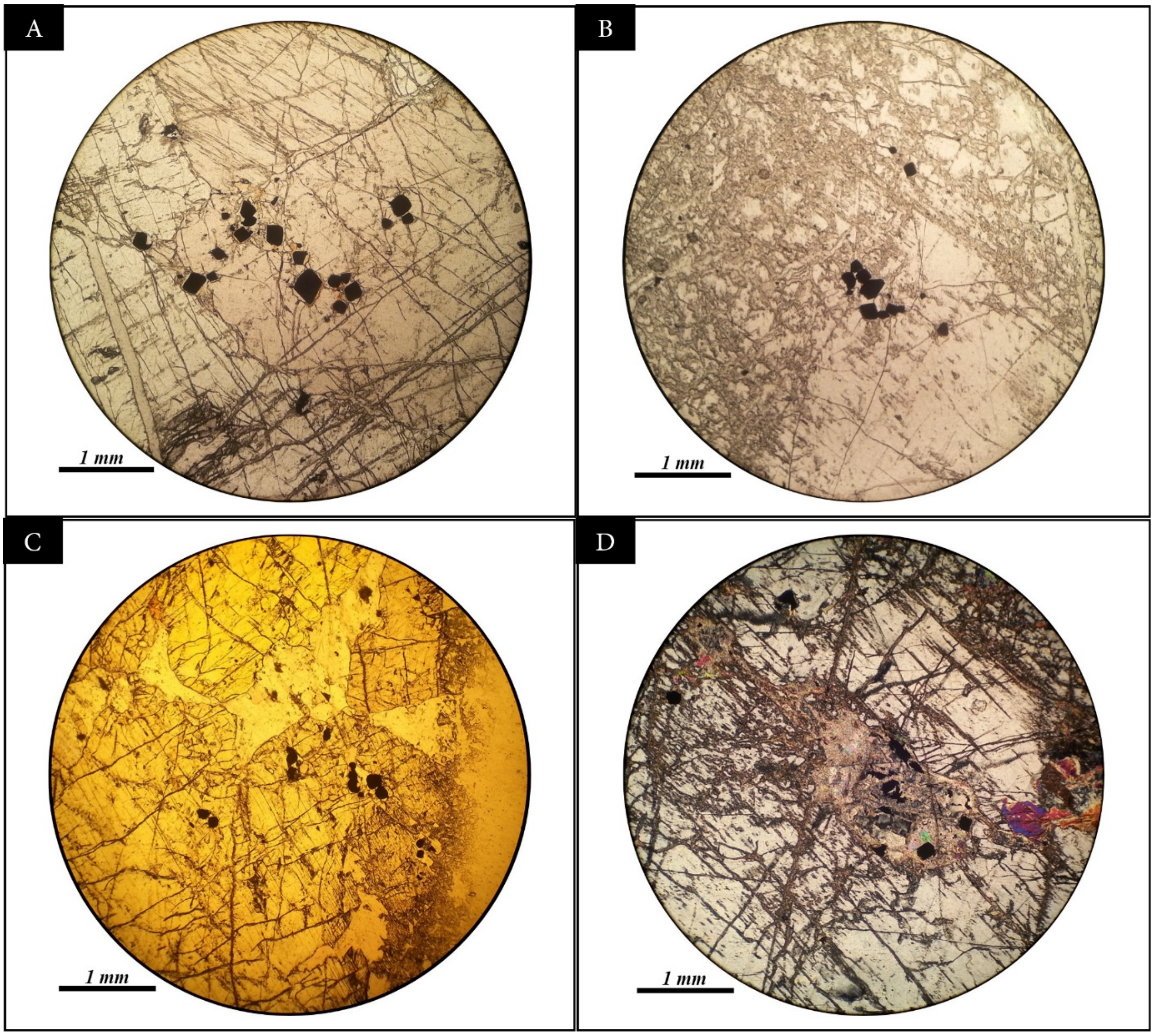


Plate 4.36. A photomicrograph of the mineralised rock samples of the two boreholes. **A–C.** The weak or poor occurrence of chromites in the serpentinised pyroxenites and harzburgites. **D.** The occurrence of weak chalcopyrite in the harzburgites at Moordkopje.

The ore mineralisation of Platreef at Moordkopje is relatively not economically viable and very weak compared to Zwartfontein at Akanani prospect area. However, mineralisation occurs at two different parts of the stratigraphy, namely, at the middle of Platreef zone where there is serpentinised pyroxenites and harzburgites where chromites and weak sulphide mineralisation occurs (Plate 4.36). Another section is at the contact between floor rock and Platreef where only sporadic sulphides occurs (Plate 4.37) in granofels which is confined within the veins in some instances.

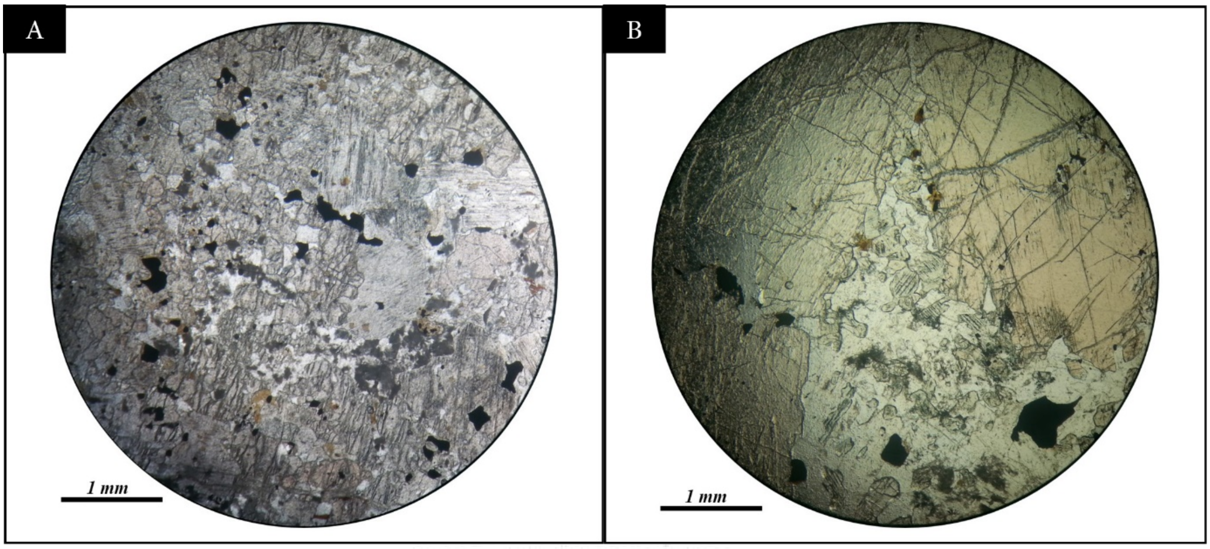


Plate 4.37. A photomicrograph of hybrid rock samples that are at the contact between the Platreef and the Floor rock. **A.** The granofels II is mineralised with chalcopyrite which sometimes confined within the veins. **B.** The sample that was collected right at the contact between the pegmatoidal feldspathic pyroxenite and the granofels which show the occurrence of weak sulphide mineralisation.

4.2.5. Summary

The petrography of the host rocks at Moordkopje has not been given much attention prior to this study. Even though it forms part of the Akanani Project, however, much focus had been given to Zwartfontein farm in the south of Akanani where the floor rock occurs with calc-silicate xenoliths. The work done by Mitchell and Scoon (2012) at Zwartfontein farm of Akanani Prospect can be related to this work in terms of individual rock descriptions in the Platreef stratigraphy, where in contrast, the current work describes the Platreef rocks at Moordkopje farm (north of Akanani Prospect) where the floor rock is purely granite with no calc-silicate involvement.

This study carries a different objective which is to understand the effects of the metasomatic fluids which may have been the driving factor on re-arranging the stratigraphy or the lithological sequence in the Platreef of Moordkopje.

The summary of the rock description above is outlined in terms of a systematic and generalised stratigraphic position of the lithologies in relation to both the boreholes (Table 4.1). The descriptions are mainly focused on the floor rocks and the Platreef package rocks, and their interaction at the contact.

The Archaean **granite** floor rock is a pink granite which is comprised mainly of quartz and k-feldspars, and it is relatively very fine grained. The assimilated units of granite during and after the emplacement of Platreef package produced the unique lithology. The name *granofels* was given to this unique lithology in literature (e.g. Holwell and McDonald, 2005). Granofels comprises of the constituents of both the floor rock granite and pyroxenites of Platreef. Granofels occurs in more than one varieties depending on the intensity of assimilation during the emplacement of Platreef magma. Two types of granofels were noted at Moordkopje from the boreholes MO009 and MO019. Granofels I and granofels II were the terms used to categorise these two rock types.

Granofels I is generally the gneiss which was formerly a granite and reworked to have assimilations of orthopyroxene (and clinopyroxene) from the pyroxenites on top of them. Generally, granofels I, has more felsic minerals of granite than the pyroxenes of pyroxenites. Another type of granofels is **granofels II** which the origin of the rock is unclear to identify or specify, even though the feldspathic pyroxenite was assumed. Granofels II has more pyroxenes than quartz and feldspars of the floor rock. One significant feature about the granofels II is the occurrence of sulphide minerals within them.

The **calc-silicates** are foreign rocks in the floor rocks vicinity of the Moordkopje area. They were transported from Central Sector of Northern Limb where the floor rock is the Malmani Dolomite of Transvaal Supergroup. These rocks occur as xenoliths which cause significant alterations to the Platreef package. As a result of calc-silicate occurrence, a different type of lithology was formed, which comprised of clinopyroxene (augite). These lithology is termed parapyroxenite in the Platreef.

Parapyroxenites are relatively at the bottom zone of the Platreef at the vicinity of calc-silicate xenoliths occurrence. Parapyroxenites have significant high clinopyroxene content as a result of additional calcium from the calc-silicate xenoliths. Parapyroxenites are highly altered, and some contain fragments of altered and ruptured olivine. These rocks have no visible inclusions of sulphides and chromite.

Another rock type at the bottom zone of Platreef is the **pegmatoidal feldspathic pyroxenites** which, however, is not associated with the occurrence of calc-silicates. Instead, these rocks (originally pyroxenites of Platreef) were partially affected by siliceous constituents from the granite floor and were reworked. The transferred material was quartz and K-feldspars, which discriminate them from other feldspathic pyroxenites in the Platreef. Some of the Platreef sulphide minerals are hosted in these rocks of which chalcopyrite dominates.

Typical Platreef **feldspathic pyroxenites** are associated with harzburgites and serpentinised pyroxenites. These types of feldspathic pyroxenites are distinct as a result of the preserved mineralogy of pristine orthopyroxene; and postcumulus clinopyroxenes at the grain boundaries. These feldspathic pyroxenites have very low intercumulus plagioclase content. The grains of these rocks are closely packed and interlocked together.

Another type of feldspathic pyroxenite is the one that is associated with the **melanorites** at the top zone of the Platreef. This feldspathic pyroxenite is mineralogically similar to the melanorites, however, the main difference is the state of plagioclase i.e. melanorites have cumulus plagioclase whereas feldspathic pyroxenites have intercumulus plagioclase. These two lithologies have euhedral orthopyroxene grains.

In short, feldspathic pyroxenites can be in three different varieties in the Platreef depending on the position in the stratigraphy (summary in Table 4.2). Namely, these are feldspathic pyroxenites proximal to:

1) the floor rock which are quartz-bearing and pegmatoidal,
2) the olivine-bearing lithologies in the middle of the Platreef zone, which are medium grain-interlocked with postcumulus clinopyroxene at the grain boundaries, and
3) the Main Zone which have euhedral orthopyroxene and more enriched in plagioclase relative to the other feldspathic pyroxenites and occasionally have postcumulus phlogopite.

Table 4.2. The generalisation of the Platreef feldspathic pyroxenites and the other rock types present.

PLATREEF ZONES	PYROXENITES	ASSOCIATED ROCK TYPES	PRIMARY MINERALS	TEXTURE	ALTERATIONS & SECONDARY MINERALS	ORE MINERALS	ALTERATION ORIGIN & IMPLICATION
UPPER	Feldspathic pyroxenites	Melanorites	Orthopyroxene Plagioclase	Medium Euhedral	Chlorite Phlogopite Sericite	Barren No visible ore minerals	Magmatic Local
MIDDLE	Serpentinised pyroxenites	Harzburgites	Orthopyroxene Olivine	Medium-coarse Interlocked grains	Clinopyroxene Actinolite Chlorite	Weak chromites Weak chalcopyrite	Magmatic Local
LOWER	Pegmatoidal feldspathic pyroxenites	Gabbronorites Parapyroxenites	Orthopyroxene Plagioclase Quartz	Coarse to pegmatoidal Subhedral	Chlorite Sericite Actinolite	Weak chalcopyrite	Non-magmatic Fluid-rock interaction Crustal contamination
	Parapyroxenites	Calcsilicate xenoliths	Olivine Clinopyroxene Orthopyroxene	Medium Anhedral	Serpentine Actinolite	Non-mineralised	Non-magmatic Contact metamorphism

Table 4.2 summarises the occurrence of pyroxenites in the Platreef at Moordkopje with respect to similarities and differences in mineralogy, mineralisation, and alterations. The summary table also addresses relationship of pyroxenites in succession with stratigraphy, and mineral alterations related to stratigraphy.

At the **Lower Platreef**, the pyroxenites were affected by the interaction and assimilation with the floor rocks. As a result, the quartz and feldspars from the granite floor were transferred to the pyroxenites, and the occurrence of calc-silicate xenoliths altered the original mineralogy of the pyroxenites. These type of alterations occur only to the pyroxenites at the bottom of the Platreef in the stratigraphy. The occurrence of mineralisation at this stratigraphic position (typically sulphide mineralisation) was based on additional external sulphur from country rocks that enhanced the magmatic sulphur content during assimilation and fluid-rock interaction (Harris and Chaumba, 2001; Pronost *et al.*, 2008; McDonald and Holwell, 2011).

At the **Middle Platreef**, the pyroxenites are the most pristine of the other pyroxenites in the Platreef stratigraphy. Imprints of external processes are not present on these pyroxenites from petrography. Relatively very low interstitial plagioclase in these rocks to other feldspathic pyroxenites in the Platreef. The mineral alterations on these rocks are local magmatic alterations (e.g. olivine to serpentine, orthopyroxene to amphiboles). The mineralisation in this part of the stratigraphy is magmatic in origin with a close relationship with chromitites.

At the **Upper Platreef**, the content of interstitial plagioclase has increased in the pyroxenites at this stratigraphic position to make feldspathic pyroxenites. The grains of orthopyroxene are very euhedral. These rocks are overlain directly by Main Zone lithologies (typically melanorites and anorthosites). The alteration of plagioclase to sericite is the dominant alteration at this stratigraphic position of Platreef.

Harzburgites are comprised of olivine and orthopyroxene as the main primary minerals. These rocks are relatively more pristine rock types than any other lithologies in the Platreef. Harzburgites host most of the mineralisation of Platreef at Moordkopje e.g. chromites and chalcopyrite.

4.3. Geochemistry

4.3.1. Introduction

The objectives of the whole rock geochemistry chapter is to ascertain the compositional and fractionation trends of major oxides and trace elements in the rock groups based on the classification done in petrography. These outcomes will be further used for trace element modelling and geochemical element ratios in order to demonstrate the role of contact metasomatic fluid action in the formation of Platreef mineralisation. Alteration geochemistry (Mass transfer) was used to identify the occurrence and effects of footwall signatures within the Platreef lithologies.

Petrography has revealed the rock types in boreholes MO009 and MO019; and how these rocks differ from each other regarding mineralogical composition. The mineralogy of the rocks types are dominated by orthopyroxene, clinopyroxene and plagioclase and to some extent olivine and quartz.

For the methods applied herein, fifty samples from two drill cores (i.e. MO009 and MO019) were analysed for geochemistry. The geochemical data was produced by XRF analysis. The data is made up of major, minor (in wt.%) and trace elements (in ppm). The LOI (loss on ignition) which is weight loss (or gain) due to volatiles content of the rock, and sulphur content (S) was included in the analysis. The data also included the PGEs (Pt, Pd and Au) which were analysed by Fire Assay in parts per billion (ppb). The analytical results are presented in the Appendix I-C.

The multivariate statistical approach (i.e. Discriminant Analysis) was use for characterising the rock groups obtained in petrography in terms of geochemical major oxides, and in terms of trace elements, spider diagrams were used. This method was used to ascertain which geochemical elements that define each group of rocks. The data evaluation was carried through using the IBM® SPSS® v22.0 and Geochemical Data Toolkit® (GCDkit) 3.00 softwares. The data was evaluated according to the following methods in their order:

A. The descriptive statistics

Geochemical data evaluation using univariate analysis such that the distribution and structure of data are understood and displayed in terms of geochemical data summary. The geochemical data generally contain more than one population, and therefore they invariably do not follow a normal distribution model. This may relate to several factors which include contrasting variation in the chemistry of the rock types, the biasness of sampling method, and/or an indication of geochemical anomalies (Reimann and Filzmoser, 2000; Carranza, 2008). The purpose is to ascertain the need for normalisation of data prior to statistical evaluation. Section 4.3.2 of this chapter shows the results of univariate data analysis and data summary.

The interrelationship of elements (i.e. correlation analysis) was included in this sub-section as another method to describe the structure of the data. The aim was find the elements that are related to each other. This is a bivariate analysis that compares two geochemical elements and evaluates the strength of the relationship between them.

B. Geochemical characterisation of rock types

The identified rock groups from petrography and geochemistry requires characterisation in terms of major oxides and trace elements. The aim is to ascertain the elements that define each group of rocks such that geochemical indices and vectors can be devised to target mineralisation. Discriminant Analysis (DA) was used in the case of major oxides, and Spider Diagrams (multi-element diagrams) in the case of trace elements.

C. Exploration data analysis

The methods used in exploration analysis attempts to model and evaluate the evolution of Platreef rocks, and also the effects of contact metasomatic fluids in the Platreef. In this study the bivariate diagrams, element ratios and alteration geochemistry are used to evaluate the objectives and outcomes of this analysis. The bivariate diagrams will identify the element patterns and fractionations such that they can be used to formulate element ratios that can model the evolution of rocks of Platreef in this area. Subsequently, the element ratios will be compared with mineral alterations and mineralisation occurrence of the area by downhole plots.

4.3.2. The descriptive statistics

4.3.2.1. Geochemical data elements

The geochemical data set for 50 samples was obtained by XRF analysis using the pressed pellets. The data comprised of major oxides which include SiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5 and LOI given in weight percentage (wt%). The trace elements are Ba, Ce, Co, Cr, Cu, Nb, Ni, Pb, Rb, Sr, Th, U, V, Y, Zn and Zr which are presented in parts per million (ppm). Sulphur content (S in ppm) was also part of the XRF analysis. The data also included the PGEs (Pt, Pd and Au) for selected eleven samples (Appendix I).

4.3.2.2. Data distribution

A. Histograms

It is necessary to check the distribution of variables (i.e. elements/oxides in geochemistry) before carrying out any multivariate analysis such as Hierarchical Cluster Analysis, Discriminant Analysis (Reimann and Filzmoser, 2000; Reimann *et al.*, 2002; and Templ *et al.*, 2006). This basic requirement is generally neglected in geochemistry (Reimann and Filzmoser, 2000) as the geochemical data is very variable and is very likely not to improve even after log-transformation (see Figure 4.4).

There were no marked improvements to the data even after the log-transformation, the raw data were used. Some examples of the oxides in their original and log transformed versions data are presented in Figure 4.4.

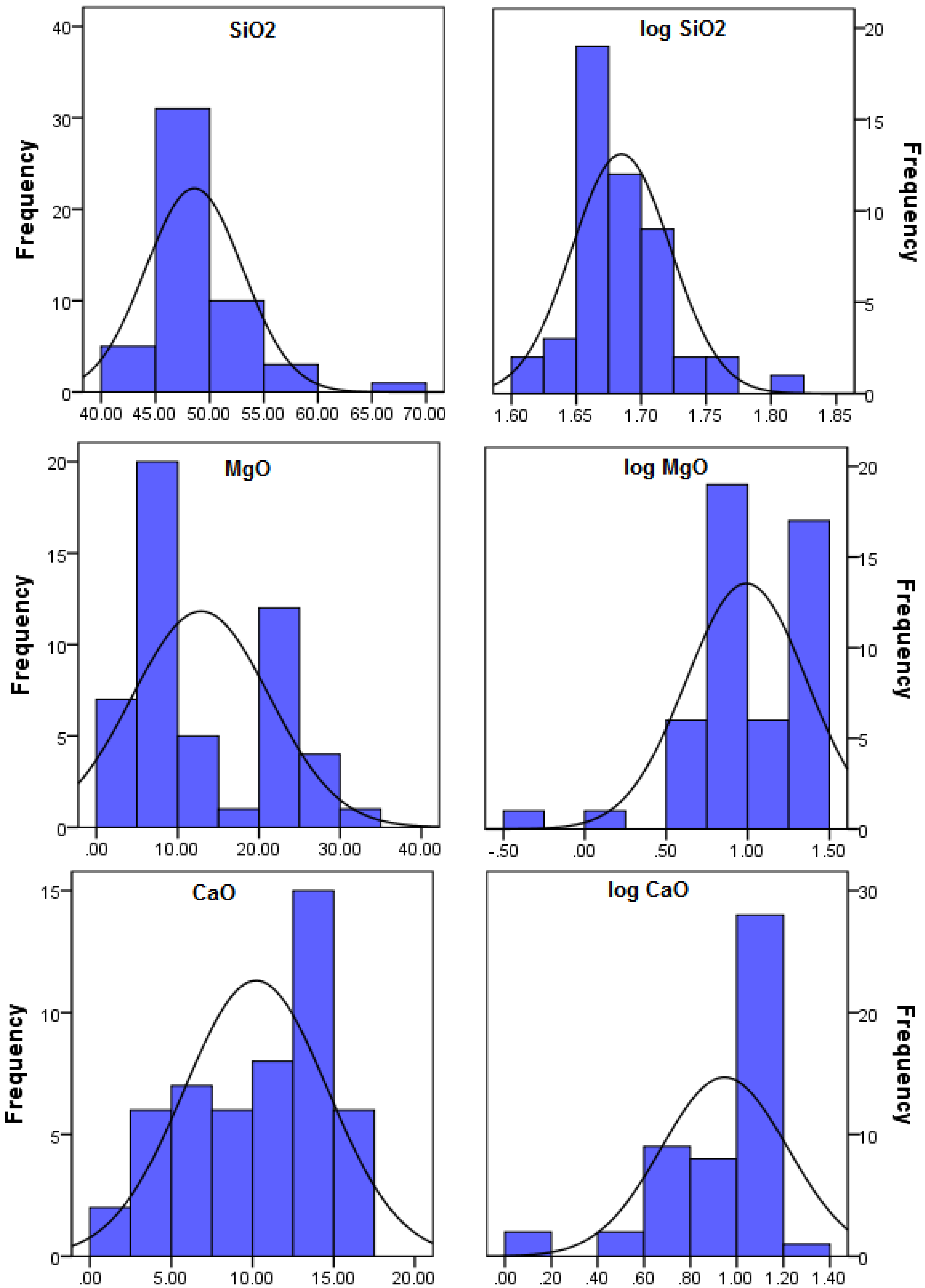


Figure 4.4.Some of the major oxides from the untransformed (original) data that are showing the distribution of data, and on the right are the log-transformed variables of the same element to evaluate the improvements to the data.

B. Data summary

The distribution patterns of elements/oxides in each rock groups are presented as average values, i.e. geometric mean, and the standard deviation (Table 4.3). The variation patterns of elements/oxides is also presented in box-plots in Figure 4.5 for each rock group to represent the visual reflection of Table 4.3. In Figure 4.5, the high values of SiO_2 in pegmatoidal feldspathic pyroxenites and granites are explained by the high quartz content in these rocks. While the high anorthite content in Main Zone rocks is shown by the substantial content of Al_2O_3. The high values of MgO is seen in Platreef lithologies, especially in harzburgites, as a result of high orthopyroxene and some olivine in these rocks. The high values of CaO occurs in Main Zone rocks and parapyroxenites, caused by the contents of high anorthite and clinopyroxene, respectively in these rocks.

Table 4.3. The statistical summary table of the different rock types in terms of geometric mean values and the standard deviations from the average value.

	MAIN ZONE		PLATREEF										FOOTWALL	
	(22)		Melanorite (4)		Feld. Pyrox (6)		Harzburgite (4)		Parapyroxenites (4)		Pegm. Feld. Pyrox (4)		Granite-gniess (6)	
	Geom. Mean	Std. Dev.	Geom. Mean	Std. Dev.	Geom. Mean	Std. Dev.	Geom. Mean	Std. Dev.	Geom. Mean	Std. Dev.	Geom. Mean	Std. Dev.	Geom. Mean	Std. Dev.
SiO_2	46.85	0.84	52.51	0.39	47.90	0.83	46.28	2.28	41.53	1.34	54.83	3.49	54.32	6.29
Al_2O_3	22.21	2.63	7.51	0.81	7.65	1.99	2.66	2.49	6.49	1.88	8.67	2.03	18.63	2.63
Fe_2O_3	5.44	1.20	10.84	0.43	12.45	1.53	14.07	0.72	11.30	2.41	12.57	4.95	4.56	3.09
MnO	0.09	0.03	0.19	0.01	0.22	0.01	0.18	0.09	0.20	0.03	0.19	0.11	0.05	0.07
MgO	6.02	2.07	21.76	1.79	21.58	0.84	28.08	2.07	24.05	0.93	12.16	0.62	3.96	3.28
CaO	14.26	1.01	5.37	0.79	6.71	1.37	2.54	1.28	9.85	2.22	4.77	3.56	8.82	2.95
Na_2O	1.84	0.30	0.52	0.18	0.58	0.29	0.03	0.11	0.16	0.32	1.54	0.61	3.11	1.12
K_2O	0.39	0.21	0.11	0.04	0.13	0.11	0.02	0.02	0.07	0.14	0.48	0.09	0.67	0.99
TiO_2	0.16	0.03	0.15	0.05	0.19	0.05	0.11	0.02	0.21	0.07	0.28	0.23	0.10	0.10
P_2O_5	0.03	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.09	0.05	0.01	0.03
LOI	1.61	0.78	0.25	0.42	1.82	0.73	4.37	1.58	5.28	1.11	0.50	3.02	1.11	0.80
Ba	101.76	19.54	48.27	7.89	52.74	12.94	35.76	15.52	37.58	35.43	114.94	56.73	188.34	204.79
Ce	0.30	11.14	0.02	0.00	0.07	2.76	0.41	12.59	0.52	1.96	1.22	62.04	0.50	15.63
Co	22.01	9.75	80.87	5.48	80.16	11.56	104.97	51.57	74.18	25.34	54.53	22.13	25.25	14.11
Cr	124.93	198.58	2833.13	639.56	2304.64	545.29	2301.63	1116.73	1476.11	305.56	511.67	417.80	314.47	258.22
Cu	96.66	21.33	211.63	203.58	137.21	49.87	678.26	648.53	123.69	66.04	88.37	86.47	78.62	32.78
Nb	1.16	2.30	2.45	0.58	1.48	1.59	1.84	1.33	1.00	1.56	3.82	2.31	3.16	2.24
Ni	146.38	63.11	882.54	347.20	811.60	344.28	2058.45	1845.17	778.26	312.17	311.68	86.92	158.15	92.85
Pb	3.16	4.63	4.23	2.50	1.29	5.11	1.11	1.42	1.93	3.80	2.62	7.01	4.47	8.22
Rb	26.22	11.23	7.90	1.41	14.10	7.16	9.47	2.37	18.31	6.45	25.14	24.29	29.58	22.08
Sr	244.42	44.70	68.51	6.70	69.88	33.02	25.92	23.72	47.15	37.91	125.14	63.59	270.06	168.35
U	4.98	6.02	0.01	1.50	0.01	0.41	0.00	0.01	0.03	0.02	0.03	14.79	4.35	6.18
V	0.23	8.16	113.85	13.82	119.83	14.41	76.48	35.61	116.28	32.31	98.00	77.33	0.00	4.79
Y	71.58	21.46	2.63	0.96	9.60	2.19	4.18	3.52	12.61	2.73	27.08	48.59	59.04	43.94
Zn	12.26	2.61	73.22	2.63	129.18	15.11	94.85	25.96	111.31	16.09	103.32	57.87	11.94	9.43
Zr	72.55	19.59	20.02	3.50	37.01	7.92	28.70	8.76	37.64	9.47	71.98	31.45	51.97	30.81
S	0.51	0.31	658.64	668.05	11.34	338.52	773.88	925.53	0.40	0.40	31.37	229.43	23.17	101.87

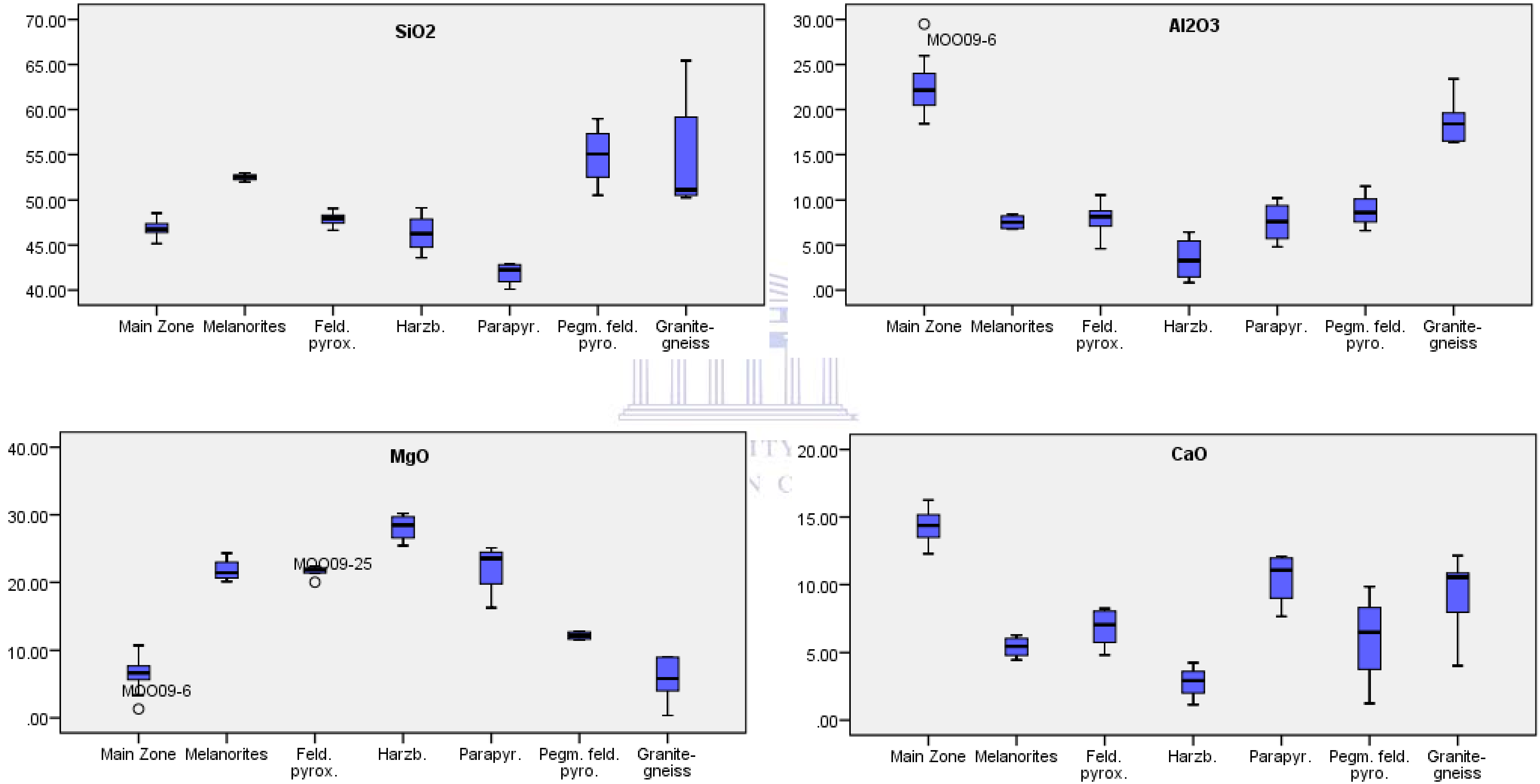


Figure 4.5. Some of the major oxide (in wt.%) variation patterns in the rock groups which includes the Main Zone, Platreef and Footwall.

