# PLATINUM-GROUP MINERAL ASSEMBLAGES IN THE PLATREEF ON TWEEFONTEIN, NORTHERN BUSHVELD COMPLEX, SOUTH AFRICA

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

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### DECLARATION

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

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(Signature of candidate) 6<sup>th</sup> day of September 2012

## ABSTRACT

The Platreef occurs at the base of the Northern Limb of the Bushveld Complex and is variably mineralised with PGE, Cu, and Ni. The Platreef varies in thickness from a few meters to a few hundred meters and rests on progressively older sediments of the Transvaal Supergroup and Archaean granite basement northwards. Recent studies have highlighted the importance of magmatic processes, contamination of the magma by footwall rocks and syn- and post metasomatic fluid activity on the observed mineralisation.

Along the Platreef strike, the PGE grade profiles are generally top-loaded from Overysel to Tweefontein North and more variable and bottom loaded from Tweefontein Hill southwards emphasizing the importance of the change in mineralisation style at Tweefontein in relation to the whole Platreef. This study presents the first significant PGM data on the Tweefontein farm, including ten boreholes along strike, providing insight into the distinctly different PGE mineralisation styles observed. Samples were selected based on assay data, varying rock types, stratigraphic position and proximity to geological features. The selected samples were investigated using petrography, geochemistry and the automated SEM techniques of QEMSCAN and MLA. Over 9000 PGM were analysed forming one of the most comprehensive PGM studies on the Platreef to date.

The lowermost footwall intersected along the Tweefontein strike is banded ironstone of the Penge Formation. This is overlain by a metasedimentary footwall package, of variable thickness, derived from the shales and dolomites of the Duitschland Formation. Iron-rich, recrystallised, noritic sills occur at the base of the Platreef and are thought to represent sills which intruded prior to the emplacement of the Platreef. A pre- and possibly syn-Bushveld structural control resulted in irregular floor topography defined by a topographic footwall high in the central Tweefontein area and topographic depressions at Tweefontein North and Tweefontein Hill. The depression areas at Tweefontein are similar to the footwall basins at Turfspruit to the south, in which the Platreef is more lithologically complex compared to the footwall high areas. The footwall basins at Tweefontein and Turfspruit contain basal massive and submassive sulphides, which may not necessarily carry significant PGE grade.

The Platreef lithologies at Tweefontein are composed of pyroxenites and norites with minor harzburgitic lithologies and contain numerous cross-cutting granitic veins. Xenoliths/interlayers of metamorphosed Duitschland lithologies occur primarily near the

base of the Platreef, but also in the middle and upper Platreef sequence reflecting roof pendants. Unlike the Platreef on the farms adjacent to Tweefontein, the Platreef and footwall lithologies are relatively unaltered, but localised serpentinisation and chloritisation occur within harzburgitic lithologies and metasedimentary interlayers.

Based on the stratigraphy and geochemical characteristics, the Platreef at Tweefontein can be subdivided into the upper and lower Platreef. The upper Platreef subdivision occurs in the top 20-40 m of the sequence and is defined by higher Mg#, Cr, Cr (ppm)/MgO and Pt/Pd values compared to the lower Platreef. In addition, the majority of the grade and base metal sulphide (BMS) content is enriched in the upper versus the lower Platreef, particularly for the northern and central parts of Tweefontein. The upper and lower Platreef may have been derived from different magma sources based on the "R Factor" concept proposed by Campbell and Naldrett in 1979 whereby the abundance of the PGE relative to the BMS content is linked to the proportion of magma with which the sulphide ore equilibrated (Naldrett, 2005b). Previous detailed geochemical studies from Tweefontein Hill southwards highlighted compositional breaks in the Platreef sequence thought to represent distinct silllike intrusions (Hutchinson and Kinnaird, 2005; Kinnaird, 2005; Manyeruke et al., 2005; Nyama et al., 2006). They reported a more primitive sill at the top of the Platreef, which correlates to the upper Platreef at Tweefontein. The lower Platreef is therefore likely to represent a different sill intrusion. A relatively homogenous pyroxenitic package characterises the upper Platreef, although a more heterogeneous package is observed close to and at Tweefontein Hill. At Tweefontein North, the base of the upper Platreef is often marked by a chromitiferous package comprising a pegmatoidal feldspathic pyroxenite unit, up to 6 m thick, capped by a chromitite layer. Due to similar stratigraphy and high PGE grades, this distinct horizon has been compared to the Merensky Reef found elsewhere in the Bushveld Complex.

The predominant base metal sulphides (BMS) in the Platreef at Tweefontein are pyrrhotite, pentlandite, chalcopyrite with minor pyrite aligned with that found elsewhere along the Platreef strike. There is an increase in BMS content, primarily pyrrhotite, towards the base of the Platreef with massive and submassive sulphide development near the base and in the footwall, particularly at Tweefontein Hill. Sulphur isotopes and detailed mineralogical studies at Turfspruit have shown that the addition of S, As and Sb into the magma from the Duitschland footwall triggered the development of a PGE-poor sulphide liquid which was then able to mix, modify and dilute the magmatic sulphides (Hutchinson and McDonald, 2008).

Due to the similarity in footwall between Turfspruit and Tweefontein, these proposed processes help to explain the increase in BMS towards the base and the development of basal massive and submassive sulphides, which are not necessarily associated with significant PGE grade.

At Tweefontein North, the processes dominating the top-loaded PGE mineralisation were primarily magmatic. The PGM assemblage, hosted by base metal sulphides and magmatic silicates, is dominated by Pt-and Pd-bismuthides and -tellurides with minor PGE-sulphides and Pt-arsenides. PGE-sulphides occur in the Platreef where the chromitiferous horizon is developed, which may indicate an environment low in volatile activity and one of the most primary mineralisation styles along the Platreef strike. The footwall high, which separates the depressions at Tweefontein North and Tweefontein Hill may have kept the Platreef at Tweefontein North relatively protected from additional processes affecting Tweefontein Hill.

In contrast, assimilation of the Duitschland footwall is thought to play a key role in the development of the variable but predominantly bottom-loaded PGE mineralisation at Tweefontein Hill. The PGM assemblage is Pd-dominant characterised by Sb-, As- and Bibearing PGM, reflecting the incorporation of Sb, As and Bi from the Duitschland footwall. The association of the PGE mineralisation with the extensive basal sulphide development implies that the mineralisation at Tweefontein Hill probably occurred due to the gravitational settling of a sulphide liquid containing a mix of sedimentary and PGE-hosting magmatic components.

Due to a significant PGM-BMS association in the mineralised footwall and metasedimentary interlayers/xenoliths, a downward migrating sulphide melt is believed to be the main mechanism responsible for the redistribution of PGE, predominantly Pd, into the mineralised metasedimentary lithologies.

Finally, the Platreef and footwall lithologies may be locally modified by late-stage felsic and hydrothermal fluids to form bismuthide- and arsenide-dominant PGM assemblages, primarily hosted in quartz and serpentine respectively.

This study shows the PGM and sulphide mineralisation at Tweefontein to be multifaceted, involving magmatic processes, assimilation of the Duitchland footwall into the Platreef magma and late-stage hydrothermal and felsic fluid activity. Footwall composition and irregular floor topography, resulting in depression areas at Tweefontein North and Tweefontein Hill, are believed to play a key role in what processes become significant along the Tweefontein strike. This research represents a significant contribution to the

understanding of the distinctly different PGE mineralisation styles at Tweefontein and allows for a complete comparison of the Platreef PGE mineralisation from Overysel to Turfspruit.

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# CHAPTER 1 INTRODUCTION

#### 1.1. PLATINUM-GROUP ELEMENT DEPOSITS

The Platinum-group elements (PGE) namely, ruthenium, rhodium, palladium, osmium, iridium and platinum are rare in the earth's crust with economic concentrations primarily occurring in mafic layered igneous intrusions. The Rustenburg Layered Suite of the Bushveld Complex is the world's largest layered intrusion (Vermaak, 1976) and is host to at least 75 % and 50 % of the world's platinum and palladium resources respectively (Cawthorn, 1999). Other layered intrusions contributing to economic PGE concentrations are the Great Dyke in Zimbabwe and the Stillwater Complex in the USA (Lee, 1996). Although PGE are produced as by-products during the treatment of large magmatic Ni-Cu sulphide deposits, these deposits are responsible for considerable PGE resources, predominantly Pd, of which the Noril'sk deposits in Russia and the Sudbury deposit in Canada are the largest contributors. In 2010, the largest platinum and palladium producers were South Africa at ~76 % Pt and ~35 % Pd and Russia at ~14 % Pt and ~51 % Pd (Butler, 2011).

#### 1.2 THE BUSHVELD COMPLEX

The Bushveld Complex is located in the north-eastern part of South Africa and has an aerial extent of 65 000 km<sup>2</sup> (Cawthorn, 1999). It intruded ~2060 Ma (Walraven *et al.*, 1990) into the Pretoria Group of the Transvaal Supergroup, except in part of the northern limb, where the floor rocks constitute Archaean granite basement (White, 1994). The Bushveld Complex is divided into four lithological subdivisions based on the variety of igneous rock compositions observed from ultrabasic to acidic (Schweitzer *et al.*, 1997). These are the intrusive Rustenburg Layered Suite, Rashoop Granophyre Suite, the extrusive Rooiberg Group and Lebowa Granite Suite. The extrusion of the Rooiberg Group, the intrusion of the Rashoop Granophyre Suite and the economically significant Rustenburg Layered Suite are thought to have occurred concurrently closely followed by the Lebowa Granite Suite (Schweitzer *et al.*, 1997).

Currently, the Bushveld Complex is exposed as four lobes, observed in Figure 1.1, namely the western, far western, northern and eastern limbs (Eales and Cawthorn, 1996). There is a fifth unexposed lobe called the south-eastern Bethal limb, which was identified using gravity highs and borehole core information from Buchanan (1975). These separate lobes

dip in towards each other, giving the Bushveld Complex an elongate-basin shape, with a maximum thickness of approximately 13 km (Eales and Cawthorn, 1996). The eastern and western limbs show strong similarities, including the positioning of the platiniferous Merensky Reef and the UG-2 chromitite layer (Eales and Cawthorn, 1996; Barnes and Maier, 2002). Further geophysical evidence led Cawthorn and Webb (2001) to propose that the eastern and western limbs were connected for most of the evolution of the Bushveld Complex.



Figure 1.1. Geology of the Bushveld complex (Cawthorn et al., 2002).

#### 1.2.1 Rustenburg Layered Suite (RLS)

The magma forming the 7-8 km thick RLS was thought to be injected as a series of magma pulses, giving rise to the laterally extensive layering of these rocks as well as their cyclicity (Eales and Cawthorn, 1996). This mafic layered sequence can be divided into five zones based on the dominant cumulus phase present (Hall, 1932). These are, from the base upward, the Marginal (MZN), Lower (LZ), Critical (CZ), Main (MZ), and Upper Zones (UZ). Figure 1.2 presents the generalised RLS stratigraphic sections for the western, eastern and northern limbs. The zones of the Bushveld are not equally laterally extensive and show

lithological and mineralogical variations vertically and along strike (Eales and Cawthorn, 1996).

The stratigraphy of the Bushveld Complex starts with the complex, multi-intrusive Marginal Zone (MZN), composed of heterogeneous noritic rocks between 0 to 800 m in thickness (Barnes and Maier, 2002). The overlying Lower Zone (LZ) comprises pyroxenites and harzburgites, with cyclic units present in some areas (Cameron, 1978). The variable thickness of the LZ reaches 1584 m in the Olifants trough of the eastern limb of the Bushveld Complex (Cameron, 1978). The LZ is poorly developed in the northern limb and is present as satellite bodies (van der Merwe 1978). The transition from the LZ to the overlying Critical Zone (CZ) is defined by the termination of significant olivine (Teigler *et al.*, 1992).

The CZ, composed of alternating layers of chromitite, pyroxenite, norites and anorthosites, can be subdivided into the lower ( $C_LZ$ ) and the upper ( $C_UZ$ ) CZ. The  $C_LZ$  is composed of a thick succession of pyroxenitic cumulates, while the  $C_UZ$  is composed of norite and anorthosite cumulates (Eales and Cawthorn, 1996). The CZ thickness of 930 m was proposed by Mitchell (1990) for the western Bushveld Complex. The CZ is host to chromitite layers termed Lower Group (LG) 1 to 7, Middle Group (MG) 1 to 4 and Upper Group (UG) 1 and 2. UG-3 is observed, but only in the eastern Bushveld (Eales and Cawthorn, 1996). The  $C_UZ$  starts with the appearance of cumulus plagioclase, usually above the MG-2 chromitite layer (Barnes and Maier, 2002). The PGE-bearing layers of the Merensky Reef and UG-2 chromitite layer occur in the  $C_UZ$  between the UG-1 and the Main Zone (MZ) in the western and eastern limbs of the Bushveld Complex. The northern limb is host to the Platreef, which occurs below the MZ, thought to represent the Merensky reef of the CZ (e.g. Wagner, 1929, Buchanan *et al.*, 1981; White, 1994). The CZ-MZ boundary is critically accepted as being at the top of the giant mottled anorthosite unit (Eales and Cawthorn, 1996).

The MZ is made up of norites and gabbronorites and reaches a thickness of 3940 m in the Roosenekal area (von Gruenewaldt, 1973). The layering of the MZ is poor compared to the CZ. Mitchell (1990) suggested that the relatively poor layering in the MZ was due to changes in magma composition and frequency of magma influxes. There is a major change in the mineral compositional trends close to a marker horizon termed the Pyroxenite Marker (Figure 1.2) situated in the upper part of the MZ. It has been suggested that this horizon should mark the base of Upper Zone (UZ), but it is critically accepted that cumulus magnetite defines the base of the UZ (Eales and Cawthorn, 1996) even though there is no

break in the mineral compositional trends at this depth (von Gruenewaldt, 1973; Molyneux 1974).

The UZ is primarily composed of anorthosites and leucogabbros (Eales and Cawthorn, 1996) and hosts numerous magnetite layers. Up to 25 magnetite layers have been found on the eastern limb of the Bushveld Complex (Molyneux, 1974). A thickness of ~1800 m was noted for the UZ in the eastern Bushveld Complex (Molyneux, 1974). The main 2 m thick magnetite layer, which is found near the base of the Upper zone, is mined for its ~1.3 %  $V_2O_3$  content.



Figure 1.2. Generalised stratigraphic sections through the RLS from the Western, Eastern and Northern Limbs. (Barnes and Maier, 2002 after Cawthorn and Lee, 1998; White 1994).

#### 1.2.2 PGE Mineralisation in the Bushveld Complex

Three ore bodies host economic PGE mineralisation in the Bushveld Complex; these are the tabular Upper Group 2 (UG-2) chromitite and the Merensky Reef, present in the upper CZ of the eastern and western limbs, and the stratiform Platreef, occurring at the base of the northern limb.

The UG-2 occurs 15-400 m below the Merensky Reef generally thickening towards the east (Lee, 1996). The 0.4-2.5 m thick UG-2 (Schouwstra *et al.*, 2000) is usually bounded by feldspathic pyroxenite where a number of low grade chromitites occur in the hanging wall (Lee, 1996). The PGE grade distribution is usually bottom and top loaded containing a low amount of sulphides, generally constituting <0.1 % (Schouwstra *et al.*, 2000). The Merensky reef comprises either a feldspathic pyroxenite or pegmatoidal feldspathic pyroxenite layer bounded by a chromitite stringer/s. The PGE grade is primarily associated with the chromitite stringers. Generally, the footwall lithologies are anorthosites and norites and the hanging wall rocks are feldspathic pyroxenites. The thickness of the Merensky Reef varies from ~10 cm in the Impala mine area in the western limb to ~14 m at Brits (Viljoen, 1999). The base-metal sulphides (BMS), and associated platinum-group minerals (PGM), constitute ~3 % of the Merensky Reef and are interstitial to the silicates (Lee, 1996). The Merensky reef and UG-2 are affected by potholes, where the reef horizons locally transgress the footwall lithologies to form a circular trough. There is generally no correlation of the Merensky Reef and UG-2 potholes (Cawthorn and Barry, 1992).

The UG-2 contains Pt and Pd each between 1000 ppb and 4000 ppb and is similar on the western and eastern limbs, although the eastern limb contains more S, Cu, Pd and Au (Barnes and Maier, 2002). In contrast the PGE grade and ratios of the Merensky Reef are relatively constant in the western and eastern limbs (Barnes and Maier, 2002; Cawthorn *et al.*, 2002).

The PGM found in the UG-2 are variable on a regional scale along strike (Kinloch 1982; Peyerl, 1982) and have a marked difference when associated with potholes, replacement bodies and faults (Penberthy and Merkle, 1999; Cawthorn *et al.*, 2002). Penberthy and Merkle (1999) and Schouwstra *et al.* (2000) noted PGE-sulphide dominant assemblages in the UG-2 with minor PGE alloys, sperrylite and sulpharsenides. A comprehensive study on the Merensky Reef PGE mineralisation by Cawthorn *et al.* (2002) reveals that although the PGE ratios are constant the PGM observed are highly variable. In the western limb the PGM are alloy-dominated in the northwest whilst sulphide-, telluride- and arsenide-dominated in

the southeast. The variability of the PGM occur on a regional and local scale are associated with disturbances in the reef suggesting that the mechanism concentrating the PGE is a first-order process and the evolution of the PGM is a second-order process. Much debate surrounds the mechanism for the concentration of PGE with support for a fluid scavenging the footwall succession or the accumulation from supernatant magma.

The Platreef consists of pyroxenitic lithologies and is between 10-400 m in thickness. The mineralisation of the Platreef is highly variable and described in detail in section 2.2.

#### 1.3 PREVIOUS WORK ON THE PLATREEF

Platinum was first reported 31 km southwest of Mokopane in 1923 by Mr. A. Erasmus, but it was Dr. Hans Merensky who announced that a platinum-bearing horizon had been located in the Rustenburg and the Mokopane, then Potgietersrus, areas (White, 1994). Wagner (1929) supplied the first description of the lithologies, the mineralisation and relationship of the mineralised horizon, subsequently named the Platreef, to the rest of the complex. He noted that the deposit consists of pyroxenites (bronzites) and norites, which were variably mineralised with sulphides, with a footwall of metamorphosed sediments and granite. He directly correlated this Platreef with the Merensky Reef, which was unchallenged until studies conducted in the last decade.

In 1976 van der Merwe further described the northern limb of the Bushveld Complex and conducted a regional gravity survey. He noted the presence of the main platiniferous horizon to be at the base of the MZ. Gravity data highlighted that the northern limb appears to be a separate compartment of the Bushveld Complex.

Buchanan *et al.* (1981) conducted sulphur isotope studies on the Platreef at the Tweefontein Farm. The study proposed that the sulphide mineralisation involved the assimilation of sedimentary-derived sulphur into the sulphur-rich Bushveld magma. Further research lead Gain and Mostert (1982) to propose that the devolatilisation of dolomite footwall and xenoliths added  $CO_2$ ,  $H_2O$  and S into the magma, lowering the S solubility and resulting in the development of an immiscible sulphide liquid. It was also noted by Gain and Mostert (1982) that although Ni and Cu correlate with Pt and Pd, the Ni and Cu values are not reliable in predicting zones of high Pt and Pd concentrations.

The first PGM data published was by Kinloch (1982) who commented on the most common PGMs present in the Platreef at Zwartfontein and Overysel. These are platinum-palladium

tellurides and sulphides, sperrylite, electrum and minor palladium alloys. In addition, Pt-Ferich samples were noted at Zwartfontein. He believed contamination of the Platreef by floor rock sediments and xenoliths affected the PGM composition.

Cawthorn *et al.* (1985) conducted major element, trace element and Sr isotope studies from the footwall and overlying pyroxenites at Overysel where Archaean granite forms the footwall to the Platreef. Their work implies that contamination of the Platreef magma likely occurred via a granite-derived fluid.

A comprehensive summary of the Platreef lithologies and mineralisation was given by White (1994). He provided descriptions of the Platreef PGE mineralisation at several locations along strike and divided the Platreef stratigraphic sequence into three pyroxenitic units termed the A, B and C reefs (see section 2.2.2). He again highlighted the importance of the footwall on the PGE mineralisation characteristics.