4.3.2.3. Element interrelationship

The correlation analysis is the measure of the strength of associations between elements (Rollinson, 1993). The significance of correlation analysis is that it provides the insights on elements that are associated or linked prior to the in-depth geochemical data analysis. In that way, the practical meaning of data will be achieved which will link or compare to the rocks studied in petrography.

The linear relationship between two variables was determined by using correlation coefficient (r). The correlation coefficient measures and quantifies the strength of the element association in terms of linear relationship. For example, the petrography has shown a negative relationship between orthopyroxene and plagioclase when pyroxenites are compared to norites. Therefore the linear relationship of MgO and Al_2O_3 would provide and confirm the trends from the petrography.

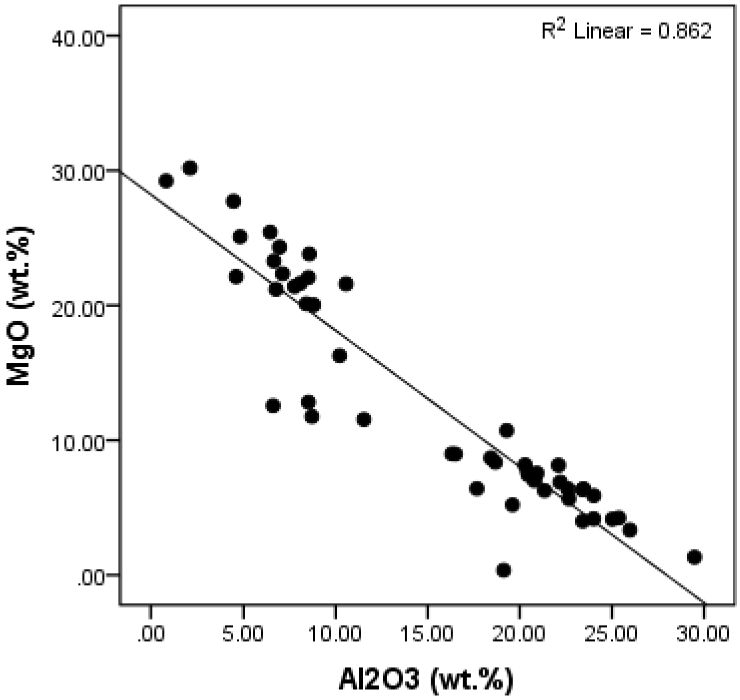
Table 4.4 depicts the oxides and elements that significantly produce high correlation coefficient values relative to the major oxides. Those trace elements are Ba, Co, Cr, Cu, Ni, Rb and Sr. Sulphur was also included in the table in order to provide the trends related to the sulphides (BMS mineralisation). The highest correlation coefficient is between MgO versus Al_2O_3 (-0.93) and between Na_2O versus Sr (+0.91) (Figure 4.6). The Na_2O-Sr relationship is a positive linear relationship, contrary to the negative relationship between MgO versus and Al_2O_3. This corroborates the petrography results that the compositions of pyroxenites and norites in terms of pyroxene and plagioclase are inversely proportioned to each other.

Table 4.4. The interrelationship of the geochemical elements expressed in terms of Pearson correlation coefficient (r). The dataset of 50 samples with different rocks.

	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI	Ba	Co	Cr	Cu	Ni	Rb	Sr	Y	S
SiO_2	1.00																			
Al_2O_3	-0.05	1.00																		
Fe_2O_3	-0.11	-0.89**	1.00																	
MnO	-0.16	-0.78**	0.88**	1.00																
MgO	-0.21	-0.93**	0.82**	0.73**	1.00															
CaO	-0.43	0.84**	-0.69*	-0.53*	-0.73**	1.00														
Na_2O	0.52*	0.72**	-0.76**	-0.66*	-0.85**	0.40	1.00													
K_2O	0.54*	0.38	-0.51*	-0.47	-0.54*	0.06	0.75**	1.00												
TiO_2	0.02	-0.15	0.27	0.18	-0.01	0.07	-0.08	-0.04	1.00											
P_2O_5	0.31	0.15	0.02	-0.09	-0.33	0.01	0.21	0.30	0.34	1.00										
LOI	-0.43	-0.36	0.15	0.16	0.39	-0.21	-0.41	-0.15	-0.18	-0.02	1.00									
Ba	0.61*	0.34	-0.50*	-0.43	-0.51*	0.01	0.81**	0.90**	-0.21	0.11	-0.19	1.00								
Co	-0.08	-0.88**	0.84**	0.65*	0.89**	-0.72**	-0.74**	-0.48	0.09	-0.27	0.23	-0.43	1.00							
Cr	-0.00	-0.80**	0.68*	0.68*	0.87**	-0.70**	-0.67*	-0.42	0.00	-0.36	0.02	-0.39	0.78**	1.00						
Cu	-0.09	-0.46	0.43	0.34	0.54*	-0.47	-0.43	-0.27	-0.17	-0.19	0.14	-0.22	0.64*	0.58*	1.00					
Ni	-0.10	-0.66*	0.59*	0.40	0.73*	-0.60*	-0.58*	-0.35	-0.09	-0.26	0.24	-0.30	0.84**	0.68*	0.92**	1.00				
Rb	0.31	0.42	-0.55*	-0.51*	-0.53*	0.21	0.58*	0.79**	-0.03	0.46	0.21	0.62*	-0.57*	-0.53*	-0.32	-0.40	1.00			
Sr	0.33	0.82**	-0.84**	-0.75**	-0.87**	0.57*	0.91**	0.71**	-0.12	0.14	-0.34	0.72**	-0.77**	-0.70**	-0.40	-0.57*	0.62*	1.00		
Y	0.25	-0.02	-0.01	-0.06	-0.14	-0.12	0.10	0.13	0.01	0.71**	0.34	0.08	-0.19	-0.28	-0.16	-0.16	0.48	-0.01	1.00	
S	0.16	-0.55*	0.46	0.20	0.55*	-0.61*	-0.41	-0.22	0.08	0.20	0.09	-0.15	0.70**	0.54*	0.70**	0.77**	-0.39	-0.44	-0.23	1.00

* Correlation is significant between: $0.5 \leq |r| < 0.7$

** Correlation is significant between: $|r| \geq 0.7$



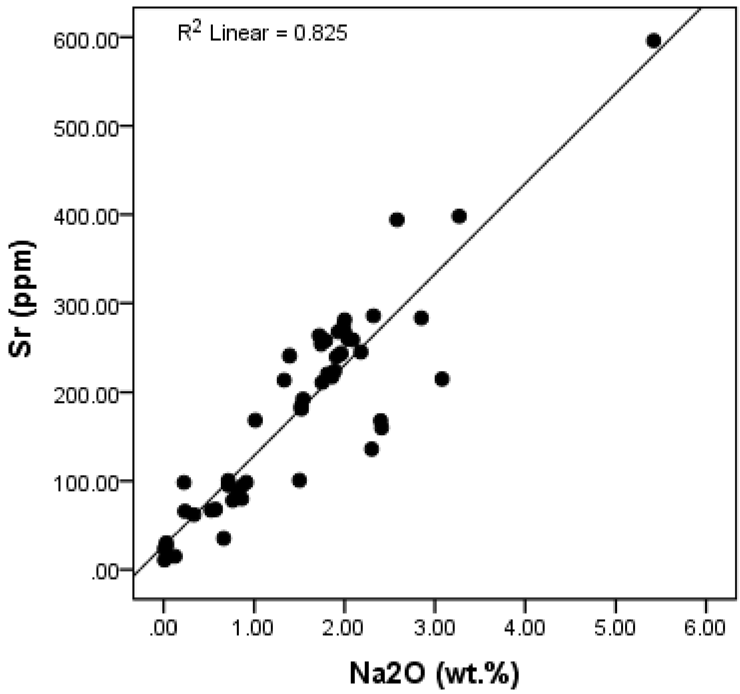


Figure 4.6. The graphical representation of correlations with a positive linear relationship shown by Na_2O versus Sr, and with a negative relationship between MgO versus Al_2O_3.

4.3.3. Geochemical characterisation of rock types

The aim of the geochemical characterisation of the rock types is to ascertain the elements/oxides that define each group of rocks such that geochemical indices and vectors can be devised to target mineralisation. The Discriminant Analysis (DA) was used to characterise the rock types in terms major oxides. In the latter, the Spider Diagrams is used in the case of trace elements.

The characterisation of rocks in the Platreef was done separately to the gabbronorites of Main Zone and the granite-gneiss floor rock. This allows a workable data for the DA statistical technique, and also it directs the focus to understanding the rocks of the Platreef package as part of the main objectives. Initially, these three zones (i.e. Main Zone, Platreef, and Footwall) are differentiated in terms of the major oxides using the Stepwise Method in order to show the main oxides that separate the zones. Afterwards, the geochemical characterisation is focused on only the Platreef rocks.

Petrography has shown that the clear compositional difference between the Platreef and Main Zone is the dominance of pyroxenes (particularly orthopyroxene) in Platreef to anorthite which is dominant in the Main Zone. Whiles, the Footwall is dominantly composed of quartz, albite and K-feldspars. This information contributes immensely to understanding the relationship of mineralogy and elements/oxides in the characterisation of rock types.

A. <u>Stepwise Method on differentiation of major zones</u>

The Stepwise Method is a part of the DA that clearly deciphers the most significant elements/oxides that mainly separate the rock types from each other. In this section, the scatter plots are useful in terms of showing how the rock groups are separated from each other by the significant elements/oxides. Out of the fifty samples, twenty-two samples are from the Main Zone, another twenty-two samples are Platreef, and the six samples are Footwall samples.

The IBM® SPSS® software selects the oxides that are best predictors from the set of all the oxides by the use of F-statistic (i.e. the F values) and Wilks' lambda. Wilks' lambda is the statistic method used to select predictor variables, and the F value is the criteria used in the method. Table 4.5 indicates that the statistic F = 3.84 and F = 2.71 were used (by defaults) for entering and removing oxides respectively. Thus, an oxide with entry F value greater than 3.84 is entered, and subsequently remove oxides with removal F value of less than 2.71. The Table 4.5 shows that Al_2O_3 and Na_2O were the only oxides that met the F value criteria used.

Table 4.5. The table shows Al_2O_3 and Na_2O the main elements that separate the three zones.

VARIABLES ENTERED/REMOVED[a,b,c,d]									
		Wilks' Lambda							
						Exact F			
Step	Entered	Statistic	df1	df2	df3	Statistic	df1	df2	Sig.
1	Al_2O_3	0.108	1	2	47.000	193.172	2	47.000	0.000
2	Na_2O	0.047	2	2	47.000	83.379	4	92.000	0.000

At each step, the variable that minimises the overall Wilks' Lambda is entered.

a. A maximum number of steps is 22.

b. Minimum partial F to enter is 3.84.

c. Maximum partial F to remove is 2.71.

d. F level, tolerance, or VIN insufficient for further computation.

Table 4.6 shows that the results of the stepwise analysis for the three zones that Al_2O_3 and Na_2O alone correctly separate the zones by 98%. Thus, these two oxides are the only very useful oxides for use when dealing with separation of the major zones (i.e. hanging wall, the reef, and the footwall) in this area. Al_2O_3 and Na_2O are the main oxides as tools for use in the early stages of discrimination of the samples into their major groups. The scatter plot of Al_2O_3 vs Na_2O (Figure 4.7) illustrates how much Al_2O_3 and Na_2O oxides can separate Main Zone, Platreef and Footwall lithologies.

Table 4.6. The summary table of the results of the analysis which shows that Al_2O_3 and Na_2O differentiate the three zones by 98%.

CLASSIFICATION RESULTS[a]						
		Zones	Main Zone	Platreef	Footwall	Total
Original	Count	Main Zone	22	0	0	22
		Platreef	0	21	1	22
		Footwall	0	0	6	6
	%	Main Zone	100.0	0.0	0.0	100.0
		Platreef	0.0	95.5	4.5	100.0
		Footwall	0.0	0.0	100.0	100.0

a. 98.0% of original grouped cases correctly classified.

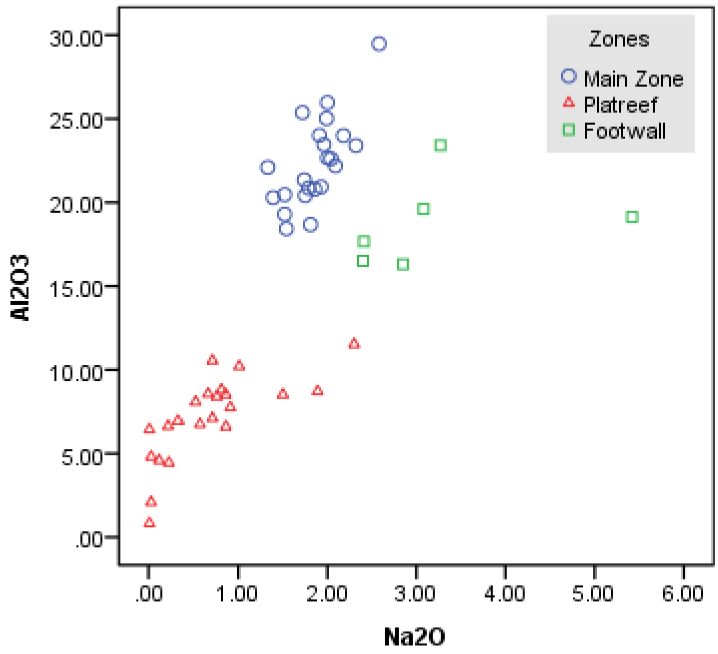


Figure 4.7. The scatter plot of Al2O3 vs Na2O illustrates how these two elements separates the three groups.

4.3.3.1. Characterisation of the Platreef samples

The main objective of geochemical characterisation was to eventually focus mainly on the Platreef lithologies, as both Main Zone and Footwall lithologies are essentially out of scope of the work. Hence, the Platreef samples were separated and characterised separately from the Main Zone and Footwall samples.

The dendrogram in Figure 4.8 shows the twenty-two Platreef samples that were classified by Petrographic analysis in their pre-defined lithological groups. The dendrogram was used to illustrate and display the Platreef samples according to their rock groups. The rock groups were assigned as melanorites (4), feldspathic pyroxenites (6), harzburgites (5), parapyroxenites (3), and pegmatoidal feldspathic pyroxenites (4).

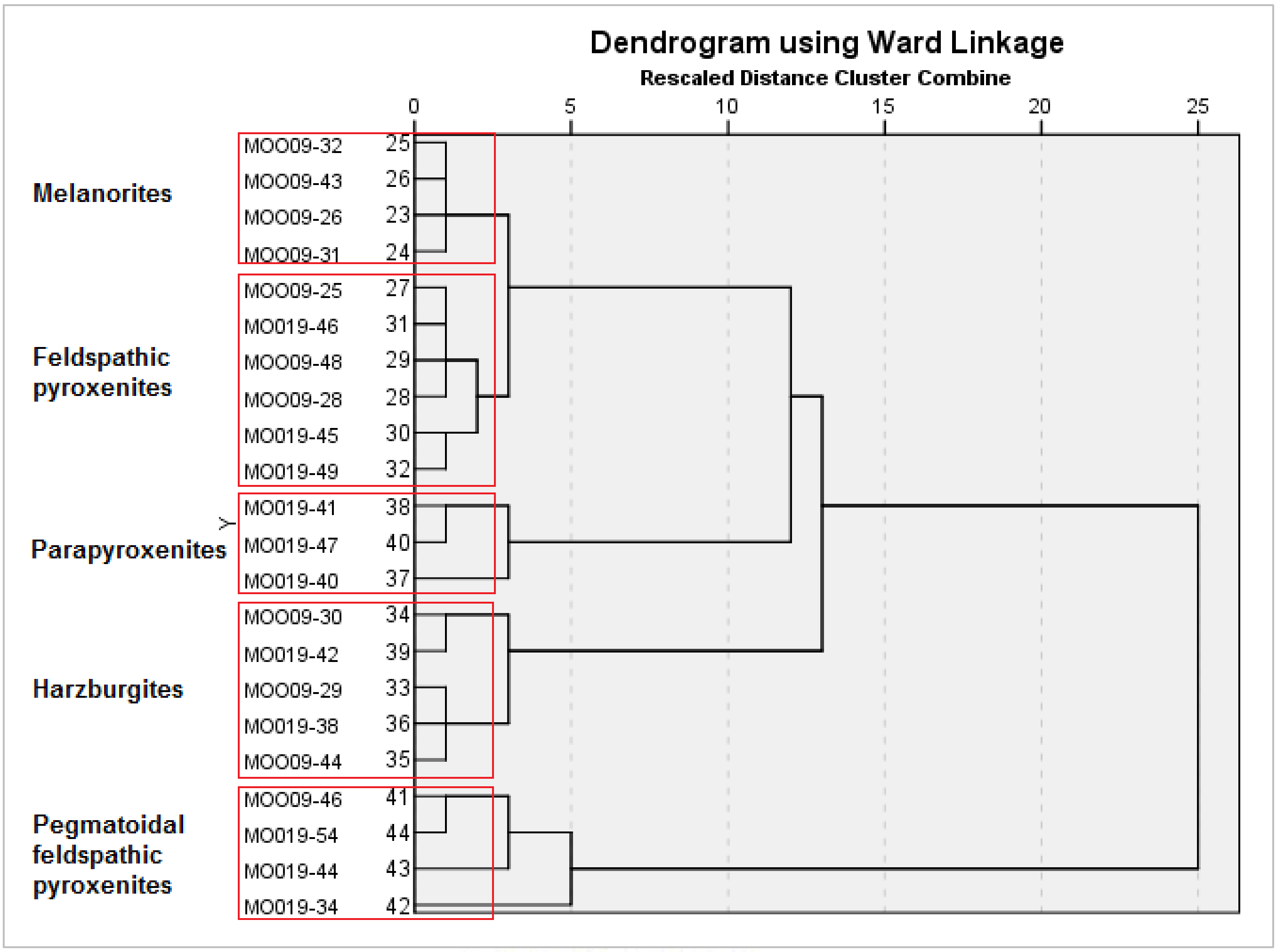


Figure 4.8. The dendrogram is showing the Platreef samples in their respective rock groups.

The purpose of Discriminant Analysis is to devise a predictive model that can separate the rock groups using the elements/oxides as the variables. The procedure of DA produces a set of discriminant functions based on linear combinations of the [elements/oxides] that provide the best overall discrimination among the [rock groups] (Leech *et al.*, 2005). Each discriminant function is a measure that allocates and differentiates each rock sample into rock groups based on their characteristics on the element/oxides.

Table 4.7 shows the correlation matrix of element/oxides with the rock groups in Table 4.8 using the four computed discriminant functions (F1, F2, F3 and F4) from the DA. In Table 4.8 are the mean discriminant scores for each rock group in each of the four discriminant functions. These scores are the computed average values that represent the characteristics of each rock group using the discriminant functions, such that each rock sample can be compared to these average scores when characterising them. Box-plots are used to illustrate and supplement the results of the correlation of the tables.

Table 4.7. The discriminant data table that shows the structure matrix of the data between the element/oxides and the samples which is linked with Table 4.8 to accomplish the association of elements/oxides to rock types

Structure Matrix

	Function			
	1	2	3	4
MgO	.182	-.085	.581*	-.035
K_2O	-.127	.220	-.577*	-.116
CaO	.027	.046	-.451*	.297
Na_2O	-.115	.078	-.322*	.149
Fe_2O_3	-.021	.092	.259*	.143
TiO_2	-.049	.076	-.082*	.046
SiO_2	-.167	-.247	.064	-.435*
P_2O_5	-.126	.191	-.157	-.398*
Al_2O_3	-.043	-.072	-.363	.385*
LOI	.066	.280	-.076	-.347*
MnO	-.008	.007	-.006	.227*

Pooled within-groups correlations between discriminating element/oxide and standardised canonical discriminant functions
Element/oxides ordered by absolute size of correlation within function.

*. Largest absolute correlation between each variable and any discriminant function

The knowledge attained from petrography on the rocks of the area plays a role when correlating the oxides in Table 4.7 to the rock groups in Table 4.8. The asterisks (*) indicate the highest correlation in the functions. Therefore, MgO and Fe_2O_3, with positive values in function 3, have high correlation with the harzburgites as these have the highest positive value at 3.174. However, feldspathic pyroxenites can also be correlated with MgO and Fe_2O_3 as these rocks also have a positive value in function 3. Petrography indicated high orthopyroxenes in both these rocks. The box-plots (Figure 4.9) show the variations of MgO and Fe_2O_3 in Platreef rocks.

Table 4.8. The mean discriminant scores for each rock group for each of the discriminant functions

Functions at Group Centroids

	Function			
Rock groups	1	2	3	4
Melanorites	-.949	-5.608	-.045	-.629
Feld. pyrox.	.379	-.765	.165	1.094
Harzb.	7.947	2.230	3.174	-.393
Parapyr.	14.820	2.065	-4.428	-.304
Pegm. feld. pyro.	-20.669	2.419	-.849	-.293

Unstandardised canonical discriminant functions evaluated at group means

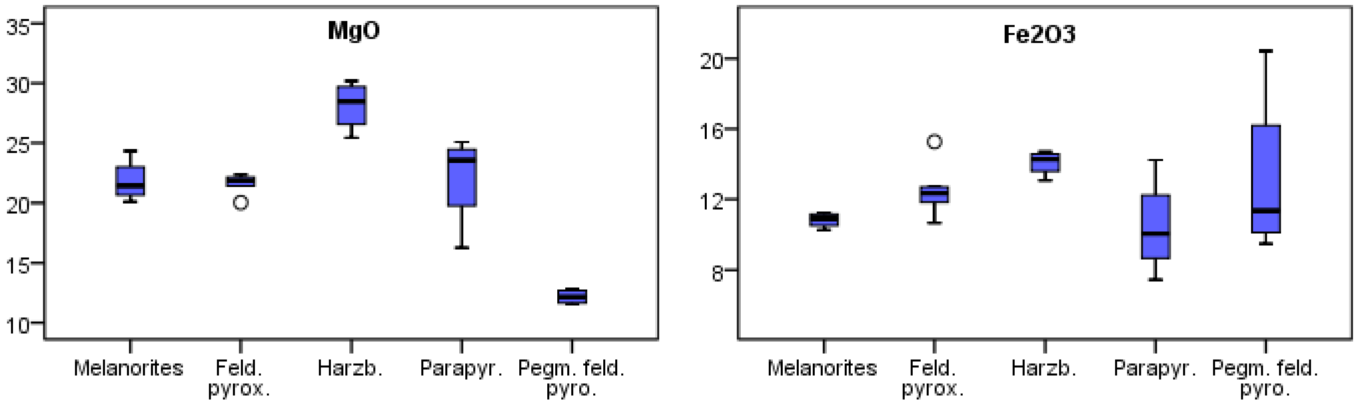


Figure 4.9. The characterisation of harzburgites by MgO and Fe2O3 relative to other rock types in Platreef.

K_2O, CaO, Na_2O, and TiO_2, with negative values in function 3 in Table 4.7, indicate high correlation with parapyoxenites (-4.428), pegmatoidal feldspathic pyroxenites (-0.849) and melanorites (-0.045) in Table 4.8. Petrography indicated high concentration of clinopyroxene in parapyoxenites, hence, the high correlation with CaO. While pegmatoidal feldspathic pyroxenites have albite, hence K_2O, Na_2O, and TiO_2 can be correlated with these rocks.

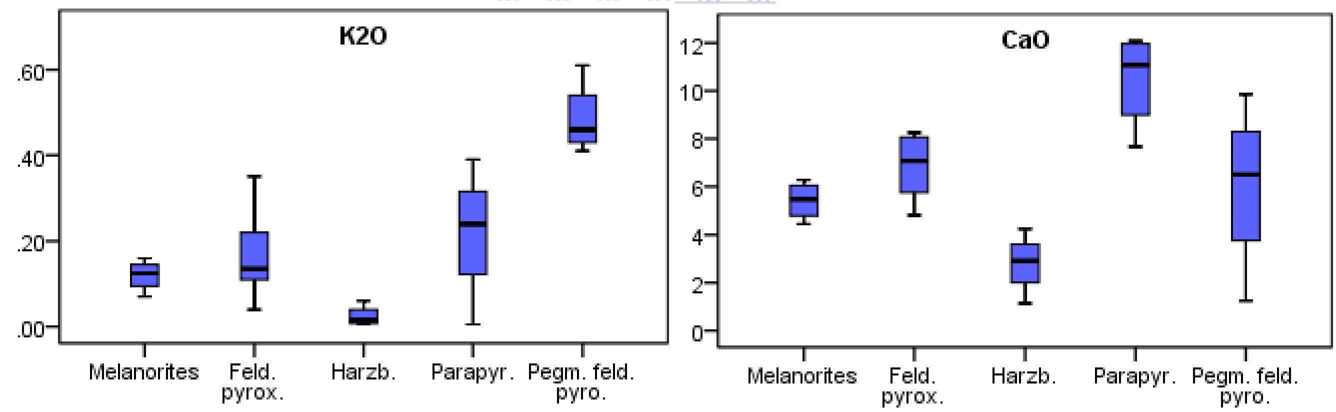


Figure 4.10. The characterisation of pegmatoidal feldspathic pyroxenites by K_2O, and that of parapyroxenites by CaO.

SiO_2, P_2O_5 and LOI, with negative values in function 4 in Table 4.7, indicate high correlation with melanorites (-0.629), harzburgites (-0.393), parapyroxenites (-0.304) and pegmatoidal feldspathic pyroxenites (-0.293) in Table 4.8. As a result of bearing quartz (and apatite in the latter), melanorites and pegmatoidal feldspathic pyroxenites can be correlated with SiO_2 (and P_2O_5). While parapyroxenites can be correlated with loss on ignition as this rock have indicated intense mineral alterations. Harzburgites also showed weak mineral alterations.

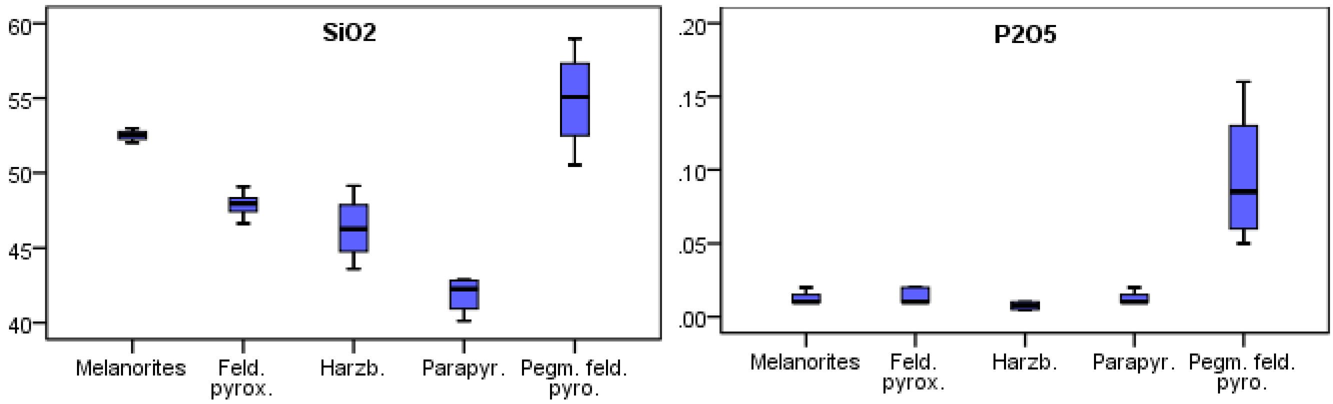


Figure 4.11. The association of SiO_2 and P_2O_5 with the melanorites and pegmatoidal feldspathic pyroxenites as a result of quartz and apatite.

Al_2O_3 and MnO, with positive values in function 4, indicate high correlation only with feldspathic pyroxenites (1.094). This correlation confirms the results of petrography that feldspathic pyroxenites have high concentration of anorthite.

4.3.3.2. Integration of geochemistry and petrography of Platreef lithologies

A. <u>Melanorites</u>

The melanorites are the rocks located in the transition zone between the Main Zone and Platreef. These rocks were considered as the Platreef however as they are much related to the feldspathic pyroxenites rocks. Melanorites are different from the other Platreef rocks by > 50wt% SiO_2 and > 20wt% MgO. In geochemistry, melanorites are characterised by:

SiO_2, Na_2O and K_2O

In petrography, the melanorites are different from feldspathic pyroxenites by the texture of the rocks. In melanorites, the plagioclase is cumulus whereas in feldspathic pyroxenites the plagioclase is interstitial, the orthopyroxenes show very well euhedral grains which may indicate some form of recrystallisation. Another different factor between melanorites and feldspathic pyroxenites is the addition of phlogopite and quartz (siliceous veins) in the melanorites.

B. <u>Feldspathic pyroxenites</u>

The feldspathic pyroxenites are the primary magmatic rocks of Platreef origin (magma) which are typically the most abundant rock type in the Platreef package. These rocks, in geochemistry, are characterised by:

MgO, Fe_2O_3, MnO, CaO and Al_2O_3

Feldspathic pyroxenite in petrography is the mainly characterised by orthopyroxene and plagioclase. The orthopyroxene is cumulus with medium to coarse grains, and the plagioclase is always interstitial between the orthopyroxene grains. These elements mentioned above are making-up these two minerals essentially.

C. Harzburgites

Harzburgites are the other primary magmatic rocks of the Platreef package similar to the feldspathic pyroxenites however with an increased content to the Mg-minerals. Harzburgites are characterised by very high (>25wt% MgO and ≈15wt% Fe_2O_3):

MgO and Fe_2O_3

The petrography of this rock which indicated high contents of orthopyroxene and olivine relative to the other pyroxenitic rock types in the Platreef. The two elements, MgO and Fe_2O_3, confirms the mineralogical composition of the rock.

D. Parapyroxenites

Parapyroxenites are hybrid rocks which some authors refer to it as clinopyroxenites and are more predominant in the Central Sector of Platreef where the footwall is dolomite. They occur as xenoliths in the Northern Sector of Platreef where the footwall is granite. The parapyroxenites are geochemically characterised by:

CaO, MgO and LOI

In petrography, parapyroxenites are characterised by incredibly high clinopyroxene content relative to the normal clinopyroxene occurrence among all other Platreef rocks. Clinopyroxene is the Ca-rich pyroxene. Therefore, the external Ca was introduced during the assimilation process between the Platreef and the calc-silicates xenoliths. Hence, the high content of CaO and LOI which are indicative of high clinopyroxene (augite) content and a high degree of alteration relative to the feldspathic pyroxenites mentioned above.

E. Pegmatoidal feldspathic pyroxenites

Pegmatoidal feldspathic pyroxenites are feldspathic pyroxenites that are relatively very coarse grained and weakly altered by siliceous veins (the Lonmin Plc log sheet refer to these veins as 'quartz feldspar veins'). The pegmatoidal feldspathic pyroxenites are characterised by:

SiO_2, Na_2O, K_2O, P_2O_5 *and* TiO_2

In petrography, pegmatoidal feldspathic pyroxenites are very coarse-grained relative to all the other Platreef lithologies. Quartz and K-feldspar grains are the main features that distinguish these rocks to the other Platreef lithologies with respect to mineralogy. As a result, these rocks have distinctly very high SiO_2, Na_2O and K_2O contents (up to 63% combined).

4.3.3.3. Spidergrams

The spidergrams section is the complement to the previous section of major oxides characterisation of Platreef rocks. This section deals with the trace elements characterisation of the Platreef rocks. The comparison is made between the magmatic rocks and product rocks.

The main objective of using the spider diagrams (multi-element diagrams) is to understand the rock (or magma) evolution in Moordkopje Platreef using trace elements i.e. LILE (Ba, Rb and Sr) and HFSE (Zr, Nb, Y, Th and U) with reference to the primordial mantle. The spidergrams is used to study the patterns of enrichment and depletion of the selected trace elements (i.e. LILE and HFSE).

The mobility of elements in rocks (especially trace elements) is generally controlled by mineralogical changes as a result of rock alteration and the nature of fluids (Rollinson, 1993). The LILE are generally mobile relative to the HFSE which are generally immobile. Therefore, these elements will assist in studying the enrichment and depletion of trace elements within different rock types of Platreef.

Spider diagrams can be presented in three different ways of estimated normalising values for trace elements (i.e. primordial or primitive mantle, chondrite and MORB). These estimates are given in literature such as in Rollinson (1993). For this study, trace element concentrations were normalized using the primitive mantle values from Sun and McDonough (1989), as this method reflects to elements that were readily analysed by XRF and highly relevant to basic igneous rocks (Rollinson, 1993). The spidergrams will be used to compare the composition of Platreef samples of Moordkopje to the primitive mantle (peridotites), with the aim of investigating the effects of fluid action on the Platreef rocks.

The spider diagrams are plotted for harzburgites, feldspathic pyroxenites, pegmatoidal feldspathic pyroxenites, parapyroxenites, and melanorites. The spidergrams results are presented in order of the most pristine magmatic rocks (harzburgites and feldspathic pyroxenites), followed by the metasomatically-affected rocks (pegmatoidal feldspathic pyroxenites and parapyroxenites) and the melanorites (the topmost layer of the Platreef).

A. Harzburgites and feldspathic pyroxenites

The Moordkopje Platreef magmatic rocks depict an anomalous enrichment of U and Pb, with other minor enrichments in Ba, Nb, Ce, and Sr (Figure 4.12). The harzburgites show depletion in K, while, the feldspathic pyroxenites show enrichment in K and Sr (Figure 4.12B) as a result of feldspathoid content. The absence of apatite minerals in these magmatic rocks is shown by the depletion in P (i.e. P_2O_5). In terms of HFSE, Ti is relatively comparable to the primitive mantle, and a slight enrichment of Zr and Y.

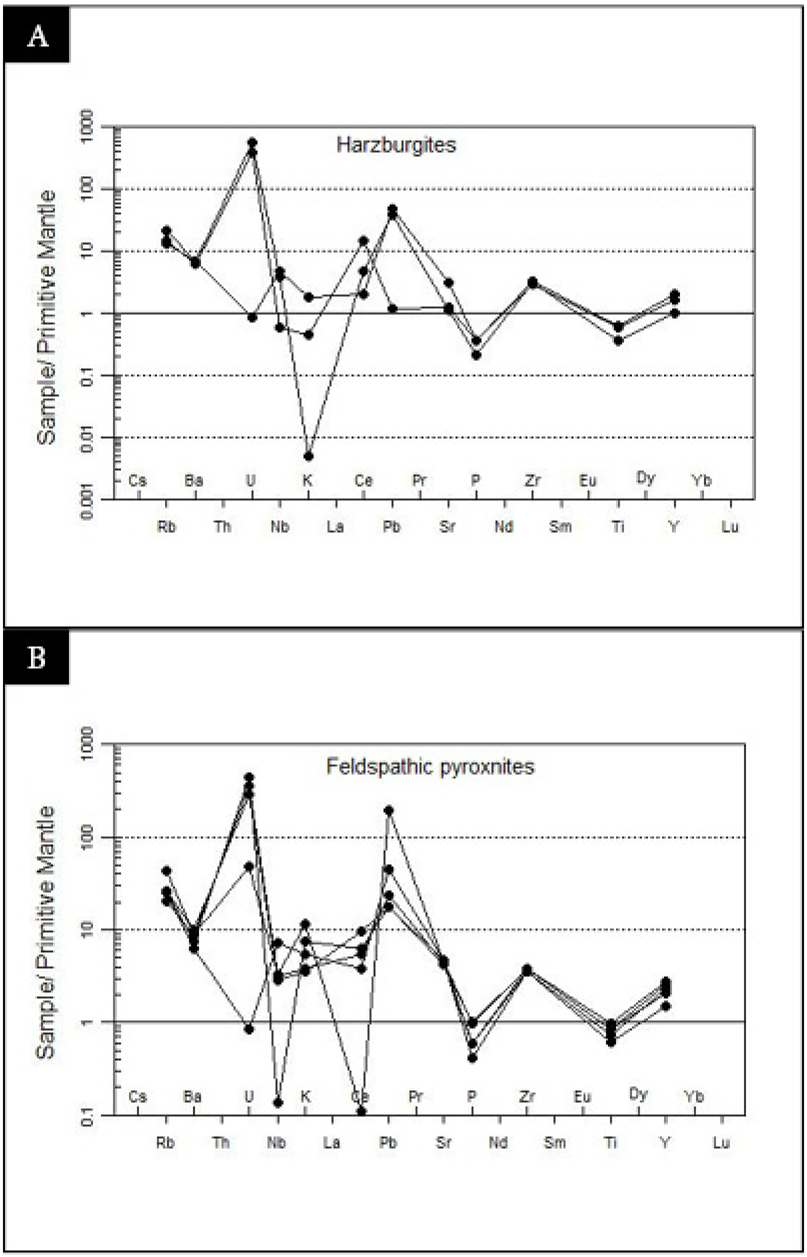


Figure 4.12. Primitive mantle normalised (Sun and McDonough 1989) spider plots for magmatic rocks of Platreef, at **A.** Harzburgites, and at **B.** Feldspathic pyroxenites.

B. Pegmatoidal feldspathic pyroxenites

The pegmatoidal feldspathic pyroxenites are consistent with feldspathic pyroxenites with respect to U and Pb peaks. However, there is a great variability in element fractionation individually (Figure 4.13). The element concentration of LILE, the mobile elements, show great variability of enrichment compared to the harzburgites and feldspathic pyroxenites. The action of siliceous metasomatic fluids may be the main medium of transport to the enrichment of mobile elements to this rock. The increased content of plagioclase, albite and occurrence of apatite in pegmatoidal feldspathic pyroxenites, relative to the magmatic feldspathic pyroxenites, is shown by the increased enrichment of Sr and Ba, K, and P respectively. This result can reasonably be explained by the action of siliceous metasomatic fluids from the granite floor rock. A notable enrichment is with element P which is the indication of phosphate mineral occurrence in rocks (i.e. apatite in this area). Generally, apatite is associated with pegmatite late stage siliceous melts as well as zircon during magma evolution (Hoskin *et al*., 2000). In terms of HFSE, other samples of pegmatoidal feldspathic pyroxenites depict enrichment in Ti and Y (Figure 4.13) which may be the result of the presence of biotite and quartz fluids respectively in pegmatoidal feldspathic pyroxenites.

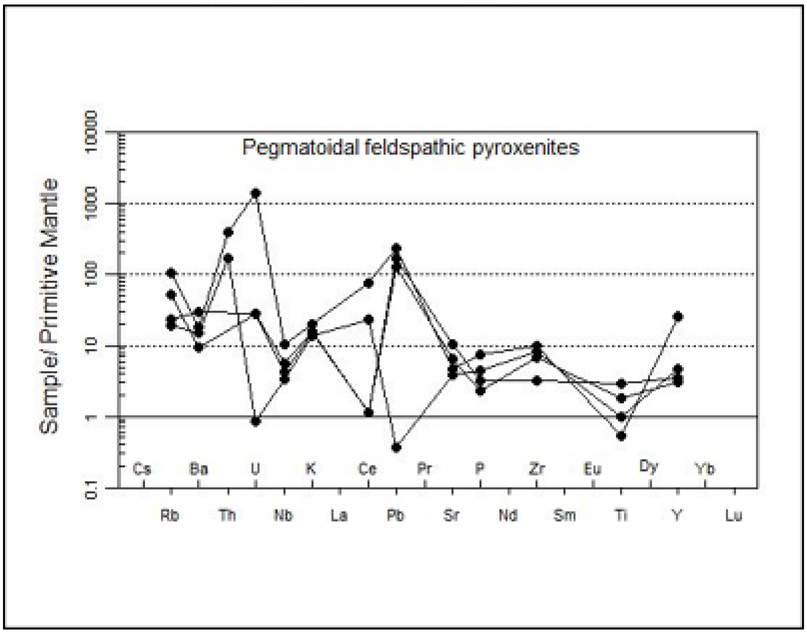


Figure 4.13. Primitive mantle normalised (Sun and McDonough 1989) spider plots for pegmatoidal feldspathic pyroxenites of Platreef.

C. Parapyroxenites

The parapyroxenites differ significantly from the other Platreef rocks with uranium (U) fractionation (Figure 4.14). However, the Pb content is consistent with the magmatic rocks of the Platreef in the area. The parapyroxenites have a lower enrichment pattern of LILE compared to the harzburgites, feldspathic pyroxenites and pegmatoidal feldspathic pyroxenites. The pattern in HFSE of this rock is magmatic rocks that is characterised by the slight enrichment of Zr and Y, with Ti comparable to the primitive mantle.

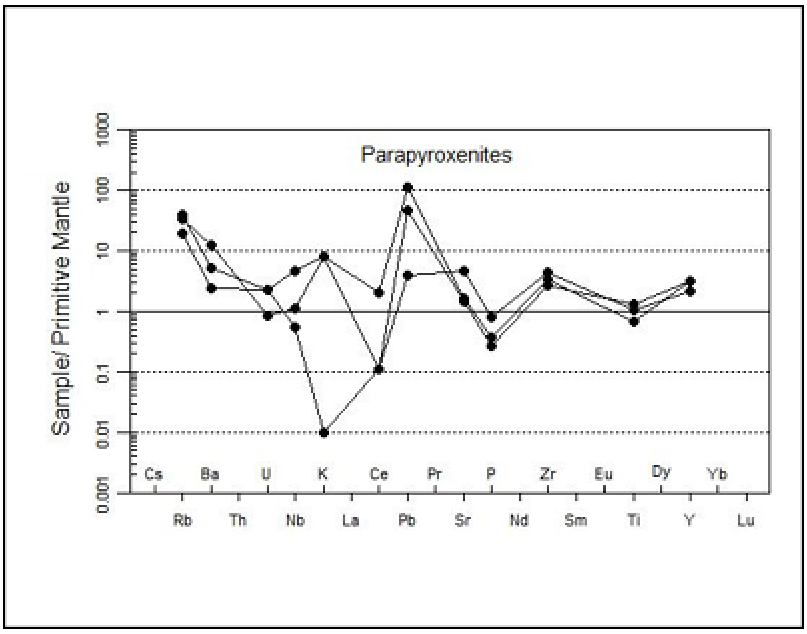


Figure 4.14. Primitive mantle normalised (Sun and McDonough 1989) spider plots for parapyroxenites of Platreef.

D. Melanorites

The melanorites significantly depicts a clear enrichment in LILE elements, with an anomalous Pb values consistent with the other Platreef rock types (Figure 4.15). Uranium also shows the enrichment in one sample of melanorite, however, the geochemical element analysis of other samples were below the detection limit, hence, did not show on the graph. As seen in petrography, melanorites has feldspathoid content as feldspathic pyroxenites which explains the relative enrichment of K and Sr. In terms of the HFS elements, melanorites have also preserved the similar pattern as the feldspathic pyroxenites, with the exception of Y.

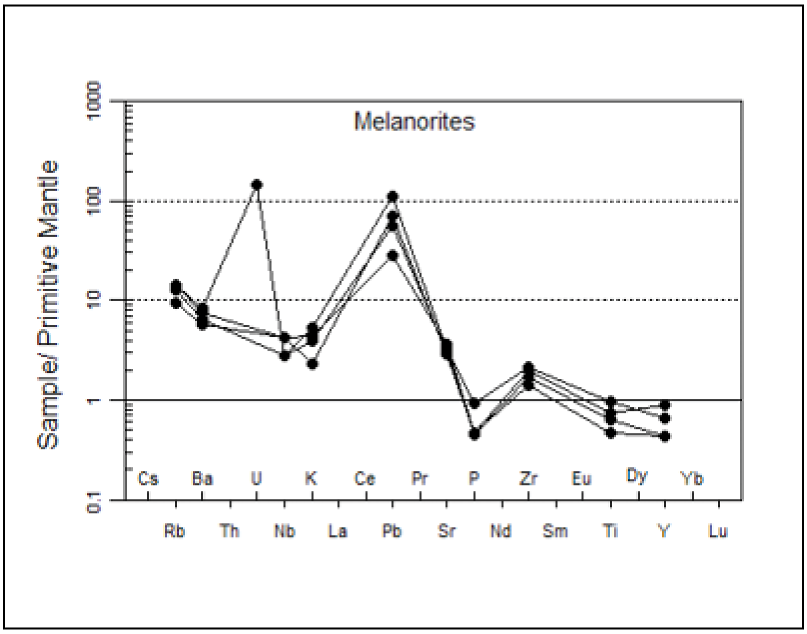


Figure 4.15. Primitive mantle normalised (Sun and McDonough 1989) spider plots for melanorites of Platreef.

E. Summary

The primitive mantle normalised spidergrams have shown that the Platreef samples at Moordkopje have very strong U and Pb anomalies consistently in all the rock types. Generally, these rocks have a strong enrichment in the LILE (i.e. mobile and more compatible elements than HFSE) which explains that the Platreef rocks are cumulate rocks and have very low concentrations of incompatible elements (HFSE i.e. Zr, (Ti), Y). However, the exception is seen in pegmatoidal feldspathic pyroxenites as these rocks have inclusions of siliceous hydrothermal fluids which can be explained by metasomatic fluids involvement.

The variation or fractionation of trace elements in parapyroxenites is not consistent with the other Platreef cumulates, which is characteristic alteration and contamination (crustal contamination). Petrography showed high intensity of alteration on parapyroxenites as a result of contact metamorphism between Platreef rocks and calcsilicates of Transvaal Supergroup.

4.3.3.4. Platreef lithology summaries

The summary on the lithologies explain the main differences and spatial relationship between the five Platreef lithologies, and also the geochemical elements that are significant within each of the Platreef lithologies. These descriptions are only based on the analysis from boreholes MO009 and MO019 of Moordkopje Farm in the Northern Sector of the Platreef. The summary table (Table 4.9) is provided at the end of the section that explains the variation in element/oxides contents in terms of average values, minimum and maximum values.

Harzburgites and **feldspathic pyroxenites** are the most pristine or least altered type of rocks of the Platreef relative to the other lithologies in the area. Many authors refer to these two rock types as Platreef Unit 2 (P2) (e.g. Van der Merwe, 2011; Mitchell and Scoon, 2012). These two rock types have relatively very high values of MgO and Fe_2O_3 (i.e. they have at least 20wt% for MgO and at least 10wt% for Fe_2O_3; Table 4.9). Petrographic analysis showed that these rock types are composed of relatively very high orthopyroxene (with olivine in harzburgites and with interstitial plagioclase in feldspathic pyroxenites). Their grain size is typically medium-to-coarse grained.

Melanorites typically cover the top of Platreef and normally referred as transition rocks because of their position (Holwell and Jordaan, 2006; Van der Merwe, 2011). Melanorites, normally, are stratigraphically between Platreef and the Main Zone. These rocks are product rocks (i.e. post-emplacement), as a result, many authors refer to them as *hybrid rocks* (e.g. Holwell and McDonald (2006), specifically the term 'hybrid norite'. Holwell and Jordaan (2006) mentioned that these rock types are post-Platreef as they occasionally cut into the Platreef package. They are geochemically much similar to feldspathic pyroxenites with the exception of their silica content. Melanorites have at least 52wt% SiO_2 where the feldspathic pyroxenites can have at most 49wt% SiO_2 (Table 4.9).

Pegmatoidal feldspathic pyroxenites are reworked feldspathic pyroxenites through footwall siliceous hydrothermal activity. The quartz-feldspar components came from the granitic footwall. Pegmatoidal feldspathic pyroxenites (and melanorites) have substantial SiO_2 contents as opposed to the other Platreef rocks (>50wt%; Table 4.9). The siliceous hydrothermal fluid action on pegmatoidal feldspathic pyroxenites (and melanorites) may have recrystallised the grains to larger grains and reworked the grain shape to euhedral grains. Mitchell and Scoon (2012) referred to these type of rocks as 'reconstituted lithologies'.

Parapyroxenites are pyroxenites of the Platreef that were assimilated with the external carbonate materials of calc-silicate xenoliths. Harris and Chaumba (2001), said that parapyroxenites are rocks that seem to be a 'mélange of variably recrystallised pyroxenites and calc-silicates rocks' which are all highly altered. The parapyroxenites have enhanced CaO contents between 7 – 12 wt% (Table 4.9) relative to the other Platreef lithologies.

Table 4.9. The Summary table of the Platreef lithologies at Moordkopje Farm. The major oxides and trace elements showing the range of each rock type and the geometric means and also the standard deviation.

	Melanorites (4)				Feldspathic pyroxenites (6)				Harzburgites (4)				Parapyroxenites (4)				Pegmatoidal feldspathic pyroxenites (4)			
	Range	Min.	Geom. Mean	Std. Dev.	Range	Min.	Geom. Mean	Std. Dev.	Range	Min.	Geom. Mean	Std. Dev.	Range	Min.	Geom. Mean	Std. Dev.	Range	Min.	Geometric Mean	Std. Dev.
SiO_2	0.95	52.02	52.51	0.39	2.42	46.65	47.90	0.83	5.55	43.59	46.28	2.28	2.66	40.11	41.53	1.34	8.46	50.52	54.83	3.49
Al_2O_3	1.64	6.76	7.51	0.81	5.97	4.59	7.65	1.99	5.61	0.83	2.66	2.49	3.76	4.81	6.49	1.88	4.93	6.60	8.67	2.03
Fe_2O_3	0.99	10.28	10.84	0.43	4.60	10.67	12.45	1.53	1.64	13.07	14.07	0.72	4.33	9.90	11.30	2.41	10.94	9.49	12.57	4.95
MnO	0.02	0.18	0.19	0.01	0.04	0.20	0.22	0.01	0.18	0.07	0.18	0.09	0.06	0.17	0.20	0.03	0.25	0.12	0.19	0.11
MgO	4.21	20.11	21.76	1.79	2.32	20.03	21.58	0.84	4.76	25.43	28.08	2.07	1.80	23.29	24.05	0.93	1.28	11.54	12.16	0.62
CaO	1.82	4.46	5.37	0.79	3.43	4.82	6.71	1.37	3.11	1.14	2.54	1.28	4.42	7.67	9.85	2.22	8.61	1.24	4.77	3.56
Na_2O	0.43	0.33	0.52	0.18	0.79	0.12	0.58	0.29	0.22	0.01	0.03	0.11	0.63	0.03	0.16	0.32	1.44	0.86	1.54	0.61
K_2O	0.09	0.07	0.11	0.04	0.31	0.04	0.13	0.11	0.06	0.01	0.02	0.02	0.24	0.01	0.07	0.14	0.20	0.41	0.48	0.09
TiO_2	0.11	0.10	0.15	0.05	0.16	0.13	0.19	0.05	0.05	0.08	0.11	0.02	0.13	0.15	0.21	0.07	0.53	0.11	0.28	0.23
P_2O_5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.11	0.05	0.09	0.05
LOI	0.86	0.07	0.25	0.42	1.97	1.09	1.82	0.73	3.58	2.76	4.37	1.58	1.94	4.08	5.28	1.11	6.40	0.06	0.50	3.02
Ba	18.00	40.00	48.27	7.89	35.37	35.00	52.74	12.94	32.46	16.00	35.76	15.52	68.56	17.19	37.58	35.43	135.00	66.00	114.94	56.73
Ce	0.00	0.02	0.02	0.00	6.80	0.02	0.07	2.76	26.15	0.02	0.41	12.59	3.39	0.20	0.52	1.96	131.57	0.02	1.22	62.04
Co	12.00	77.00	80.87	5.48	30.13	71.87	80.16	11.56	112.05	54.00	104.97	51.57	45.43	60.47	74.18	25.34	52.76	28.06	54.53	22.13
Cr	1325.00	1941.00	2833.13	639.56	1370.94	1885.58	2304.64	545.29	2519.86	1378.71	2301.63	1116.73	602.61	1167.35	1476.11	305.56	931.01	96.99	511.67	417.80
Cu	448.00	50.00	211.63	203.58	134.93	57.00	137.21	49.87	1360.11	424.00	678.26	648.53	114.75	94.70	123.69	66.04	195.62	40.00	88.37	86.47
Nb	1.00	2.00	2.45	0.58	4.97	0.10	1.48	1.59	2.90	0.42	1.84	1.33	2.88	0.39	1.00	1.56	5.19	2.36	3.82	2.31
Ni	779.00	540.00	882.54	347.20	888.47	608.53	811.60	344.28	4219.19	768.00	2058.45	1845.17	589.43	579.48	778.26	312.17	198.03	243.00	311.68	86.92
Pb	6.00	2.00	4.23	2.50	13.71	0.04	1.29	5.11	3.31	0.08	1.11	1.42	7.54	0.28	1.93	3.80	16.63	0.03	2.62	7.01
Rb	3.00	6.00	7.90	1.41	22.15	5.00	14.10	7.16	5.15	8.00	9.47	2.37	12.48	11.96	18.31	6.45	52.73	12.40	25.14	24.29
Sr	16.00	62.00	68.51	6.70	85.49	15.00	69.88	33.02	54.85	11.00	25.92	23.72	67.98	30.29	47.15	37.91	144.05	79.95	125.14	63.59
U	3.00	0.00	0.01	1.50	1.01	0.00	0.01	0.41	0.02	0.00	0.00	0.01	0.03	0.02	0.03	0.02	29.59	0.00	0.03	14.79
V	30.00	97.00	113.85	13.82	39.21	105.24	119.83	14.41	77.01	42.66	76.48	35.61	62.12	83.31	116.28	32.31	183.00	21.00	98.00	77.33
Y	2.00	2.00	2.63	0.96	5.84	6.81	9.60	2.19	8.16	1.00	4.18	3.52	5.04	9.69	12.61	2.73	100.01	14.00	27.08	48.59
Zn	6.00	71.00	73.22	2.63	40.55	102.08	129.18	15.11	57.94	60.00	94.85	25.96	28.35	102.27	111.31	16.09	122.69	75.00	103.32	57.87
Zr	8.00	16.00	20.02	3.50	20.35	22.00	37.01	7.92	18.60	17.00	28.70	8.76	18.92	29.22	37.64	9.47	74.36	36.00	71.98	31.45
S	1321.62	200.25	658.64	668.05	840.43	0.60	11.34	338.52	2118.16	124.15	773.88	925.53	0.70	0.10	0.40	0.40	520.54	0.10	31.37	229.43

4.3.4. Exploration data analysis

The exploration data analysis is the type of analysis that investigates the geochemical behavior of elements/oxides within the rock types. The geochemical behavior is devised through geochemical modelling of elements/oxides and the trace element patterns. The patterns are a way of identifying relationships between individual rock types that may have undergone similar geochemical processes.

The patterns of trace elements are more relevant in this section because of their capability to preferably partition into specific minerals during the differentiation process of magma, as they substitute for major oxides in the rock-forming minerals (Rollinson, 1993). The patterns of trace elements may be useful to detect external geochemical and geological processes.

Furthermore, in this section, the behavior of trace elements is considered in order to assess coherence within the major rock types of the Platreef. The 'coherence' refers to the trends in trace elements content within each rock type in order to model the evolution of magma within the Platreef package of the Moordkopje area. When trace elements are compared to major oxides: the variations in the concentration is much larger in the trace elements, and also, trace elements are more sensitive to geochemical and geological processes as opposed to the major oxides (White, 2013).

The importance of trace elements varies widely in terms of their geochemistry in the geochemical analysis depending on the objectives of the work. This work seeks to demonstrate the role of metasomatism in the formation of the ores in the Platreef. Other trace elements have preference for fluid or melt (i.e. incompatible) while others prefer mineral phases. The former can be useful in this section when detecting the metasomatic fluids in different rocks, and later interpret the influence of these fluids in the alteration geochemistry and mineralisation sections. The methods that were used in order to model and evaluate the magma evolution and effects of metasomatic fluids in the Platreef in this study are bivariate diagrams, element ratios and alteration geochemistry. The bivariate diagrams will identify the element patterns such that they can be used to formulate element ratios that can model the evolution of rocks of Platreef in this area. Subsequently, the element ratios will be compared with mineral alterations and mineralisation occurrence of the area by downhole plots.

4.3.4.1. Bivariate diagrams – interelement variations

Bivariate diagrams are graphical representation of the variation in the concentrations between individual elements. The variation in the concentrations is displayed between two elements/oxides that are aligned with the objectives of the work.

In this study, the bivariate diagrams were done with the aim of evaluating the behavior of elements in the orthopyroxene-dominated rock series of the Platreef. Hence, MgO was selected for the *x*-axis to represent the variation of orthopyroxene within the rock groups. In this way, the patterns and relationships of element/oxides in rock types can be identified. By using the observations by Harris and Chaumba (2001) that magmatic rocks show coherent variations since the chemical variation are much dependent on modal mineralogy. However, the influence of metasomatism can affect the coherence of elements in the magmatic rocks.

The Platreef rocks are generally cumulate rocks which form under constant and consistent magmatic processes in a presumably closed system, until they are exposed to external processes. The bivariate diagrams will show the relationships in magmatic rocks in terms of element variation compared to the product rocks which formed as a result of assimilation and metasomatic processes.

The minerals that are dominant in the studied rocks by petrography in the study area are orthopyroxene and plagioclase. Orthopyroxene (and plagioclase) vary the most in the rock types of this area. Therefore, MgO was plotted against the other elements, as the main oxide that appropriately characterise orthopyroxene-rich rocks compared to the other elements/oxides. Rollinson (1993) and White (2013) stated that bivariate plots which use MgO on the *x*-axis are appropriate for rock series that are comprised abundantly of mafic members. Thus, the representation of variation of orthopyroxene in the rock groups (i.e. MgO) was plotted against the selected oxides and trace elements to ascertain their fractionation patterns.

The selection of the other elements/oxides was based on correlation matrix and the oxides that characterise each lithology. The linear correlation between elements in section 4.3.2.3 assists by identifying elements with the best linear relationships to MgO. The criteria also includes the representation of each lithology by selecting elements/oxides that characterise each lithology. Al_2O_3 (-0.93), Na_2O (-0.85), CaO (-0.73) and K_2O (-0.54) are oxides with considerable high negative correlation with MgO, whereas, Fe_2O_3 (+0.82) and MnO (+0.73) represent the positive. The addition of SiO_2 to the selection was due to its relevance with the siliceous metasomatic fluids and characterisation of pegmatoidal feldspathic pyroxenites.

In terms of trace elements, the selection was also based on mineral affinity where these trace elements have a probability to substitute for major elements, and also based on evaluation of sulphide mineralisation. Namely, Ni in olivine, Cr in orthopyroxene and chromite content, Sr in plagioclase and Ba in K-feldspar, Cu for sulphides, including the total sulphur content distribution (S in ppm).

The variation diagrams are presented in two sections of oxides and trace elements. The evaluation of these diagrams is presented by first reviewing the elements/oxides with similar patterns, followed by those that differ from the patterns. The comparison of patterns is focused among cumulates rocks and product rocks as a way to show the effects of footwall assimilations to the Platreef rocks.