Lee (1996) compared the sulphide mineralisation of the Platreef to that from the Duluth complex where the sulphides were concentrated in a staging chamber prior to the emplacement of the Platreef. Contamination of the Platreef magma was therefore considered to be an ore deposit-modifying process.

In 1998 Viljoen and Schürmann further described the dominant PGM species from north to south. On the farm Drenthe in the north, tellurides and lesser arsenides dominate the PGM assemblage, tellurides and sulphides on Overysel, PGE alloys become significant on Zwartfontein and Sandsloot, PGE sulphides on Tweefontein north and tellurides on Tweefontein Hill.

Harris and Chaumba (2001) suggested that O and H contamination at Sandsloot occurred in a staging chamber prior to the emplacement of the Platreef based on  $\delta^{18}$ O values from the Platreef compared to that of the Upper and Main Zones.

A PGE mineralisation study was undertaken by Armitage *et al.* (2002) at Sandsloot. Their studies revealed that the PGE mineralisation at Sandsloot is complex being subject to a number of different processes, such as redistribution of PGE by hydrothermal fluids.

Kinnaird (2005) and Manyeruke *et al.* (2005) conducted petrographic and geochemical investigations of the southern Platreef at Turfspruit and Townlands respectively. Their studies proposed that the compositional breaks in the Platreef sequence represent distinct

sill-like intrusions. It was also noted that the upper Platreef contains more primitive rocks whereas enhanced crustal contamination occurred in the lower Platreef layers. Kinnaird (2005) concluded that "The Platreef is, therefore, a complex zone of sill inter-fingered lithologies reflecting a multiphase emplacement".

McDonald *et al.* (2005) proposed that compared to the CZ of the western and eastern limbs, the "CZ" of the Platreef was derived from a separate magma or a mixing of magmas due to the lithologies, mineral textures and geochemistry, including that of the rare earth elements (REE) and PGE.

Sulphur isotope data presented by Sharman-Harris *et al.* (2005) indicates that an additional sulphur source was responsible for the sulphides in the Platreef. They propose that local rather than regional contamination processes are responsible due to the local differences in sulphur isotopes and a decrease in crustal sulphur further away from the footwall.

The structural setting of Tweefontein Hill was investigated by Nex (2005). The study revealed that two pre-Bushveld ductile events resulted in a major south-west plunging fold at this locality. This structure is thought to control the abundant massive sulphide mineralisation near the base of the Platreef in this area.

Detailed PGE mineralisation studies by Kinnaird *et al.* (2005) and Hutchinson and Kinnaird (2005) on the farms Macalacaskop and Turfspruit, Holwell *et al.* (2006) on Sandsloot and Holwell and McDonald (2007) on Overysel showed differing PGM assemblages along the Platreef strike providing insight into the complex Platreef mineralisation in these areas (see section 2.2.3). Hutchinson and Kinnaird (2005) proposed that in addition to metasomatic fluid alteration, late-stage felsic melts were responsible for the redistribution of sulphides and PGM in the Turfspruit area.

An extensive sulphur isotope study lead Holwell *et al.* (2007) to propose that the Platreef magma was sulphur saturated, possibly in a staging chamber, prior to contamination. They believe that the assimilation of sulphur from country rocks upgraded the sulphur content on a strictly local scale.

Due to the relative depletion of Ni and Cu in the Lower Zone, McDonald and Holwell (2007) proposed a new model for the development of the Platreef. Their theory involves the concentration of Ni, Cu and PGE in conduits which fed the Lower Zone magma chamber. The concentrated sulphides were subsequently transported by a later magma into the

Platreef. Jones *et al.* (2011) presented data to support this model using variable sulphide inclusions within chromite.

Sulphur isotope studies performed by Penniston-Dorland *et al.* (2008) support the theory that the Platreef magma was sulphur-saturated prior to the emplacement of the Platreef, but lost sulphur during the formation of the present Platreef deposit.

Hutchinson and McDonald (2008) conducted a laser ablation ICP-MS study of PGE in sulphides from the Platreef at Turfspruit. They observed that Pd, Os, Ir and some Pd are present in solid solution and as discrete PGM hosted in BMS. In contrast, Pt and some Pd were present as discrete PGM occurring on the grain boundaries of BMS particles and on grain boundaries or within silicate particles. They explain these textural observations by the introduction of sedimentary-derived As, Sb, Te and Bi into the Platreef magma causing the Pt- and some of the Pd-bearing PGM to be expelled to the edge of the sulphide droplet. If these sulphide droplets came into contact with a felsic melt, the PGM were further redistributed.

The laser ablation studies of chromite-hosted sulphide inclusion by Holwell and McDonald (2008) supports the theory that the sulphides were pre-concentrated with PGE in staging chambers or conduits prior to the emplacement of the Platreef.

Naldrett *et al.* (2008) explores the links between the Platreef and the upper CZ proposing a model for the origin of the Platreef. Their model suggests that the RLS is a result of a bowl-shaped intrusion where magma escaped up the sides of the "bowl". They suggest the differences observed in the different limbs are a result of erosion depth. They propose that the magma escaped on at least two occasions; the first perhaps giving rise to the UG-2 and associated strata and the second responsible for the development of the Merensky Reef. Regarding the Platreef, the first occasion may have produced the lower Platreef and the second to the upper Platreef more aligned with the Merensky Reef.

Nichol and Kinnaird (2008) provided the first detailed PGM assemblage data for Tweefontein North. McCutcheon (nèe Nichol) and Kinnaird (2011) looked at the PGM deportment from Tweefontein North to Tweefontein Hill emphasising the significance of secondary processes, such as contamination and metasomatic fluids, on the Tweefontein PGE mineralisation. Both of these references were derived from this MSc research.

A recent study by Yudovskaya and Kinnaird (2010) focussed on the chromitites present in the Platreef along strike. Their study concluded that the localisation of chromitites supports the separate development of the northern limb during the emplacement of the CZ, but that the chromitites are of CZ affinity aligned with the western and eastern limbs.

Kinnaird and Naldrett (2011) studied the PGE tenor through the Platreef along strike and with depth. They concluded that there are typically three, sometimes four, Platreef packages that can be recognised, although this is often masked by metamorphism, assimilation of country rocks and serpentinisation.

Holwell (2011) summarised the PGM assemblages along strike and emphasized the importance of establishing the "primary" style of mineralisation so as to determine secondary processes involved in the observed PGE mineralisation along the Platreef strike.

#### 1.4 AIMS OF THE PROJECT

Due to the lack of mining activity in the Northern Limb until recently, little literature exists on the PGM mineralisation of the Platreef. Previous studies focussed primarily on the central region of the Platreef due to historical mining and exploration. A recent boom in exploration has allowed for research along most of the Platreef strike. Recent studies provide insight into the varying PGM mineralisation at Macalacaskop and Turfspruit in the south, Sandsloot, in the central area and Overysel in the North. This study uses samples along the strike of the Tweefontein and presents the first significant data on the PGE mineralisation on the farm.

Apart from grade, an important aspect of PGE mineralisation is the composition, association, and size of the PGM present as these factors have a significant impact on the potential to exploit the deposit. This project involves the study of the Platreef from Tweefontein North through to Tweefontein Hill, therefore establishing the possible variation in PGM deportment along strike, with depth, host rock type and level of alteration. This study is defined by four areas of research.

- Detailed logging of the Platreef package from ten Tweefontein drill cores was conducted. This provided the localised geology of the Platreef on which to base sampling as well as to aid any further mineralogical understanding.
- Petrographic studies were used to ascertain overall mineralogy, texture and level of alteration present.

- The whole rock and trace element geochemical investigation aimed to confirm and further define the lithologies at Tweefontein and provide insight into the mineralisation style present.
- Automated SEM analyses on the bulk modal and base metal sulphides with a particular focus on the PGM mineralogy provided comprehensive information on the composition, association and grain size of the valuable minerals.

This study integrates results obtained from the four areas of research described above, providing significant insight into the understanding of the PGE mineralisation at Tweefontein. This data also allows a complete comparison of the PGE mineralisation from Overysel to Turfspruit for the first time.

# CHAPTER 2 THE PLATREEF

### 2.1. INTRODUCTION TO THE NORTHERN LIMB

The northern limb of the Bushveld Complex is situated ~275 km NNW of Johannesburg. It has a sinuous outcrop, striking N-S and dipping ~WSW, with a length and width of 100 km and 15 km respectively (van der Merwe, 1976). Based on gravity data, van der Merwe (1976) estimated the northern limb to cover an area of 7275 km<sup>2</sup> and be triangular in shape, which included the southerly dipping exposure in the Villa Nora segment ~110 km NW of Mokopane. However, based on geophysical data, Kinnaird *et al.*, (2005) suggested that the exposed northern limb is the eastern edge of a much larger 'basin', 100 x 130 km in size, which includes the Villa Nora segment. The Zebedielia Fault, which forms part of the Thabazimbi-Murchison Lineament, separates the northern limb from the eastern and western limbs of the Bushveld Complex (Good and de Wit, 1997). The layered mafic rocks rest on progressively older rocks of the Transvaal Supergroup and Archaean granite basement towards the north (Wagner, 1929; van der Merwe, 1976; Buchanan *et al.*, 1981). The northern limb is overlain by the Waterberg sediments and contemporaneous volcanic rocks (Gain and Mostert, 1982). A geological map of the northern limb is given in Figure 2.1.

### 2.2. STRATIGRAPHY OF THE NORTHERN LIMB

The subdivisions of Marginal (MZN), Lower (LZ), Critical (CZ), Main (MZ) and Upper (UZ) Zones are also used for the northern limb although there are significant differences in the Rustenburg Layered Suite (RLS) present in the northern limb compared to the eastern and western limbs of the Bushveld Complex. The Platreef, which generally forms the mafic floor to the northern limb, has been correlated with the Merensky Reef of the CZ (Wagner, 1929; White, 1994; Kinnaird *et al.*, 2005; Naldrett *et al.*, 2008). The putative relationship between the northern limb and the eastern and western limbs is summarised in Figure 2.2.

The MZN norites are poorly developed and are found sporadically on farms Macalacaskop and Turfspruit (Kinnaird *et al.*, 2005; Sharman-Harris *et al.*, 2005). Van der Merwe (1976) describes the MZN as a noritic and doleritic rock which varies in thickness from centimetres to tens of meters.



Figure 2.1. Geological map of the northern limb of the Bushveld Complex highlighting the northern, central and southern sectors (Modified by Nex and Kinnaird, 2004 after van der Merwe, 1978).



Figure 2.2. Stratigraphic cross-sections of the RLS correlating the western and eastern limbs with the northern limb of the Bushveld Complex (After White, 1994; Kinnaird *et al.*, 2005).

The LZ is well developed 16 km south of Mokopane reaching 1600 m in thickness where it comprises 37 cyclic units of olivine-chromite, orthopyroxene-chromite and orthopyroxene cumulates respectively (Hulbert and von Gruenewaldt, 1982). This LZ succession differs from that in the eastern and western limbs due to the presence of Mg-rich orthopyroxene and olivine, chromitite layers containing the highest Cr<sub>2</sub>O<sub>3</sub> content in the entire Bushveld complex (van der Merwe, 1976; Hulbert and von Gruenewaldt, 1982) and the presence of PGE, Ni and Cu mineralisation at two levels in the sequence (Hulbert and von Gruenewaldt, 1982). North of the Planknek-Ysterberg Fault, the LZ is developed as satellite sheet-like bodies, which may be connected at depth (van der Merwe, 1976). Recent deep exploration drilling has revealed thick LZ lithologies on Sandsloot (Winch, 2011) and Turfspruit (Yudovskaya *et al.*, 2011). The LZ and the CZ formed from two very different magmas due to the pronounced structural, mineralogical, and chemical differences between the two zones (Hulbert and von Gruenewaldt, 1985).

The CZ is poorly developed in the northern limb compared to the eastern and western limbs, with significant differences in thickness, stratigraphy, grade and Pt/Pd ratios (Gain and Mostert, 1982). Except where there are localised thick packages of LZ, the Platreef forms the base of this mafic succession and is described in section 2.2. The UG-2 and the Merensky Reef of the CZ found elsewhere in the Bushveld Complex, have been equated

with the chromitite layer of the Grasvalley norite-pyroxenite-anorthosite (GPNA) member and the Platreef respectively (e.g. Wagner, 1929; White, 1994; Hulbert, 1983). However, McDonald *et al.* (2005) have suggested that the GPNA and the Platreef may not have formed from the same magma that formed the CZ of the rest of the Bushveld Complex, but may have involved a separate magma or mixing of magmas. A recent study on the chromitites of the Platreef was conducted by Yudovskaya and Kinnaird (2010) where the chemical composition of the chromites and co-existing silicates indicates CZ affinity, but due to the localised development of chromitites suggests an independent development of the northern limb.

The Platreef is overlain by the MZ. This unit is 2200 m thick comprising homogeneous gabbros and gabbronorites (van der Merwe, 1976). The MZ of the northern limb and the rest of the Bushveld complex are comparable, but there are four pyroxenite layers present and an olivine bearing horizon in the MZ unique to the northern limb of the Bushveld Complex (Ashwal *et al.*, 2005).

The UZ comprises cyclic units of magnetite, magnetite gabbros, gabbros and anorthosites. The lowermost magnetites found in the northern limb UZ are comparable to the magnetites mined in the eastern and western limbs (Ashwal *et al.*, 2005). The UZ is also exposed in the Villa Nora segment where Hattingh and Pauls (1994) noted the presence of leuconorites, leucogabbros and anorthosites.

#### 2.3. PLATREEF

The N-NW striking Platreef occurs at the base of the northern limb and generally dips approximately 40°W to SW (Viljoen and Schürmann, 1998). Kinnaird *et al.* (2005) defines the Platreef as 'the lithologically variable unit, dominated by pyroxenite, which is irregularly mineralised with PGE, Cu and Ni, between the Transvaal metasedimentary footwall or Archaean basement and the overlying Main Zone gabbronorite'. The lithological variability of the Platreef along strike can be attributed to the interaction of the Platreef magma with the local footwall lithologies (e.g. Buchanan *et al.*, 1981; White, 1994). The thickness of the Platreef reaches 400 m in the south (Kinnaird *et al.*, 2005) and ranges between a few meters and 30 m at Sandsloot (Armitage *et al.*, 2002). Recent data on Sandsloot presented by Winch (2011), however, revealed a secondary Platreef horizon, >250 m in thickness, below a ~200 m dolomite raft. The variations in Platreef thickness along strike are thought to be partially controlled by structures in the footwall rocks (Friese and Chunnett, 2004; Nex, 2005).

Geochemical and petrographic studies on the farms Turfspruit and Townlands (Kinnaird, 2005; Manyeruke *et al.* 2005) and Tweefontein Hill (Nyama *et al.*, 2005) imply that the Platreef intruded as a number of discrete sills.

#### 2.3.1. Footwall lithologies

Northward, the Platreef rests on progressively older rocks of the Transvaal Supergroup, shown in Figure 2.3, and Archaean granite basement (Wagner, 1929, van der Merwe, 1976, Buchanan *et al.*, 1981). The Platreef can be divided into the northern, central and southern sectors based on the variation in footwall lithologies along strike (Kinnaird *et al.*, 2005). Archaean granite basement forms the footwall in the northern sector on Overysel, Drenthe and northwards whilst a footwall of Malmani dolomite occurs in the central sector on Zwartfontein, Sandsloot, Vaalkop and Tweefontein. The footwall in the southern sector extends from Tweefontein Hill to Townlands in the south and is characterised by Transvaal Supergroup shales, banded ironstones, calcsilicates mudstones and siltstones.



Figure 2.3. Schematic stratigraphy of the Transvaal Supergroup forming the footwall to the Platreef (Nex, 2005).

The Platreef magma interacted with variable footwall lithologies to form hybrid rock types such as the serpentinised websterites found at Sandsloot (McDonald *et al.*, 2005). Thermal metamorphism also gave rise to highly altered lithologies such as clinopyroxenites termed 'parapyroxenite' and calcsilicate hornfelses, which formed between the Platreef and the underlying calcsilicate footwall (Harris and Chaumba, 2001; Armitage *et al.*, 2002; Holwell *et al.*, 2006). During the emplacement of the Platreef, the partial melting of the Archaean Basement in the north gave rise to a rock type termed granofels described by Cawthorn *et al.* (1985). Serpentinites are also observed which formed due to a hydrothermal reaction halo around calcsilicate lithologies (Viljoen and Schürmann, 1998; Armitage *et al.*, 2002).

#### 2.3.2. Platreef lithologies

White (1994) divided the largely pyroxenitic lithologies of the Platreef into three basic units that were named the A, B and C reefs. The A reef forms the lowermost pyroxenitic unit comprising a heterogeneous, highly feldspathic unit, which contains some BMS mineralisation. The B reef is the main ore zone and consists of a coarse-grained feldspathic pyroxenite, which normally contains equal amounts of orthopyroxene and clinopyroxene. It has a fair to good mineralisation. The C reef is situated at the top of the Platreef package and is poorly mineralised. It comprises a fine-grained homogeneous poikilitic feldspathic pyroxenite, which can contain up to 70 % clinopyroxene.

The A, B and C reef classification has been incorporated into the literature (e.g. Viljoen and Schürmann, 1998; Maier, 2002) and mining terminology, but studies have subsequently shown that the classification may not be applicable along the strike of the Platreef. Nex and Kinnaird (2004) have shown that this classification cannot be applied to Drenthe due to a thick noritic package that cannot be assigned to the A, B or C reefs. The re-logging of cores from Tweefontein, the Mohlosane stream section and more recent work on the southern sector has also shown that the classification was based more on the central sector and may not be applicable elsewhere along the Platreef strike (Nex and Kinnaird, 2004).

The Platreef on the southern farm of Townlands overlies the quartzites and shales of the Timeball Hill Formation. Manyeruke *et al.* (2005) subdivided the gabbronorites and feldspathic pyroxenites of the Platreef into the lower, middle and upper Platreef layers based on geochemical data. These Platreef layers are separated by hornfels interlayers and were thought to represent different sill intrusions.

The Platreef at Macalacaskop and Turfspruit comprises a relatively thick sequence with a relatively large variation of rock types, which overlie the shales and dolomites of the Duitschland Formation. The Platreef in this area has more recently been described by Hutchinson *et al.* (2004), Hutchinson and Kinnaird (2005), Kinnaird (2005), Kinnaird *et al.* (2005), Le Grange and White (2005), Mothetha and Kinnaird (2005) and Sharman-Harris *et al.* (2005). Feldspathic pyroxenite is the predominant rock type, but the Platreef package also includes norite, melanorite, serpentinites, dunites, peridotites and norite cycles. Micronorites are also present classified as MZN. Kinnaird *et al.* (2005) noted the presence of serpentinised peridotites classified as LZ rocks. Xenoliths commonly composed of quartzites, hornfels and shales occur at Macalacaskop whereas calcsilicate xenoliths also occur at Turfspruit. Similarly to Townlands, breaks in the geochemical data in the Platreef are thought to represent distinct sills (Kinnaird, 2005).

The footwall on Tweefontein is banded ironstone, which has been metamorphosed to magnetite-bearing hornfels (White, 1994; Viljoen and Schürmann, 1998). On Tweefontein Hill, shales of the Duitschland Formation form the footwall (Nex, 2005; Nyama *et al.*, 2005), where net-textured and massive sulphides are present near the base of the Platreef. The basal sulphides are believed to have formed due to the gravitational settling of a sulphide liquid into a structural downwarp (White, 1994; Nex, 2005). The Platreef on Tweefontein Hill has been described by Nyama *et al.* (2005) as a 220 m thick pyroxenitic package with norites and basal micronorite, where whole rock data suggests that the Platreef is made up of at least three sill intrusions. The pyroxenitic Platreef found at Tweefontein North is described by White (1994) as having a chromitite layer underlain by a coarse-grained pyroxenite up to 6 m thick near the upper portion of the Platreef package. This unique horizon hosts significant PGE mineralisation and was found at the same stratigraphic position in approximately 80 % of the boreholes drilled at this time (White, 1994). It was therefore linked with the Merensky Reef found in the eastern and western limbs of the Bushveld Complex.