A. Variations in Oxides

Harzburgites and feldspathic pyroxenites (including the norites of the Main Zone) are relatively pristine cumulate rocks, as a result, they show coherence in the oxides with the variation of MgO. Whereas, the product rocks, pegmatoidal feldspathic pyroxenites and parapyroxenites, which formed due to assimilation of country rocks (granite-gneiss and calc-silicates, respectively) with the Platreef pyroxenites, show variations that are incoherent.

The patterns displayed by Al_2O_3, Na_2O, CaO and K_2O show decrease with increasing MgO content (Figure 4.16). The variation in these oxides in magmatic rocks ascertains the coherent fractionation during the evolution of magma, while incoherent variation is shown by product rocks. Paraproxenites show scattered and higher values of CaO than the magmatic rocks which is consistent with the findings of characterisation by geochemistry and petrography. The assimilated amounts of calc-silicates into these rocks have enhanced the content of CaO in these rocks. Pegmatoidal feldspathic pyroxenites show different, almost perpendicular, trends of the oxides especially K_2O. The geochemical characterisation of these rocks have shown considerably high values of K_2O which are a result of siliceous fluids with alkali-feldspars from the granite footwall.

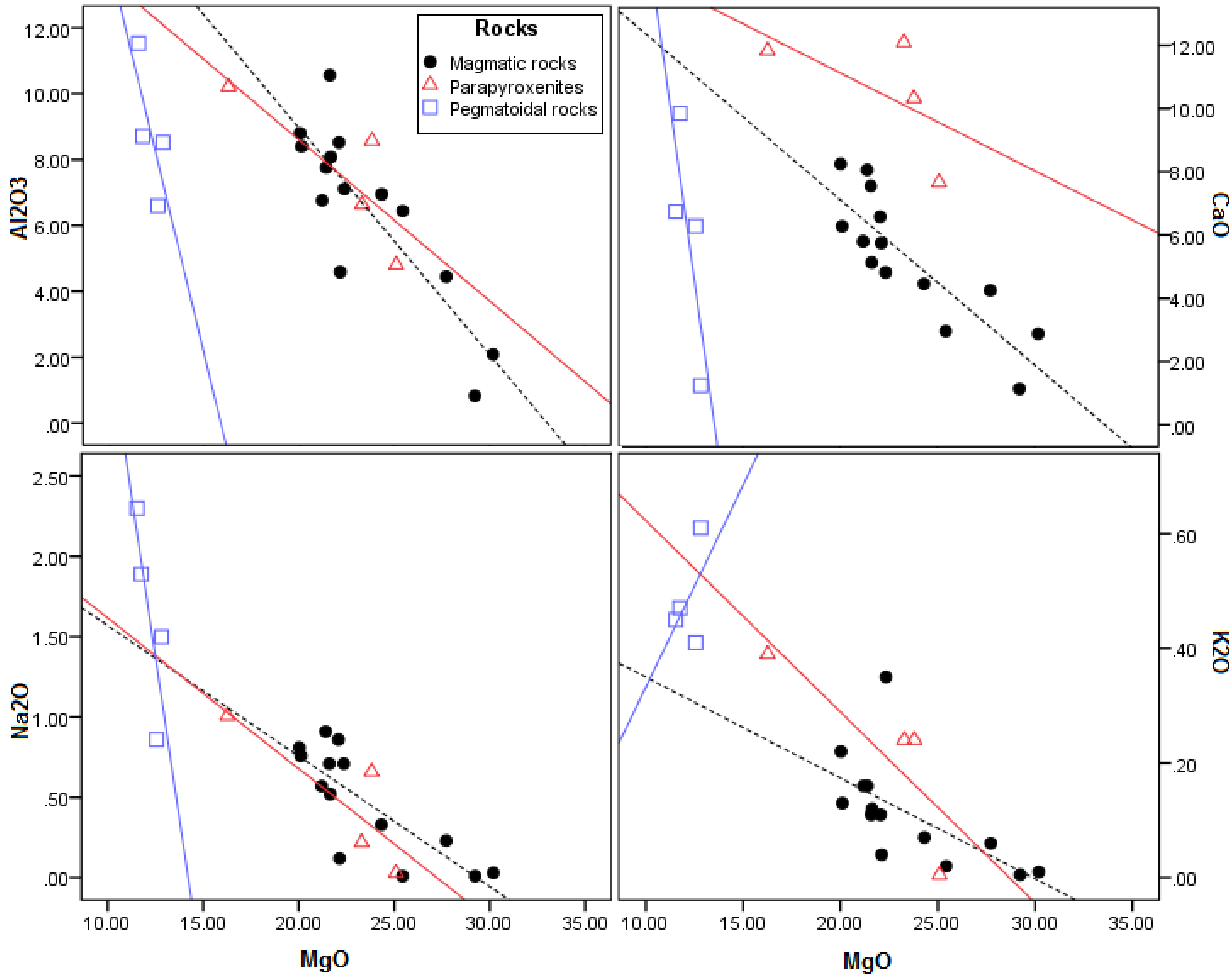


Figure 4.16. The negative variation of Al_2O_3, Na_2O, CaO and K_2O with MgO in magmatic rocks (harzburgites and feldspathic pyroxenites) and product rocks (parapyroxenites and pegmatoidal feldspathic pyroxenites).

The patterns of Fe_2O_3 and MnO show a positive relationship with increasing MgO content (Figure 4.17). These oxides characterise harzburgites and feldspathic pyroxenites (the magmatic rocks) which ascertains the magmatic relationship during the evolution of magma. The trends of parapyroxenites show no substantial difference to the magmatic rocks in terms of Fe_2O_3 and MnO. Pegmatoidal feldspathic pyroxenites with lower MgO content to other Platreef rocks is not consistent with the trends of magmatic rocks and parapyroxenites. This significant inconsistence in these rocks may be explained by the effects of footwall contamination that was initiated by metasomatic fluids.

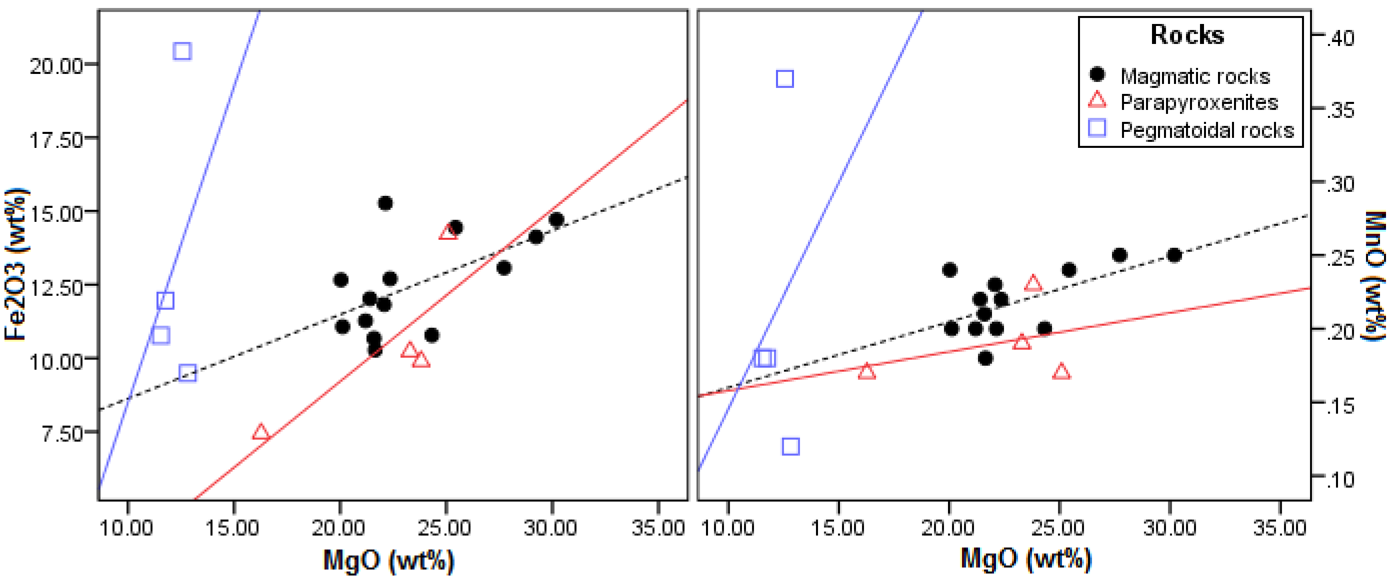


Figure 4.17. The variation diagrams of Fe_2O_3 and MnO in the magmatic rocks and product rocks which depicts a positive correlation with MgO.

B. <u>Variations in trace elements</u>

The variations in trace elements are presented into elements with negative correlation with MgO, and those with positive correlation. The former is represented by Sr, Ba, Y and Zr where Sr and Ba were used to assess the evolution of plagioclase and K-feldspar. The incompatible and immobile elements Y and Zr were used to evaluate the effects of metasomatic fluids in the Platreef rocks.

The positive correlation is represented by Ni, Cr, Cu and S. Nickel and chromium are employed to monitor the crystallisation process of basalts as they both commonly concentrate in early-formed minerals (Schreiber, 1979). Whereas, Cu and S were used to assess the mineralisation in the magmatic and product rocks.

Strontium decreases with the increasing MgO content (Figure 4.18), which explains the inverse proportion between plagioclase content and orthopyroxene content in the Platreef rocks. The petrography analysis showed high content of plagioclase in the pegmatoidal feldspathic pyroxenites and feldspathic pyroxenites, and no visible plagioclase in parapyroxenites. The variation diagram of Sr is consistent with these findings from the petrography. Harzburgites have no considerable plagioclase content, hence the magmatic rocks display no systematic trends in Sr variation.

The trend of Ba in pegmatoidal feldspathic pyroxenites are similar to that of Sr (Figure 4.18). The pegmatoidal feldspathic pyroxenites depicts the considerable contents of K-feldspar which explains the effects of contamination and assimilation from the granite floor rock with Platreef. K-feldspar in the Platreef can be explained as the felsic patches which originated from the Archaean granite basement. The magmatic rocks, harzburgites and feldspathic pyroxenites, and parapyroxenites display no systematic patterns in the variation of Ba as these rocks have no k-feldspar content.

Yttrium behaves systematically in rocks series due to its incorporation in a predictable and uniform manner in Ca minerals (Lambert and Holland, 1974). Hence, Y was used to monitor the content of Ca-rich pyroxene (i.e. clinopyroxene) in Platreef rocks. Yttrium and zirconium are immobile and incompatible elements that have preference of concentrating more where hydrous alteration occurs (Stevens, 2007). Parapyroxenites show high values of Y to indicate the presence of high clinopyroxene content (Figure 4.18). Petrography analysis showed about 60% modal composition of clinopyroxene in the parapyroxenites. The high values of Y are also displayed by pegmatoidal feldspathic pyroxenites which may indicate the presence of metasomatic fluids that affected these rocks.

Zirconium, like yttrium, is an immobile incompatible element, hence, has very low abundance in cumulate rocks (Harris and Chaumba, 2001), however more abundant in rocks affected by trapped liquid (Stevens, 2007). The Platreef rocks affected by siliceous metasomatic fluids may be detectable by the variation of Zr. The high concentration of Zr in pegmatoidal feldspathic pyroxenites can be explained by the presence of quartz-feldspar veins that affected these rocks as seen in petrography. While the cumulate rocks (harzburgites and feldspathic pyroxenites) and parapyroxenites display no systematic patterns and low values in the variation of Zr.

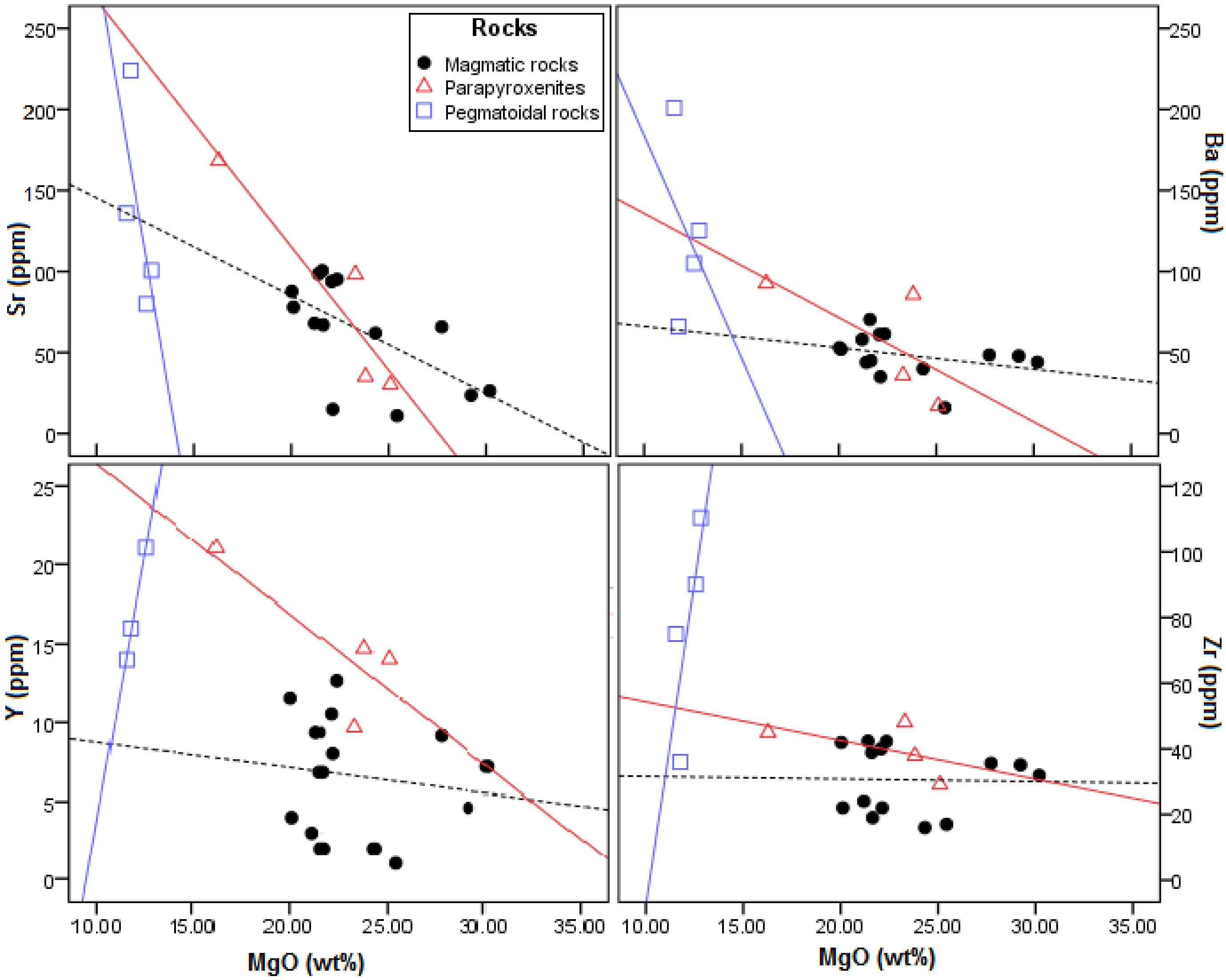


Figure 4.18. The variations of Sr, Ba, Y and Zr with MgO between the magmatic rocks, parapyroxenites and pegmatoidal feldspathic pyroxenites.

Nickel and chromium have very high values in harzburgites and feldspathic pyroxenites as these rocks have olivine and high orthopyroxene (Figure 4.19). Hence, Ni and Cr increase with increasing MgO. Petrography showed some fragments of reworked olivine in parapyroxenites which explains the relative similarities in Ni and Cr with the magmatic rocks. The anomalous values of Ni and Cr in magmatic rocks may indicate the occurrence of primary mineralisation of magmatic origin. Element ratios in the following section will show the results on this regard.

Copper and sulphur provides a relatively appropriate outline of the distribution of sulphides content in the Platreef. The trends in copper and sulphur elements are very similar since Cu relates to the sulphide minerals occurrence (e.g. chalcopyrite) and S reflects the total sulphur in the rocks of Platreef. Copper and sulphur are the highest in the magmatic rocks with relatively substantial concentrations depicted on the Cu and S graphs (Figure 4.19). Parapyroxenites contain no significant sulphide content. Pegmatoidal feldspathic pyroxenites show considerable sulphur contents which are related to increasing MgO values. These findings are consistent with the findings of ore microscopy in the petrography where parapyroxenites had no visible ore minerals.

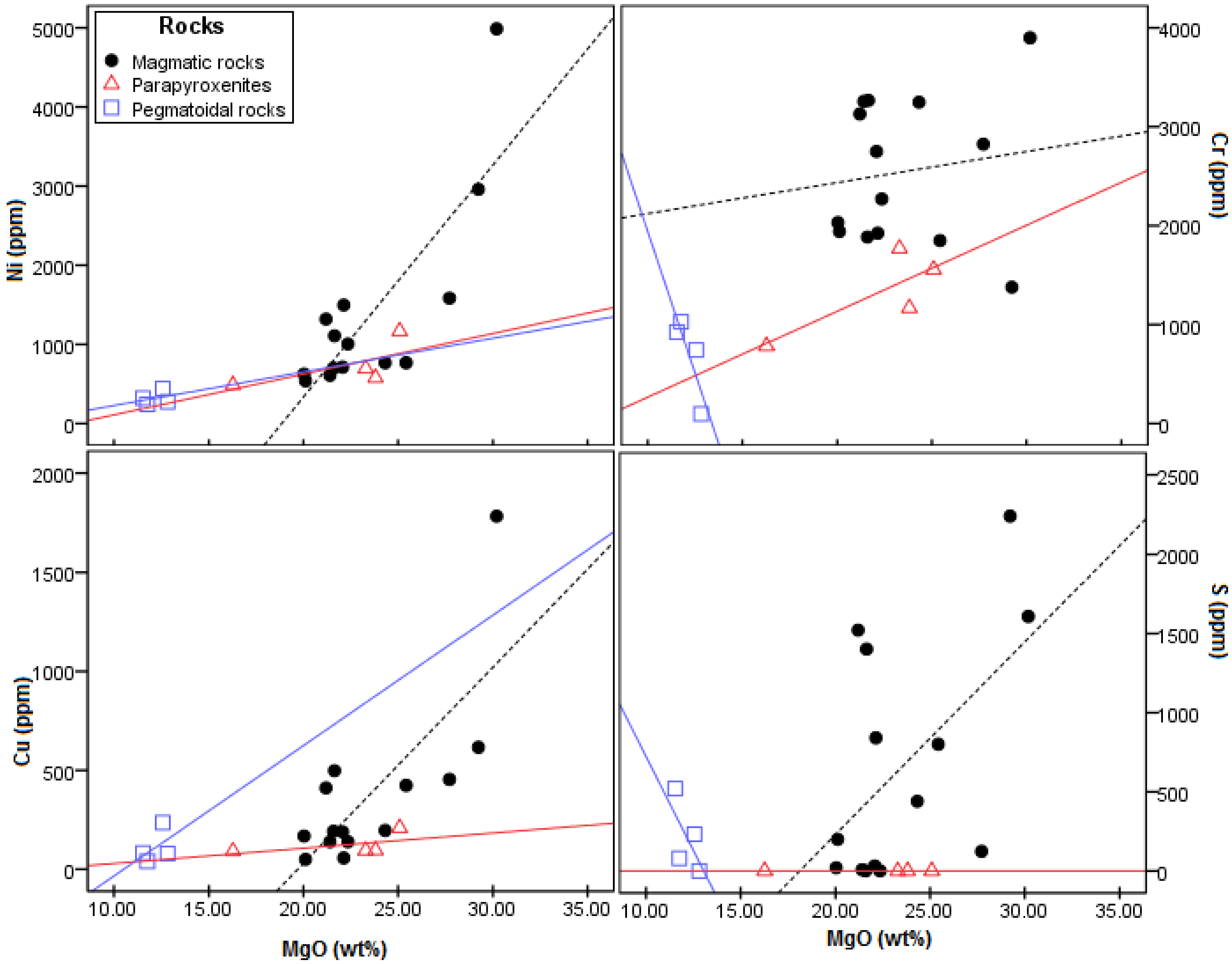


Figure 4.19. The elements Ni, Cr, Cu and S that have a positive correlation with MgO in the magmatic rocks (harzburgites and feldspathic pyroxenites), parapyroxenites and pegmatoidal feldspathic pyroxenites.

C. <u>Summary</u>

The varying proportions of plagioclase and orthopyroxene are the main control on whole-rock composition of the magmatic rocks in Platreef in this area. The fractionation and incorporation of other minerals (i.e. clinopyroxene in parapyroxenites, and quartz and Kfeldspar in pegmatoidal feldspathic pyroxenites) affect the main control formed by plagioclase and orthopyroxene. Hence, parapyroxenites and pegmatoidal feldspathic pyroxenites display different element patterns to magmatic rocks.

The inverse proportion of plagioclase and orthopyroxene in harzburgites and feldspathic pyroxenites was shown by the negative correlation in oxides Al_2O_3, Na_2O, CaO, and K_2O and trace elements Sr and Ba against MgO. Elements/oxides that produce positive correlation with MgO (namely, Fe_2O_3, MnO, Ni, Cr, Cu and S) may indicate magmatic fractionations that are related to mineralisation.

4.3.4.2. Element ratios

The bivariate diagrams in the previous section have established diametric and similar element patterns and associations with respect to major oxides and trace elements. The patterns can be used to formulate element ratios that can used to model the mineral evolution in the rocks of Platreef. The element ratios can also be used to detect mineralogical alterations and indicate mineralised zones, and their correlation. The outcomes of this section will indicate whether the effects of floor rock contamination through metasomatic fluids and assimilation had controls over the genesis of mineralisation. In this way, the element ratios formulated in this study may be further used in exploration in the Moordkopje area to target potential occurrence of mineralisation.

The findings of petrography and geochemical characterisation have shown that the Platreef was affected by the hydrothermal fluids from the granite floor rock and the assimilated units of calc-silicate xenoliths. As stated in Rollinson (1993), any suite of rocks that was subjected to hydrothermal alteration or metamorphism is likely to suffer element mobility. Therefore, in formulating the element ratios in the study of the rocks of this area, it is essential to associate immobile elements (i.e. Y, Zr, Ti and Al) with compatible elements that characterise each lithology based on the geochemical characterisation of this study.

Parapyroxenites are essentially characterised by high clinopyroxene content mineralogically, and geochemically by CaO. Pegmatoidal feldspathic pyroxenites are characterised essentially by high content of K-feldspars and quartz, and geochemically by K_2O. Therefore, the association of CaO and K_2O with their respective immobile elements was devised as CaO/Al_2O_3 and K_2O/TiO_2 based on the correlation in the pristine magmatic rocks (Figure 4.20). The fractionation of these elements should relatively remain the same in magmatic systems as depicted by Figure 4.20. The changes and peaks generated by these ratios will indicate external enhancement of Ca and K as a result of granite and calc-silicate contamination respectively. These ratios were also used by Cawthorn and Lee (2005) to demonstrate variable amounts of contamination or overprinting of original chemistry.

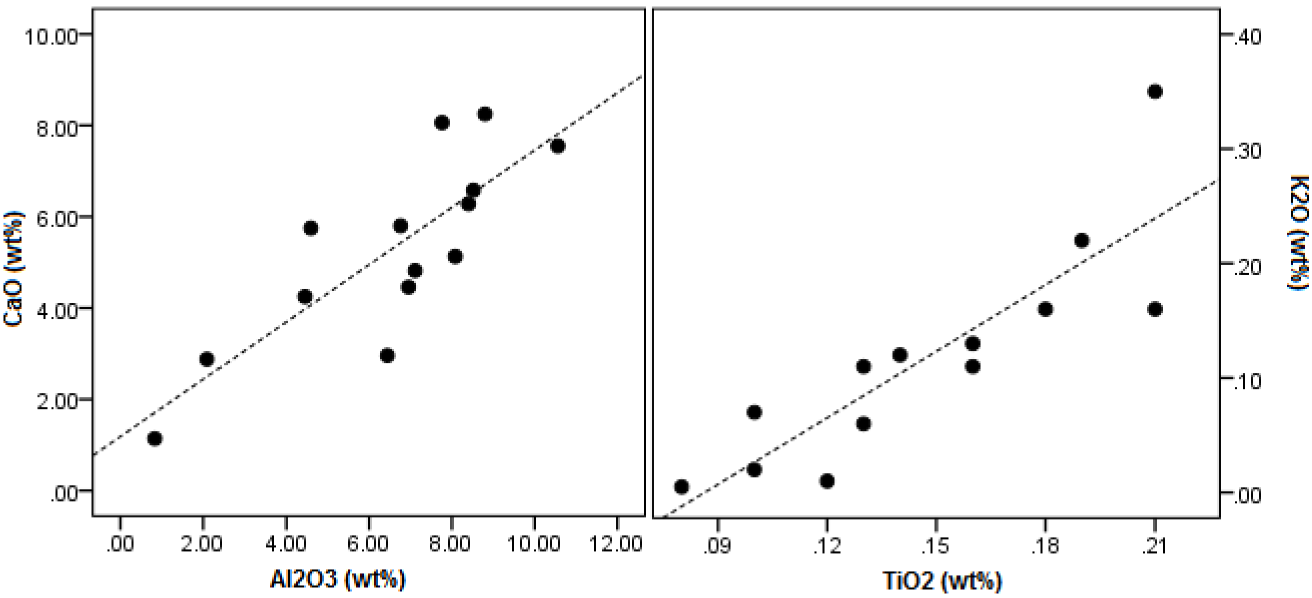


Figure 4.20. The high positive correlation between CaO and K2O and their respective immobile elements Al_2O_3 and TiO_2 using the least altered magmatic rocks.

Copper was used to indicate sulphide mineralisation in the rocks of this area. The association of Cu with immobile element Zr was used to devise the ratio Cu/Zr as an indicator of mineralisation peaks within the Platreef lithologies. This ratio was also used by Stevens (2007) against depth to identify the occurrence of mineralisation. The genesis around the ratio is that Cu and Zr are incompatible during magma fractionation, and therefore their concentrations increase with fractionation. Hence the ratio should remain constant, and only can be changed when sulphide immiscibility is reached where Cu becomes compatible, and as sulphides are removed the ratio decreases (Stevens, 2007).

Nickel and chromium are compatible with orthopyroxene and they form sulphide and chromite mineralisation respectively. These elements are largely controlled by the abundance of orthopyroxene, and Ni alone is not a good indicator of sulphides due to its ability to enter olivine and orthopyroxene structure (Seabrook, 2005). The ratio Ni/Cr in this study was used to indicate the primary occurrence of olivine-related mineralisation. Although this ratio has not been used in literature of Bushveld Complex, however, the results of the ratio are consistent with the findings of the petrography and geochemical characterisation of this work. The olivine-bearing rocks (i.e. harzburgites and serpentinised pyroxenites, and to some extent parapyroxenites contain ruptured olivine fragments), in ore petrography, have shown occurrences of chromite and sulphide mineralisation.

These ratios were plotted with depth for both boreholes, MO009 and MO019 (Figure 4.25 and Figure 4.26 respectively). The ratios of K_2O/TiO_2 and CaO/Al_2O_3 assess overprinting or granite and assimilation of dolomite (respectively) within the Platreef rocks at the contact with floor rocks. Cawthorn and Lee (2005) referenced these ratios at K_2O/TiO_2 = 0.75 for typical feldspathic pyroxenites, and at CaO/Al_2O_3 = 0.5 to 0.8 for Main Zone rocks. The values that significantly exceeds these reference values may indicate granitic material is overprinting as for K_2O/TiO_2, and indicate dolomite assimilation as for CaO/Al_2O_3. Figure 4.21 show that pegmatoidal feldspathic pyroxenites were imprinted with granitic materials with significant high values of K_2O/TiO_2. This occurrence is consistent with the observations of petrography where orthoclase and quartz-feldspar imprints were seen on these rocks. Figure 4.22 demonstrate the assimilation of dolomite in parapyroxenites as the ratio of CaO/Al_2O_3 in this lithology has significantly exceeded the buffered zone between 0.5 and 0.8. The significant high values of CaO/Al_2O_3 indicate the occurrence of clinopyroxene that occurs substantially in the parapyroxenites. The results of petrography for parapyroxenites are consistent with this demonstration. The parapyroxenites contain significantly high clinopyroxene relative to all the other Platreef lithologies.

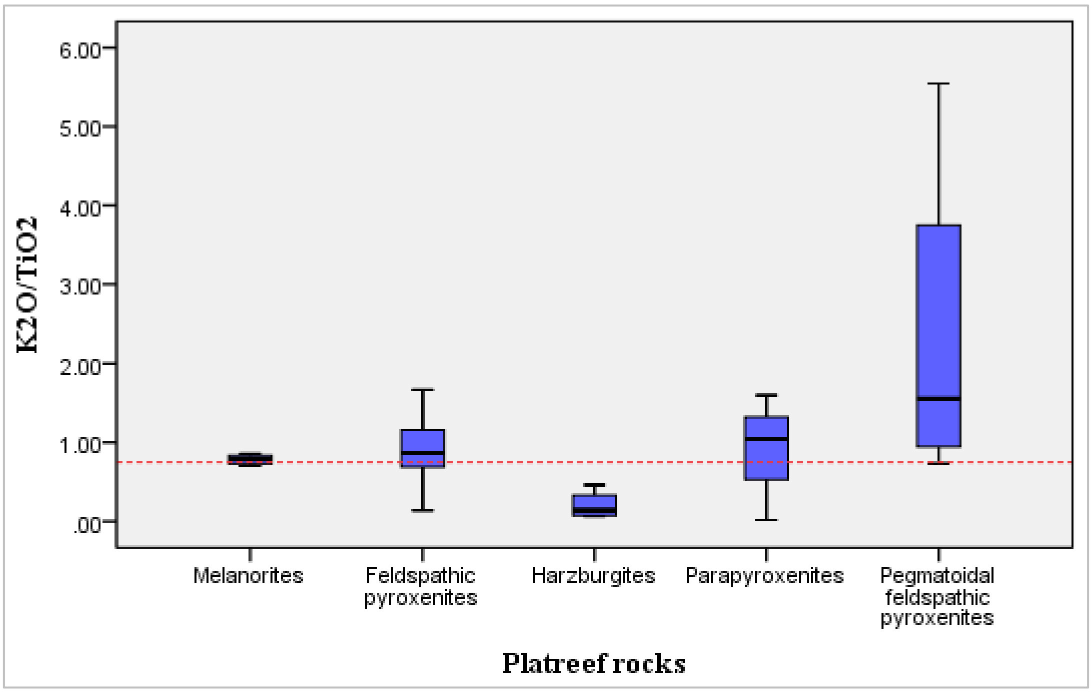


Figure 4.21. The box-plot diagram showing the variation of K_2O/TiO_2 with the Platreef lithologies. The red-dotted line at 0.75 is the reference ratio for typical feldspathic pyroxenites values.

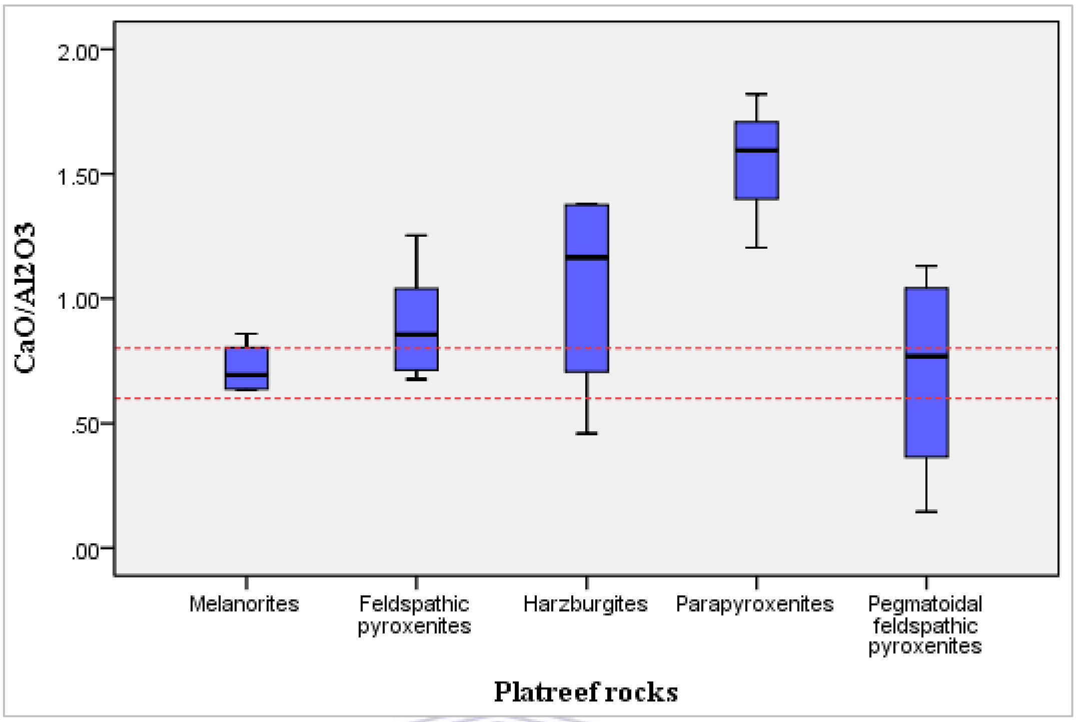


Figure 4.22. The box-plot diagram showing the variation of CaO/Al_2O_3 with the Platreef lithologies. The red-dotted lines between 0.5 and 0.8 are the reference ratios of Main Zone values.

The peaks of mineralisation occurrence are demonstrated by the ratio of Cu/Zr, as was demonstrated by Li *et al*. (2001) and Stevens (2007). According to Stevens (2007), Cu/Zr remains the same, except if the sulphide immiscibility is reached where the ratio will show

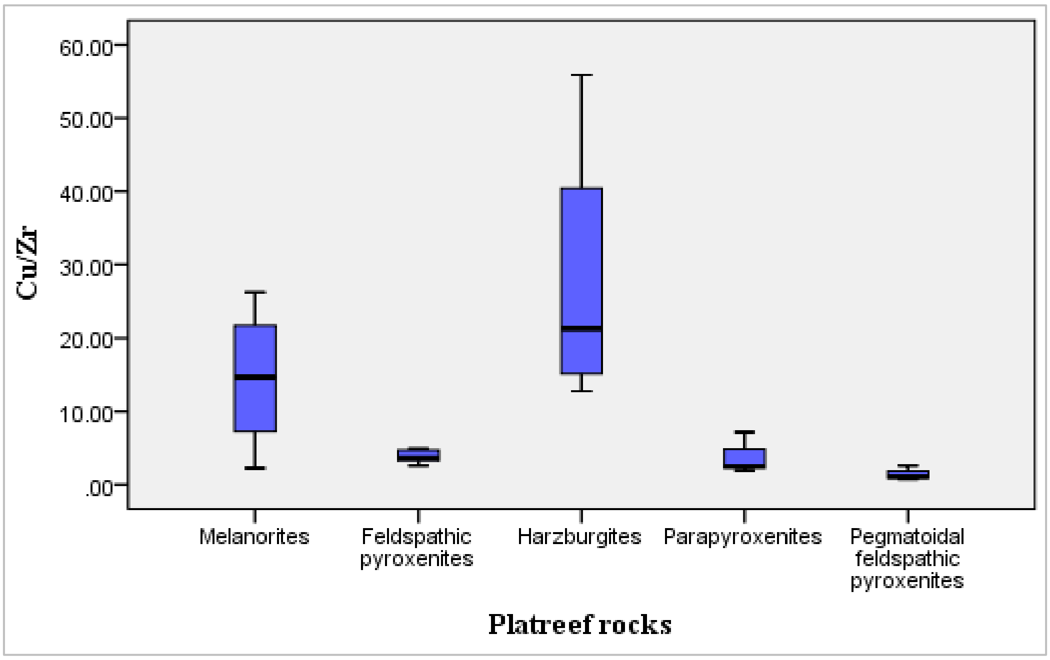


Figure 4.23. The box-plot showing the occurrence of mineralisation by using Cu/Zr ratio in different rock types in Platreef.

peaks (Figure 4.23). The mineralisation occurrence at Moordkopje is dealt with in the Mineralisation section.

The occurrence of olivine is indicated in harzburgites and minimal in parapyroxenites of the Platreef lithologies (Figure 4.24). The control line was indicated at Ni/Cr = 0.5 to show the significance. The findings of ore petrography have shown that at Moordkopje, the presence of olivine in the rocks is likely related to the primary mineralisation of the Platreef. The Ni/Cr ratio is associated with floor rock imprints on Platreef rocks (i.e. K_2O/TiO_2 and CaO/Al_2O_3) in the downhole plots in order to evaluate the effects of contact metasomatism on magmatic mineralisation of Platreef.

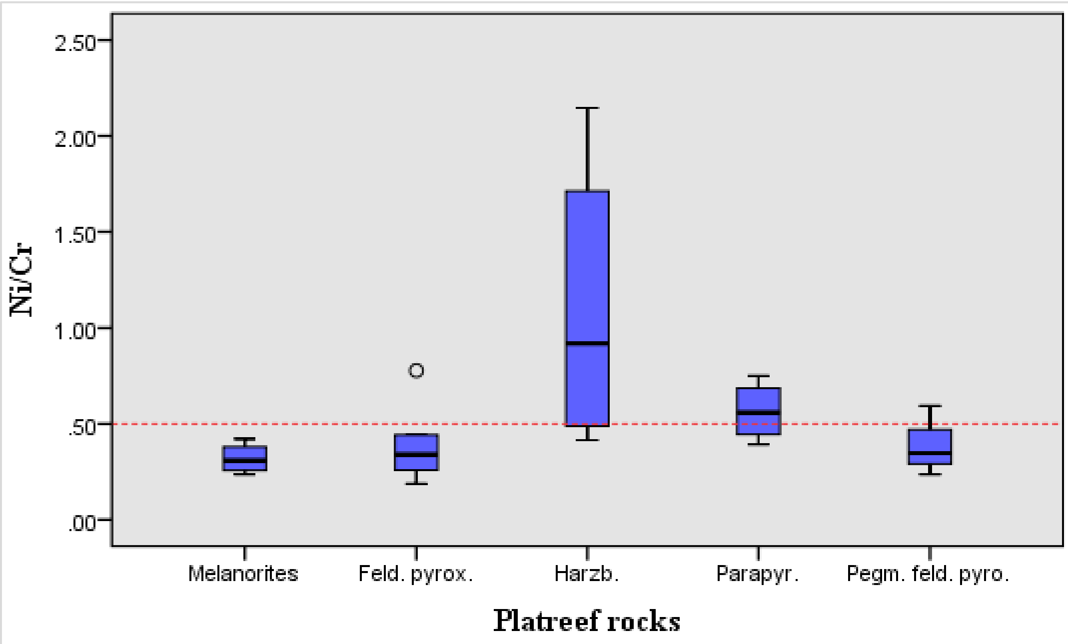


Figure 4.24. The box-plot showing the peaks generated by Ni/Cr ratio as an indication of olivine-related mineralisation in Platreef rocks.

The downhole plots in Figure 4.25 and Figure 4.26 show minimal and insignificant effects of K_2O/TiO_2 to Cu/Zr, than the effects by CaO/Al_2O_3 which are notable (the red dotted lines indicates the peaks). These findings provide the indication that granite floor rock have less effects on Platreef mineralisation than dolomitic floor rock have. The highest peak of Ni/Cr in borehole MO019 is not related to olivine occurrence, rather related to the low Cr value in pegmatoidal feldspathic pyroxenite.

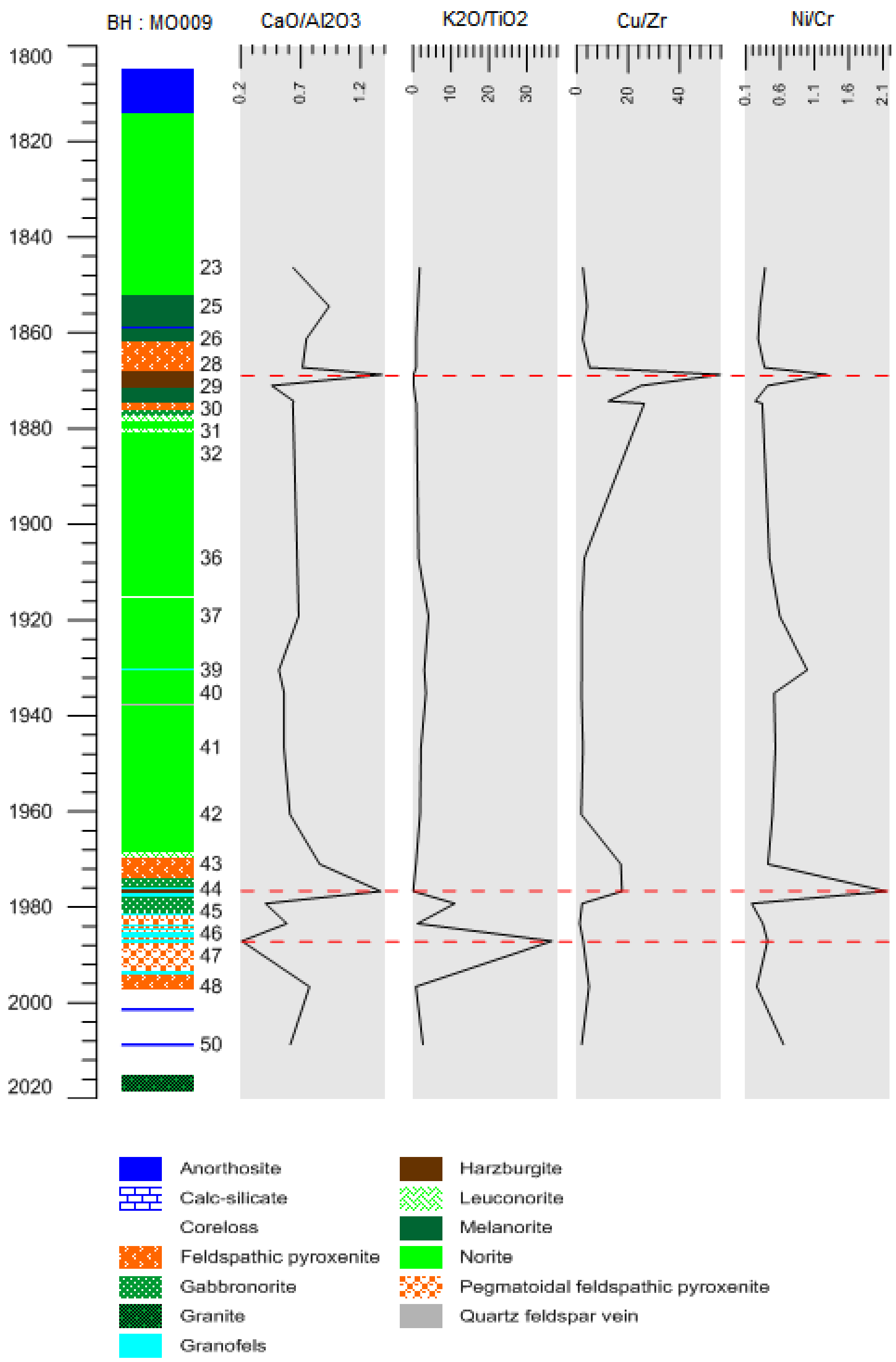


Figure 4.25. The downhole representation of MO009 with the ratios CaO/Al_2O_3, K_2O/TiO_2, Cu/Zr and Ni/Cr.

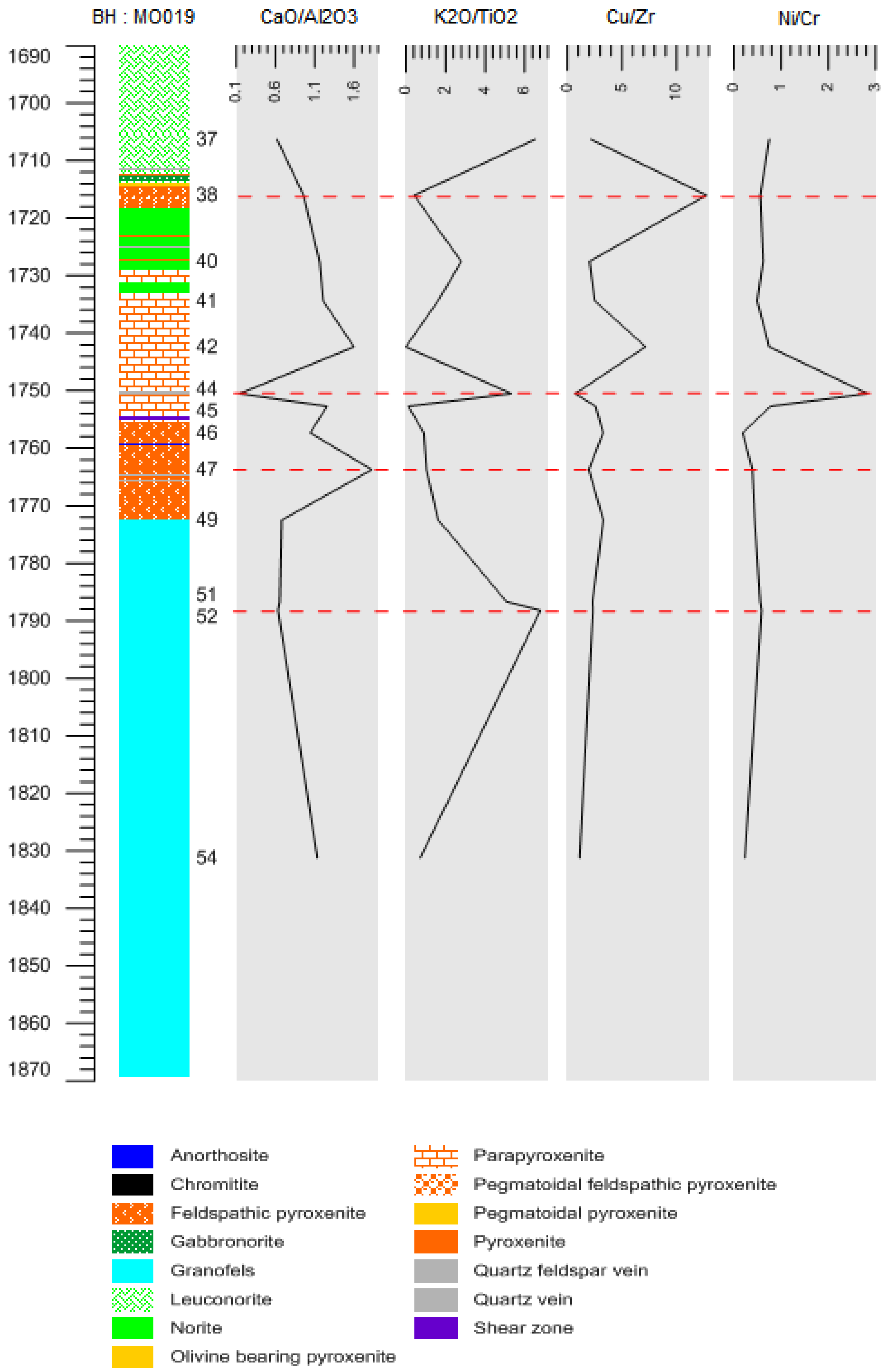


Figure 4.26. The downhole representation of MO019 with the ratios CaO/Al_2O_3, K_2O/TiO_2, Cu/Zr and Ni/Cr.

4.3.4.3. Alteration geochemistry and Mass transfer

Alteration geochemistry focuses on modifications/alterations that occur to the rock during fluid-rock interaction systems. Mass transfer was incorporated in this section as it quantifies the degree of element activity before and after alteration of a rock. The mass transfer will show element loss or gain after rock alterations, as a way to explain the minerals that were altered from the original rocks. This section complements the findings of petrography, geochemically, on the alterations of rocks of Platreef.

The objectives of alteration geochemistry and mass transfer is to understand and review the elements that were lost or gained during the fluid-rock activity. For example, in the current study, element enrichment or loss that occurred to the Platreef pyroxenites as a result of metasomatic fluids from granite floor rock during partial melting is reviewed. The aims of the study to resolve the stratigraphy of the layered intrusions of the Platreef and understand the distribution of mineralisation may be explained with reference to alteration activity whether it had any effects. This section provides a way of quantifying geochemical alterations to the original rocks in terms of explaining the effects of the floor rock materials.

The procedure in this section focuses mainly on immobile elements with guidelines based on MacLean and Barrett (1993) and Grant (1986, 2005). The element immobility is a useful measure in geochemical exploration as immobile elements are not susceptible to hydrothermal alterations on the rock. The results from MacLean and Barrett (1993) showed that elements Al_2O_3, TiO_2, HFSE (Zr, Nb and Y) and REE are highly immobile during the alteration interaction in the rocks. These elements generally maintain their magmatic concentrations and magmatic mass/volumes throughout the fluid-rock interaction phase.

In identifying the ideal immobile elements in both the original and altered rocks of the current study, the steps by Grant (1986) were followed based on equation (1) explained in Chapter three. The determination of mass transfer was done separately for *pegmatoidal feldspathic pyroxenites* and for *parapyroxenites* as these rocks had undergone different types of alterations.

$$C_i^A = M^O/M^A(C_i^O + \Delta C_i) \qquad \textit{eq. (1)}$$

An isocon is reasonably chosen based on the slope of data (C_i^A/C_i^O) of species. The elements with $C_i^A/C_i^O = 1.00 \pm 0.05$ were selected as immobile in order to construct an isocon slope. The identified immobile elements are then used to determine a factor which is used to calculate the mass gain/loss ($\Delta C_i/C_i^O$) in the altered rock with respect to the original host rock.

Table 4.10 shows the average compositions of the rock types of the Platreef, and additionally the average composition of melanorites of Main Zone. The data presented in the table was used for graphical representations of mass transfer between lithologies (Figure 4.27 to Figure 4.30). The main objective of this evaluation is to compare the feldspathic pyroxenites as the most pristine rocks of Platreef rocks to product rocks (i) pegmatoidal feldspathic rocks and (ii) parapyroxenites. These two rock types generally occur at the base of Platreef near the granite-gneiss floor rock with associations of calc-silicate xenoliths. Hybrid rocks form their own distinctive suite on the stratigraphy of the Platreef, which is formed from assimilated units of Platreef pyroxenites with either the granite-gneiss floor rock (i.e. pegmatoidal feldspathic pyroxenites) or partially with calc-silicates (i.e. parapyroxenites).

The evaluation assesses the degree of exchange in mass compositions shared between these lithologies. Most pristine Platreef rocks are harzburgites and feldspathic pyroxenites, however, in this exercise, feldspathic pyroxenites were regarded as the main original rocks at Moordkopje as they represent the generic primitive composition of the Platreef.

Table 4.10. The average concentration of major oxides and trace elements in each of the rock types of the Platreef. Most pristine rock types on the left and the altered rocks on the right of the table.

	ROCK TYPES				
	Feldspathic pyroxenites	Harzburgites	Parapyroxenites	Pegmatoidal feldspathic pyroxenites	Melanorites
SiO_2	47.90	46.32	41.88	54.91	52.51
Al_2O_3	7.89	3.45	7.56	8.84	7.55
Fe_2O_3	12.52	14.09	10.45	13.16	10.85
MnO	0.22	0.20	0.19	0.21	0.20
MgO	21.60	28.14	22.12	12.17	21.82
CaO	6.84	2.81	10.48	6.03	5.42
Na_2O	0.69	0.07	0.48	1.64	0.55
K_2O	0.17	0.02	0.22	0.49	0.12
TiO_2	0.19	0.11	0.20	0.34	0.15
P_2O_5	0.01	0.01	0.01	0.10	0.01
LOI	1.93	4.59	6.44	2.06	0.44
Total	**99.96**	**99.80**	**100.02**	**99.93**	**99.60**
Ba	54.14	39.10	57.94	124.33	48.75
Ce	1.18	7.45	1.02	43.26	0.02
Co	80.79	114.90	69.79	58.47	81.00
Cr	2352.96	2487.51	1319.55	698.29	2896.00
Cu	147.18	819.58	122.65	109.13	288.75
Nb	2.30	2.38	2.36	4.23	2.50
Ni	858.21	2574.64	732.87	319.84	934.00
Pb	3.52	2.04	4.48	9.42	4.75
Rb	15.76	9.66	28.25	31.38	8.00
Sr	81.80	31.71	83.06	135.16	68.75
U	0.17	0.01	9.17	7.40	0.75
V	120.51	82.77	114.28	129.64	114.50
Y	9.81	5.49	14.88	41.27	2.75
Zn	129.98	97.98	105.49	112.30	73.25
Zr	37.91	29.90	40.09	77.87	20.25

A. Mass transfer from feldspathic pyroxenites to pegmatoidal feldspathic pyroxenites

Based on the slope data point in Table 4.11, it was assumed that Fe_2O_3 and MnO were immobile species (indicated in bold font) during alteration of feldspathic pyroxenites to pegmatoidal feldspathic pyroxenites.

Table 4.11. The isocon analysis of rock alteration from feldspathic pyroxenite to pegmatoidal feldspathic pyroxenites.

	Unaltered	Altered	Slope data point	Gain/Loss relative to C_i^0	Gain/Loss in wt.% or ppm
	Feldspathic pyroxenites	Pegmatoidal feldspathic pyroxenites	C_i^A/C_i^0	$\Delta C_i/C_i^0$	ΔC_i
SiO_2	47.90	54.91	1.15	0.09	4.34
Al_2O_3	7.89	8.84	1.12	0.07	0.52
Fe_2O_3	12.52	13.16	**1.05**	0.00	0.00
MnO	0.22	0.21	**0.96**	-0.09	-0.02
MgO	21.59	12.17	0.56	-0.46	-10.01
CaO	6.84	6.03	0.88	-0.16	-1.10
Na_2O	0.69	1.64	2.38	1.26	0.87
K_2O	0.17	0.49	2.88	1.74	0.30
TiO_2	0.19	0.34	1.79	0.70	0.13
P_2O_5	0.01	0.10	10.00	8.51	0.09
Ba	54.14	124.33	2.30	1.18	64.15
Ce	1.18	43.26	36.66	33.88	39.98
Co	80.79	58.47	0.72	-0.31	-25.16
Cr	235.30	69.83	0.30	-0.72	-168.86
Cu	147.18	109.13	0.74	-0.29	-43.35
Nb	2.30	4.23	1.84	0.75	1.72
Ni	257.46	95.95	0.37	-0.65	-166.17
Pb	3.52	9.42	2.68	1.55	5.44
Rb	15.76	31.38	1.99	0.89	14.09
Sr	81.80	135.16	1.65	0.57	46.79
U	0.17	7.40	43.53	40.41	6.87
V	120.51	129.64	1.08	0.02	2.83
Y	9.81	41.27	4.21	3.00	29.45
Zn	129.98	112.30	0.86	-0.18	-23.14
Zr	37.91	77.87	2.05	0.95	36.17

According to the petrography results of the current study, the pegmatoidal feldspathic pyroxenites are generally the feldspathic pyroxenites (or pyroxenites) that were affected by the quartz-feldspar fluids from the granite footwall as a result of contact metasomatic fluids activity during or post-emplacement of Platreef. The imprints of granite materials were seen on thin sections of pegmatoidal feldspathic pyroxenites under the microscope. The imprints confirm the transfer of mass from footwall to Platreef rocks. The K-feldspars and quartz (and other accessory minerals e.g. apatite) were incorporated into the composition of feldspathic pyroxenites to form a hybrid rock referred herein as the pegmatoidal feldspathic pyroxenite.

Figure 4.27 shows that gain of elements is significant in P_2O_5, K_2O, Na_2O and TiO_2 consecutively from highest to lowest with respect to the original host rock. There was a significant addition of these elements to the feldspathic pyroxenites of Platreef at the contact zone to form pegmatoidal feldspathic pyroxenites. Other mobile elements gained were Ba, Ce, Pb, Rb, Sr, U, Y and Zr, whiles Co, Cr, Cu, Ni and Zn were lost.

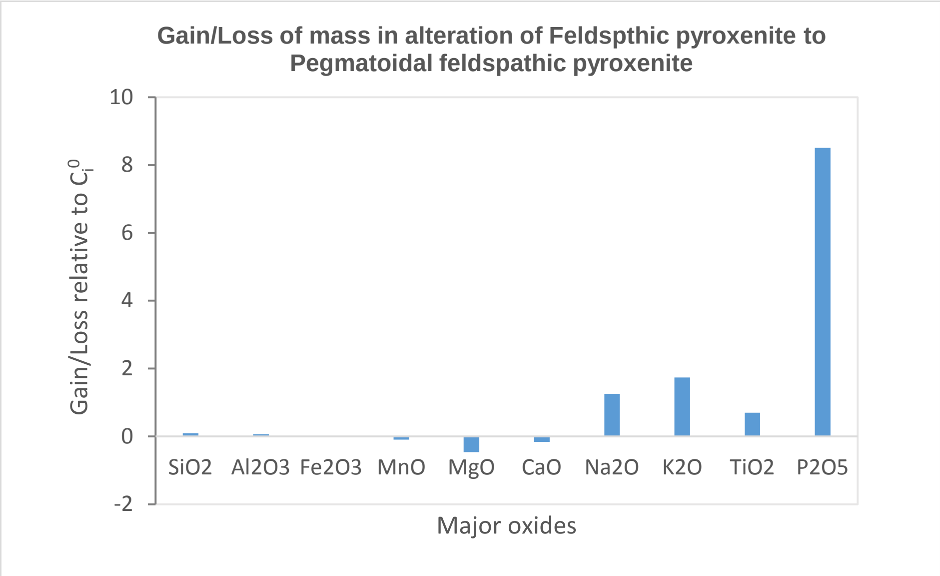


Figure 4.27. Gain or loss of mass from feldspathic pyroxenites to pegmatoidal feldspathic pyroxenites relative to Fe_2O_3 and MnO as an identified immobile species.

K_2O and Na_2O are characteristic of granite composition (i.e. the K-feldspars and albite), and the significant relative addition of P_2O_5 may suggest the presence of accessory mineral apatite. The relative gain in K_2O and Na_2O sufficiently supports the findings of petrography and geochemical characterisation of pegmatoidal feldspathic pyroxenites. Figure 4.28 systematically and graphically shows the gained and lost elements during the alteration of feldspathic pyroxenite to pegmatoidal feldspathic pyroxenite with scaled values as suggested by Baumgartner and Olsen (1995).

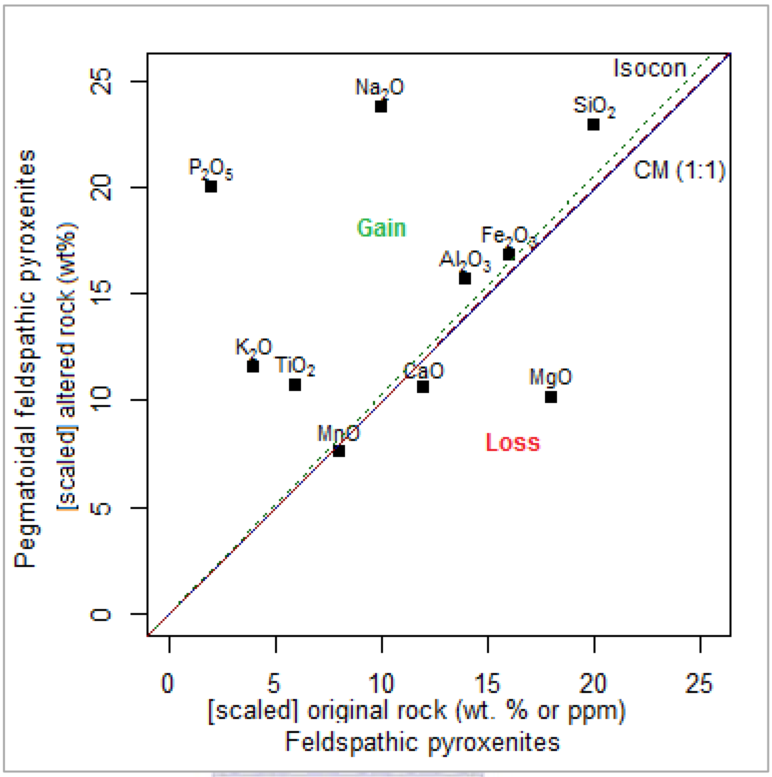


Figure 4.28. A graphical representation of gain or loss of elements from feldspathic pyroxenites to pegmatoidal feldspathic pyroxenites. CM denotes constant mass represented by a solid 1:1 line, and the dotted line is the constructed isocon line based on identified immobile elements.

B. <u>Mass transfer from feldspathic pyroxenites to parapyroxenites</u>

The slope data point in Table 4.12 shows that Al_2O_3, MgO, TiO_2, P_2O_5, Nb, Sr and V were immobile species (indicated in bold font) during alteration of feldspathic pyroxenites to parapyroxenites. A subset of Al_2O_3 and TiO_2 was chosen as ideal immobile species based on the common immobility of Al and Ti.