The platinum division of Anglo American started mining at Sandsloot in 1993 and is therefore relatively well studied (Harris and Chaumba, 2001; Armitage *et al.*, 2002; Holwell *et al.*, 2005; McDonald *et al.* 2005; Holwell *et al.*, 2006). The Platreef at Sandsloot has a dolomitic footwall, is ~65 m thick and primarily comprises medium-grained to pegmatoidal pyroxenites and gabbros with phlogopite, base metal sulphides and oxides present as minor phases. Other lithologies include peridotites, serpentinites and calcsilicate xenoliths. 'Parapyroxenite' and calcsilicate hornfelses of varying thickness form the boundary between

the igneous Platreef lithologies and the dolomitic footwall. Holwell and Jordaan (2006) describe Zwartfontein South, to the north of Sandsloot, as having a similar footwall as Sandsloot, but with a thicker Platreef package and a larger amount of serpentinised lithologies.

The Archaean granite basement forms the footwall to the Platreef on the northern portion of Zwartfontein, Overysel and Drenthe. Partial melting of the Archaean granitic footwall has resulted in a hybrid rock type termed granofels (Cawthorn *et al.*, 1985). Holwell and McDonald (2006) describe the Platreef from two Overysel borehole cores as comprising feldspathic pyroxenite, intrusive norites with xenoliths of calcsilicate and chromitite. The Platreef at Drenthe was described by Gain and Mostert (1982) as being ~250 m thick comprising a feldspathic pyroxenite sequence at the base overlain by a thick sequence of norites and melanorites capped by another feldspathic pyroxenite sequence. Calcsilicate xenoliths are found throughout the sequence. North of Drenthe where the Platreef pinches out, the MZ rests on the Archaean Granitic basement where significant PGE and BMS mineralisation is associated with calcsilicate xenoliths (Kinnaird *et al.*, 2005).

#### 2.3.3. PGE Mineralisation

The PGE and base metal sulphide (BMS) mineralisation of the Platreef is variable and complex with different styles of mineralisation observed along strike (Viljoen and Schürmann, 1998; Kinnaird, 2004) and in different pyroxenitic packages from the same region (Kinnaird et al., 2005). The Platreef may have a top-, middle- or bottom-loaded mineralisation with footwall mineralisation that is inconsistent in thickness and grade (White, 1994; Hutchinson and Kinnaird, 2005). Mineralisation was also found at the base of the hanging wall from samples taken between Sandsloot and Overysel (Holwell et al., 2006). PGE tenors along the strike of the Platreef support the theory that the Platreef was intruded as a series of sills whereby individual sills vary along strike and down dip (Kinnaird and Naldrett, 2011). The top Platreef sill has the highest tenor, the highest Pt/Pd ratio and has the most 'magmatic' ore assemblage with the highest PGE grades. The basal Platreef is usually the most variable due to interaction with floor rocks and rafts. The PGE mineralisation is often associated with sulphide minerals, but decoupling of the PGE from the BMS is common (Gain and Mostert, 1982; Hutchinson and Kinnaird, 2005; Kinnaird, 2005; Holwell et al., 2006). High PGE and low BMS contents may be explained by latestage hydrothermal redistribution of PGE and/or BMS.

The generalised PGE mineralisation trend down sequence at various locations along the strike of the Platreef is given in Figure 2.4. The primary PGE, Cu and Ni mineralisation in the southern region of the Platreef (Macalacaskop, Turfspruit, Rietfontein and Tweefontein Hill) is generally bottom-loaded. (Kinnaird et al., 2005). Net-textured and massive sulphides are relatively common in this region (Nex, 2005; Hutchinson and Kinnaird, 2005) and are thought to have occurred due to gravitational settling of a sulphide melt, which may have involved the assimilation of sulphide from the footwall (Sharman-Harris et al., 2005). The PGE mineralisation at Tweefontein North is closely associated with a pegmatoidal pyroxenite unit usually below a thin chromitite layer about 10-20 m from the top Platreef contact (White, 1994; Nichol and Kinnaird, 2008). Variable mineralisation is found at Sandsloot, but it is commonly found near the top of the Platreef package, whereas Zwartfontein is characterised by low BMS values with sporadic high PGE values (White, 1994; Hutchinson and Kinnaird, 2005). At Overysel, significant PGE mineralisation, closely associated with Cu and Ni values, was reported over considerable thicknesses (White, 1994; Holwell and McDonald, 2006). Overysel is therefore thought to represent the most 'primary' mineralisation style preserved along strike (Howell and McDonald, 2006; Holwell and McDonald, 2007). Variable accumulations of BMS close to the Platreef footwall contact were also observed at Overysel associated with a basal granofels unit (White, 1994; Holwell and McDonald, 2006). Howell and McDonald (2006) also noted the depletion of Ir, Ru and Rh with depth compared to Pt, Pd and Au which is not observed at Zwartfontein and Sandsloot where the footwall is composed of carbonates.

The sulphide content is enriched in the Platreef compared to the rest of the Bushveld Complex, containing higher Ni contents (Hutchinson and Kinnaird, 2005). The BMS occur as interstitial blebs comprising pyrrhotite, pentlandite and chalcopyrite (Gain and Mostert, 1982; Viljoen and Schürmann, 1998; Armitage *et al.*, 2002). Pyrite can become significant in the basal part of the Platreef and has been noted on Tweefontein North associated with the chromitite layer (White, 1994; Viljoen and Schürmann, 1998).

Little data regarding the PGM assemblages within the Platreef have been published. Kinloch (1982) commented on the most common PGMs present in the Platreef at Zwartfontein. These are platinum-palladium tellurides and sulphides, sperrylite with minor palladium alloys. Viljoen and Schürmann (1998) summarised the dominant PGM species from north to south. On the farm Drenthe in the north, tellurides and lesser arsenides dominate the PGM assemblage, tellurides and sulphides on Overysel, PGE alloys become significant on Zwartfontein and Sandsloot, PGE sulphides on Tweefontein north and tellurides on

Tweefontein Hill. Recent detailed studies by Kinnaird *et al.* (2005) on the farms Macalacaskop and Turfspruit, Holwell *et al.* (2006) on Sandsloot and Holwell and McDonald (2007) on Overysel showed differing PGM assemblages providing insight into the complex Platreef mineralisation in these areas, described below. McCutcheon and Kinnaird (2011) presented a detailed PGM study at Tweefontein based on data from this MSc research.



Figure 2.4. Summary of the geology and 4E (PGE+Au) mineralisation recorded on different farms of the Platreef (After White, 1994).

Kinnaird *et al.* (2005) found the predominant PGE phases to be tellurides, arsenides and antimonides of Pd, Pt, Rh, Ag and Bi occurring as bismuthoantimonides and complex

bismuthotellurides. The PGM are often situated around sulphide minerals and within alteration assemblages in serpentinised zones.

The PGM at Overysel are predominantly Pt and Pd tellurides, in equal amounts, Pt arsenides, Pt sulphides and Pt and Pd bismuthides (Howell and McDonald, 2007). Minor phases are PGE alloys, antimonides and sulpharsenides. Howell and McDonald (2007) found that the PGM assemblages appeared to be dependent on the host rock type. The feldspathic pyroxenites and the footwall gneisses were found to have similar PGM assemblages dominated by tellurides. An arsenide dominant assemblage is found in the serpentinised xenoliths. The Lower Zone-like pyroxenite is dominated by Pt and Pd bismuthides, whilst the altered footwall granite is dominated by Pd bismuthides.

The PGM assemblages at Sandsloot as described by Holwell *et al.* (2006) are dominated by Pt and Pd tellurides and devoid of PGE sulphides. The PGM assemblages at Sandsloot seem to also be dependent on host rock type. The footwall is host to PGE arsenides, alloys and antimonides which are thought to have formed due to redistribution of PGE into the footwall by hydrothermal fluids. An antimonide-dominant PGM assemblage is found where the footwall has been serpentinised. Ultramafic zones are found at Sandsloot where an alloy-dominant assemblage occurs due to the recrystallisation by a late-stage Fe-rich fluid.

A summary of the Platreef PGM data was given by Holwell (2011) where emphasis was put on the establishment of the 'primary' Platreef mineralisation style present so as to determine the secondary processes involved in the observed PGE mineralogy. He surmised that the common 'primary' style of mineralisation was PGE-bismuthotellurides spatially associated with base metal sulphides primarily based on data from Overysel and Tweefontein where the footwall is relatively unreactive.

The mineralisation of the Platreef is thought to be the result of a complex interplay of magmatic processes, contamination of the magma by footwall rocks (Buchanan *et al.*, 1981; Gain and Mostert, 1982; Kinloch, 1982; Harris and Chaumba, 2001) and hydrothermal activity (Armitage *et al.*, 2002; Holwell *et al.*, 2005; Holwell *et al.*, 2006). The recent Platreef mineralisation studies have highlighted the importance of magmatic processes and syn- and post-emplacement fluids on the Platreef mineralisation and the different interactions these processes may have had along strike. Based on their findings at Overysel, Holwell and McDonald (2007) suggest that Overysel represents a primary mineralisation style with minimum assimilation and metamorphism by the footwall rocks. They proposed that the
mineralisation of the Platreef is orthomagmatic where the PGE were present in an immiscible sulphide liquid within the Platreef magma. It is still unclear whether the PGE already formed part of the immiscible sulphide liquid prior to its intrusion or if the PGE were scavenged by the sulphide liquid from the Platreef magma.

There is a unique style of mineralisation found around some calcsilicate xenoliths in the Main Zone gabbronorites to the north of the limb, where the Main Zone rests on Archaean basement. This style of mineralisation is excluded from Platreef mineralisation as it does not occur in the Platreef rocks and is termed "Platreef-style' mineralisation (Kinnaird *et al.*, 2005).

The rock types and general geology of the Tweefontein farm will be described in Chapter 3 using hand specimen descriptions and petrography.

# CHAPTER 3 LITHOLOGIES OF THE PLATREEF AT TWEEFONTEIN

# 3.1. INTRODUCTION

This study involved the detailed logging of ten borehole cores from the farm Tweefontein in the exploration core yard at Platinum's Mogalakwena operation. The boreholes were chosen based on the original logs made available by Platinum, the local geology and their locality along strike. The location of the ten boreholes is given in Figure 3.1. Southwards from Tweefontein North the selected boreholes are TN228, TN223, TN221 TN240, TN197, TN198, TN199, TN201, TN203, and TN205.



Figure 3.1. Generalised geological map of Tweefontein, including the location of the ten studied boreholes.

One deflection from each of the selected boreholes was logged, from a few metres above the top Platreef contact to the intersected footwall lithologies. The footwall to the Platreef at Tweefontein is banded ironstone from the Penge Formation and hornfels derived from the Duitschland Formation (Kinnaird *et al.*, 2005). A variety of rock types are observed in the

studied boreholes which can be broadly divided into igneous, dominated by pyroxenites and norites, and metasedimentary lithologies, dominated by hornfels, calcsilicate and parapyroxenite, which is a recrysallised clinopyroxenite. Net textured and massive sulphide layers are present in boreholes from Tweefontein North and Hill, close to or in the footwall. Granitic veins and thin layers of serpentinite are present in the footwall and Platreef package. Two faults, trending north-north east, cross cut the stratigraphy on Tweefontein, illustrated in Figure 3.1. One fault is situated between boreholes TN197 and TN198, whilst the other is found at TN199, which is host to a breccia zone at the top of the Platreef sequence.

This study defines the lithologies of the Platreef at Tweefontein using hand specimen descriptions and a petrographic investigation of eighty-eight selected samples.

## 3.2. TWEEFONTEIN ROCK TYPES

The rock types found on Tweefontein were logged and described with assistance of Nex *et al.* (2006); a Platreef Rock Type manual produced for Anglo American's platinum operations by the University of the Witwatersrand. Internationally agreed terminology for the Platreef rock types were used where possible, but more qualitative and informal rock names, which are in common use in industry, were also used.

#### 3.2.1. Footwall lithologies

The lowermost rock type intersected in the studied boreholes is a banded ironstone formation. Distinct banding comprising thin layers of iron-oxide rich minerals and light silicate-bearing minerals were observed, which define this rock type (Bates and Jackson, 1987). Base-metal sulphide mineralisation is common, often mimicking the characteristic banding.

The banded iron stone is usually overlain by hornfels. The hornfels at Tweefontein are finegrained and dark grey as shown in Figure 3.2, brown or green in colour. They are homogeneous, although layers are occasionally observed. Hornfels interlayers and rafts are also sporadically present within the Platreef package.



Figure 3.2. Dark grey hornfels interlayer observed in borehole TN228, ~80 m below the top Platreef contact.

A calcsilicate is defined by Bates and Jackson (1987) as a metamorphic rock consisting of calcium-bearing silicates formed from the metamorphism of impure limestone or dolomite. A calcsilicate is identified by its texture and diagnostic colours, such as pale cream, yellow and apple green. At Tweefontein, calcsilicates predominantly occur as interlayers within the Platreef package, although calcsilicate layers are occasionally observed within the footwall. They are cream, yellow and olive in colour and are often serpentinised as observed in Figure 3.3. They are typically inhomogeneous, but layering is occasionally observed.



Figure 3.3. Calcsilicate interlayer observed in borehole TN228, ~65 m below the top Platreef contact.

Parapyroxenite is not an internationally defined rock term, but has been widely used since it was introduced to the Platreef by Wagner in 1929. According to Bates and Jackson (1987), parapyroxenite should be termed a calcsilicate as it is predominantly composed of clinopyroxene, but parapyroxenites are distinct in colour and texture, as shown in Figure 3.4, from the calcsilicate described above. The parapyroxenite observed at Tweefontein is usually green in colour and homogeneous with recrystallised 120° triple junctions. Feldspar-rich inclusions are commonly observed in the parapyroxenites from Tweefontein and form part of the footwall and occur as interlayers within the Platreef package.



Figure 3.4. Homogeneous parapyroxenite from the footwall in borehole TN198, ~10 m below the bottom Platreef contact.

#### 3.2.2. Platreef lithologies

The main Platreef lithologies observed at Tweefontein are pyroxenites, feldspathic pyroxenites, harzburgites, melanorites and norites. These lithologies are largely homogeneous in nature, but heterogeneous units are observed showing variation in grain size and feldspar content. The current nomenclature used for the igneous rock types on the Platreef uses a more qualitative approach than the internationally recognised classification schemes (Hutchinson and Kinnaird, 2005) as the rock names used describe igneous rocks according to the distinction between cumulus and intercumulus minerals. Thus a feldspathic pyroxenite, which is not an internationally recognised rock type, describes a rock that has cumulus orthopyroxene with minor clinopyroxene and intercumulus plagioclase as shown observed in Figure 3.5. For example, a rock containing between 10-15% plagioclase and 85-90% orthopyroxene would be named a norite in the IUGS scheme, but is termed a feldspathic pyroxenite due to cumulus orthopyroxene and intercumulus plagioclase. This has economic implications as feldspathic pyroxenites often carry good PGE grades whereas norites are generally barren unless they are in the footwall.

Pyroxenites and feldspathic pyroxenites are the most abundant Platreef lithologies found at Tweefontein. Pyroxenite is described as a rock consisting of >90% cumulus orthopyroxene and clinopyroxene with minor intercumulus plagioclase. Pegmatoidal pyroxenite and feldspathic pyroxenite are also commonly observed, the latter of which is highlighted in Figure 3.6.



Figure 3.5. Feldspathic pyroxenite observed in borehole TN223, ~54 m below the top Platreef contact.



Figure 3.6. Pegmatoidal feldspathic pyroxenite observed in borehole TN201, ~33 m below the top Platreef contact.

Like feldspathic pyroxenite, feldspathic harzburgite is a classification not recognised by the IUGS scheme, but refers to a harzburgite containing cumulus olivine and orthopyroxene and intercumulus plagioclase. On Tweefontein, feldspathic harzburgites are serpentinised due to the breakdown of olivine and orthopyroxene and commonly display magnetite banding as seen in Figure 3.7.



Figure 3.7. Feldspathic harzburgite observed in borehole TN197, ~57 m below the top Platreef contact.

Norites contain both cumulus plagioclase (35-65 %) and orthopyroxene (35-65 %) and can be medium-grained to pegmatoidal (Figure 3.8). The prefixes leuco- and mela- are used to distinguish between more felsic and mafic varieties respectively. There are also heterogeneous, fine-grained norites located close to or in the footwall as shown in Figure 3.9. These units vary in felsic content and are often associated with massive sulphide layers.



Figure 3.8. Norite and pegmatoidal norite observed in TN201, ~26 m below the top Platreef contact.



Figure 3.9. Heterogeneous norite observed ~80 m into the footwall in TN240, associated with a massive sulphide layer (TN240).

Chromitite is rare on the Platreef at Tweefontein. It occurs in the upper Platreef at Tweefontein North as a discontinuous layer/s, reaching up to 10 cm in thickness as observed in Figure 3.10.



Figure 3.10. Chromitite layer observed in borehole TN223, ~20 m from the top Platreef contact.

Massive and net-textured sulphides are composed of >90 % and >40 % base metal sulphides respectively. At least one massive or net-textured sulphide layer is found in or close to the footwall, which reaches 50 cm in thickness on Tweefontein North and up to 2.7 m in thickness on Tweefontein Hill (Figure 3.11). The sulphides are dominated by pyrrhotite and lesser pentlandite and chalcopyrite.



Figure 3.11. Massive sulphide layer hosted within feldspathic pyroxenite observed in borehole TN205, ~30 m above the bottom Platreef contact.

Granites and quartz-feldspar veins, serpentinisation and faulting (breccia) have affected the footwall, the Platreef and/or hanging wall lithologies syn or post the intrusion of the Platreef. The term granite is used here as a more general term for all the fields in the IUGS QAP diagram, where the proportions would roughly be 20-60 % quartz and 10-65 % feldspar (Nex *et al.*, 2006). The granites present at Tweefontein cross-cut the stratigraphy and reach up to ~10 m in thickness. They are either coarse-grained and pink in colour or display a graphic texture (Figure 3.12). The quartz-feldspar veins are relatively thin, cream and white, but have an inhomogeneous or non-granitic texture (Nex *et al.*, 2006). They can be zoned, indicating an intrusive nature, and chloritised.



Figure 3.12. Granitic vein in borehole TN198, ~8 m above the bottom Platreef contact, showing a graphic texture in places.

A breccia zone, which displays an unusual texture occurs at the top Platreef contact in TN199 (Figure 3.13). This is thought to represent a fault trending north-north east illustrated in Figure 3.1. It consists of large, angular felsic and mafic rock fragments within a matrix of mafic material.



Figure 3.13. Breccia zone observed in borehole TN199, which forms the top Platreef contact.

Serpentinite is a rock consisting of >90 % of serpentine-group minerals. On the Platreef, it can either be formed from the alteration of olivine or pyroxene in igneous lithologies, usually harzburgite, or from the hydration of olivine and pyroxenes associated with country rock calcsilicates.

# 3.2.3. Hanging wall lithologies

The borehole deflections studied included a few metres of the hanging wall. The predominant hanging wall lithology encountered was an anorthosite assigned to the Main Zone. According to internationally recognised classifications, anorthosites contain <10 % pyroxene but in the Platreef can contain up to 15 % (Nex *et al.*, 2006). This is due to the characteristic texture of the anorthosites observed where the pyroxene crystals cluster together in circular patches creating a mottled effect. Leuconorite and norite were also observed in the intersected hanging wall lithologies on Tweefontein. All boreholes, except TN228 and TN199 where the top Platreef contact was fractured, have sharp contacts between the hanging wall and Platreef lithologies shown in Figure 3.14.



Figure 3.14. Sharp Platreef contact between mottled anorthosite and pyroxenite in borehole TN221.

## 3.3. SAMPLING

The ~1 m quarter core samples selected for this study correlate with samples used by Platinum for chemical assay. Between six and ten samples were chosen from each borehole Samples were only considered if the assays were above 1 g/t 3E (Pt+Pd+Au). This limit was chosen due to the statistics required for valid PGM analysis. Once the intersections above 1 g/t were identified, the samples were chosen to incorporate varying rock types, proximity to geological features, such as granitic veins and stratigraphic position. The samples were selected for petrographic and XRF analyses of which a subset were chosen for detailed bulk mineralogical, base metal sulphide (BMS) and platinum-group mineral (PGM) studies.

A total of eighty-eight intersections were sampled (Table 3.1). The majority of the samples were taken from the Platreef igneous lithologies including, in order of abundance, feldspathic pyroxenite, norite, pegmatoidal feldspathic pyroxenite, pyroxenite, heterogeneous norite and harzburgite. Metasedimentary lithologies from the footwall and from interlayers within the Platreef sequence were sampled, primarily composed of parapyroxenite (19) including two hornfels and calcsilicate samples. The samples were labelled based on their borehole number and the depth below the top Platreef contact. For example, a sample taken from borehole TN228 at 9 m below the top Platreef contact is labelled TN228\_9.

Rock type	No. of samples
Pyroxenite	8
Feldspathic pyroxenite	24
Pegmatoidal feldspathic pyroxenite	9
Harzburgite	5
Norite	13
Heterogeneous norite	6
Parapyroxenite	19
Hornfels	2
Calcsilicate	2
Total	88

Table 3.1. List of rock types sampled, including the number of samples selected per rock type.

#### 3.4. PETROGRAPHY

A thin section was made for each intersection sampled, totalling 88, which were petrographically described using transmitted and reflected light microscopy. The modal abundance of the minerals present, which was visually estimated, the textures observed and the level of alteration were documented. The rock nomenclature described above was applied to this petrographic study. Following the petrographic study, the lithology termed heterogeneous norite was subsequently re-named recrystallised norite. The petrographic samples were classified into pyroxenites, harzburgites, norites, recrystallised norites, calcsilicates, parapyroxenite and cordierite hornfels. The level of alteration was documented as low, medium and high pertaining to an area percent of <5, 5-15 and >15 alteration minerals respectively.

#### 3.4.1. Pyroxenites

The Platreef in the studied boreholes is dominated by feldspathic pyroxenite and pyroxenite composed of cumulus orthopyroxene, clinopyroxene and interstitial plagioclase, with feldspathic pyroxenite and pyroxenite containing between 10 to 25 % and <10 % plagioclase

respectively. Photomicrographs of these rock types are given in Figure 3.15. Figure 3.15(a) demonstrates cumulus orthopyroxene, whilst Figure 3.15(b) presents cumulus orthopyroxene with interstitial plagioclase. Minor and accessory minerals are base metal sulphides (BMS), oxides (chromite and magnetite), olivine, biotite, quartz and alteration minerals. Figure 3.15(c) shows olivine, biotite and BMS grains hosted within an orthopyroxene crystal. These lithologies are primarily medium- to coarse-grained, although pegmatoidal varieties are commonly observed. The anhedral to euhedral orthopyroxene grains vary in size (0.2 mm – 5 mm) and often show exsolution textures. The modal abundances of major rock forming minerals, BMS, oxides and alteration minerals for pyroxenite and feldspathic pyroxenite are given in Table 3.2.

Minerals	Pyroxenite	Feldspathic pyroxenite
Orthopyroxene	60-70%	55-75%
Clinopyroxene	3-20%	0-20%
Plagioclase	<10%	10-25%
Olivine	0-3%	0-6%
BMS	1-9%	0-10%
Oxides	0-5%	0-6%
Alteration minerals	1-3%	0-20%

Table 3.2. Major and minor mineral abundances for pyroxenite and feldspathic pyroxenite

A low degree of alteration is observed in ~50 % of the thin sections occurring in this category. The remaining ~50 % have a medium to high level of alteration which includes serpentinisation, observed in Figure 3.15(d), chloritisation and the alteration of plagioclase to sericite and dark brown clay minerals, highlighted in Figure 3.15(e). The dark brown clay minerals appear as fine-grained isotropic clusters within the plagioclase grains. Significant alteration was observed in thin section TN198\_46, constituting ~60 % serpentine, and TN205\_55 where alteration minerals of sericite, clay, talc and serpentinite constitute ~20 %. The deformation of orthopyroxene and clinopyroxene grains was observed in TN199\_3, displayed in Figure 3.15(f), which is situated directly below a breccia zone at the top Platreef contact. In altered samples the chalcopyrite often occurs along fractures or grain boundaries, implying late-stage remobilisation.



Figure 3.15. Photomicrographs of pyroxenite and feldspathic pyroxenite from the Platreef at Tweefontein. (a) Cumulus orthopyroxene, sample TN205\_64, (b) cumulus orthopyroxene and interstitial plagioclase, samples TN240\_46, (c) Olivine, BMS (opaque mineral) and biotite grains displaying radiating fractures hosted in an orthopyroxene grain, sample TN198\_34, (d) Serpentinised feldspathic pyroxenite showing remnant orthopyroxene grains and opaque minerals of BMS and magnetite, sample TN203\_44, (e) Cumulus orthopyroxene and interstitial plagioclase altered to dark brown clays (isotropic), sample TN228\_123, (f) Highly altered feldspathic pyroxenite situated close to a breccia fault zone, showing deformation of clinopyroxene and orthopyroxene crystals, sample TN199\_3. All photomicrographs are under cross polars.

## 3.4.2. Harzburgites

Harzburgitic lithologies are uncommon in the Platreef at Tweefontein. The sample suite only includes five harzburgitic intersections (TN228\_20, TN221\_28, TN197\_23, TN203\_39, TN205\_147). The majority of these thin sections are significantly or completely serpentinised. Only TN221\_28 and TN197\_23 still contain visible cumulus olivine at ~5 % and ~12 % respectively. Cumulus orthopyroxene (<40 %) with intercumulus plagioclase (<15 %) were also noted. Accessory minerals are BMS (<5 %), magnetite, chlorite, hornblende and sericite. The observed olivine and orthopyroxene grains vary between 0.5-10 mm and 0.2-20 mm respectively. An unaltered orthopyroxene grain hosting olivine chadacrysts is observed in Figure 3.16(a), whilst Figure 3.16(b) shows serpentinised olivine and the development of secondary biotite.



Figure 3.16. Photomicrographs of harzburgitic rocks from the Platreef at Tweefontein. (a) Olivine chadacrysts hosted within orthopyroxene, sample TN197\_23. Plane polarised light. (b) Olivine showing serpentinisation and development of secondary biotite, sample TN221\_28. Crossed polars.

## 3.4.3. Noritic rocks

Noritic rocks comprise cumulus plagioclase (25-55 %) and orthopyroxene (25-50 %) with minor clinopyroxene (<15 %), highlighted Figures 3.17(a) and (b). The majority of the Platreef noritic rocks at Tweefontein are melanorites, which refer to a more mafic norite variety. Accessory minerals are BMS (1-9 %), biotite, magnetite, quartz and alteration minerals. Grain sizes of plagioclase and orthopyroxene crystals vary between 0.1-1.5 mm and 0.1-4 mm respectively. The majority of the norites have low to medium degrees of alteration, primarily to sericite and dark brown, isotropic clay minerals from the alteration of plagioclase highlighted in Figure 3.17(c). Significant alteration comprising ~50 % sericite and clay minerals and ~20 % serpentine was observed in sample TN203\_55 (Fig. 3.17(d)).



Figure 3.17. Photomicrographs of noritic lithologies from the Platreef at Tweefontein. (a) and (b) Cumulus orthopyroxene and plagioclase with interstitial clinopyroxene, samples TN223\_35 and TN197\_54, (c) Cumulus orthopyroxene and plagioclase which has been altered to fine-grained clusters of isotropic clay minerals, sample TN197\_32, (d) Highly altered sample showing extensive seritisation and hornblende grains replacing orthopyroxene, sample TN203\_55. All photomicrographs are under cross polars.

## 3.4.4. Recrystallised norite

Six recrystallised norite samples were identified from thin section (TN228\_247, TN228\_253, TN221\_185, TN221\_196, TN221\_204, TN240\_214) all of which are from Tweefontein North. Three of these samples are closely associated with massive sulphide layers in the Platreef footwall. They are generally fine-grained and show little change in modal abundances relative to unaltered norites. The cumulus orthopyroxene (30-50 %) and plagioclase (30-60 %) are relatively fine-grained and often display 120° triple junctions. The majority of the grains are <0.5 mm and <0.8 mm respectively. Accessory phases are clinopyroxene, quartz, BMS, magnetite, garnet, sericite and dark brown clay minerals. As with the norites, the primary alteration minerals, derived from the breakdown of plagioclase, are sericite and dark brown clay minerals. Sample TN240\_214 has a high degree of sericitisation (~40 %). Figures 3.18(a) and (b) demonstrate the fine-grained recrystallised orthopyroxene and plagioclase

grains with Figure 5.18(a) showing alteration of plagioclase and 3.18(b) containing finegrained magnetite (opaque minerals).



Figure 3.18. Photomicrographs of recrystallised norites from the Platreef at Tweefontein. (a) and (b) Fine-grained recrystallised orthopyroxene and plagioclase grains. Samples TN221\_204 and TN240\_214. The alteration of plagioclase to dark brown clay minerals is observed in (a), whilst fine-grained magnetite (opaque minerals) is observed in (b). Plane polarised light.

## 3.4.5. Calcsilicates

The sample suite includes two serpentinised calcsilicate samples (TN228\_65 and TN197\_161). The thin section of sample TN228\_65 is composed of ~80 % serpentine with lesser magnetite (~10 %), dolomite (~5 %) and garnet (5 %) as shown in Figure 3.19, whilst TN197\_161 is composed of ~95 % serpentine and magnetite.



Figure 3.19. Photomicrograph of a highly serpentinised calcsilicate sample containing relict dolomite grains within serpentine and minor garnet, sample TN228\_65. Cross polarised light.

## 3.4.6. Parapyroxenites

Parapyroxenites are common in the Platreef at Tweefontein. The parapyroxenites observed are composed of 70-95 % clinopyroxene with minor plagioclase (<20 %), BMS (<10 %),

garnet (<10 %), magnetite (<10 %) and alteration minerals. The clinopyroxene grains have a granoblastic texture and are between 0.4 mm and 2 mm in size (see Figure 3.20(a) and 3.20(b)). Fine-grained garnet is observed in Figure 3.20(b). The alteration minerals are serpentine, chlorite and actinolite. The majority of the parapyroxenite samples have low degrees of alteration, although two samples contain ~70 % serpentine (TN228\_185 and TN205\_160), sample TN205\_167 contains ~50 % sericite, sample TN223\_161 contains ~30 % actinolite and sample TN197\_246 contains significant quartz (~20 %) thought to be a part of a quartz vein. Serpentinised and actinolite-rich parapyroxenite examples are shown in Figure 3.20(c) and 3.20(d) respectively.



Figure 3.20. Photomicrographs of parapyroxenites from the Platreef at Tweefontein. (a) Recrystallised clinopyroxene with a granoblastic texture, sample TN198\_62, (b) Recrystallised clinopyroxene with a granoblastic texture and sporadic fine-grained garnet, sample TN201\_99, (c) Recrystallised clinopyroxene with a granoblastic texture, which has undergone extensive serpentinisation, sample TN228\_185, (d) Recrystallised clinopyroxene which has been almost totally replaced by actinolite, sample TN223\_161. All photomicrographs are under cross polars.

#### 3.4.7. Cordierite hornfels

The sample suite includes two cordierite hornfels samples (TN228\_81 and TN205\_185). These two intersections have typical metapelite compositions of cordierite (30-90 %),

plagioclase (0-30 %), orthopyroxene (<15 %), magnetite (5-15 %), BMS (5-15 %) and alteration minerals. The grain size is very fine with the majority of the grains <0.2 mm, although some cordierite grains can reach ~1 mm (Figure 3.22(a)). In addition sample TN205\_185 contains coarser-grained areas with orthopyroxene, plagioclase and net-textured BMS (Figure 3.22(b)).



Figure 3.21. Photomicrographs of cordierite hornfels from the Platreef at Tweefontein. (a) Cordierite grains, varying in size, with one large cordierite grain showing sector twinning, sample TN228\_81, (b) Grain boundary between cordierite hornfels, comprising cordierite and recrystallised orthopyroxene, and relatively coarser grained orthopyroxene, plagioclase and net-textured BMS, sample TN205\_185. Both photomicrographs are under crossed polars.

## 3.5. SUMMARY

This study involves ten boreholes along the strike of the Tweefontein farm. Two faults, trending north-north east, affect the Platreef in the central Tweefontein area, one of which may have affected the Platreef in TN199 as represented by a breccia zone. The rock types of the Platreef on Tweefontein can be divided into igneous lithologies, which include feldspathic pyroxenite and melanorite with lesser pegmatoidal feldspathic pyroxenite, pyroxenite, harzburgite and norite, and footwall lithologies comprising recrystallised norite, hornfels, parapyroxenite, calcsilicate and banded iron formation. Recrystallised norites are grouped with the footwall metamorphic lithologies due to their recrystallised textures and footwall proximity. Serpentinite and granitic veins were found in the footwall and Platreef lithologies. The immediate hanging wall is predominantly anorthosite, with clusters of pyroxene creating a mottled texture, with lesser norite.

Eighty-eight intersections, ~1m in thickness, were sampled for further analysis. The samples contained a 3E (Pt+Pd+Au) grade in excess of 1 g/t and were selected to incorporate varying rock types, geological features and stratigraphic position. The majority of the samples were

taken from the Platreef igneous lithologies including, in order of abundance, feldspathic pyroxenite, norite, pegmatoidal feldspathic pyroxenite, melanorite, norite, pyroxenite and harzburgite. Metamorphic or altered samples from the footwall and from xenolithic layers within the Platreef sequence were selected, primarily composed of parapyroxenite with lesser recrystallised norite, hornfels and calcsilicate. The relatively large number of parapyroxenite intersections available for sampling indicates that at Tweefontein, parapyroxenite has the highest mineralisation potential after the igneous lithologies.

Petrographically, the major minerals present in the igneous lithologies at Tweefontein are orthopyroxene  $\pm$  plagioclase  $\pm$  clinopyroxene  $\pm$  olivine. Accessory minerals are quartz  $\pm$  biotite  $\pm$  magnetite  $\pm$  chromite  $\pm$  alteration minerals, including serpentine, chlorite, tremolite, actinolite, talc and the alteration of plagioclase to sericite and dark brown clay minerals. The majority of the igneous lithological samples have low to medium degrees of alteration but a few highly altered samples were observed, primarily affected by serpentinisation and seritisation.

Recrystallised norite, sampled from the footwall at Tweefontein North, demonstrated recrystallised textures in the petrographic study. Three of these samples were closely associated with massive sulphide layers. This lithology may represent igneous sills which pre-date the emplacement of the Platreef.

The parapyroxenite samples are composed of recrystallised clinopyroxene grains with  $120^{\circ}$  triple junctions. The minor and accessory minerals are plagioclase  $\pm$  base metal sulphides  $\pm$  garnet  $\pm$  magnetite  $\pm$  alteration minerals, predominantly serpentinite and amphiboles. The calcsilicate sample studied was predominantly composed of serpentine with minor magnetite  $\pm$  garnet  $\pm$  dolomite, whilst the fine-grained hornfels samples comprise cordierite  $\pm$  plagioclase  $\pm$  base metal sulphides  $\pm$  orthopyroxene  $\pm$  magnetite with low degrees of alteration.

A detailed description of the stratigraphy, the intersections sampled and the down-hole grade profile will be given for each borehole in Chapter 4. This information provides a comprehensive foundation to which further research can be applied.

# CHAPTER 4 GEOLOGY AND GENERAL MINERALISATION OF THE PLATREEF AT TWEEFONTEIN

## 4.1. INTRODUCTION

The location of the ten boreholes involved in this study was given in Figure 3.1 of Chapter 3. One deflection from each of the selected boreholes was logged on a metre scale, from a few metres above the top Platreef contact down to the various intersected footwall lithologies. Table 4.1 gives the depth below surface at which the detailed logging commenced, the top Platreef contact, the thickness of the Platreef and the end of borehole depth for the selected boreholes. The simplified geological logs of the ten boreholes are given in Figures 4.1(a) and 4.1(b).

A mineralisation log (Minlog) was generated for each borehole, which notes the approximate area % of base metal sulphides (BMS) down sequence. As previously mentioned, the Platreef in each borehole was chemically assayed by Platinum prior to this study. The 3E (Pt+Pd+Au) grade profile of each borehole is included to assist borehole characterisation. This chapter will describe each borehole in terms of its stratigraphy and sampling as well as general base metal sulphide (BMS) and PGE mineralisation. The Platreef in the studied boreholes was divided into the lower Platreef (L) and the upper Platreef (U) based on stratigraphy and grade distributions.

BH	Start	Top Platreef	Platreef	End of
ID	Depth (m)	Contact (m)	Thickness (m)	Borehole (m)
TN228	268.5	274.8	194.4	579.2
TN223	287.3	289.2	142.2	555.2
TN221	283.7	294.9	196.2	572.5
TN240	244.5	251.8	111.0	548.5
TN197	238.7	245.3	177.8	500.1
TN198	234.0	237.1	63.1	366.3
TN199	198.6	202.9	49.5	326.7
TN201	215.1	225.9	84.1	395.8
TN203	246.6	254.3	83.8	376.9
TN205	245.9	260.4	166.3	549.0

Table 4.1 Significant depths for the ten selected boreholes.



Figure 4.1(a). Simplified geological logs of the first five boreholes from Tweefontein North, along strike from north to south.



Figure 4.1(b). Geological logs of the second five boreholes along strike from north to south.

#### 4.2. TN228

#### 4.2.1. Stratigraphy

A simplified stratigraphic column of TN228 is given in Figure 4.2, which includes the 3E grade profile, minlog, significant stratigraphic positions and selected samples. The lowermost footwall lithology intersected in TN228 is banded iron formation (BIF) overlain by ~20 m of parapyroxenite. The uppermost 100 m of the footwall is predominantly composed of hornfels interlayered with parapyroxenite and calcsilicate. Numerous thin layers of fine-grained melanorite sills, ranging between 0.2 m and 4 m in thickness, were observed within the footwall, some of which were confirmed petrographically to be recrystallised norite. A distinct increase in igneous lithologies relative to metasedimentary lithologies marks the bottom Platreef contact (~469 m).

The Platreef in TN228 is ~194 m thick with an igneous to metasedimentary ratio of ~2.6. The ~176 m thick lower Platreef contains numerous metasedimentary interlayers of parapyroxenite, hornfels and calcsilicate, one of which is ~40 m thick. This large metasedimentary interlayer is composed of hornfels (~25 m) overlain by calcsilicate (~15 m) and contains a few feldspathic pyroxenite layers (<2.7 m in thickness). The lithologies of the lower Platreef comprise mostly coarse-grained feldspathic pyroxenite and melanorite with minor harzburgite and pegmatoidal feldspathic pyroxenite. The upper Platreef constitutes the top ~18 m of the igneous package and is predominantly composed of pyroxenite with a serpentinised harzburgitic layer at its base. Hornfels rafts are sporadically present in the upper Platreef. Thin quartz-feldspar veins occur throughout the Platreef in this borehole. The Platreef lithologies occurring in TN228 are medium to highly altered in places primarily associated with harzburgites and metasedimentary interlayers.

The borehole core between the hanging wall lithologies and the Platreef was broken so the top Platreef contact could not be defined. Anorthosite is the immediate hanging wall to the Platreef, which is gradationally replaced by a norite after 0.7 m above the Platreef contact.



Figure 4.2. Simplified geological log of TN228 highlighting major stratigraphic positions. FW = footwall; L = lower Platreef; U = upper Platreef; HW = hanging wall. Graphs showing the down-hole 3E grade profile and the BMS mineralisation log (Minlog) are included. Figures in bold to the left of the lithological log are the samples selected for this borehole defined by depth below surface. For lithological key, see Figure 4.1.

#### 4.2.2. Mineralisation

The BMS present in the footwall and Platreef sequences are primarily interstitial with an average of ~1 mass percent in the Platreef. There is a relative increase in the BMS content in the upper Platreef with a peak of ~20 % found in a footwall parapyroxenite.