Table 4.12. The isocon analysis of rock alteration from feldspathic pyroxenite to parapyroxenites.

	Unaltered	Altered	Slope data point	Gain/Loss relative to C_i^0	Gain/Loss in wt.% or ppm
	Feldspathic pyroxenites	Parapyroxenite	C_i^A/C_i^0	$\Delta C_i/C_i^0$	ΔC_i
SiO_2	47.90	41.88	0.87	-0.09	-4.19
Al_2O_3	7.89	7.56	**0.96**	0.00	0.00
Fe_2O_3	12.52	10.45	0.84	-0.13	-1.61
MnO	0.22	0.19	0.86	-0.10	-0.02
MgO	21.59	22.12	**1.02**	0.07	1.49
CaO	6.84	10.48	1.53	0.60	4.10
Na_2O	0.69	0.48	0.70	-0.27	-0.19
K_2O	0.17	0.22	1.29	0.35	0.06
TiO_2	0.19	0.20	**1.05**	0.10	0.02
P_2O_5	0.01	0.01	**1.00**	0.04	0.00
Ba	54.14	57.94	1.07	0.12	6.33
Ce	1.18	1.02	0.86	-0.10	-0.12
Co	80.79	69.79	0.86	-0.10	-7.96
Cr	235.30	131.96	0.56	-0.41	-97.59
Cu	147.18	122.65	0.83	-0.13	-19.18
Nb	2.30	2.36	**1.03**	0.07	0.16
Ni	257.46	219.86	0.85	-0.11	-28.02
Pb	3.52	4.48	1.27	0.33	1.16
Rb	15.76	28.25	1.79	0.87	13.72
Sr	81.80	83.06	**1.02**	0.06	4.88
U	0.17	9.17	53.94	55.29	9.40
V	120.51	114.28	**0.95**	-0.01	-1.25
Y	9.81	14.88	1.52	0.58	5.72
Zn	129.98	105.49	0.81	-0.15	-19.89
Zr	37.91	40.09	1.06	0.10	3.93

The parapyroxenites had generally been studied in the literature by many authors as a mixture of pyroxenite and calc-silicate (e.g. Harris and Chaumba (2001); Kinnaird *et al.* (2005); Holwell *et al.* (2005)). Parapyroxenites form another type of mass transfer in Platreef rocks which involves the calc-silicate xenoliths. The petrography results showed that parapyroxenites were altered by the significant addition of calc-silicate components through contact metamorphism. This feature in parapyroxenites was characterised by irregular high content of clinopyroxene (Ca-rich pyroxene) for generic Platreef rocks. Figure 4.29 and 4.30 ascertains the significant addition of CaO into the Platreef rocks to form a hybrid rock referred to as parapyroxenite. The significant gain of elements is with CaO and K_2O, and the loss of elements is significant with Na_2O and Fe_2O_3. The loss in sodium ions can be explained by petrography as parapyroxenites did not have plagioclase under the microscope, while the feldspathic pyroxenite has relatively high plagioclase content. The figures (Figure 4.29 and Figure 4.30) graphically represents the descriptions given above on the elements that were gained and lost during the process of contact metasomatism at the contact between the footwall and Platreef. Other mobile elements gained were MgO, TiO_2, Pb, Rb, U and Y, whiles Ce, Co, Cr, Cu, Ni and Zn were lost.

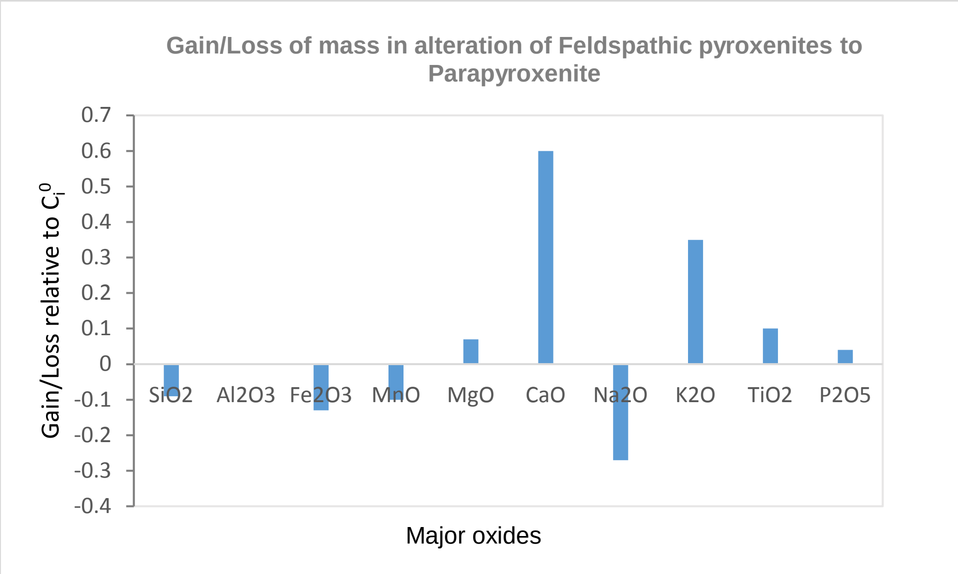


Figure 4.29. Gain or loss of mass from a feldspathic pyroxenites to pegmatoidal feldspathic pyroxenites relative to Al_2O_3 as an identified immobile species.

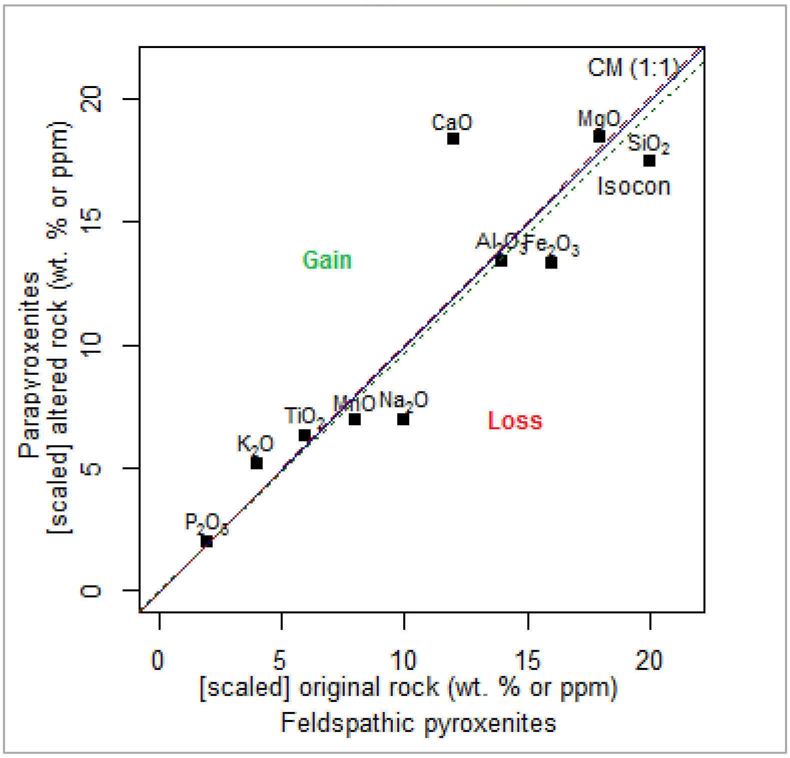


Figure 4.30. A graphical representation of gain or loss of elements from feldspathic pyroxenites to parapyroxenites. CM denotes constant mass represented by a solid 1:1 line, and the dotted line is the constructed isocon line based on identified immobile elements.

4.3.4.4. Mineralisation

In this section, the mineralisation is described in terms of its distribution within the Platreef in the two boreholes. As part of the aims and objectives, it is necessary to understand the distribution of the platinum and palladium, and also the base metals (Ni-Cu). Gold and chromium were also included in this section, even though it is out of the scope of the aims of the work. The distribution of mineralisation is described in terms of the Platreef reserve as a package and is further described per lithology reserve within the Platreef.

A. General distribution of mineralisation at Moordkopje

The typical occurrence of Pt and Pd with Au is shown in Figure 4.31 which represents the occurrence of PGEs at Moordkopje. The averages are approximately 1 000 ppb Pt, 2 000 ppb Pd, and about 300 ppb Au (Figure 4.31). The samples that were analysed for the values of Platinum, Palladium and Gold, are in presented in Appendix I-C.

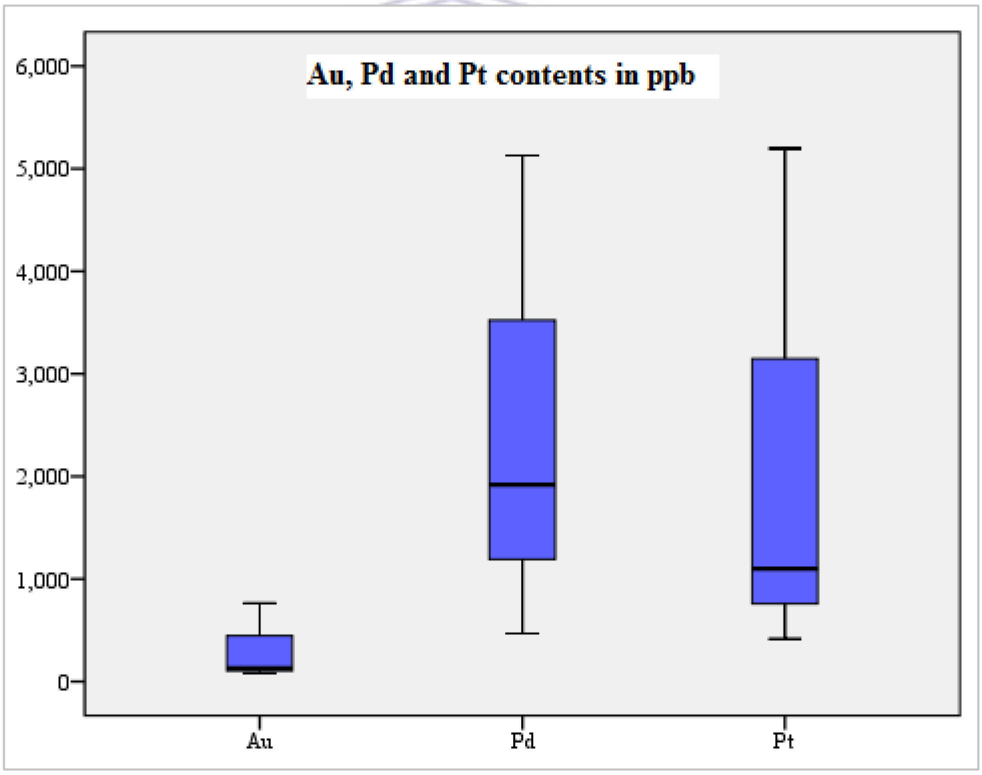


Figure 4.31. The representation of the occurrence of Pt and Pd with Au from boreholes MO009 and MO019, showing the average values of occurrence.

In terms of base metals (Ni, Cu-Co) and chromium (Cr), in Figure 4.32, the mineralised zones as discussed in ore petrography section occurs in two conditions. The first one is the magmatic occurrence which is associated with serpentinisation in the middle zone of Platreef which includes chromium as well. The other occurrence is the quartz-feldspar fluid-related occurrence which is at the stratigraphic contacts at the base and cap of Platreef. The basal contact is explained in terms of assimilation and partial melting between the granitic floor rock and the Platreef pyroxenites. However, the upper contact is not very well understood where there is a zone of melanorites as a cap of the Platreef. Nevertheless, the upper contact between Platreef and Main Zone is out of the scope of the current study, and there was no much focus intended for the understanding of this zone for this work. The average values of nickel-copper and chromium within the Platreef from the two boreholes at Moordkopje are summarised in Table 4.13.

Table 4.13. The average values (in ppm) of Ni, Cu-Co and Cr occurrence within the Platreef from 21 samples of MO009 and MO019 at Moordkopje farm.

	Minimum	Maximum	Mean	Std. Deviation
Ni	243.00	4987.19	1090.83	1077.54
Cu	40.00	1784.11	292.98	379.37
Co	28.06	166.05	82.49	30.10
Cr	96.99	3898.57	2044.71	989.11

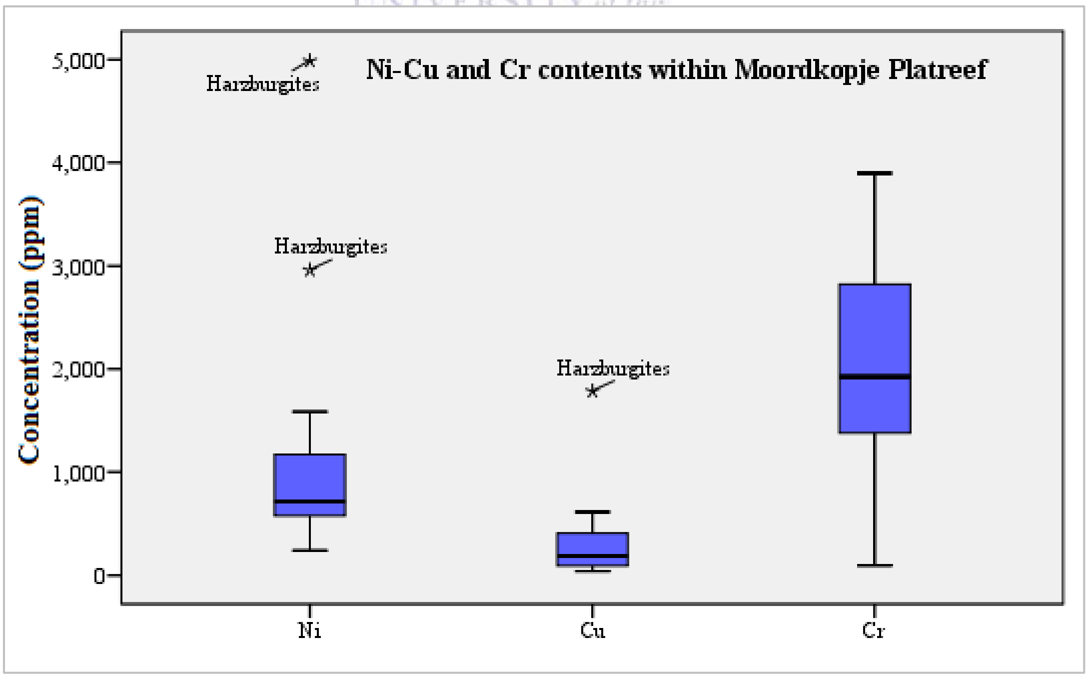


Figure 4.32. The representation of the occurrence of Ni, Cu with Cr within the Platreef from boreholes MO009 and MO019, showing the average values of occurrence. The outliers are dominantly within the harzburgites.

B. Mineralisation and associated rock types at Moordkopje

The occurrence of mineralisation has the preference of specific rock types that contain specific minerals that favour mineralisation to be hosted during fractionation and deposition. The mineralisation occurrence in Moordkopje was reviewed based on total sulphur content (Figure 4.33) with the guide from ore microscopy from Petrography section, and associations with base metals and chromium. Petrography has shown that there are two types of mineralisation at Moordkopje. One is the primary type of mineralisation where there are chromites and chalcopyrite as the main ore minerals, and the other type is mineralisation that is associated with fluids at the contact which is analogous with the occurrence in the melanorites. The ore minerals of this type are mainly sulphide minerals.

The associated rock type with the mineralisation at the contact or basal Platreef is pegmatoidal feldspathic pyroxenite, while the mineralised middle Platreef is associated with harzburgites. The occurrence of mineralisation within the melanorites is not very clear (Figure 4.33).

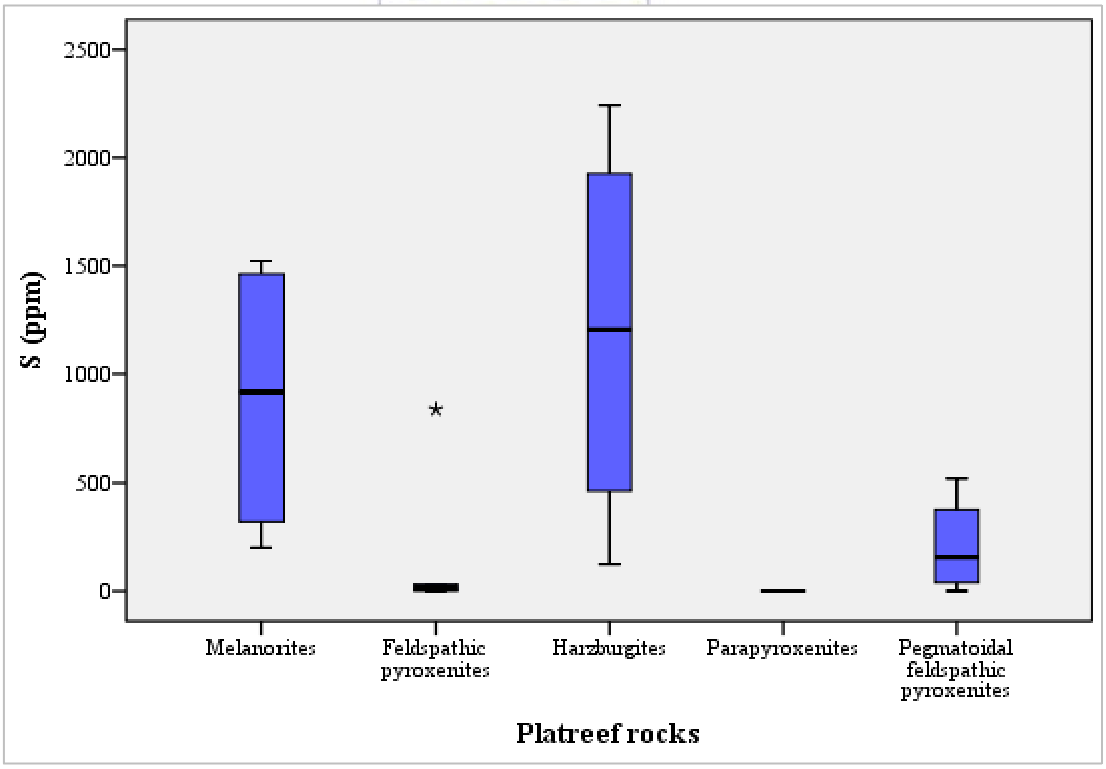


Figure 4.33. The content of total sulphur in the Platreef lithologies.

The occurrence of platinum (PGEs) is well associated with harzburgites (Figure 4.34), this may be the result of chromite occurrence within this rock. Kinnaird *et al.* (2002) have suggested great affinity of platinum with chromite.

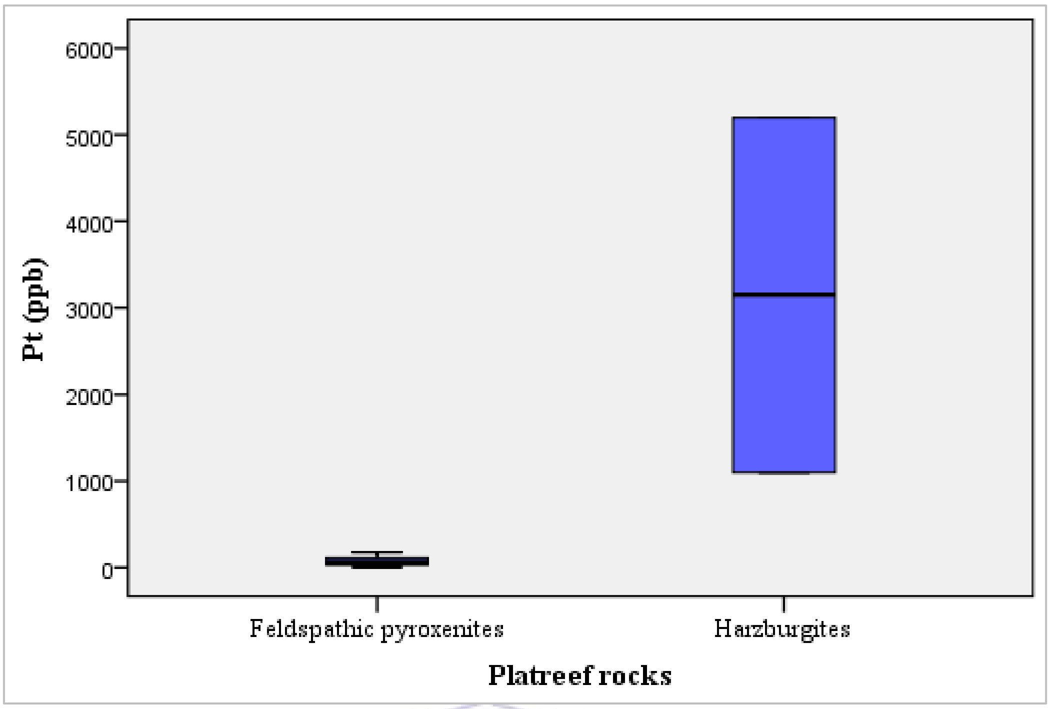


Figure 4.34. The concentration of Platinum (Pt) in ppb within the Platreef magmatic rock types.

The key elements that can predict the occurrence of mineralisation at Moordkopje are Cu/Zr, Cr, and S (Figure 4.35 and Figure 4.36). These elements can discriminate the two types of mineralisation occurrence, which are olivine-serpentinisation-related (chromite in harzburgites) and sulphide-related (base metal sulphides in both harzburgites and contact zone mineralisation). Ore microscopy in Petrography confirmed these occurrences of mineralisation within the Platreef. However, the elevated sulphide content that occurs in the melanorites is still not clear on this project. Further investigations may be required in the future in order to assess the importance of this occurrence. This area of study is not part of the current scope and aims of this project. The next chapter discusses further on the overall setup of the Platreef and its mineralisation occurrence with regards to the effects from the floor rock interaction.

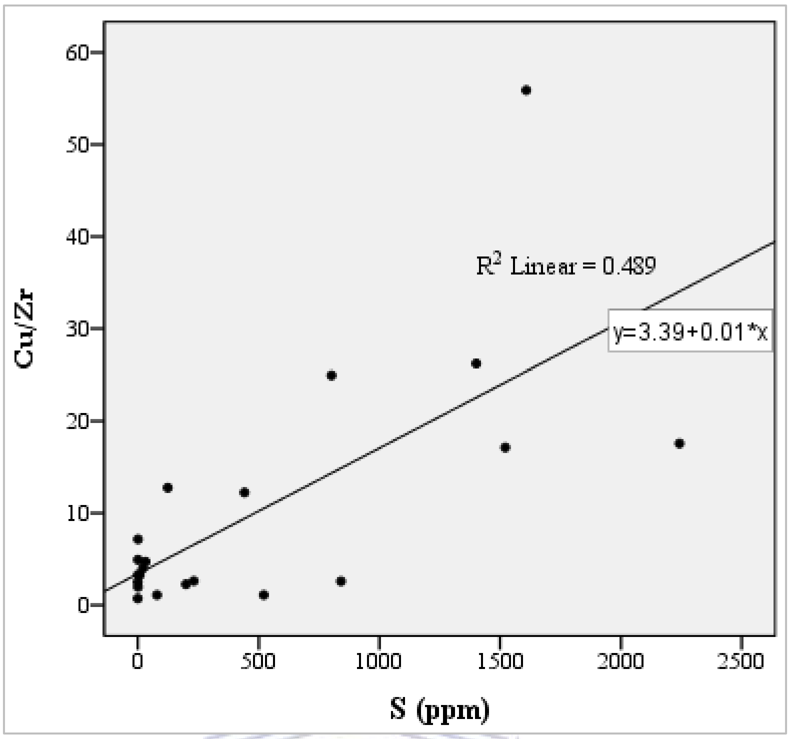


Figure 4.35. The ratio of Cu/Zr with the sulphur content showing the relationship of the ratio with the occurrence of sulphur.

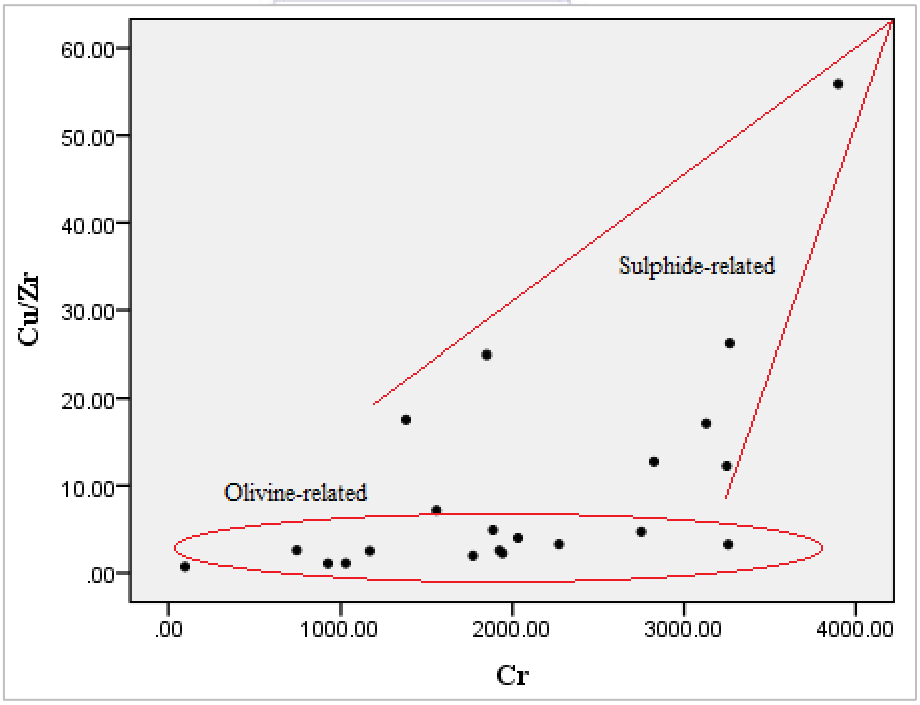


Figure 4.36. The Cu/Zr in relation with the Cr occurrence showing the magmatic mineralisation related to olivine occurrence (i.e. chromite), and the sulphides of the Platreef.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1. Introduction

The aim of this study was to assess and evaluate the effects of contact metasomatism and fluid-rock interaction on the nature and/or style of the PGE-mineralisation (and BMS-mineralisation) of the Platreef at Moordkopje farm, after the emplacement of Platreef intrusion on the country rock in the local area which is the Archaean granite-gneiss.

In this study, the term of "nature" of the PGE mineralisation refers to two concepts. The first one is the type of the mineralisation occurring in the Platreef relative to the 'typical' original type of mineralisation occurring in the Merensky Reef in the Western and Eastern Limbs where the mineralised zone does not rests directly onto the country rock. The second one, which is considered the most important in this study, is the position of the mineralisation in the stratigraphy of the Platreef package. The position of the occurrence of mineralisation in the Platreef is so complex, relative to the occurrence of mineralisation in the other limbs of the Bushveld Complex. In the other limbs; the distribution of the mineralised zones follow certain distinguishable patterns. Cawthorn (2010) highlighted that as highly variable the vertical distributions of the PGEs in the Merensky and UG2 chromitite reefs as they are, however, they do follow certain patterns that can allow testing of geological models. However, in the Northern Limb it is a very different occurrence. There is no distinct patterns in the distribution of the mineralisation, and the complexity further occurs on to the lithologies in the package.

The main idea on the investigation of the Platreef rocks and mineralisation sequence was to further understand the generic stratigraphic succession of the layered intrusions of the Platreef, and schematically unfold the current existing complexity into a comprehensible order. The meaning of 'comprehensible order' refers to the schematic generic stratigraphy of the lithologies and mineralisation of the Platreef package at Moordkopje. In order to schematically unfold the Platreef complexity, the study focused on metasomatic fluids as the main factor that played a role in modifying the generic conditions. However, there are many other factors or processes that may have occurred during and after the assimilation process between the pyroxenitic rocks of the Platreef and the granite floor rock. However, the process of post-metasomatic fluids activity was specifically evaluated as the main factor. This post-contact metasomatic fluid activity is the type of contamination which was referred to as "second contamination" by Ihlenfeld and Keays (2011). The contamination which was caused by the country rock components on to the Platreef package through metasomatic fluids transportation. Essentially in the current study, the focus is brought towards the fluids that arose from the granitic floor rock due to partial melting (i.e. the quartz-feldspar fluids) during and after Platreef emplacement at Moordkopje local area. Harris and Chaumba (2001) mentioned the presence of fluid that passed through the cooling Platreef. The hypothesis which is carried in this study, substantially due to the involvement of post-fluid activity in the Platreef, is that the fluids had played a significant role onto modifying the general stratigraphy of the Platreef intrusive layers. As of that result, the generic position and normal distribution of the PGE and BMS mineralisation were affected. The terms "generic position" and "normal distribution" are with reference to the studied position and distribution of the intrusive layers and mineralisation of the Western and Eastern Limbs of the Bushveld Complex. This is the induced reasoning that has been brought along in the current study that explains the Platreef complexity in both the layered intrusions and the existing PGE and BMS mineralisation. The descriptions of the rocks by petrography was the main method to provide supporting information to the hypothesis of the work. However, whole rock geochemistry was also used in order to supplement the findings achieved in the petrography.

The importance of the current study is that it brings new information to geological and geochemical exploration on the descriptions of the Platreef rocks of Moordkopje farm, the area that is under-explored. The descriptions of rocks involves both mineralogical and geochemical characterisation of Platreef rocks at Moordkopje. This is the gap that has not been covered in the Northern limb of Bushveld Complex (the Moordkopje prospect area). The study will also determine the sustainability and productivity of Moordkopje area as a prospect area. In order to assist the mining industry in search for new prospects. Most of the work that has been conducted in the Northern limb of Bushveld Complex does not involve Platreef package at Moordkopje. Roelofse and Ashwal (2012) worked at Moordkopje area, however, their work dealt with the lower Main Zone of the area. None has been done on the Platreef rocks descriptions. The current study brings new information and research that will cover the gap in the geological and geochemical research of Bushveld Complex.