The 3E grade trend shows that the Platreef at TN228 contains significant PGE grade closely associated with thin igneous layers within or close to metasedimentary interlayers/xenoliths. A notable amount of PGE grade also occurs in the top ~25 m of the reef.

## 4.2.3. Sampling

Ten samples were chosen from TN228, highlighted in Figure 4.2. Table 4.2 lists the sample name, description and an estimate of the degree of alteration ranging between 1 (little or no alteration) and 5 (completely altered). This sample suite is diverse, including rare mineralised calcsilicate and hornfels interlayers and highly serpentinised igneous and metasedimentary lithologies. A parapyroxenite interlayer and two recrystallised norite samples within the footwall were also included.

Table 4.2. Samples selected from TN228 showing the lithological type and an estimate of the degree of alteration.

Sample Name	Sample description	Degree of alteration
TN228_9	Pyroxenite	3
TN228_20	Serpentinised harzburgite	4
TN228_65	Calcsilicate	2
TN228_81	Hornfels	1
TN228_123	Feldspathic pyroxenite	4
TN228_149	Feldspathic pyroxenite	3
TN228_185	Serpentinised parapyroxenite	4
TN228_201	Feldspathic pyroxenite	2
TN228_247	Recrystallised norite	1
TN228_253	Recrystallised norite	2

## 4.3. TN223

## 4.3.1. Stratigraphy

Figure 4.3 displays a simplified stratigraphic column of TN223, including the 3E grade profile, minlog, significant stratigraphic positions and selected samples. A BIF is the lowermost lithology intersected overlain by a ~20 m thick parapyroxenite layer. The overlying ~70 m of metasedimentary footwall comprises thick layers of hornfels and parapyroxenite with calcsilicate becoming significant towards the base of the Platreef at ~431 m. A ~6 cm thick massive sulphide layer is present at a depth of ~498 m, ~67 m below the bottom Platreef contact.

The Platreef in TN223 is ~142 m thick with an igneous to metasedimentary ratio of ~10.8. The lower Platreef relates to the bulk of the Platreef sequence from the bottom Platreef contact to the base of a pegmatoidal feldspathic pyroxenite layer at ~314 m. The package is predominantly composed of feldspathic pyroxenite and melanorite with minor layers of pyroxenite, norite and pegmatoidal feldspathic pyroxenite. Two calcsilicate layers are present within this sequence at depths of 394-402 m and 345-350 m. A ~0.9 m highly chloritised shear zone is situated at ~315 m. The ~26 m thick upper Platreef is marked by a basal ~4 m

thick pegmatoidal feldspathic pyroxenite layer, which is capped by two ~10 cm thick chromitite layers. A ~0.4 m thick granitic vein occurs within the pegmatoidal feldspathic pyroxenite unit. The remainder of the upper Platreef comprises homogeneous coarse-grained pyroxenite. Alteration has not significantly affected the Platreef in TN223, although localised chloritisation and serpentinisation are observed.

A sharp top Platreef contact exists between pyroxenite and anorthosite, assigned to the Main Zone.



Figure 4.3. Simplified geological log of TN223 highlighting major stratigraphic positions. FW = footwall; L = lower Platreef; U = upper Platreef; HW = hanging wall; MSL = massive sulphide layer; Cr = chromitite layer. Graphs showing the down-hole 3E grade profile and the BMS mineralisation log (Minlog) are included. Figures in bold to the left of the lithological log are the samples selected for this borehole defined by depth below surface. For lithological key, see Figure 4.1.

## 4.3.2. Mineralisation

The BMS present in the footwall and Platreef sequences are primarily interstitial. A thin (~6 cm thick) massive sulphide layer is present in the footwall, ~67 m below the bottom Platreef contact, but is not associated with any PGE grade. The percentage of BMS present down sequence is ~2 % on average. Two thin chromitite layers, hosted in pyroxenite, are situated ~25 m below the top Platreef contact.

The 3E grade trend shows that the grade is primarily top-loaded, associated with the chromitite layers and underlying pegmatoidal feldspathic pyroxenite, although an increase in grade occurs from the mid-Platreef towards the bottom Platreef contact. No significant 3E grade is found in the footwall.

## 4.3.3. Sampling

Eleven samples were chosen from TN223 (Figure 4.3). Table 4.3 lists the sample name, description and an estimate of the degree of alteration ranging between 1 (little or no alteration) and 5 (altered). The sample suite is dominated by various igneous lithologies, including the chromitite layer and a sample hosting a granitic vein.

Table 4.3. Sa	amples s	elected	from <sup>·</sup>	TN223	showing t	ne lithol	ogical	type	and a	an	estimate	of t	he (	degree
of alteration.	-						-							
	-										_			

Sample ID	Sample description	Degree of alteration
TN223_8	Pyroxenite	1
TN223_23	Feldspathic pyroxenite hosting a chromitite layer.	2
TN223_25	Pegmatoidal feldspathic pyroxenite and a granitic vein (~0.4 m)	1
TN223_35	Norite	1
TN223_40	Pegmatoidal norite	1
TN223_77	Feldspathic pyroxenite and pegmatoidal feldspathic pyroxenite	2
TN223_103	Pegmatoidal feldspathic pyroxenite	1
TN223_135	Pegmatiodal norite	1
TN223_147	Norite	1
TN223_156	Melanorite	1
TN223_161	Parapyroxenite	2

## 4.4. TN221

## 4.4.1. Stratigraphy

A simplified stratigraphic column of TN221 is given in Figure 4.4, which includes the 3E grade profile, minlog, significant stratigraphic positions and selected samples. The lowermost footwall intersected is a BIF overlain by a hornfels layer ~71 m in thickness. The hornfels layer includes a ~4 m thick parapyroxenite layer at a depth of 528-532 m and five thin granitic

veins (0.14-1 m in thickness) which crosscut the stratigraphy. The bottom Platreef contact is situated at a depth of ~496 m.



Figure 4.4. Simplified geological log of TN221 highlighting major stratigraphic positions. FW = footwall; L = lower Platreef; U = upper Platreef; HW = hanging wall; MSL = massive sulphide layer; Cr = chromitite layer. Graphs showing the down-hole 3E grade profile and the BMS mineralisation log (Minlog) are included. Figures in bold to the left of the lithological log are the samples selected for this borehole defined by depth below surface. For lithological key, see Figure 4.1.

In TN221, the Platreef is ~196 m thick with an igneous to metasedimentary ratio of ~3.9. Two massive sulphide layers, ~20 cm in thickness, mark the base of the lower Platreef which has a thickness of ~171 m. The massive sulphide layers are overlain by ~30 m of parapyroxenite and fine-grained noritic sills petrographically classified as recrystallised norites. The remaining lower Platreef is composed of feldspathic pyroxenite, melanorite with minor pyroxenite and pegmatoidal feldspathic pyroxenite. Metasedimentary interlayers of hornfels, up to 5 m in thickness, and numerous thin (<1 m) layers of calcsilicate and parapyroxenite occur towards the base of the lower Platreef. As in TN223, the upper Platreef, at a depth of

~295-320 m, is composed of a ~4 m thick pegmatoidal feldspathic pyroxenite layer, overlain by a ~7 cm thick disseminated chromitite layer, followed by ~20 m of homogeneous pyroxenite. Alteration has not significantly affected the Platreef in TN221.

A sharp top Platreef contact exists with an anorthosite assigned to the Main Zone.

#### 4.4.2. Mineralisation

The BMS present in the footwall and Platreef sequences are primarily interstitial with an average of ~2 % in the Platreef. Two ~20 cm thick net-textured sulphide layers are situated at the base of the lower Platreef associated with basal recrystallised norite units. A chromitite layer, ~7 cm in thickness, is situated ~20 m below the top Platreef contact.

A top-loaded 3E grade trend is observed mainly associated with a chromitiferous package at the base of the upper Platreef. The remainder of the Platreef has intermittent PGE mineralisation, with a relatively significant PGE concentration linked to the basal net-textured sulphide layers.

## 4.4.3. Sampling

Eleven intersections were chosen from TN221, highlighted in Figure 4.4. Table 4.4 lists the sample name, description and an estimate of the level of alteration ranging between 1 (little or no alteration) and 5 (altered). As in TN223, the chromitite layer was sampled as well as various igneous lithologies. Three recrystallised norite samples, one of which is host to a massive sulphide layer, were included in the sample suite.

Sample name	Sample description	Degree of alteration
TN221_11	Pyroxenite	1
TN221_25	Feldspathic pyroxenite hosting a chromitite layer	1
TN221_28	Serpentinised feldspathic harzburgite	1
TN221_33	Feldspathic pyroxenite	1
TN221_65	Pegmatoidal feldspathic pyroxenite	1
TN221_73	Feldspathic pyroxenite and pegmatoidal feldspathic pyroxenite	1
TN221_185	Recrystallised norite	2
TN221_196	Recrystallised norite	2
TN221_204	Recrystallised norite hosting a massive sulphide layer (~0.4 m)	2
TN221_264	Parapyroxenite	1

Table 4.4. Samples selected from TN221 showing the lithological type and an estimate of the degree of alteration.

#### 4.5. TN240

#### 4.5.1. Stratigraphy

Figure 4.5 presents a simplified stratigraphic column of TN240, including the 3E grade profile, minlog, significant stratigraphic positions and selected samples. The lowermost footwall intersected is a BIF overlain by a ~180 m thick metasedimentary package of hornfels, calcsilicate and parapyroxenite. Two fine-grained noritic sills occur at depths of 464-472 m and 481-491 m, one of which was petrographically confirmed to be recrystallised norite. A pink granitic layer (~9 m thick) crosscuts the footwall lithologies close to the base of the Platreef at a depth of ~363 m. Three net-textured and massive sulphide layers, <50 cm in thickness, are present within the footwall, one of which is hosted in recrystallised norite.

The ~111 m thick Platreef in TN240 has an igneous to metasedimentary ratio of ~12.9. The lower Platreef is  $\sim 81$  m in thickness and is feldspathic pyroxenite-rich with lesser melanorite, pyroxenite and pegmatoidal feldspathic pyroxenite. Serpentinite layers are sporadically present in this subdivision ranging between 0.3-1.7 m in thickness. A ~0.9 m shear zone is present at a depth of ~336 m. Two calcsilicate interlayers (<5 m), are found near the top of the lower Platreef. The ~30 m thick upper Platreef is dominated by pyroxenite and minor pegmatoidal feldspathic pyroxenite and melanorite, with a ~4 cm disseminated chromitite layer at ~21 m below the top Platreef contact. Unlike TN221 and TN223 where a chromitite caps a pegmatoidal feldspathic pyroxenite unit, the chromitite layer in TN240 is underlain by heterogeneous feldspathic pyroxenite until a calcsilicate interlayer. The close proximity of the calcsilicate interlayer may have played a role in its uncharacteristic development. A thin (~5 cm thick) massive sulphide layer is located close to the top Platreef contact. Localised chloritisation and serpentinisation are observed, usually associated the with metasedimentary interlayers.

A sharp top Platreef contact exists with an anorthosite assigned to the Main Zone.

#### 4.5.2. Mineralisation

The BMS present in the footwall and Platreef sequences are primarily interstitial. Four massive sulphide layers are present in TN240, three of which occur in the footwall closely associated with the recrystallised noritic sills and one  $\sim$ 5 cm net-textured sulphide layer situated close to the top Platreef contact. The percentage of BMS present in the Platreef is  $\sim$ 3 % on average. A chromitite layer is situated  $\sim$ 25 m below the top Platreef contact.

The 3E grade trend shows that the grade is top loaded, closely associated with the chromitite layer and underlying lithologies. The 3E grade tapers off towards the bottom Platreef contact with two significant grade peaks at ~80 m and ~100 m into the footwall associated with recrystallised noritic sills.



Figure 4.5. Simplified geological log of TN240 highlighting major stratigraphic positions. FW = footwall; L = lower Platreef; U = upper Platreef; HW = hanging wall; MSL = massive sulphide layer; Cr = chromitite layer. Graphs showing the down-hole 3E grade profile and the BMS mineralisation log (Minlog) are included. Figures in bold to the left of the lithological log are the samples selected for this borehole defined by depth below surface. For lithological key, see Figure 4.1.

#### 4.5.3. Sampling

Ten intersections were chosen from TN240, the positions of which are highlighted in Figure 4.5. Table 4.5 lists the sample name, description and an estimate of the degree of alteration ranging between 1 (little or no alteration) and 5 (altered). In addition to various igneous

lithologies, the sample suite includes two footwall parapyroxenite samples and a recrystallised norite sample, which is host to a massive sulphide layer.

Table 4.5. Samples selected from TN240 showing the lithological type and an estimate of the degree of alteration.

Sample ID	Sample description	Degree of alteration
TN240_6	Pyroxenite	1
TN240_22	Pyroxenite	2
TN240_25	Pegmatoidal feldspathic pyroxenite	1
TN240_46	Feldspathic pyroxenite	1
TN240_53	Melanorite	1
TN240_71	Pegmatoidal feldspathic pyroxenite	1
TN240_89	Melanorite	1
TN240_144	Parapyroxenite	3
TN240_214	Recrystallised norite hosting a massive sulphide layer (~0.5 m)	2
TN240_231	Parapyroxenite	2

#### 4.6. TN197

#### 4.6.1. Stratigraphy

A simplified stratigraphic column of TN197 is given in Figure 4.6, which includes the 3E grade profile, minlog, significant stratigraphic positions and selected samples. The lowermost footwall intersected is a BIF overlain by a ~72 m thick parapyroxenite unit. A ~15 m thick hornfels layer is situated within the footwall parapyroxenite. The bottom Platreef contact is situated at a depth of ~423 m.

In TN197, the ~178 m thick Platreef has an igneous to metasedimentary ratio of ~7.7. The ~153 m thick lower Platreef is primarily composed of feldspathic pyroxenite and lesser pyroxenite and pegmatoidal feldspathic pyroxenite. A ~4 cm thick massive sulphide layer occurs ~16 m above the bottom Platreef contact. Interlayers of calcsilicate and parapyroxenite are found within this sequence near the base of the lower Platreef as well as a crosscutting ~9 m thick, pink granitic vein. The upper Platreef is characterised by a ~6 m thick basal pegmatoidal feldspathic pyroxenite layer, overlain by ~16 m of homogeneous coarse-grained pyroxenite. The upper Platreef is similar to that of TN223 and TN221, but does not contain a chromitite layer. The lithologies in TN197 are relatively unaltered.

A sharp top Platreef contact exists with an anorthosite assigned to the Main Zone.



Figure 4.6. Simplified geological log of TN197 highlighting major stratigraphic positions. FW = footwall; L = lower Platreef; U = upper Platreef; HW = hanging wall; MSL = massive sulphide layer. Graphs showing the down-hole 3E grade profile and the BMS mineralisation log (Minlog) are included. Figures in bold to the left of the lithological log are the samples selected for this borehole defined by depth below surface. For lithological key, see Figure 4.1.

#### 4.6.2. Mineralisation

The BMS present in the footwall and Platreef sequences primarily occur either as sporadic small blebs or as an interstitial network. A massive sulphide layer, ~4 cm thick, is present ~16 m above the bottom Platreef contact. The percentage of BMS present in the Platreef is ~2 % on average.

The 3E grade is top loaded, with the highest 3E grades situated in the upper Platreef. By a depth of 430 m, the 3E grade tapers off to less than 1 g/t with a small increase at ~45 m into the footwall.

#### 4.6.3. Sampling

Table 4.6 lists the ten selected samples, highlighted in Figure 4.6, including the sample name, description and an estimate of the degree of alteration ranging between 1 (little or no alteration) and 5 (altered). The selected igneous lithologies include a harzburgite sample, whilst the metasedimentary lithologies are represented by a calcsilicate interlayer near the base of the reef and footwall parapyroxenite.

Table 4.6. Samples selected from TN197 showing the lithological type and an estimate of the degree of alteration.

Sample ID	Sample description	Degree of alteration
TN197_8	Pyroxenite	1
TN197_23	Harzburgite	3
TN197_32	Melanorite	1
TN197_47	Feldspathic pyroxenite and pegmatoidal feldspathic pyroxenite	1
TN197_54	Melanorite	1
TN197_70	Pegmatoidal feldspathic pyroxenite	1
TN197_88	Feldspathic pyroxenite and pegmatoidal feldspathic pyroxenite	1
TN197_145	Feldspathic pyroxenite	1
TN197_161	Calcsilicate	3
TN197_246	Parapyroxenite	1

## 4.7. TN198

## 4.7.1. Stratigraphy

Figure 4.7 displays a simplified stratigraphic column of TN198, including the 3E grade profile, minlog, significant stratigraphic positions and selected samples. The lowermost footwall lithology intersected is a BIF overlain by a ~45 m thick parapyroxenite unit beneath the basal Platreef contact at a depth of ~300 m.

In TN198, the Platreef is relatively thin with a thickness of ~63 m and an igneous to metasedimentary ratio of ~23.8. The ~32 m thick lower Platreef is predominantly composed of feldspathic pyroxenite, norite and melanorite. Parapyroxenite interlayers, which contain significant visible interstitial feldspar, and granitic veins (0.1-1 m in thickness) are common in the lower Platreef. The upper Platreef contains a ~3 m thick serpentinised pegmatoidal feldspathic pyroxenite layer capped by a ~2 cm thick disseminated chromitite layer, followed by ~28 m of feldspathic pyroxenite. Unlike the upper Platreef in boreholes from Tweefontein North, the homogeneous pyroxenite unit has been replaced by feldspathic pyroxenite which is variable in grain size and feldspar content. The lithologies in TN198 have not been affected by significant alteration.

A sharp top Platreef contact exists with an anorthosite assigned to the Main Zone. The anorthosite unit transitionally changes into a norite after 0.7 m.



Figure 4.7. Simplified geological log of TN198 highlighting major stratigraphic positions. FW = footwall; L = lower Platreef; U = upper Platreef; HW = hanging wall; Cr = chromitite layer. Graphs showing the down-hole 3E grade profile and the BMS mineralisation log (Minlog) are included. Figures in bold to the left of the lithological log are the samples selected for this borehole defined by depth below surface. For lithological key, see Figure 4.1.

#### 4.7.2. Mineralisation

The BMS present in the footwall and Platreef sequences are primarily interstitial. The percentage of BMS present in the Platreef is ~1 % on average. A 2 cm chromitite layer is situated ~28 m below the top Platreef contact.

The 3E grade profile is middle- to bottom-loaded from the chromitiferous layer to ~8 m within the footwall.

## 4.7.3. Sampling

Eight samples were chosen from TN198 (Figure 4.7). The eight selected intersections are listed in Table 4.7 providing the sample name, description and an estimate of the degree of alteration ranging between 1 (little or no alteration) and 5 (altered). Due to the grade distribution and relatively thin reef in this area, only three igneous lithologies were selected, one of which hosts a chromitite layer. The majority of the samples are parapyroxenite interlayers and footwall parapyroxenite.

Table 4.7. Samples selected from TN198 showing the lithological type and an estimate of the degree of alteration.

Sample ID	Sample description	Degree of alteration
TN198_32	Feldspathic pyroxenite hosting a chromitite layer	1
TN198_34	Pegmatoidal feldspathic pyroxenite	2
TN198_46	Melanorite	1
TN198_55	Parapyroxenite (Contains feldspathic inclusions)	3
TN198_62	Parapyroxenite (Contains feldspathic inclusions)	2
TN198_69	Parapyroxenite (Contains feldspathic inclusions)	2
TN198_75	Parapyroxenite (Contains feldspathic inclusions)	1
TN198_78	Parapyroxenite	1

## 4.8. TN199

#### 4.8.1. Stratigraphy

A simplified stratigraphic column of TN199 is given in Figure 4.8, which highlights the 3E grade profile, minlog, significant stratigraphic positions and selected samples. The lowermost footwall lithology intersected is a BIF overlain by a ~60 m thick parapyroxenite layer, which is host to a number of crosscutting granitic veins, ranging from 0.1 to 1.5 m in thickness. The base of the Platreef is situated at ~251 m.

The Platreef in TN199 is only ~49 m thick with a breccia zone located at the top Platreef contact. The igneous to metasedimentary ratio is high at ~59.0. The Platreef sequence is relatively simple comprising a noritic lower Platreef and an upper Platreef of heterogeneous feldspathic pyroxenite. A ~1 m thick calcsilicate layer and a number of 0.1-0.3 m thick quartz-feldspar veins crosscut the stratigraphy within the lower Platreef. The lithologies in TN199 are relatively unaltered.

The top Platreef boundary is broken and marked by a ~1.8 m thick breccia zone, thought to represent a fault situated in the central Tweefontein area, highlighted in Figure 3.1.

The hanging wall lithology is leuconorite assigned to the Main Zone.



Figure 4.8. Simplified geological log of TN199 highlighting major stratigraphic positions. FW = footwall; L = lower Platreef; U = upper Platreef; HW = hanging wall. Graphs showing the down hole 3E grade profile and the BMS mineralisation log (Minlog) are included. Figures in bold to the left of the lithological log are the samples selected for this borehole defined by depth below surface. For lithological key, see Figure 4.1.

#### 4.8.2. Mineralisation

The BMS present in the footwall and Platreef sequences are primarily interstitial with an average of ~2 % in the Platreef. The BMS mineralisation in TN199, however, is primarily situated in the footwall parapyroxenite unit.

The 3E grade profile illustrates that the grade in TN199 is situated in the upper Platreef with very little grade below.

## 4.8.3. Sampling

Six samples were chosen from TN199 (Figure 4.8). Table 4.8 gives the sample name, description and an estimate of the degree of alteration ranging between 1 (little or no alteration) and 5 (altered). The majority of the grade and selected samples occur in the upper Platreef, composed of feldspathic pyroxenite
Table 4.8. Samples selected from	TN199 showing the lithologica	I type and an e	estimate of the o	degree
of alteration.				-

Sample ID	Sample description	Degree of alteration
TN199_3	Feldspathic pyroxenite (directly after breccia zone)	3
TN199_7	Feldspathic pyroxenite	2
TN199_19	Feldspathic pyroxenite	1
TN199_24	Feldspathic pyroxenite	2
TN199_30	Feldspathic pyroxenite	1
TN199_60	Parapyroxenite	2

#### 4.9. TN201

#### 4.9.1. Stratigraphy

Figure 4.9 presents a simplified stratigraphic column of TN201, incorporating the 3E grade profile, minlog, significant stratigraphic positions and selected samples. The lowermost footwall lithology intersected is a BIF. This is overlain a ~46 m thick parapyroxenite unit, which is host to a ~3 m thick granitic vein, near its base, and a ~5 m thick calcsilicate layer close to the basal Platreef contact at ~310 m.

In TN201, the ~84 m thick Platreef has an igneous to metasedimentary ratio of ~8.5. The lower Platreef consists of a complex interlayering of melanorite, feldspathic pyroxenite, pegmatoidal feldspathic pyroxenite and norite with an overlying homogeneous feldspathic pyroxenite unit ~16 m in thickness. Metasedimentary interlayers of parapyroxenite and calcsilicate are found near the base of the lower Platreef. The upper Platreef is dominated by homogenous pyroxenite. Localised chloritisation and serpentinisation are observed near the base of the Platreef in TN201.

The Platreef is in sharp contact with the hanging wall consisting of norite, varying in grain size, assigned to the Main Zone.

#### 4.9.2. Mineralisation

BMS present in the footwall and Platreef sequences are primarily interstitial. The BMS mineralisation in the Platreef is  $\sim$ 2 % on average with an increase in BMS mineralisation (up to  $\sim$ 25 %) in the BIF footwall.

TN201 has an intermittent grade profile throughout the Platreef with a significant kick at the bottom Platreef contact, tapering off into the footwall.



Figure 4.9. Simplified geological log of TN201 highlighting major stratigraphic positions. FW = footwall; L = lower Platreef; U = upper Platreef; HW = hanging wall. Graphs showing the down hole 3E grade profile and the BMS mineralisation log (Minlog) are included. Figures in bold to the left of the lithological log are the samples selected for this borehole defined by depth below surface. For lithological key, see Figure 4.1.

#### 4.1.1. Sampling

Figure 4.9 highlights the positions of the eight samples from TN201, whilst Table 4.9 lists the sample name, description and an estimate of the degree of alteration ranging between 1 (little or no alteration) and 5 (completely altered). The selected igneous samples are evenly distributed down sequence with three parapyroxenite samples in or close to the footwall.

Sample description	Degree of alteration
Pyroxenite	1
Feldspathic pyroxenite. ~2m below a granitic vein	1
Feldspathic pyroxenite	1
Pegmatoidal feldspathic pyroxenite	3
Pegmatoidal feldspathic pyroxenite	1
Parapyroxenite	1
Parapyroxenite	2
Parapyroxenite	1
	Sample description Pyroxenite Feldspathic pyroxenite. ~2m below a granitic vein Feldspathic pyroxenite Pegmatoidal feldspathic pyroxenite Parapyroxenite Parapyroxenite Parapyroxenite

Table 4.9. Samples selected from TN201 showing the lithological type and an estimate of the degree of alteration.

#### 4.2. TN203

#### 4.2.1. Stratigraphy

A simplified stratigraphic column of TN203 is given in Figure 4.10, which includes the 3E grade profile, minlog, significant stratigraphic positions and selected samples. The footwall consists of a BIF overlain by a ~12 m thick parapyroxenite unit. Two parapyroxenite layers (<5 m thick) occur within the BIF footwall. The base of the Platreef is at a depth of ~338 m.

In TN203, the Platreef reaches a thickness of ~84 m and has an igneous to metasedimentary ratio of ~5.0. The lower Platreef is composed of feldspathic pyroxenite followed by melanorite, which is overlain by a complex unit (~31 m in thickness) of interlayered pegmatoidal feldspathic pyroxenite, melanorite, feldspathic pyroxenite, norite, harzburgite and serpentinite. Finally a ~5 m thick, pink granitic vein marks the top of the lower Platreef. A number of metasedimentary interlayers of parapyroxenite (<3 m thick) and hornfels (<0.6 m thick) occur in the lower Platreef but are primarily located near its base. A 20 cm thick nettextured sulphide layer occurs at a depth of ~307 m. The upper Platreef constitutes ~15 m of pyroxenite and feldspathic pyroxenite units. The lithologies in TN203 have not been affected by significant serpentinisation and chloritisation, although an increase is observed in the complex interlayered section.

The Platreef is in sharp contact with the hanging wall of anorthosite assigned to the Main Zone.

#### 4.2.2. Mineralisation

The BMS present in the footwall and Platreef sequences are primarily interstitial with an average of ~2 % in the Platreef. A ~20 cm thick net-textured massive sulphide layer is situated ~31 m above the bottom Platreef contact, but is not associated with significant PGE grade.

TN203 has a middle-loaded 3E grade profile associated with the unit of complex interlayering.



Figure 4.10. Simplified geological log of TN203 highlighting major stratigraphic positions. FW = footwall; L = lower Platreef; U = upper Platreef; HW = hanging wall; MSL = massive sulphide layer. Graphs showing the down hole 3E grade profile and the BMS mineralisation log (Minlog) are included. Figures in bold to the left of the lithological log are the samples selected for this borehole defined by depth below surface. For lithological key, see Figure 4.1.

#### 4.2.3. Sampling

Six samples from the lower Platreef were chosen from TN203. Table 4.10 lists the sample name, description and an estimate of the degree of alteration ranging between 1 (little or no alteration) and 5 (completely altered). Contrary to previous boreholes, TN203 does not contain grade in the upper Platreef or footwall which were therefore not sampled.

Table 4.10. Samples selected from	TN203 showing the lithological	type and an estimate	of the degree
of alteration.			-

Sample ID	Sample description	Degree of alteration
TN203_33	Pegmatoidal feldspathic pyroxenite and feldspathic pyroxenite	1
TN203_39	Serpentinised feldspathic harzburgite	2
TN203_44	Serpentinised feldspathic pyroxenite	2
TN203_55	Serpentinised melanorite	4
TN203_60	Melanorite	2
TN203_65	Melanorite	2

#### 4.3. TN205

#### 4.3.1. Stratigraphy

Figure 4.11 incorporates a simplified stratigraphic column of TN205 as well as the 3E grade profile, minlog, significant stratigraphic positions and selected samples. The lowermost footwall lithology intersected is a BIF overlain by a ~118 m thick Duitschland hornfels unit with minor parapyroxenite. A ~20 cm thick massive sulphide layer is present ~2 m below the bottom Platreef contact, which occurs at ~427 m.

The Platreef in TN205 is ~166 m thick with an igneous to metasedimentary ratio of ~2.3. The ~121 m thick lower Platreef consists of pegmatoidal feldspathic pyroxenite, feldspathic pyroxenite, pyroxenite and serpentinite. The package is sulphide-rich and is host to five massive sulphide layers between 0.2-2.7 m in thickness. A ~16 m thick granitic vein as well as numerous thin granitic veins crosscut the stratigraphy. Numerous parapyroxenite layers ranging between 0.2-9 m are present within the lower Platreef. The ~45 m thick upper Platreef unit is marked by a basal harzburgite, ~17 m in thickness, overlain by layers of feldspathic pyroxenite layers and granitic veins are present in the upper Platreef. The Platreef. The Platreef. The Platreef. The Platreef. The metasedimentary interlayers.

A sharp contact exists between the Platreef and the anorthosite assigned to the Main Zone.

#### 4.3.2. Mineralisation

The footwall and Platreef lithologies are relatively enriched in BMS in this area. They are primarily interstitial, net-textured or massive with five massive and net-textured sulphide layers present near the base of the Platreef. Excluding the massive sulphide layers, the Platreef still has an average BMS content of ~4 %.

The 3E grade profile for TN205 is intermittent throughout the Platreef with the highest 3E grade associated with the harzburgite unit found at the base of the upper Platreef.



Figure 4.11. Simplified geological log of TN205 highlighting major stratigraphic positions. FW = footwall; L = lower Platreef; U = upper Platreef; HW = hanging wall; MSL = massive sulphide layer. Graphs showing the down-hole 3E grade profile and the BMS mineralisation log (Minlog) are included. Figures in bold to the left of the lithological log are the samples selected for this borehole defined by depth below surface. For lithological key, see Figure 4.1.

#### 4.3.3. Sampling

Nine were selected from the lower Platreef, highlighted in Figure 4.11. The assay data, supplied by Platinum, was not available at the time of sampling which resulted in a sampling regime focussed on different rock types, degrees of alteration and abundance of sulphides.

Table 4.11 lists the sample name, description and an estimate of the degree of alteration ranging between 1 (little or no alteration) and 5 (completely altered). The sample suite includes relatively altered igneous and metasedimentary lithologies and a footwall hornfels sample.

Table 4.11. Samples selected from TN205 showing the lithological type and an estimate of the degree of alteration.

Sample ID	Sample description	Degree of alteration
TN205_55	Pyroxenite	4
TN205_64	Feldspathic pyroxenite	2
TN205_115	Feldspathic pyroxenite	4
TN205_147	Serpentinised feldspathic harzburgite	4
TN205_152	Parapyroxenite hosting a massive sulphide layer (~0.5 m)	2
TN205_160	Serpentinised parapyroxenite	5
TN205_167	Parapyroxenite hosting a massive sulphide layer (~0.05 m)	2
TN205_177	Parapyroxenite	1
TN205_185	Hornfels	1

#### 4.12. DISCUSSION

The stratigraphy and mineralisation vary considerably along the Tweefontein strike with major differences in Platreef thickness and down-hole base metal sulphide and 3E grade distribution. The Platreef thickness varies between ~111 m and ~196 m on Tweefontein North, between ~50 m and 84 m in the central Tweefontein area and increases to ~166 m at Tweefontein Hill. The differences in Platreef thickness may be due to irregular floor topography prior to the emplacement of the Platreef (White, 1994; Nex, 2005). The thin reef of the central Tweefontein area represents a topographic footwall high separating a structural depression at Tweefontein North and Tweefontein Hill. A structural downwarp, due to a south-west plunging fold, is believed to have affected the Platreef and Transvaal Supergroup rocks in the Tweefontein Hill area (Nex, 2005). A NNE-SSW trending fault, shown in Figure 3.1, crosscuts the central Tweefontein area. It is thought to be responsible for the breccia zone at the top Platreef contact in TN199. The hanging wall, which comprises anorthosites and norites are similar to those found in the Main Zone elsewhere in the Bushveld Complex and displays a sharp contact with the underlying Platreef.

The sampling regime employed during this study tried to capture the variation in mineralisation, along strike, with depth, in different lithologies and in proximity to geological features. This included intersections of different igneous lithologies, making up the bulk of the samples, and metasedimentary footwall lithologies and interlayers >1 g/t, excluding banded ironstone.

#### 4.1.1. Stratigraphy

The footwall comprises a metasedimentary package of hornfels, parapyroxenite and calcsilicate overlying banded ironstone. The Platreef along the strike of Tweefontein is believed to have intruded into shales and dolomites of the Duitschland Formation which overlie banded ironstone of the Penge Formation. Nex (2005) also assigned Duitschland Formation to the footwall lithologies at Tweefontein Hill. The metasedimentary footwall lithologies overlying the banded ironstone are relatively thick at Tweefontein North and Hill, reaching ~180 m, but are significantly thinner in the central Tweefontein area (<60 m thick), where the footwall package is devoid of hornfels. The narrowing of the metasedimentary package and the lack of hornfels in the central Tweefontein area further emphasizes a structural control, resulting in irregular floor topography, during the formation of the Transvaal Supergroup rocks underlying the Platreef.

The metasedimentary footwall lithologies may be intruded by thin noritic or pyroxenitic sills close to the bottom Platreef contact and/or granitic veins. The sampled noritic sills were classified as recrystallised norites from petrography, discussed in Chapter 3, and are thought to represent sills which pre-date the Platreef, which have been subsequently metamorphosed. These lithologies may correlate to the "Marginal Zone" norites found at Sandsloot (Yudovskaya and Kinnaird, 2010), at Tweefontein by Buchanan *et al.* (1981) and Nyama *et al.* (2005) and in the southern sector (Kinnaird *et al.*, 2005; Manyeruke *et al.*, 2005; Sharman-Harris *et al.*, 2005; Mothetha, 2006; Kekana *et al.*, 2011). In two boreholes from Tweefontein North net-textured or massive sulphide layers are hosted in recrystallised norites and are associated with increases in 3E grade. It is likely from the observed texture in hand specimen that a portion of the igneous layers in the footwall represent sills which intruded concurrently with the Platreef.

The Platreef lithologies in the studied boreholes are predominantly composed of feldspathic pyroxenite and melanorite with lesser pyroxenite, pegmatoidal feldspathic pyroxenite, feldspathic harzburgite, melanorite and norite. In addition, the Platreef contains serpentinite layers, granitic veins and metasedimentary rafts of parapyroxenite, hornfels and calcsilicate. A greater amount of ultramafic rocks are present in the Platreef to the south of Tweefontein (Kinnaird, 2005; Manyeruke *et al.*, 2005) with only minor ultramafic lithologies to the north on Sandsloot (Holwell *et al.*, 2006), Overysel (Holwell and McDonald, 2006) and Drenthe (Gain and Mostert, 1982). A complex interlayering of lithologies is not common, but is characteristic in TN228 and TN205 where there is an observed increase in metasedimentary interlayers

and harzburgite. Based on the stratigraphy and the 3E grade, the Platreef at Tweefontein was divided into an upper Platreef, which is located in the top 20-40 m of the Platreef, and a lower Platreef, which accounts for the bulk of the Platreef thickness. The Platreef lithologies do not demonstrate significant continuity across the studied boreholes except for two semicontinuous features in the upper Platreef. The first is the relatively homogenous pyroxenitic package comprising the majority of the upper Platreef, although this layer is less homogenous close to and at Tweefontein Hill. The second feature is a pegmatoidal feldspathic pyroxenite unit up to 6 m thick at the base of the upper Platreef, which may be capped by a chromitite layer in TN223, TN221, TN197 and TN198. It has been suggested that this feature resembles the Merensky Reef found elsewhere in the Bushveld Complex (e.g. White, 1994; Viljoen and Schürmann, 1998). Borehole TN240 does contain a chromitite layer in the upper Platreef, but is underlain by heterogeneous feldspathic pyroxenite layers and a calcsilicate interlayer. The presence of the calcsilicate interlayer in the upper part of the Platreef may have influenced the atypical development of the chromitiferous layer in this area. The characteristics of the upper Platreef, which include a basal chromitiferous package in some boreholes, imply that it may have formed from a separate intrusive sill compared to the lower Platreef.

The igneous to metasedimentary ratio is highest in TN199 at 59, where the Platreef package is at its thinnest and lowest in TN205 and TN228 at 2 and 3 respectively. Along strike from north to south, the metasedimentary rafts within the Platreef are predominantly hornfels and calcsilicate at Tweefontein North, parapyroxenite with minor calcsilicate in the central Tweefontein area and parapyroxenite near Tweefontein Hill. Whilst footwall interlayers are primarily found near the base of the Platreef, they may also occur in the middle and upper Platreef packages as seen in TN228, TN223 and TN240. The interlayers may have originated from the hanging wall or footwall rocks during the emplacement of the Platreef sills.

Generally the Platreef lithologies present in the studied boreholes are only slightly altered with localised increases of chloritisation and serpentinisation. However, lithologies in boreholes TN228 and TN205 show medium to high degrees of alteration, primarily serpentinisation, associated with the harzburgitic lithologies and metasedimentary interlayers.

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The whole rock and minor element geochemical data of the Platreef and footwall lithologies sampled during this study will be presented in Chapter 5. The geochemical investigation, in part, aims to confirm and further define the lithologies observed.

#### 4.1.2. Mineralisation

The BMS present in the footwall and Platreef lithologies are primarily interstitial. Massive and net-textured sulphide layers, primarily pyrrhotite, occur near the base of the Platreef and/or in the footwall in Tweefontein North, with numerous massive and net-textured sulphide layers found near the base of the Platreef at Tweefontein Hill. The development of massive and net-textured sulphide layers is due to the gravitational settling of sulphides as described at Tweefontein Hill by Nex (2005). Sulphide segregation however, could have involved a number of different processes such as an additional source of sulphur from the country rocks (Buchanan *et al.*, 1981; Sharman-Harris *et al.*, 2005), an increase the oxygen fugacity due to the devolatilisation of the country rocks (De Vaal, 1977) and the presence of iron-rich fluids which have been experimentally shown to dissolve more sulphur than iron-poor fluids (Buchanan and Nolan, 1979). The presence of PGE-poor net-textured and massive sulphides in the footwall at Tweefontein North emphasises the role of other processes, apart from primary magmatic sulphide segregation.

The 3E grade is generally top loaded primarily in the upper Platreef in the boreholes from Tweefontein North, middle-loaded in the boreholes from the central Tweefontein area and variable in the borehole from Tweefontein Hill with an increase near the upper Platreef and a notable amount of 3E grade associated with the basal massive and net-textured sulphides. Please note that in other studies at Tweefontein Hill, the PGE grade profile has been reported as relatively bottom-loaded (White, 1994, Nyama *et al.*, 2005). The PGE grade is associated with the chromitiferous package where developed at Tweefontein North, but starts higher up in the sequence when it is absent. There are significant increases in grade where igneous lithologies have intruded into metasedimentary interlayers as seen in boreholes TN228 and TN240. Buchanan *et al.* (1981) also noted an elevated grade associated with xenoliths of dolomite at Tweefontein. The presence of massive or nettextured sulphides does not necessarily indicate enrichment in PGE grade. A geochemical investigation presented in Chapter 5, includes PGE data provided by Platinum for each borehole as well as whole-rock geochemical data, which will provide more insight into the mineralisation style present.