An overview of existing knowledge on the subject related to the current study could not be left unmentioned especially the work that carries very similar investigations to this study. The subject of the complexity in the Platreef stratigraphy dates back to the field work by Van der

Merwe (1976).The similar work to the current study was previously investigated by Cawthorn *et al.* (1985) which was in Overysel Farm adjacent to the study area in the east border of the farm. The footwall in Overysel Farm is also the pink granite-gneiss similar to the footwall of Moordkopje. Another similar study that was done, however, further in the southern area of the Moordkopje study area was by Harris and Chaumba (2001) for Sandsloot Farm where the footwall is dominantly dolomite of the Transvaal Supergroup. Therefore, the fluid-rock interaction or assimilation between the area with a dolomite footwall (e.g. Sandsloot) and an area with granite footwall (i.e. Moordkopje and/or Overysel) has significantly different effects on the Platreef lithologies and mineralisation overlying them. In terms of rock descriptions, there is great relation to the rock descriptions done by Mitchell and Scoon (2012) who were also using the data from Akanani area (Zwartfontein). The Moordkopje 813 LR Farm of the Northern Sector of Platreef in the Northern Limb of the Bushveld Complex was used as the case study for this research. The work by these mentioned authors will be further discussed later in the chapter, and other authors who have investigated on similar research as the current work will be discussed for their work and findings below. Authors like Cawthorn and Lee (2005); Pronost *et al.* (2008); Mitchell and Scoon (2012); to mention a few, have been referenced here in the Discussion in relation to the findings of the current study.

The background information given above has provided the aim and the importance of the study. A short review on the objectives of the work can be given precisely as follows. The objectives of the work were to understand the lithostratigraphy in the Platreef at Moordkopje by using two boreholes, which are MO009 and MO019. Hence, the relationship between the lithologies in terms of succession and lithogeochemistry in the two boreholes was the main factor to be understood. And, subsequently, to find whether or not there is any spatial lithological correlations between the boreholes. Another aspect to be evaluated was the effects of assimilation (i.e. mass transfer) and intensity of alteration between the granite footwall and the Platreef lithologies as a result of fluid-rock interaction.

These above were the outlines and descriptions of the aims and objectives of the project. Hereafter, the descriptions of the main contents of the chapter are discussed. The Discussion chapter will focus on the findings and observations with regards to what the project was set out to do. The findings and observations are based on the results in Chapter 4, and these are compared to other previous workers. The outcomes of the work are also related to the current knowledge and to the previous knowledge on Platreef that was contributed by a collection of authors. Within the chapter, the achievements and outcomes of the study are aligned to the aims of the study. Moreover, the objectives that were not fulfilled in the study will also be outlined and explained to justify reason not to fulfil those objectives. The achievements and outcomes of the study will be framed and aligned to the following aspects:

a) Rock types of the Platreef stratigraphy in Moordkopje
b) PGE (and BMS) mineralisation in Moordkopje
c) Effects by contact metasomatism and fluid-rock interaction on mineralisation

These three points above cover the scope of the study in terms of the aims and objective of the work. The observations, views and conclusions drawn here which are related to the three aspects mentioned above were substantially based on petrography and also on geochemical characterisation.

5.2. Rock types and mineralogical trends of Moordkopje Platreef stratigraphy

In the previous chapter in the results, petrography descriptions has presented a substantial understanding of the Moordkopje Platreef rock types. The descriptions that have enabled a construction of a general schematic stratigraphy of the layered intrusions (see Figure 5.2). Petrography has assisted in understanding the pristine rock types, the mineralised rock types, and the altered rock types which are found at the contacts of the Platreef with the other magmatic layers/zones. Generally, most of the previous work or research done on Platreef have described the Platreef complexity in a broad context of layers of homogenous units, rather than the specific rock types that are present. Mitchell and Scoon (2012) have mentioned the idea of describing specific lithologies of the Platreef, and they succeeded as seen in their work. They specifically described each of the existing rock types of the Platreef, however, it was for Zwartfontein farm. While the current study puts the focus on Moordkopje farm.

In this section, the focus is on describing the primary lithologies which are mentioned as the pristine or original rocks, and the secondary lithologies which are mentioned as the product or altered rocks. In terms of the mineralised lithologies, the mineralisation occurs in two different types, however, both the primary and secondary lithologies are the host rocks to their specific type of mineralisation occurrence.

5.2.1. Primary lithologies and secondary lithologies in the Platreef

The mineralogical variations in the Platreef lithologies described in Petrography in Chapter four have shown that in the Platreef there is primary lithologies which mainly consists of cumulus olivines and orthopyroxenes with minor interstitial plagioclase, these rocks are (1) harzburgites and feldspathic pyroxenites. There is also some secondary lithologies or altered lithologies which were mainly altered due to either quartz-feldspar metasomatic fluid action from the granite floor rock or by contact metamorphism with calc-silicate xenoliths. These rocks are (2) pegmatoidal feldspathic pyroxenites (and melanorites) and (3) parapyroxenites rocks respectively. The mineralogical trends of these rocks are explained shortly below:

1. *Harzburgites and feldspathic pyroxenites*

The most pristine rock types of the Platreef to other Platreef lithologies are harzburgites and feldspathic pyroxenites, including the (serpentinised) pyroxenites. Primary lithologies are located within a division referred to as Middle Platreef which is far from the contacts where contamination is predominant. These rocks are characterised by the presence of olivine or olivine-remnants in a serpentine state. However, cumulus orthopyroxene is the prominent mineral in the pristine rocks at 60-70 % modal composition. The texture in these rocks is interlocking which makes limited interstitial spaces between the grains. The interstitial spaces are filled, generally, with clinopyroxenes especially in the harzburgites, whereas in the feldspathic pyroxenites the interstitial spaces are filled with anorthite. The primary lithologies host primitive or magmatic mineralisation, which includes also the PGEs and Chromite occurrence. The occurrence of ore minerals from the ore microscopy section have shown great affinity with olivine cumulates, and a relatively insubstantial affinity with the orthopyroxene cumulates. Most of the mineralisation occurrence in primary lithologies is hosted within the harzburgites.

2. *Pegmatoidal feldspathic pyroxenites and melanorites*

Pegmatoidal feldspathic pyroxenites and melanorites are the lithologies that consist of variably significant quartz-feldspar veins. The dominant minerals within these rocks are orthopyroxene and plagioclase, however, in melanorites the plagioclase occurs as cumulates. These rocks are the only quartz-bearing rocks with phlogopite and muscovite at the grain boundaries. The quartz occurrence in these rocks is the effect of contamination from the granite floor. The contamination was initiated as a result of partial melting on to the granite floor during the emplacement of Platreef intrusions.

Pegmatoidal feldspathic pyroxenites are generally located at the "Lower Platreef" package relative to the melanorites which are located at the "Upper Platreef" package. The locality basically of these lithologies are at the contacts between Platreef and floor rock in the case of pegmatoidal feldspathic pyroxenites; and the contact between Platreef and Main Zone in the case of melanorites. These rocks are closely related to feldspathic pyroxenites discussed above.

3. Parapyroxenites

The parapyroxenites are predominantly comprised of clinopyroxene (augite) which makes about 65% of the rock. These rocks depicts a variably intense alteration relative to any other altered and contaminated rocks. The result of that occurrence is connected to the contact metamorphism brought upon these rocks by the surrounding calc-silicate xenoliths. As seen in mass transfer section, great range of element variation and mass transfer occurred when parapyroxenites were formed, relative to when the other secondary lithologies were formed. The resultant clinopyroxene was formed through the sorption process of addition of calcium ions (Ca^{2+}) into the orthopyroxene by contact metamorphism. The occurrence of parapyroxenites in the Platreef is at the bottom zone referred to here as the "Lower Platreef", which most literature refer to this zone of contamination as P1 (Van der Merwe, 2011; Mandende, 2014).

4. Mineralogical relationships

Mineralogical relationships is the systematic representation of mineralogical distribution and connection between the primary and secondary rock types (as seen in Figure 5.1). The orthopyroxene is the primary mineral that comprise all the rocks of the Platreef, regardless of the origin and alteration of the rock. Orthopyroxene is found in granofels as imprints or foreign contents which originally came from the pyroxenites of the Platreef. The granofels also comprise of clinopyroxene which were sourced by the interaction of pyroxenite and calc-silicate, and eventually imprinted on the granofels as a result of sharing same vicinity. At this vicinity, the zone of contamination, another rock type is pegmatoidal feldspathic pyroxenite (quartz-bearing feldspathic pyroxenite) which has contents of granite floor rock as veins. The relationship of these minerals is represented in Figure 5.1.

Plagioclase in another primary mineral after the orthopyroxene, which occurs in almost all the main rock types of Platreef. The occurrence of plagioclase in Platreef rocks is in a form of interstitial phase, where it fills the spaces between the mineral grains. However, at the upper contact of Platreef with Main Zone, plagioclase occurs as the cumulate mineral as seen in all the norites of the Main Zone including melanorites.

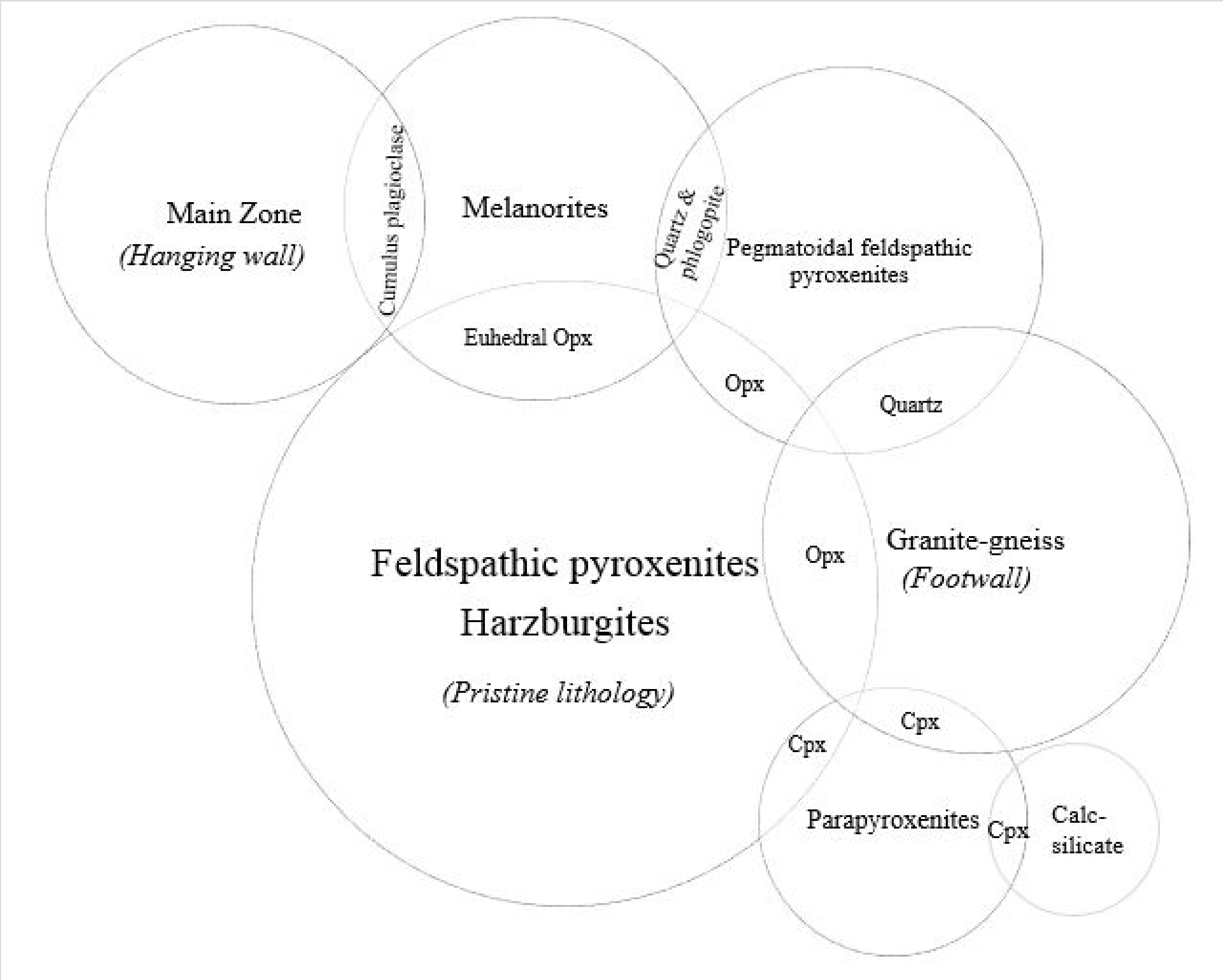


Figure 5.1. The schematic representation of mineralogical relationships of the Platreef lithologies with Main Zone and Footwall effects in terms of mineralogical distribution and occurrence. The figure also displays the mineralogical trends amongst the rock types in difference vicinities from the floor to the cap of Platreef.

5. *Rock textures*

The textures in the rocks of Moordkopje area are generally exhibiting igneous and some metamorphic textures (relict textures). The primary rock types have igneous textures like poikilitic and intergranular textures. The Main Zone norites typically exhibit ophitic to sub-ophitic textures. While the anorthosites of Main Zone exhibit a coarse intergranular texture where large poorly-sorted grains of cumulus anorthite are filled with interstitial orthopyroxenes (occasionally clinopyroxene) in between them. However, commonly the gabbronoritic rocks show ophitic texture where the clinopyroxenes encloses the plagioclase laths of average size of 4 mm.

In the Platreef zone, the interlocking texture is primarily occurs in the "Middle Platreef", where harzburgites and local pyroxenites occurs. At this vicinity, only mafic grains settled together to produce interlocking grains with no interstitial spaces between them. This texture may be the primitive occurrence of Platreef, where primitive mineralisation took place. Another textural occurrence which generally occurs erratically across the Platreef and is not very well understood in this study, is the development of clinopyroxene (augite) at the grain boundaries of the orthopyroxenes. However, the study by Roelofse and Ashwal (2008) have explained the development of augite (as invading augite) which represented the symplectitic texture.

At the "Upper Platreef", the poikilitic texture is dominant, where widely spread interstitial plagioclase encompasses the euhedral orthopyroxene grains. The euhedral orthopyroxene occurs only at this zone, Mitchell and Scoon (2012) refers to these types of rocks as the *reconstituted lithologies*.

The "Lower Platreef" show particularly the sub-ophitic texture where the local feldspars (alkali and plagioclase laths) are not completely enclosed within the pyroxenes. Another textural feature which occasionally occurs in the "Lower Platreef" (erratically in the "Upper Platreef" as well) is that where the orthopyroxenes possess semi-parallel lamellae of clinopyroxenes. The pegmatoidal feldspathic pyroxenites show a myrmekitic texture, the development of quartz within the plagioclase, as a result of metasomatic conditions occurring at "Lower Platreef" near the granite floor rock.

6. *Mineral alterations*

The alterations in the Moordkopje rocks are not very intense, lithologies are weakly altered. However, the "Lower Platreef" has relatively intense alterations occurring on parapyroxenites as a result of contact metamorphism; and pegmatoidal feldspathic pyroxenites as a result of vein-fluid activity. The type of alteration that is very common throughout the Platreef is the alteration of plagioclase and pyroxenes to fine materials. The plagioclase alters to fine material of sericite, through sericitisation process. The orthopyroxene alters to fine material of chlorite, through chloritisation; while the clinopyroxene alters to fine material of actinolite typically in the "Lower Platreef".

Another alteration type that occurs only in the "Middle Platreef" is the serpentinisation of olivine in the harzburgites and olivine-bearing pyroxenites. The effects of this type of alteration is due to local metamorphism as a result of locally induced heat. In contrast to the alterations occurring at the contacts which is related to metasomatism.

Another occurring alteration feature is the fracturing of the orthopyroxene grains. This feature is common within the feldspathic pyroxenites in the "Middle Platreef" and "Upper Platreef". At the orthopyroxenes are likely to alter to pale green material. In the literature the type of alteration is suggested to be uralitisation where the pyroxenes alter to amphiboles.

5.2.2. Lithostratigraphy and correlations in the Platreef package

A representation of the generalised schematic Platreef at Moordkopje is given in Figure 5.2 as a way of representing the lithostratigraphy findings from this project. However, the generalised representation only explains the zones and the geological occurrences within the zone. This generalisation cannot be used uniformly in all the Platreef farms, however, it can be used as a lithological guide for the northern Platreef where the floor rock is granite. Moreover, the generalised representation may not be regarded as the representation of the actual lithostratigraphy of the Platreef in the northern sector. However, it may rather be used as the zonal representation of the geological occurrences in the Platreef. The zones are divided into three as Lower Platreef, Middle Platreef, and the Upper Platreef.

The Lower Platreef is the lowermost base of Platreef which is in contact with the granite-gneiss floor rock. The assimilation and partial melting of granite and Platreef rocks is evident at this zone. The geological occurrences at this zone are formation of hybridised rocks, depending on the type of assimilation. At Moordkopje, the occurrences are pegmatoidal feldspathic pyroxenites as a result of quartz-feldspar fluids; and partly parapyroxenites as a result of partial occurrence of calc-silicate xenoliths locally.

The Middle Platreef is the zone that is regarded as the most pristine occurrence of Platreef rocks. This is the pristine main body of the Platreef where primitive mineralisation also occurs. The zone geochemically distinguished from the Lower Platreef by means of the extent of alteration head. The geological occurrences at this zone are olivine-bearing lithologies and the affinity of mineralisation (e.g. chromites and sulphides). Harzburgites, serpentinised pyroxenites and feldspathic pyroxenites are found at this zone.

The Upper Platreef is the zone that is regarded as the cap of Platreef where there is a variation of feldspathic pyroxenites and melanorites. This zone requires further investigations such that the geological occurrences in the zone are sufficiently comprehensive. There are shortfalls which remain inconclusive in this project as for this zone. Namely, the geological formation of melanorites and the relationship of Platreef lithologies and Main Zone lithologies at the contact. Holwell (2006) identified a significant time-break between the intrusion of the Platreef and the Main Zone magma that formed the hangingwall gabbronorites. However, to describe this zone, it is geochemically distinguished from the Middle Platreef by the degree of fractionation and recrystallisation.

Therefore, the lithostratigraphy of Platreef is very complex and not straightforward to simplify it. The findings of the projects still concurs with Lishman (2009) that the attempts to correlate the Platreef with the stratigraphy of the other limbs of Bushveld Complex has been left inconclusive. Additionally, it is very much inapplicable and inappropriate to correlate Platreef from one borehole to another borehole locally, regardless of the distance between the boreholes. The attempt to correlate rock-to-rock stratigraphy of the Platreef is not appropriate to resolve the stratigraphy of the Platreef. Mitchell and Scoon (2012) dismissed the idea to simplify the stratigraphy of the Platreef into a series of successive, upward-younging units or reefs. The current study is in favour with the dismissal of the correlation and simplification of Platreef stratigraphy. The Platreef stratigraphy cannot be successively simplified as a result of:

1. Floor rock variation which interacts variably with the Platreef locally,
2. The extent of alteration head varies considerably locally, which is worsened by the variation of Platreef thicknesses locally,
3. The degree of metasomatic effects locally,
4. The occurrence of calc-silicate xenoliths locally,
5. The intercalation of layers of the Main Zone within the Platreef stratigraphy locally, which is the case in MO009.

These complications mentioned above are the fundamental reasons it is complicated to correlate Platreef lithologies. The study finds it preferential to categorise the Platreef in terms of geological and geochemical zonal occurrences, as it is currently done in terms of P1, P2, P3 and P4 units by the authors of the latest literature (Van der Merwe, 2011; Mandende, 2014) which is quite the similar way that Mitchell and Scoon (2012) did with PU1, PU2, and PU3. These units can still be distinguished in Figure 5.2.

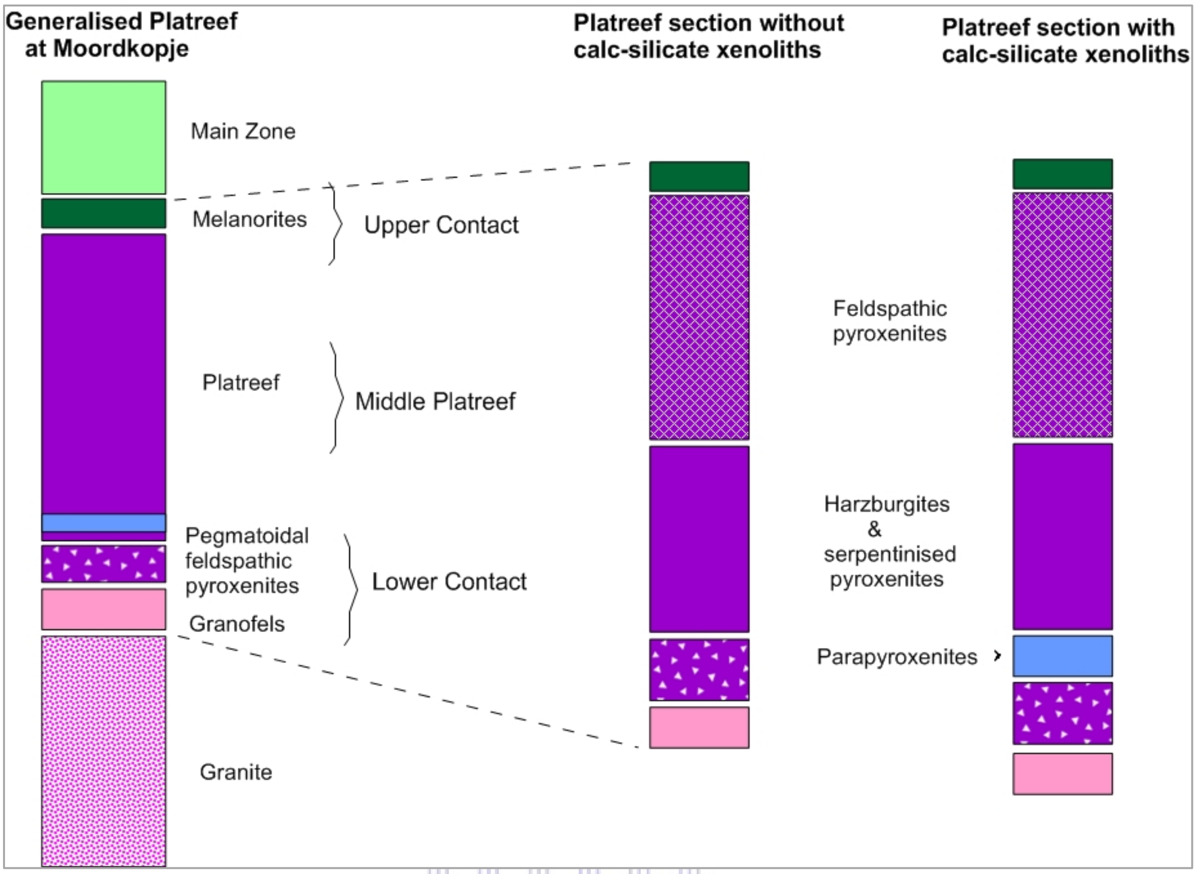


Figure 5.2. The generalised schematic representation of the Platreef stratigraphy at Moordkopje farm. The stratigraphic sections can vary in different sections as a result of the presence of calc-silicate xenoliths.

5.3. PGE mineralisation in Platreef and Moordkopje

An outline about the history and background on PGE-mineralisation in the Northern Limb (Platreef) was well reviewed by Kinnaird and McDonald (2005). They have raised the concern about the lack of mining activities in the Platreef as a result of its complexity. It is only now in recent years that exploration in the Platreef has been carried by the mining companies (Holwell and McDonald, 2006) which also involves the support from the academic research to basically understand the stratigraphy and mineralisation; and the relationship between lithostratigraphy and mineralisation. The current study also partakes in understanding the relationship between the lithologies and the mineralisation in the Moordkopje prospect area, such that the mining companies have a clear understanding of the position of mineralisation.

Moordkopje Farm is an area which is not very well mineralised with PGEs and BMS as much as the farms that are adjacent to the farm (i.e. Overysel, Zwartfontein and Sandsloot). The gap between Moordkopje farm and the other adjacent farms does not only revolves around mineralisation, however, it extends even further to lack of geological research. The Moordkopje area can be considered as under-explored with very limited academic research on the area. The most probable reason for this situation lies upon the lack of viable and economic mineralisation within the area.

According to ore petrography, as explained in the petrography chapter, there are two zones of mineralisation at Moordkopje (according to the observations from the two boreholes of this study). One zone is considered as the primary zone of mineralisation where there is chromites and chalcopyrite as the main ore minerals and the mineralisation was a magmatic generation. The mineralisation of this zone is associated with serpentinisation where the host rocks are harzburgites and serpentinised pyroxenites. These rocks are the pristine magmatic rocks of the Platreef, and are situated in the 'middle zone' of Platreef. Mitchell and Scoon (2012) describe this zone as the Main Mineralised Reef (MMR) and they put emphasis on harzburgite as the main rock type within this zone. This study concurs with these views by Mitchell and Scoon (2012) for Moordkopje area.

Another zone of mineralisation is the zone at and proximal to the contact between the granite floor and the basal Platreef. The ore minerals at this zone are mainly sulphides (i.e. chalcopyrite), no PGEs are related to this zone. This type of mineralisation was considered as the secondary type of mineralisation which is associated with quartz-feldspar fluid transportation from the granite floor as a result of partial melting. The main rock types that are associated with this zone are pegmatoidal feldspathic pyroxenites and occasionally granofels. Mitchell and Scoon (2012) talks about this type of mineralisation, they said that the most significant mineralisation is developed at some height above the contact with the floor rocks. However, this type of mineralisation also occurs in the upper contact of Platreef and Main Zone. The rock type associated with this mineralisation is the melanorite in the upper Platreef. Holwell and Jordaan (2006) mentioned this type of occurrence, and they explained the associated lithology as the 'irregularly shaped, intrusive, fine-grained melagabbronorite at the base of hanging wall', and explained the occurrence of minor PGE and BMS mineralisation in these melanorites intrusions. As outlined in the Petrography chapter, melanorites have quartz as one of the main component minerals. This occurrence is very similar to the occurrence at the bottom of the Platreef in the pegmatoidal feldspathic pyroxenites. Kinnaird *et al.* (2005) had similar observations in the southern Platreef, they characterised this mineralisation zone as 'a secondary phase associated with an interstitial plagioclase or quartz-feldspar symplectites'.

In general, the mineralisation of Platreef at Moordkopje is zoned into three localities. However, the type of occurrence is characterised into two, namely:

1. The magmatic occurrence in the middle zone of Platreef which is regarded as the primary mineralisation of Platreef. At this zone, the mineralisation occurrence is PGEs and BMS with chromite mineralisation.

2. The quartz-feldspar fluid-related occurrence at the base of the Platreef and at the cap of the Platreef which is regarded as the secondary mineralisation of Platreef. The mineralisation occurrence at these zones is mainly the BMS mineralisation, and minor chromite.

5.4. Effects by contact metasomatism and fluid-rock interaction on mineralisation

The effects by the fluid-rock interaction on the Platreef mineralisation have caught so much attention to various authors (including Harris and Chaumba (2001); Holwell and McDonald (2005) and Pronost *et al.* (2008)).

The main questions that have remain unanswered with regards to the fluids and its interactions with the rocks were:

1. Whether the fluids have any significant effects to the emplacement or deposition of the mineralisation and post-emplacement of the mineralisation in the Platreef.

2. Whether the fluids during the fluid-rock interaction had any significant change to the grade of the Platreef mineralisation.

3. If the metasomatic fluids had any effects to the stratigraphy (the layered intrusions) of the Platreef itself.

After the petrography and geochemical data analysis, the findings and observations listed below were deduced. The findings are based on the stratigraphy of the Platreef; the ‘presumed’ metasomatic fluids from the granite footwall; and the effects caused after assimilation between the granite footwall and the Platreef lithologies. The Figure 5.3 is a schematic representation of the idea to explain and model the assimilation occurrence of the fluid-rock interaction between the Platreef and the floor rock. The findings in this study have shown that:

1. There is no clear lithological correlations between the two boreholes (MO009 and MO019), the position of similar lithologies on either borehole is very erratic and complex, and not consistent as well.

2. There is no chronological lithostratigraphic sequence in each borehole, from the base of the Platreef to the upper contact of the Platreef.

3. The fluid-rock effects have insignificant or no confirmed modifications to the Ni-Cu-PGE mineralisation under a granite floor rock, in contrast to when the floor rock is dolomite, the sulphides mineralisation was enhanced and transported by fluids (Harris and Chaumba, 2001).

4. As a result of the granite footwall being very low permeable and low hydrous mineral content, there was minimal fluid-rock interaction imprints during Footwall-Platreef assimilation into the floor rock in this area (Holwell, 2006's contribution).

5. Pegmatoidal feldspathic pyroxenites and melanorites are incorporated with foreign quartz-feldspar material from the footwall, as a result of contact metasomatic fluid transportation.

Particularly, the result of fluid-related-interaction of Platreef and the footwall rocks significantly varied the 'primary' stratigraphic succession of the Platreef. Holwell *et al.* (2005) and Holwell and McDonald (2005) mentioned that the post-emplacement fluid activity is also an effect on the variations in style of distribution of mineralisation regionally in the Platreef along the strike. Similar study was done by Mathez (1995) in the Merensky Reef. He also mentioned in his paper the work by Kelemen and colleagues (reference therein) who recognised that the Merensky Reef was modelled accordingly by magmatic metasomatism which was represented as the combined processes of assimilation and fractional crystallisation. Harris and Chaumba (2001) concluded that the rocks within and just above the Platreef were affected by fluid-rock interaction and the involvement of some external fluids. Another work by Pronost *et al.* (2008) interprets that the lack of documented correlation between PGE and sulphides content is probably from the post-crystallisation fluid-rock interaction.