# CHAPTER 5 WHOLE ROCK GEOCHEMISTRY

#### 5.1. INTRODUCTION

Whole rock major, minor and trace elements were analysed for the eighty-eight intersections sampled. The sample list and complete whole rock geochemical dataset is presented in Appendix I and IIIb respectively. The assay data, which includes Pt, Pd, Au, Cu and Ni from the ten studied boreholes, was provided by the platinum division of Anglo American. Important trends regarding the assay data will be highlighted in this chapter, but the PGE dataset will not be included in the appendices due to a confidentiality agreement. This geochemical investigation aims to confirm and further define the lithologies at Tweefontein and provide insight into the mineralisation style present.

The samples were analysed for whole-rock major, minor and trace elements using X-ray fluorescence (XRF). The analyses were conducted at the Earth Laboratory in the School of Geosciences at the University of the Witwatersrand. The sample preparation and methodology is given in Appendix IIIa.

#### 5.2. MAJOR AND MINOR ELEMENT GEOCHEMISTRY

Due to the variety of rock types found and sampled at Tweefontein, numerous binary plots were selected to define and characterise the lithologies present. The igneous lithologies were divided into samples from the upper and lower Platreef, as defined in Chapter 4, to highlight additional trends within the Platreef. The igneous lithologies do not display noteworthy geochemical differences along strike, hence this data is not presented. Selected binary plots of the major elements are given in Figure 5.1, whilst selected major and trace element binary plots are given in Figures 5.2 and 5.3. Typical MgO or FeO contents of olivine, orthopyroxene, clinopyroxene and cordierite as well as typical Al<sub>2</sub>O<sub>3</sub> contents of plagioclase and cordierite are indicated on the binary plots in Figure 5.1 where applicable. Figure 5.4 presents the whole rock Mg#, Cr(ppm)/MgO and Ti values against depth, highlighting downhole trends. The volatile content was measured for all samples and is expressed as loss of ignition, which is included in the geochemical dataset in Appendix IIIb. The geochemical data will be described in terms of igneous lithologies and metamorphic lithologies.



Figure 5.1. Binary plot of (a)  $AI_2O_3$  versus CaO, (b) FeO versus MgO, (c)  $AI_2O_3$  versus FeO and (d)  $AI_2O_3$  versus MgO for the sampled Tweefontein intersections. Also plotted are average compositions of olivine, orthopyroxene, clinopyroxene, plagioclase and cordierite where applicable.

#### Igneous lithologies

In general for the igneous samples, the aluminum, calcium and sodium contents reflect the modal proportion of feldspars whilst the MgO and FeO values reflect the modal proportion of pyroxene. These positive correlations are demonstrated in the binary plots of  $AI_2O_3$  versus CaO and FeO versus MgO in Figures 5.1(a) and (b). Figures 5.1(c) and (d) plot an inverse relationship between  $AI_2O_3$  and FeO as well as  $AI_2O_3$  and MgO, where the majority of the igneous lithologies plot along the orthopyroxene-plagioclase tieline. This trend highlights that the chemistry of the igneous lithologies are controlled by the relative proportions of orthopyroxene and feldspar. Igneous samples in Figure 5.1(d) containing relatively more clinopyroxene plot to the left of this tieline, whilst samples which contain olivine plot to the right of this tieline. These results indicate that only minor olivine is present in the intersections sampled. The harzburgitic samples have relatively high loss on ignition values

compared to the other igneous lithologies due to the presence of hydrous minerals such as serpentine, chlorite and amphibole.

The upper and lower Platreef samples show distinct differences. The upper Platreef exhibits relatively high MgO and FeO values presented in Figure 5.1(b), indicating a dominance of pyroxene in these samples. A good homogeneity is displayed by the upper Platreef compared to the more scattered lower Platreef lithologies, which have increased and variable feldspar contents, observed in Figure 5.1(a). A number of lower Platreef samples plot to the right of the plagioclase-orthopyroxene tieline in Figure 5.1(d), indicating a relative enrichment in iron. These samples either contain an elevated BMS content or may contain an increased amount of Fe-oxides or more Fe-rich silicate minerals.

A compatible relationship is demonstrated between the Cr and MgO values for the igneous samples given in Figure 5.2(a), excluding samples that contained cumulus chromite. This implies that Cr is mainly controlled by the pyroxene minerals. Samples from the upper Platreef contain the highest Cr values, further emphasising the relatively mafic nature of the upper Platreef.

Due to the sampling regime employed, all selected samples are mineralised. For this reason the majority of the Ni content occurs in base metal sulphides which will mask any Ni included in olivine and pyroxene. The broadly positive correlation between MgO and Ni, given in Figure 5.2(b), therefore indicates that the Ni content, which is linked to the BMS content, is loosely controlled by the modal proportion of pyroxene.

Positive correlations are observed between the trace elements of Sr and Ga with  $AI_2O_3$  in Figures 5.2(c) and (d). This relationship indicates that these traces elements are controlled by the feldspar content.

Figures 5.3(a) and (c) present the trace elements of Ti and Ba versus the cumulus components of MgO and CaO respectively. The trace elements of Ti, Ba as well as Y, Zr (not shown) are incompatible indicating that they are controlled by the intercumulus component. A positive correlation therefore exists between Ti and the trace elements of Y, Zr and Ba in Figures 5.3(d)-(f).



Figure 5.2. Binary plot of (a) Cr versus MgO, (b) Ni versus MgO, (c) Sr versus  $Al_2O_3$  and (d) Ga versus  $Al_2O_3$  for the sampled Tweefontein intersections. Note that the igneous samples with anomalously high Cr values, indicating cumulus chromite, were excluded from Figure 5.2(a).

The difference between the upper and lower Platreef is further highlighted by the whole rock Mg#, Cr(ppm)/MgO and Ti values plotted against depth, presented in Figure 5.4(a) to (c). The Mg# is generally between 60 and 70 for the upper and some lower Platreef samples but is distinctly lower, between 44 and 60 for most of the lower Platreef samples. The Cr(ppm)/MgO ratio demonstrates a similar trend with most of the upper and some lower Platreef samples attaining a Cr(ppm)/MgO ratio above 80, indicating Critical Zone affinity (Seabrook *et al.*, 2005), with a number of lower Platreef samples situated below 80. Figure 5.4(c) highlights a relative enrichment in Ti values in the metasedimentary lithologies, including recrystallised norite, compared to the igneous lithologies.



Figure 5.3. Binary plots of (a) Ti versus MgO, (b) Ti versus CaO, (c) Ba versus CaO, (d) Y versus Ti, (e) Zr versus Ti, (f) Ba versus Ti for the sampled Tweefontein intersections.



Metamorphic lithologies

Although the number of metamorphic samples is small, the geochemical data does show interesting trends. The metamorphic lithologies are set apart from the Platreef igneous lithologies by their low Cr, Mg#, Cr/MgO and elevated Ti values, highlighted in Figures 5.2(a), 5.4(a)-5.4(c). Apart from the parapyroxenite samples the loss on ignition values are generally higher for the metamorphic samples particularly the calcsilicates. Elevated Ni values, observed in Figure 5.2(b), are present in some metamorphic lithologies which are linked to samples containing massive or net-textured sulphide layers.

The geochemical data shows major differences between the recrystallised norite and the Platreef igneous samples. A significant Fe-enrichment characterises the recrystallised norite samples, highlighted in Figures 5.1(b) and 5.1(d). The factors contributing to the high Fe values are likely related to the presence of more Fe-rich silicate minerals and oxides as well

as a relatively high BMS content. In addition the recrystallised norite samples contain relatively high Ti and lower Mg# values, which align these samples with the metamorphic rather than igneous lithologies.

The parapyroxenite samples contain high calcium levels primarily due to the dominance of clinopyroxene, observed in Figure 5.1(a). An inverse correlation between Al<sub>2</sub>O<sub>3</sub> and MgO is demonstrated in Figure 5.1(c), where the parapyroxenite samples plot along the plagioclaseclinopyroxene tieline. This relationship indicates that the modal proportion of plagioclase and clinopyroxene control the chemistry in the parapyroxenite samples. Due to the presence of feldspar in the parapyroxenite rocks, Sr and Ga, which are controlled by feldspar, show positive correlations. A compatible relationship exists between Ti and CaO for the parapyroxenite samples in Figure 5.3(b), whilst Ba and CaO have an inverse correlation as shown in Figure 5.3(c). The trace elements of Ti, Y and Zr are compatible in the parapyroxenite samples and are therefore likely to be controlled by the clinopyroxene component in these rocks, whilst Ba is likely to be controlled by the interstice. A few samples do not follow the parapyroxenite trends described above and are linked to samples which contain significant BMS and/or alteration minerals.

The calcsilicate samples are shown to contain significant CaO within clinopyroxene, as highlighted in Figure 5.1(a). Elevated amounts of MgO in these samples may, in part, be due to serpentinisation, identified petrographically and in hand specimen. The hornfels are set apart from the other rock types due to the high Al content nearing the Al value for cordierite in Figure 5.1(a). The hornfels sample which has a lower Al value and an elevated in Fe content (Figure 5.1(b)) can be correlated to a significant BMS content in this sample. The trace elements of Ti, Y and Zr observed in Figures 5.3(d) and 5.3(e) highlight compositional differences between the hornfels and calcsilicate samples from interlayers close to the top Platreef contact compared to hornfels and calcsilicate layers sampled in or close to the footwall. This highlights that different layers from the Duitschland Formation, in which the Platreef intruded, may have different geochemical characteristics.

#### 5.3. BASE METAL AND PGE MINERALISATION

The Ni and Cu content of the sampled lithologies is linked to the base metal sulphide component present. Figure 5.5 presents binary plots of certain trace elements with Ni, thus highlighting their relationship with the base metal sulphides. Figure 5.6 focuses on the relationship between the 3E (Pt+Pd+Au) grade and the base metal sulphides, whilst Figure 5.7 illustrates the downhole assay trends of Pt, Pd, Au, Pt/Pd, Ni, Cu and Ni/Cu values,

supplied by Platinum, for a borehole from Tweefontein North, the central Tweefontein area and Tweefontein Hill.

Cu and Ni have a compatible relationship for the majority of the lithologies but in some metamorphic footwall rocks, there are Cu-rich and Ni-poor versus Ni-rich and Cu-poor areas. This is thought to indicate the remobilisation of Cu over Ni, due to late-stage magmatic or hydrothermal processes (Armitage *et al.*, 2002). The strong correlation between Cu, Co and Se with Ni, observed in Figures 5.5(a) to (c), reflects the presence of these elements in pyrrhotite, pentlandite and chalcopyrite. Pb, Bi and Zn have broadly positive correlations with Ni, presented in Figures 5.5(d) to 5.5(f), and are likely to occur in the trace minerals of galena, bismuthinite and sphalerite respectively. These above mentioned trends are not as well defined in the metamorphic lithologies implying that other controls are responsible for the distribution of these trace elements in addition to a base metal sulphide influence.

Platinum and palladium have a closely compatible relationship in the igneous lithologies and a broader correlation in the metamorphic lithologies, highlighted in Figure 5.6(a). The igneous samples which deviate to the right of the general correlation are from the upper Platreef, implying that more Pt-rich areas are found in the upper Platreef. This is further evidenced by higher Pt/Pd ratios present in the upper Platreef, 1.3 on average, ranging between 0.7 and 2.2, whilst samples from the lower Platreef have a Pt/Pd ratio of 0.8 on average, ranging between 0.3 and 1.4. The metamorphic lithologies have similar average Pt/Pd ratios to that of the lower Platreef, but show a broader variation between 0.1 and 2.7. Hydrothermal fluids are thought to play an important role in the redistribution of PGE, often creating lower Pt/Pd ratios in altered areas and in the footwall. This trend was reported to the south of Tweefontein (Hutchinson and Kinnaird, 2005; Kinnaird, 2005; Manyeruke *et al.*, 2005) and at Sandsloot to the north (Armitage *et al.*, 2002; Holwell *et al.*, 2006).



Figure 5.5. Binary plots of (a) Cu versus Ni, (b) Co versus Ni, (c) Se versus Ni, (d) Pb versus Ni, (e) Bi versus Ni and (f) Zn versus Ni. All plots display positive correlations, except Zn versus Ni in Figure 5.5(f).



Figure 5.6. Binary plots of (a) Pd versus Pt, (b) Au versus Pt, (c) Ni versus Pt, (d) Cu versus Pt, (e) Pd versus Ni and (f) Pd versus Cu. The data presented was provided by the platinum division of Anglo American. The Pt, Pd and Au values have been excluded due to requested confidentiality. All plots demonstrate strongly or broadly compatible relationships.



Figure 5.6 Cont. Binary plots of (g) Ni versus Au and (h) Cu versus Au. All plots demonstrate broadly compatible relationships. The Au values have been excluded due to requested confidentiality.

The relationship between Au and Pt in the igneous lithologies is broadly positive, as seen in Figure 5.6(b), although some samples from the upper Platreef have an incompatible relationship due to relatively elevated Au amounts. Au and Pt are incompatible in the metamorphic lithologies. The Cu and Ni are broadly compatible with Pt, Pd and Au, illustrated in Figures 5.6(c) to 5.6(h), for a large portion of the analysed samples. There are a group of samples, primarily from the footwall, which display high Ni and Cu values relative to PGE values. These samples host massive sulphide layers, highlighting the presence of PGE-poor massive sulphide layers in the footwall. In contrast, a portion of samples, primarily from the upper Platreef or from metasedimentary interlayers found close to the upper Platreef, contain high PGE values with poor corresponding Cu and Ni values.

The Pt and Pd distribution through the Platreef sequence and footwall, presented in Figure 5.7, is top loaded at Tweefontein North and the central Tweefontein area, primarily associated with the chromitiferous layer at Tweefontein North. Tweefontein Hill has a relatively variable grade distribution with a significant increase associated with a harzburgitic layer ~50 m below the top Platreef contact and near the base of the Platreef linked to abundant net-textured and massive sulphide layers. An intermittent grade distribution was also noted in boreholes from the central Tweefontein area towards Tweefontein Hill, as described in Chapter 4.

Generally, the downhole assay trends (see Figure 5.7) demonstrate good PGE and BMS (Cu+Ni) associations, but the relative concentrations between the PGE and BMS do however vary creating high-grade PGE zones, with poor BMS values and vice versa. As shown by the

binary plots, the PGE-rich and BMS-poor areas are usually in the upper Platreef along the Tweefontein strike, with basal BMS-rich and PGE-poor areas close to and in the footwall confirming the deductions from the binary plots above.



Figure 5.7. Down hole assay values of Pt, Pd, Au, Pt/Pd, Cu, Ni and Ni/Cu for a borehole from Tweefontein North, the central Tweefontein area and Tweefontein Hill including the geological logs. Note that there are sporadic assay samples missing from the Tweefontein Hill borehole dataset.

The Pt/Pd ratios indicate a Pt dominant upper Platreef (>1) with Pd-dominant PGE concentrations below and into the footwall (<1), although there are sporadic increases in the Pt/Pd ratio in places lower in the sequence, but these are usually in places of low grade. The

Pt/Pd profile at Tweefontein is very similar to that found by Kinnaird (2005) and Hutchinson and Kinnaird (2005) to the south of Tweefontein, where the distinct and elevated Pt/Pd values near the top of the Platreef are likely to represent a different sill intrusion. Although this Pt/Pd trend is observed at Tweefontein Hill, the majority of the PGE grade is found in the lower Platreef, implying a more Pd-dominant mineralisation compared to Tweefontein North where the majority of the grade is in the upper Platreef. In contrast, Overysel has very little variation in Pt/Pd values with depth demonstrated by Holwell and McDonald (2006), although this study only included two boreholes.

There is a dominance of Ni over Cu in the Tweefontein Platreef and footwall lithologies. This is in line with that found elsewhere along the Platreef strike (Kinnaird, 2005; Hutchinson and Kinnaird, 2005; Holwell and McDonald, 2006). Tweefontein North and central Tweefontein display higher Ni/Cu values in the upper Platreef, generally >2, decreasing towards the footwall. In addition, Tweefontein Hill demonstrates intermittent increases in the Ni/Cu ratio through the sequence, particularly associated with the net-textured and massive sulphides near the base of the reef. In contrast, Kinnaird (2005) and Hutchinson and Kinnaird (2005) showed higher Ni/Cu ratios in the upper Platreef, displaying the same trend as the Pt/Pd ratio profile.

#### 5.4. DISCUSSION

The analytical data shows that the chemistry of the igneous and parapyroxenite lithologies is controlled by the relative proportions of pyroxene and feldspar, with a dominance of orthopyroxene and clinopyroxene for the igneous and parapyroxenite samples respectively. Those samples that deviate from chemical trends defined by pyroxene and feldspar chemistry are either enriched in base metal sulphides, alteration minerals and/or Fe-rich silicate and oxide minerals.

The abundance of feldspar in the parapyroxenites from Tweefontein has not been previously described in parapyroxenites from elsewhere in the Platreef. Parapyroxenites found at Sandsloot are believed to have formed from the contact metamorphism of calcsilicates and contain relatively low Cr values indicating a non-igneous genesis (Harris and Chaumba, 2001). The parapyroxenites at Tweefontein demonstrate similar characteristics as those from Sandsloot but some contain higher Cr and Ti contents closer associated with values from igneous lithologies, suggesting a closer link to an igneous genesis.

The Duitschland calcsilicate and hornfels interlayers, located near the top of the Platreef package, give slight compositional differences compared to those located in the footwall. This indicates that separate layers of the Duitschland Formation, into which the Platreef at Tweefontein intruded, are not the same. The impact of these differences to the observed lithologies and mineralisation is unknown, but should be considered. Kinnaird (2005) also highlighted that country rock formed the hanging wall to the Platreef prior to Main Zone emplacement, which implies that xenoliths may have been derived from the hanging wall as well as the footwall lithologies.

Nyama *et al.* (2006) describes an interaction or basal Platreef unit at Tweefontein Hill, which is characterised by a lower Mg# and Na<sub>2</sub>O values and higher TiO<sub>2</sub> values, which is comparable to the recrystallised norite samples and some samples from the base of the lower Platreef at Tweefontein. It is probable that an increase in the Fe content in the recrystallised norite samples and samples from the lower Platreef are linked to pyroxenes relatively enriched in Fe and/or Fe-Oxides. The basal Fe-rich characteristics may be due to the original composition of the basal sill intrusions and/or a basal interaction zone, whereby Fe-rich fluids, from the BIF footwall rocks, may have influenced the observed assemblages (Buchanan *et al.*,1981). On a global scale, the presence of more evolved Fe-rich chill margins at the base of mafic and ultramafic intrusive bodies was noted by Latypov *et al.* (2007), although the mechanism is still unclear.

The upper and lower Platreef lithologies exhibit geochemical differences, particularly evidenced by higher Mg#, Cr, Cr (ppm)/MgO and Pt/Pd values in the upper Platreef. Previous detailed geochemical studies at Tweefontein Hill (Nyama *et al.*, 2006) and to the south of Tweefontein (Hutchinson and Kinnaird, 2005; Kinnaird, 2005; Manyeruke *et al.*, 2005) revealed compositional breaks in the Platreef sequence thought to represent distinct sill-like intrusions. They reported a more primitive sill at the top of the Platreef, similar to that observed in the upper Platreef at Tweefontein. The lower Platreef is therefore likely to represent a different sill intrusion. Due to non-continuous sporadic sampling involved in this study, it is difficult to establish if the lower Platreef could be derived from more than one sill intrusion.

The Cr/MgO ratio of >80 was used by Seabrook *et al.* (2005) to characterise Critical Zone magmas in the eastern and western limbs of the Bushveld Complex. At Tweefontein, most of the upper and some lower Platreef intersections have Cr/MgO values above 80, indicating

Critical Zone affinity, with a number of lower Platreef samples situated below 80, which may, in part, be due to different sill intrusions or contamination of the magma from floor rocks.