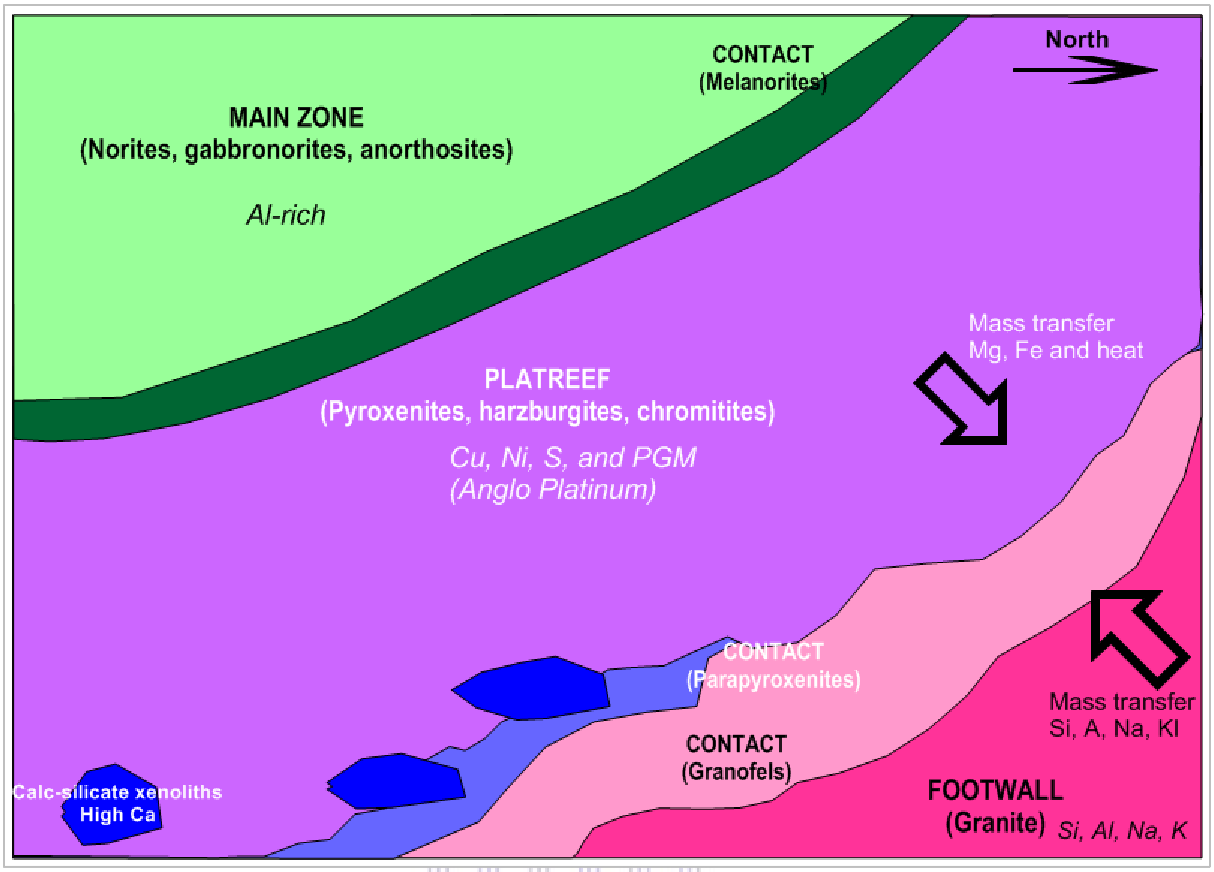


Figure 5.3. The schematic representation of the idea to explain the geological occurrences at the vicinity of the Main Zone, Platreef, Floor rock contacts. The figure imitates the mass transfer occurrences and alteration occurrences.

5.5. Summary and recommendations

The Platreef in the Northern Sector of the Northern Limb rests directly on the Archaean granite-gneiss floor. However, the emplacement of Platreef onto the floor rock had produced definite features at the bottom zone of the Platreef which have produced substantial rock units within the stratigraphy of the Platreef unit. Definite rock types have been categorised as hybrid rock types or product rocks. Kruger (2010) explained this occurrence as the mingling of mafic and felsic rocks which formed felsic patches onto the Platreef rocks. The effects of fluid-rock interaction with granite floor were very minimal and insignificant to have modified the primary mineralisation of the Platreef at Moordkopje, as a result of granitic rock being very less reactive as opposed to the dolomite in the southern parts. Holwell (2006) had similar conclusions on this regard.

The shortfalls and the gaps that remain unresolved even in this project are the stratigraphy of Platreef, and the position of the mineralisation that is related with the contact zones. The study on isotope geochemistry of Moordkopje Platreef rocks may be advantageous at improving the information presented in this project on stratigraphy. The mineralisation occurrence at Moordkopje has proved to be very insignificant to be mineable for economic benefits. However, the number of rocks analysed (11) for PGEs and Au in this project was not sufficient to quantify a representable mineralisation occurrence of Moordkopje for this PGE-occurrence farm where mineralisation is very low. It is recommended that a greater number of non-biased sample analysis for PGEs may draw an improved conclusion with regards to the mineralisation occurrence at Moordkopje. However, the effects of assimilation from the granite floor did not significantly enhance or degrade the primary mineralisation occurrence at Moordkopje as much as calc-silicates in the southern Platreef did. This study also recommends that magmatic mineralisation is targeted than the minimal mineralisation occurrence at the contact zone when mining at Moordkopje where the floor rock is granite.

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APPENDIX I

SAMPLING AND GEOCHEMISTRY ANALYTICAL DATA

A. Core logging data

		MO009	
SAMPLE #	DEPTH FROM	DEPTH TO	LITHOLOGY
1	120.14	120.33	K-feldspar/granite vein
2	179.675	179.93	Norite
3	305.08	305.27	Mottled anorthosite
4	317.26	317.415	Norite
5	407.34	407.51	K-feldspar/granite vein
6	431.12	431.28	Mottled anorthosite
7	568.12	568.305	Norite
8	637.29	637.51	Mottled anorthosite
9			
10	906.22	906.445	Leuconorite
11	956.33	956.54	Mottled anorthosite
12	1058.74	1058.985	Leuconorite
13	1127.23	1127.43	Norite
14	1150.675	1150.895	Mottled anorthosite
15	1243.66	1243.835	Norite
16	1357.345	1357.55	Anorthosite
17			
18	1552.485	1552.675	Norite
19	1668.47	1668.655	Norite
20	1700.23	1700.545	Pyroxenite
21	1724.37	1724.59	Mottled anorthosite
22	1837.89	1838.3	Norite
23	1846.37	1846.66	Leuconorite
24	1848.56	1848.73	Norite
25	1854.46	1854.635	Pyroxenite
26	1861.26	1861.45	Melanorite
27	1865.53	1865.735	Pyroxenite
28	1867.26	1867.395	Pyroxenite
29	1868.74	1868.975	Serpentinised pyroxenite
30	1871.06	1871.24	Harzburgite
31	1874.29	1974.51	Pyroxenite
32	1874.79	1874.925	Feldspathic pyroxenite
33	1878.785	1878.985	Leuconorite
34	1890.53	1890.695	Leuconorite
35			
36	1907.07	1907.26	Leuconorite
37	1919.155	1919.34	Norite
38	1928.13	1928.31	Norite
39	1930.42	1930.555	Granofels
40	1935.25	1935.43	Leuconorite
41	1946.62	1946.85	Leuconorite
42	1960.58	1960.78	Leuconorite
43	1971.03	1971.2	Pyroxenite
44	1976.69	1976.85	Harzburgite
45	1979.25	1979.39	Leuconorite
46	1983.43	1983.59	Pyroxenite
47	1987.105	1987.245	Granite
48	1996.635	1996.835	Pyroxenite
49	2001.32	2001.52	Dolomite
50	2008.713	2008.88	Dolomite
51	2015.09	2015.44	Granite
52	2018.47	2018.66	Granite

		MO019	
SAMPLE #	DEPTH FROM	DEPTH TO	LITHOLOGY
1	23.995	24.22	Norite
2	41.76	41.95	Norite
3	106.71	106.85	Norite
4	229.44	229.58	Norite
5	261.45	261.67	Norite
6	378.73	378.92	Norite
7	398.41	398.59	Norite
8	446.16	446.39	Anorthosite+norite
9	519.37	519.56	Norite
10	543.73	543.87	Norite
11	598.81	598.94	Norite
12	731.7	731.88	Leuconorite
13	796.56	796.72	Norite
14	865.09	865.27	Leuconorite
15	955.72	955.85	Norite
16	1009.63	1009.78	Leuconorite
17	1076.54	1076.76	Leuconorite
18	1107.62	1107.76	Leuconorite
19	1132.58	1132.76	Spotted & mottled anorthosite
20	1200.59	1200.69	Leuconorite
21	1234.44	1234.61	Leuconorite
22	1274.82	1275.09	Mottled anorthosite with epidote
23	1291.38	1291.92	Leuconorite
24	1313.7	1313.87	Leuconorite
25	1372.11	1372.31	Leuconorite
26	1435.76	1435.63	Leuconorite
27	1485.43	1485.6	Leuconorite
28	1527.43	1527.68	Leuconorite
29	1543.32	1543.61	Leuconorite
30	1573.37	1573.62	Leuconorite
31	1591.15	1591.3	Leuconorite
32	1605.54	1605.63	Feldspathic pegmatite vein
33	1614.13	1614.27	Norite
34	1615.81	1615.97	Pyroxenite
35	1639.47	1639.56	Mottled anorthosite
36	1666.64	1666.85	
37	1706.31	1706.55	Leuconorite
38	1717.02	1717.19	Feldspathic pyroxenite
39	1716.23	1716.47	Feldspathic pyroxenite
40	1727.53	1727.7	Pyroxenite
41	1734.38	1734.59	Feldspathic pyroxenite
42	1742.38	1742.52	Pyroxenite
43	1746.32	1746.5	Pyroxenite
44	1750.52	1750.67	Pegmatoidal feldspathic pyroxenite
45	1752.73	1752.9	Pyroxenite
46	1757.33	1757.53	Feldspathic pyroxenite
47	1763.73	1763.84	Chromitite
48	1764.53	1764.68	Feldspathic pyroxenite
49	1765.45	1765.65	Feldspathic pyroxenite
49B	1772.5	1772.72	Feldspathic pyroxenite
50	1778.18	1778.4	Feldspathic pyroxenite
51	1786.64	1786.84	Feldspathic pyroxenite
52	1788.2		Granofels
53	1812.85	1813.04	Feldspathic pyroxenite
54	1831.22	1831.41	Feldspathic pyroxenite
55	1845.64	1845.89	Feldspathic pyroxenite
56	1847.67	1847.79	Feldspathic pyroxenite
57	1865.5	1865.67	Feldspathic pyroxenite
58	1868.21	1868.37	Reaction zone of granofels

B. Geochemistry data

Sample	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI	SUM	SO_3	Ba	Ce	Co	Cr	Cu	Mo	Nb	Ni	Pb	Rb	Sr	Th	U	V	Y	Zn	Zr
MO009-2	46.79	20.93	6.67	0.12	7.57	13.23	1.93	0.36	0.16	0.02	2.01	99.81	0.00	112.04	47.37	30.35	59.62	115.34	0.82	4.12	153.80	5.54	24.86	267.68	2.39	6.61	81.28	8.57	89.02	56.57
MO009-6	46.40	29.48	2.10	0.02	1.33	14.89	2.58	0.88	0.18	0.07	1.92	99.83	0.00	139.96	0.02	3.05	16.68	68.34	0.81	0.78	13.37	1.86	54.56	394.12	2.39	28.94	22.51	15.29	57.50	72.01
MO009-7	46.01	22.66	5.34	0.09	5.66	14.98	2.00	0.29	0.15	0.02	2.72	99.93	0.00	104.94	20.87	15.26	58.35	75.77	0.80	3.24	136.78	1.26	22.49	267.49	2.39	0.00	71.06	13.30	60.09	55.72
MO009-10	46.43	20.86	6.51	0.11	7.33	12.96	1.79	0.62	0.21	0.04	3.02	99.88	0.00	101.43	0.02	29.84	65.03	112.73	0.82	0.10	179.38	1.62	36.40	257.83	2.39	0.00	70.57	14.05	81.33	65.30
MO009-15	46.69	18.43	7.43	0.13	8.69	14.78	1.54	0.36	0.23	0.04	1.60	99.92	0.00	75.65	0.02	42.16	215.00	118.22	0.85	0.22	224.20	5.85	17.34	192.32	2.39	0.00	114.14	17.76	88.92	58.43
MO009-16	46.73	21.35	5.81	0.08	6.27	15.19	1.74	0.39	0.17	0.03	2.08	99.83	0.00	93.24	0.02	18.17	86.82	103.34	1.11	0.10	130.02	1.48	26.84	254.03	2.39	0.00	67.45	16.09	74.12	143.62
MO009-21	46.54	25.97	4.33	0.06	3.34	15.58	2.00	0.53	0.23	0.10	1.21	99.87	0.00	91.76	0.02	23.43	94.45	82.36	0.86	4.78	73.94	8.33	28.67	281.20	2.39	13.06	71.31	14.42	51.45	66.24
MO009-23	46.53	19.29	7.28	0.13	10.72	12.28	1.52	0.26	0.15	0.02	1.82	100.00	0.00	85.30	1.16	37.39	865.17	110.92	0.78	3.79	328.27	7.01	18.84	184.24	2.39	0.00	74.92	12.80	66.34	46.60
MO009-25	47.44	8.80	12.66	0.24	20.03	8.25	0.81	0.22	0.19	0.02	1.30	99.95	0.01	52.89	0.02	71.87	2,031.42	167.95	0.79	0.10	625.09	1.26	16.84	87.72	2.39	0.00	144.45	11.53	134.37	41.95
MO009-26	52.97	8.40	11.07	0.20	20.11	6.28	0.76	0.13	0.16	0.01	-0.14	99.95	0.05	52.00	0.02	77.00	1,941.00	50.00		3.00	540.00	2.00	9.00	78.00	2.39	0.00	124.00	4.00	77.00	22.00
MO009-28	46.65	10.56	10.67	0.21	21.59	7.55	0.71	0.11	0.13	0.01	1.80	99.99	0.00	70.37	0.02	77.22	1,885.58	191.93	0.79	2.02	700.29	1.26	16.88	100.49	2.39	0.00	105.24	6.81	142.63	38.89
MO009-29	46.62	2.09	14.71	0.25	30.19	2.88	0.03	0.01	0.12	0.01	2.76	99.66	0.40	44.10	26.17	148.10	3,898.57	1,784.11	0.78	0.42	4,987.19	0.08	9.16	26.35	2.39	0.00	104.74	7.19	103.91	31.92
MO009-30	43.59	6.44	14.44	0.24	25.43	2.96	0.01	0.02	0.10	0.00	6.34	99.58	0.20	16.00	0.02	54.00	1,849.00	424.00		3.00	768.00	2.00	8.00	11.00	2.39	0.00	64.00	1.00	60.00	17.00
MO009-31	52.51	6.95	10.78	0.20	24.32	4.46	0.33	0.07	0.10	0.01	-0.20	99.54	0.11	40.00	0.02	80.00	3,248.00	196.00		3.00	768.00	5.00	6.00	62.00	2.39	0.00	97.00	2.00	73.00	16.00
MO009-32	52.02	8.08	10.28	0.18	21.64	5.13	0.52	0.12	0.14	0.01	0.93	99.05	0.35	45.00	0.02	78.00	3,266.00	498.00		2.00	1,109.00	4.00	8.00	67.00	2.39	0.00	110.00	2.00	72.00	19.00
MO009-36	47.19	22.61	5.69	0.10	6.39	15.17	2.04	0.16	0.11	0.01	0.51	99.98	0.00	94.37	1.46	26.56	380.88	138.45	0.78	0.10	168.85	1.26	18.51	259.30	2.39	0.00	70.83	6.32	91.61	47.42
MO009-37	46.23	20.29	6.01	0.13	8.17	13.85	1.39	0.53	0.13	0.01	3.03	99.76	0.00	108.54	0.02	38.31	248.88	87.38	0.78	0.10	147.90	1.26	40.21	240.98	2.39	2.78	62.49	10.33	111.69	46.50
MO009-39	50.53	23.41	5.43	0.11	4.00	12.15	3.27	0.24	0.08	0.01	0.70	99.91	0.02	157.22	0.02	37.33	106.85	95.71	0.77	4.53	106.08	6.87	19.55	398.00	2.39	8.10	55.32	10.99	65.38	48.54
MO009-40	47.66	24.01	5.55	0.08	5.89	13.50	1.91	0.43	0.13	0.02	0.80	99.99	0.00	124.89	0.94	22.82	365.93	93.47	0.79	2.39	187.21	1.26	28.57	239.90	2.39	0.00	55.65	10.16	57.79	52.04
MO009-41	48.55	23.40	4.79	0.08	6.34	13.14	2.32	0.32	0.15	0.03	0.90	100.01	0.00	107.65	0.02	22.66	339.85	142.19	0.80	0.40	179.84	1.26	25.77	285.76	2.39	4.71	75.01	11.44	113.52	58.78
MO009-42	48.20	22.19	5.18	0.09	6.89	13.54	2.09	0.26	0.15	0.02	1.42	100.04	0.00	107.74	0.02	20.40	393.77	92.90	0.79	0.10	191.91	2.45	22.09	258.62	2.39	0.00	85.33	10.93	49.72	55.19
MO009-43	52.54	6.76	11.27	0.20	21.19	5.80	0.57	0.16	0.21	0.02	0.64	99.35	0.38	58.00	0.02	89.00	3,129.00	411.00		2.00	1,319.00	8.00	9.00	68.00	2.39	3	127.00	3.00	71.00	24.00
MO009-44	49.14	0.83	14.12	0.07	29.23	1.14	0.01	0.00	0.08	0.00	5.36	99.98	0.56	47.84	0.02	166.05	1,378.71	616.15	0.77	2.78	2,959.47	2.68	8.35	23.65	2.39	0.00	42.66	4.62	110.06	35.10
MO009-45	59.16	19.61	3.15	0.06	5.21	7.98	3.08	0.55	0.05	0.01	0.50	99.37	0.01	150.00	0.02	24.00	795.00	31.00		2.00	147.00	12.00	17.00	215.00	2.39	0.00	37.00	4.00	29.00	15.00
MO009-46	55.66	11.53	10.77	0.18	11.54	6.74	2.30	0.45	0.39	0.05	0.11	99.71	0.13	201.00	0.02	65.00	925.00	82.00		3.00	321.00	9.00	15.00	136.00	2.39	0.00	150.00	14.00	75.00	75.00
MO009-47	65.42	19.13	1.04	0.00	0.36	4.02	5.42	2.91	0.08	0.03	0.84	99.24	0.07	641.00	8.00	5.00	171.00	64.00		1.00	71.00	23.00	77.00	596.00	2.39	7	22.00	6.00	19.00	26.00
MO009-48	47.75	8.52	11.82	0.23	22.07	6.58	0.86	0.11	0.16	0.01	1.90	100.01	0.01	61.15	0.02	72.30	2,749.97	188.74	0.79	2.25	712.64	1.67	12.87	93.87	2.39	0.00	111.70	10.53	123.80	40.02
MO009-50	50.73	17.67	9.30	0.15	6.41	10.85	2.41	0.84	0.33	0.09	1.21	99.99	0.01	66.59	0.02	36.17	273.21	113.27	0.85	5.46	176.92	8.40	35.00	159.87	2.39	0.00	139.04	20.57	99.97	58.70
MO019-3	46.31	18.68	6.27	0.13	8.36	15.33	1.81	0.19	0.15	0.01	2.78	100.01	0.00	85.18	3.58	34.14	59.46	91.13	0.77	3.15	190.64	12.61	15.87	220.60	14.37	0.02	123.05	10.23	60.38	50.81
MO019-5	47.37	20.79	5.81	0.11	7.01	15.17	1.86	0.26	0.16	0.03	1.45	100.01	0.00	90.30	0.20	23.90	40.22	57.53	0.78	2.37	165.51	0.28	18.94	217.49	14.36	8.19	93.06	10.28	49.81	49.78
MO019-11	47.01	20.41	6.08	0.12	7.70	14.35	1.75	0.23	0.15	0.02	2.19	100.01	0.00	94.59	0.20	24.95	88.09	99.09	0.78	4.94	188.96	3.24	18.89	211.13	14.36	0.05	96.21	12.30	97.18	49.37
MO019-14	47.89	23.46	5.64	0.09	6.40	13.23	1.96	0.43	0.17	0.02	0.71	100.01	0.00	97.59	0.20	25.11	58.03	82.51	0.80	9.46	159.03	14.45	26.45	243.48	14.36	7.91	65.12	14.22	66.15	57.77
MO019-17	45.45	25.37	4.62	0.07	4.24	16.25	1.72	0.33	0.16	0.04	1.76	100.01	0.00	90.17	0.20	17.08	78.70	86.51	0.82	3.29	109.60	16.90	23.71	263.43	14.36	1.81	61.59	12.94	52.70	61.14
MO019-19	47.00	25.02	4.25	0.05	4.15	14.40	1.99	0.57	0.19	0.01	2.36	100.00	0.00	107.73	3.58	13.48	40.37	126.76	0.80	1.68	136.27	6.04	37.71	274.72	14.37	11.37	49.34	12.46	96.13	65.08
MO019-25	46.79	20.47	7.37	0.13	7.43	14.90	1.52	0.39	0.20	0.03	0.77	100.01	0.00	76.25	17.37	30.65	283.55	103.15	0.83	4.08	195.29	6.99	17.41	181.25	14.36	0.05	97.71	13.72	82.67	54.31
MO019-34	50.52	6.60	20.43	0.37	12.56	6.28	0.86	0.41	0.21	0.10	1.61	99.94	0.06	104.99	41.41	80.82	743.18	235.62	0.96	2.36	441.03	0.03	12.40	79.95	14.37	0.02	143.54	21.07	197.69	90.10
MO019-35	47.95	24.00	4.92	0.08	4.18	14.02	2.18	0.64	0.17	0.05	1.82	100.00	0.00	143.89	0.20	9.11	132.30	85.34	0.81	3.39	106.51	3.88	37.38	245.26	14.36	24.00	73.55	14.24	77.29	57.19
MO019-37	45.15	22.10	5.54	0.10	8.15	13.70	1.33	0.96	0.15	0.04	2.80	100.01	0.00	141.76	11.69	34.74	343.99	101.95	0.77	2.90	257.76	3.31	54.98	213.68	14.36	12.41	68.62	14.23	73.07	47.61
MO019-38	45.93	4.45	13.07	0.25	27.72	4.25	0.23	0.06	0.13	0.01	3.88	99.97	0.03	48.46	3.58	91.44	2,823.77	454.07	0.76	3.32	1,583.91	3.40	13.15	65.85	14.37	0.02	119.67	9.16	117.94	35.60
MO019-40	42.87	10.21	7.44	0.17	16.27	11.83	1.01	0.39	0.14	0.01	9.67	100.01	0.00	92.83	0.09	49.06	784.21	91.04	0.76	4.98	487.16	6.54	55.60	168.47	14.36	36.55	98.62	21.06	85.84	45.06
MO019-41	40.11	8.57	9.90	0.23	23.81	10.32	0.66	0.24	0.15	0.01	6.02	100.01	0.00	85.75	3.58	63.74	1,167.35	95.42	0.78	0.80	579.48	7.83	21.00	35.21	14.37	0.02	129.77	14.72	102.27	37.92
MO019-42	41.76	4.81	14.23	0.17	25.09	7.67	0.03	0.00	0.28	0.01	5.98	100.02	0.00	17.19	0.20	105.90	1,556.68	209.45	0.78	0.39	1,168.91	3.26	11.96	30.29	14.36	0.05	145.43	14.05	130.62	29.22
MO019-44	58.98	8.52	9.49	0.12	12.82	1.24	1.50	0.61	0.11	0.16	6.45	100.01	0.00	125.32	131.59	28.06	96.99	78.90	1.04	7.55	274.33	16.65	65.13	100.69	33.86	29.59	21.00	114.01	98.53	110.36
MO019-45	48.32	4.59	15.27	0.20	22.13	5.75	0.12	0.04	0.29	0.01	3.06	99.78	0.21	35.00	0.02	102.00	1,924.00	57.00		2.00	1,497.00	0.04	5.00	15.00	2.39	0.00	119.00	8.00	139.00	22.00
MO019-46	48.19	7.76	12.02	0.22	21.40	8.06	0.91	0.16	0.18	0.01	1.09	100.00	0.00	43.97	6.81	85.86	3,256.52	138.42	0.79	5.07	608.53	3.14	15.83	98.53	14.37	0.02	130.05	9.35	102.08	42.35
MO019-47	42.77	6.64	10.23	0.19	23.29	12.09	0.22	0.24	0.23	0.02	4.08	100.00	0.00	35.99	0.20	60.47	1,769.95	94.70	0.80	3.27	695.93	0.28	24.44	98.27	14.36	0.05	83.31	9.69	103.24	48.14
MO019-49	49.07	7.11	12.70	0.22	22.35	4.82	0.71	0.35	0.21	0.02	2.44	100.00	0.00	61.44	0.20	75.48	2,270.30	139.03	0.79	2.36	1,005.72	13.75	27.15	95.19	14.36	1.01	112.65	12.65	138.02	42.27
MO019-51	50.25	16.51	8.02	0.17	8.98	10.78	2.40	0.51	0.10	0.01	2.26	99.99	0.01	178.37	40.28	36.01	445.93	93.78	0.76	6.94	248.65	0.28	28.35	168.00	14.36	10.69	105.32	18.80	68.07	40.90
MO019-52	51.55	16.31	6.82	0.16	8.99	10.32	2.85	0.56	0.08	0.01	2.33	100.00	0.00	248.57	10.98	44.41	546.45	117.09	0.76	2.90	321.28	1.77	26.39	283.24	14.37	0.38	64.24	28.46	80.37	50.12
MO019-54	54.48	8.71	11.96	0.18	11.76	9.85	1.89	0.47	0.64	0.07	-0.11	99.91	0.02	66.00	0.02	60.00	1,028.00	40.00		4.00	243.00	12.00	33.00	224.00	2.39	0.00	204.00	16.00	78.00	36.00

C. Pd-Pt analytical data

Samples	n	Pd (ppb)	Pt (ppb)
MO009-25	1	20.47	61.41
MO009-28	2	88.89	113.13
MO009-29	3	5127.79	5196.75
MO009-44	4	1918.53	1099.80
MO009-48	5	16.36	28.63
MO009-50	6		12.18
MO019-34	7	53.00	45.00
MO019-38	8	468.00	416.00
MO019-41	9		8.00
MO019-46	10	101.00	178.00
MO019-47	11	12.00	8.00

APPENDIX II

NORMALISED DATA BY PRIMITIVE MANTLE (SUN AND MCDONOUGH, 1989)

A. Melanorites

	MOO09-26	MOO09-31	MOO09-32	MOO09-43
Cs				
Rb	15	10	13.33	15
Ba	7.88	6.06	6.82	8.79
Th				
U				150
Nb	4.56	4.56	3.04	3.04
Ta				
La				
Ce	0.01	0.01	0.01	0.01
Pb	13.33	33.33	26.67	53.33
Pr				
Sr	3.92	3.12	3.37	3.42
P	0.48	0.48	0.48	0.97
Nd				
Zr	2.1	1.52	1.81	2.29
Sm				
Eu				
Ti	0.8	0.5	0.7	1.04
Dy				
Y	0.93	0.47	0.47	0.7
Yb				
Lu				

B. Feldspathic pyroxenites

	MOO09-25	MOO09-28	MOO09-48	MO019-45	MO019-46	MO019-49
Cs						
Rb	28.06	28.14	21.44	8.33	26.38	45.24
Ba	8.01	10.66	9.26	5.3	6.66	9.31
Th						
U	0.16	0.16	0.16		0.9	50.4
Nb	0.15	3.06	3.42	3.04	7.7	3.59
Ta						
La						
Ce	0.01	0.01	0.01	0.01	4.07	0.12
Pb	8.37	8.37	11.13	0.27	20.91	91.65
Pr						
Sr	4.41	5.05	4.72	0.75	4.95	4.78
P	0.97	0.48	0.48	0.48	0.48	0.97
Nd						
Zr	4	3.7	3.81	2.1	4.03	4.03
Sm						
Eu						
Ti	0.95	0.65	0.8	1.44	0.9	1.04
Dy						
Y	2.68	1.58	2.45	1.86	2.17	2.94
Yb						
Lu						

C. Harzburgites

	MOO09-29	MOO09-30	MOO09-44	MO019-38
Cs				
Rb	15.26	13.33	13.92	21.91
Ba	6.68	2.42	7.25	7.34
Th				
U	0.16		0.16	0.9
Nb	0.63	4.56	4.23	5.05
Ta				
La				
Ce	15.62	0.01	0.01	2.14
Pb	0.56	13.33	17.83	22.64
Pr				
Sr	1.32	0.55	1.19	3.31
P	0.48			0.48
Nd				
Zr	3.04	1.62	3.34	3.39
Sm				
Eu				
Ti	0.6	0.5	0.4	0.65
Dy				
Y	1.67	0.23	1.07	2.13
Yb				
Lu				

D. Parapyroxenites

	MO019-41	MO019-42	MO019-47
Cs			
Rb	34.99	19.93	40.73
Ba	12.99	2.6	5.45
Th			
U	0.9	2.4	2.4
Nb	1.21	0.59	4.96
Ta			
La			
Ce	2.14	0.12	0.12
Pb	52.17	21.73	1.89
Pr			
Sr	1.77	1.52	4.94
P	0.48	0.48	0.97
Nd			
Zr	3.61	2.78	4.58
Sm			
Eu			
Ti	0.75	1.39	1.14
Dy			
Y	3.42	3.27	2.25
Yb			
Lu			

E. Pegmatoidal feldspathic pyroxenites

	MOO09-46	MO019-34	MO019-44	MO019-54
Cs				
Rb	25	20.66	108.55	55
Ba	30.45	15.91	18.99	10
Th				
U		0.9	1479.45	
Nb	4.56	3.59	11.47	6.08
Ta				
La				
Ce	0.01	24.72	78.56	0.01
Pb	60	0.17	111.02	80
Pr				
Sr	6.83	4.02	5.06	11.26
P	2.42	4.85	7.76	3.39
Nd				
Zr	7.14	8.58	10.51	3.43
Sm				
Eu				
Ti	1.94	1.04	0.55	3.18
Dy				
Y	3.26	4.9	26.51	3.72
Yb				
Lu				

APPENDIX III

MASS TRANSFER DATA ANALYSIS

A. Feldspathic pyroxenite vs Melanorites

	Feldspathic pyroxenites	Melanorites					
	Original rock	Altered rock	Slope data point	G/L rel.(LQ)	G/L rel.(avg)	G/L wt%/ppm(LQ)	G/L wt%/ppm(avg)
SiO2	47.90	52.51	1.10	0.18	0.26	8.53	12.27
Al2O3	7.89	7.55	0.96	0.03	0.10	0.22	0.76
Fe2O3	12.52	10.85	0.87	-0.07	-0.01	-0.86	-0.09
MnO	0.22	0.20	0.89	-0.05	0.02	-0.01	0.00
MgO	21.59	21.82	1.01	0.09	0.16	1.85	3.40
CaO	6.84	5.42	0.79	-0.15	-0.09	-1.01	-0.63
Na2O	0.69	0.55	0.79	-0.15	-0.09	-0.10	-0.06
K2O	0.16	0.12	0.73	-0.22	-0.17	-0.04	-0.03
TiO2	0.19	0.15	0.79	-0.15	-0.10	-0.03	-0.02
P2O5	0.01	0.01	0.94	0.01	0.07	0.00	0.00