The broadly positive correlation of base metal sulphides with the pyroxene component of the igneous lithologies is noteworthy. The Ni/Cu ratios generally increase from the footwall to the top of the Platreef (>2) at Tweefontein North and central Tweefontein, whilst Tweefontein Hill demonstrates intermittent increases in the Ni/Cu ratio particularly associated with the nettextured and massive sulphides near the base of the reef. The Ni/Cu profile does not illustrate breaks in the sequence to indicate differing sills as is displayed by the distinct Ni/Cu profile to the south of Tweefontein (Kinnaird, 2005; Hutchinson and Kinnaird, 2005). Overysel, however, did not show any systematic Ni/Cu ratio variation with depth (Holwell and McDonald, 2006). The PGE grade from Tweefontein North and the central Tweefontein area is primarily top loaded in the upper Platreef moving into a more variable, top- and bottomloaded PGE grade distribution close to and at Tweefontein Hill where significant basal nettextured and massive sulphides carry notable PGE grade. The PGE concentrations are generally well correlated with the base metal sulphides in the Platreef and metamorphic lithologies to a lesser extent. Relative concentrations do however vary creating high-grade PGE, generally in the upper Platreef and high grade BMS regions, commonly near the base of the Platreef in Tweefontein North and Hill.

The Pt/Pd ratios indicate a Pt dominant upper Platreef with an average Pt/Pd value of 1.3, whilst the lower Platreef and footwall lithologies are more Pd-dominant with an average Pt/Pd value of 0.8. Although the lower Platreef and footwall lithologies have similar average Pt/Pd ratios, the footwall values show a wider variation thought to be related to increased hydrothermal fluid activity. The PGE mineralisation associated with Tweefontein North and the central Tweefontein area is relatively Pt-dominated, as most of the grade is in the upper Platreef, whilst Tweefontein Hill is defined by Pd-dominant mineralisation located lower down in the sequence. Wood (2002) highlighted that the mobility of Pt and Pd by hydrothermal fluids is poorly understood, but will depend on the fluid chemistry. In the Platreef, it has been proposed that Pd is more mobile than Pt due to lower Pt/Pd ratios in altered areas and in the footwall at Sandsloot, (Armitage *et al.*, 2002; Holwell *et al.*, 2006), Turfspruit (Hutchinson and Kinnaird, 2005; Kinnaird, 2005) and Townlands (Manyeruke *et al.*, 2005), which is further supported by this study.

The bulk modal, BMS and detailed PGM mineralogy for a subset of samples, is presented in Chapter 6. This information provides significant insight into the PGM deportment and the processes involved in the PGE mineralisation in the Platreef at Tweefontein.

## **CHAPTER 6**

## BULK MODAL, BASE METAL SULPHIDE AND PLATINUM-GROUP MINERAL MINERALOGY

#### 6.1. INTRODUCTION

A detailed mineralogical analysis was undertaken on a subset of forty-nine samples using automated scanning electron microscope (SEM) technologies, namely QEMSCAN and the Mineral Liberations Analyser (MLA). A list of samples and associated rock types is given in Appendix IVa, whilst the automated SEM techniques are described in Appendix IVc. Between four and six samples were chosen from each borehole ensuring a diversity of rock types, including varying alteration levels and samples associated with granitic veins. The rock type groups, including the number of samples is given in Table 6.1. The bulk modal and base metal sulphide (BMS) mineralogy was investigated using QEMSCAN whilst the platinum-group minerals (PGM) were examined by the MLA. The bulk modal, the BMS and PGM type, association and grain size were determined.

Rock types	No. of samples
Norites	13
Pyroxenites	13
Harzburgites	3
Recrystalised norites hosting massive sulphides	2
Parapyroxenite	14
Calcsilicate	2
Hornfels	2
Total	49

Table 6.1 Forty-nine samples listed in relevant geological groups.

The samples were crushed to -425  $\mu$ m or -3 mm and prepared into between 6 to18 polished blocks for analysis on the automated SEM instruments. The analysis of particulate material improves sample representivity compared to the analysis of larger intact rock samples and the crush size of -3 mm still retains the PGM mineral association data.

Due to the amount and complexity of the data produced, only the summarised information and trends will be presented in this chapter whilst the full bulk modal, BMS and PGM datasets are presented in Appendices IVd, IVe and IVf respectively.

#### 6.2. BULK MODAL MINERALOGY

The bulk modal results are quantitative reaching ~100 000 X-ray spot analyses per sample. This data represents some of the first information on the quantitative bulk modal mineralogy of the Platreef rock types. The bulk mineralogy is summarised and described in terms of the igneous lithologies, which include norites, pyroxenites and harzburgites, and metamorphic footwall lithologies, which include recrystallised norites, parapyroxenites, calcsilicates and hornfels.

The summarised bulk modal mineralogy for the igneous lithologies is given in Table 6.2. The data is reported as ranges in mineral mass percent based on the samples occurring in each rock type group. A typical modal composition for each igneous lithological group is graphically represented in Figure 6.1.

Table 6.2 Summarised bulk modal for the three igneous lithologies given in mineral mass percent ranges, including the number of samples in each group.

Mineral	Norites	Pyroxenites	Harzburgites
BMS	1-10	1-7	2-6
Orthopyroxene	17-61	38-71	30-46
Clinopyroxene	4-20	6-19	4-15
Olivine	-	-	1-3
Feldspar	22-50	6-22	2-26
Talc	0-1	0-2	1-4
Serpentine	0-1	0-1	15-26
Amphibole	0-1	0-2	1-3
Chlorite	1-4	0-10	3-11
Mica	0-4	1-3	1-3
Garnet	0-1	0-1	0-1
Quartz	0-9	0-7	0-1
Fe-oxides	0-4	0-1	0-3
AI oxides	0-3	-	-
Chromite	0-1	0-21	0-2
Carbonates	0-1	0-1	0-2
Other Minerals	0-1	0-1	0-1
No. of samples	11	12	3

There are between one and five noritic and pyroxenitic samples from each borehole, which allows for a good igneous lithological comparison along strike. The noritic and pyroxenitic samples, which are relatively unaltered, are dominated by orthopyroxene and feldspar with minor clinopyroxene. Varying amounts of chromite occur in three pyroxenitic intersections which were host to thin chromitite layers identified in the borehole core. The noritic and pyroxenitic samples have BMS contents ranging between 1 to 10 %. The alteration minerals, which include chlorite, amphibole, talc and serpentine, constitute ~4 mass percent on average, but can reach up to 13 mass percent. Minor and accessory minerals are quartz, micas, iron-oxides, carbonates and garnet. Quartz and chlorite are present in almost all the igneous samples, but are slightly elevated in the five igneous samples from borehole TN199.

The three harzburgitic samples are similar to the noritic and pyroxenitic lithologies, but contain a significantly higher amount of alteration minerals, particularly serpentinite, reaching  $\sim$ 27 %, with lesser chlorite. The olivine content is relatively low between 1-3 %, but is likely to have been higher prior to serpentinisation.



Figure 6.1. A typical bulk modal for the norite, pyroxenite and harzburgite lithologies from Tweefontein as analysed by the QEMSCAN instrument. The igneous lithologies are dominated by orthopyroxene and feldspar with minor clinopyroxene. The harzburgite samples contain additional serpentine with lesser Fe-oxides and olivine.

The bulk modal analyses of the four metamorphic footwall lithologies are given in Table 6.3. The recrystallised norite, parapyroxenite and calcsilicate data is reported as ranges in mineral mass percent based on samples occurring in this group, whilst the two hornfels samples are reported separately due to the major differences observed. A typical modal composition for each metamorphic lithological group is graphically represented in Figure 6.2.

Mineral	Recrystallised norite	Parapyroxenite	Calcsilicate	Hornfels interlayer	Hornfels footwall
BMS	41-49	2-17	1-3	2	27
Orthopyroxene	17-61	1-9	2-6	<1	18
Clinopyroxene	4-20	25-82	32-38	<1	ND
Olivine	ND	0-4	ND	ND	<1
Feldspar	22-50	3-48	2-7	4	3
Talc	0-1	<1	<1	<1	<1
Serpentine	0-1	<1	23-38	<1	ND
Amphibole	0-1	1-4	2-6	<1	<1
Chlorite	1-4	1-4	1	<1	2
Mica	0-4	0-6	<1	4	2
Garnet	0-1	0-6	14-18	1	4
Cordierite	ND	ND	ND	83	27
Quartz	0-9	0-2	ND	<1	0
Fe-oxides	0-4	0-2	ND	<1	5
Al-oxides	0-3	ND	ND	<1	8
Chromite	0-1	<1	ND	3	ND
Carbonates	0-1	<1	ND	<1	ND
Other Minerals	0-1	0-2	ND	2	3
No of samples	11	8	2	1	1

Table 6.3 Bulk modal mineralogy of the four metamorphic lithologies. The recrystallised norite, parapyroxenite and calcsilicate data is reported as ranges in mineral mass percent based on samples occurring in this group, whilst the two hornfels samples are reported separately.

The two recrystallised norite samples, from the immediate footwall, are host to massive sulphide layers and have bulk mineralogies dominated by BMS with lesser feldspar and Ferich orthopyroxene. The alteration minerals are minor, primarily chlorite. Minor and accessory minerals are Fe-oxides, quartz, garnet and micas. The high BMS content, Fe-rich orthopyroxene and presence of iron-oxide and garnet set these samples apart from the primary norite samples described in Table 6.2.

The majority of the parapyroxenite samples are unaltered, primarily composed of clinopyroxene and feldspar, which commonly have elevated amounts of BMS when compared to the igneous lithologies. Uncharacteristic parapyroxenite samples were observed, including a sample containing significant quartz at ~32 % (TN197) and a sample hosting a massive sulphide layer at ~63 % BMS (TN205). Four of the parapyroxenite samples were altered, two of which were serpentinised constituting ~20 % and ~50 % serpentine minerals respectively (TN228 and TN205), whilst the other two samples contained elevated amounts of amphibole at ~17 % each (TN223 and TN201). Only the unaltered parapyroxenite samples were used to calculate the results reported in Table 6.3.

Although one calcsilicate interlayer occurs near the top and the other near the base of the Platreef, the bulk modal composition of both interlayers is very similar. The bulk composition is dominated by clinopyroxene, serpentine and garnet with minor BMS (1-3 %), amphibole, orthopyroxene and feldspar.

The bulk mineralogies of the two hornfels samples highlight significant differences. The first is derived from an interlayer near the top Platreef package and is composed of cordierite (>80 %) with minor feldspar, mica, Fe-oxides and BMS (~2 %). The second hornfels sample occurs in the footwall and includes a ~25 cm thick massive sulphide layer. It is predominantly composed of cordierite, significant BMS (~27 %) and iron-rich orthopyroxene with lesser Al-oxides, Fe-oxides, garnet, feldspar, mica and chlorite. It appears that although this sample was logged and petrographically determined as hornfels, it is likely to be a mixture of hornfels and possibly recrystallised norite due to the high Fe-rich orthopyroxene and BMS content as well as the presence of Fe-oxides and garnet.



Figure 6.2. Typical bulk modal mineralogy for the recrystallised norite, parapyroxenite, calcsilicate and hornfels lithologies from Tweefontein, analysed by the QEMSCAN instrument. The recrystallised norites contain abundant BMS, Fe-rich orthopyroxene and feldspar. The parapyroxenite and calcsilicate lithologies are dominated by clinopyroxene but the parapyroxenite usually contains significant feldspar whilst calcsilicate contains significant garnet and is serpentinised.

#### 6.3. BASE METAL SULPHIDE MINERALOGY

The BMS data generated includes the BMS distribution and association, derived from the analysis of two polished blocks per sample. The sample crush size used to produce the polished blocks was optimised for PGM analysis, but not for BMS analysis. For this reason, the association data is merely qualitative and the BMS grain size data was not included.

#### 6.3.1. BMS distribution

Both the igneous and metamorphic samples are predominantly composed of pyrrhotite, pentlandite, chalcopyrite and lesser pyrite. Accessory phases identified include galena, gersdoffite and sphalerite. The BMS distribution is variable, highlighting trends with depth and host rock type.

Although samples are limited, the Platreef igneous lithologies show a change in BMS distribution with depth. The pyrrhotite content generally increases towards the bottom Platreef contact, which is often associated with an increase in BMS abundance. This trend is clearly evident in borehole TN223, which contains five Platreef igneous samples and one parapyroxenite sample. Figure 6.3 shows the BMS abundance and distribution of the six samples from TN223 as well as the stratigraphic location of the samples.

The metamorphic footwall samples of recrystallised norite, parapyroxenite and hornfels are generally dominated by pyrrhotite, some of which are host to massive sulphide layers. Figure 6.3 includes one parapyroxenite sample (TN223\_161) highlighting a pyrrhotite dominant BMS distribution. Pyrite is significant in a few of the parapyroxenite samples. The BMS distribution of both calcsilicate samples is similar, but distinct compared to the other studied samples. The calcsilicate samples, although low in BMS content, are dominated by pyrite and chalcopyrite with lesser millerite.

#### 6.3.2. BMS association

The qualitative BMS association shows trends which are specific to host rock type and level of alteration. The BMS present in the noritic and pyroxenitic lithologies are primarily associated with feldspar and lesser orthopyroxene and quartz. An example of BMS hosted in an interstitial assemblage of feldspar and quartz is given in Figure 6.4(a). Quartz is the dominant BMS association mineral in the pyroxenitic samples from TN199, which correlates to an increase in bulk modal quartz content. The BMS from the serpentinised harzburgitic lithologies are additionally associated with serpentine, depending on the degree of serpentinisation.



Figure 6.3. BMS abundance and distribution of the six samples from TN223, including the sample name, defined by the depth below the top Platreef contact, and whether the sample is an igneous lithology (i) or a parapyroxenite (p). The BMS and pyrrhotite is enriched in samples close to and in the Platreef footwall compared to near the top of the Platreef package.

The BMS found in the parapyroxenite samples is primarily associated with clinopyroxene and feldspar. The serpentinised parapyroxenite sample displays an additional BMS serpentine association, which is highlighted in Figure 6.4(b). Similarly, both serpentinised calcsilicate samples have a BMS association dominated by serpentine as well as garnet. The BMS association of the two hornfels samples are notably different. The hornfels sample near the top Platreef contact has a strong cordierite-BMS association, whilst the BMS in the footwall hornfels is primarily associated with Fe-rich orthopyroxene and feldspar with a minor Al-oxide and cordierite association. Figure 6.4(c) shows BMS blebs within a cordierite particle from the hornfels interlayer.



Figure 6.4. (a) BMS hosted in an interstitial assemblage of feldspar and quartz bounded by orthopyroxene from a feldspathic pyroxenite, sample TN199\_7. (b) BMS hosted in clinopyroxene and serpentine alteration from a serpentinised parapyroxenite, sample TN205\_160. (c) Cordierite particle host to fine BMS blebs from the hornfels interlayer, sample TN228\_81.

### 6.4. PLATINUM-GROUP METAL MINERALOGY

The PGM were measured from 6-18 polished blocks depending on the PGE grade. The PGM distribution, grain size and association were determined. Approximately 100 particles hosting PGM were analysed for each sample resulting in an average of ~190 PGM per sample. The total number of PGM analysed was 9217 providing one of the most comprehensive PGM study along the Platreef to date.

The PGM analysed were divided into twelve groups, based on the PGE present and the dominant associated element/s. Table 6.4 lists the twelve groups, in order of abundance, including the area percent PGM and number of grains analysed for each group. For the purpose of this study, electrum was included as a PGM.

PGM	Area percent	No. of grains
Pd-Te-bismuthides	37.3	4267
Pt-arsenide	20.7	1223
Pt-Bi-tellurides	17.8	1436
Pt-Pd-Bi-tellurides	8.3	531
Pd-Te-Sb-bismuthides	4.0	289
Electrum (AuAg)	3.8	712
PGE-sulphides	3.0	172
Pd-antimonides	2.5	328
PGE-sulpharsenides	2.0	199
Pt-antimonides	0.3	51
Pd-Hg-telluride	0.3	8
Pd-selenide	<0.1	1
Total	100.0	9217

Table 6.4 List of summarised PGM groups including the overall area % and number of grains analysed in this study.

The PGM data will be presented using area percent, which is the preferred method due to errors associated with using number of grains. This is clearly demonstrated by the PGM groups Pt-antimonides and Pd-Hg-telluride as they have the same area percent value, but contain a significantly different number of grains. The PGM assemblages at Tweefontein are dominated by Pt- and Pd-bismuthides and -tellurides as well as Pt-arsenide. It is important to note that in addition to fine-grained examples, Pt-arsenides are often relatively coarse-grained, highlighted in Figure 6.6 (b), which may bias the data. The minor PGM are Pd-Te-Sb-bismuthides, electrum, PGE-sulphides, Pd-antimonides and PGE-sulpharsenides with rare PGM being Pt-antimonides, Pd-Hg-telluride and Pd-selenide. As with other PGM studies (Holwell *et al.*, 2006; Holwell and McDonald, 2007), PGM containing Os were not identified, but Ir-, Ru- and Rh-bearing sulpharsenides were identified.

The PGM assemblages vary according to different lithologies and along strike within the same lithology. The major trends observed at Tweefontein can be grouped into (i) igneous, (ii) felsic fluid-affected igneous and (iii) metamorphic lithologies.

#### 6.4.1. Igneous lithologies

The relevant igneous samples from each borehole indicate that the PGM assemblage appears to be similar in the Platreef igneous lithologies with depth, although samples from

the upper Platreef contain increased Pt-bearing PGM as indicated by a higher Pt/Pd ratio. The igneous samples from each borehole could therefore be averaged and are presented in Figure 6.5. The igneous lithologies display differences along strike defining three PGM assemblage groups.

The first group occurs only at Tweefontein North in boreholes where a distinct package, comprising a 3-6 m thick pegmatoidal feldspathic pyroxenite which may be capped by a chromitite layer, marks the base of the upper Platreef. The PGM assemblage is dominated by Pt- and Pd-tellurides and -bismuthides and to a lesser extent PGE-sulphides, Pt-arsenide and electrum. Please note that the PGE-sulphides group includes a few laurite (Ru-sulphide) particles in the samples containing the chromitite stringer.

The second group includes boreholes from the central Tweefontein area as well as two boreholes from Tweefontein North where the distinct package was either not developed or not typically developed. The PGM assemblage is devoid of PGE-sulphides and is dominated by Pt- and Pd-tellurides and -bismuthides, which may have relatively elevated amounts of Pt-arsenide. Large Pt-arsenide grains were found in borehole TN240, but due to the relatively low Pt/Pd ratio, this is likely to be a nugget affect. The Pt-arsenide content generally increases in the igneous lithologies from central Tweefontein. Please note that a chromitiferous package is developed in a borehole from central Tweefontein (TN198) but the PGM assemblage does not contain PGE-sulphides and falls into group 2.

The third group consists of one sample from Tweefontein Hill which is predominantly composed of Pd-Te-Sb-bismuthides with lesser Pd-bismuthides, Pt-arsenides, Pt-antimonides, PGE-sulpharsenides, Pt-tellurides, electrum and Pd-antimonides.

The PGM grain size of the igneous samples varies between 7-83 µm and is ~18 µm on average. The increased grain sizes observed in some samples generally correlate to an increase in Pt-arsenide content, whilst no significant grain size trends are observed for the other PGM types. In the igneous lithologies, the PGM are primarily associated with magmatic silicates, which are usually in close proximity to sulphide grains, on the grain boundary or included in BMS, and the interstitial minerals of feldspar and quartz. Figures 6.6 (a)-(c) are back-scattered electron (BSE) images of PGM hosted within or on the boundary of BMS and orthopyroxene. Figure 6.6 (d) shows very fine-grained Pt-arsenide mineralisation on the grain boundary between BMS and secondary amphiboles, indicating possible redistribution by hydrothermal fluids. The partially serpentinised igneous samples have an additional PGM-serpentine association directly dependant on the degree of serpentinisation.


Figure 6.5. Geological log and associated average igneous PGM assemblage for each borehole along strike. The igneous PGM assemblage group assigned to each borehole is indicated. Pt- and Pd-tellurides and -bismuthides dominate all PGM assemblages, with GRP 1, 2 and 3 having charcatristic PGE-sulphides, elevated amounts of Pt-arseinde and Sb- and As-bearing PGM respectively.



Figure 6.6. BSE image of (a) Pt-Bi-telluride rimming a chalcopyrite (cpx) grain hosted within orthopyroxene (opx), sample TN221\_25. (b) Large Pt-arsenide grain hosted within pyrrhotite (pyrr), sample TN199\_7. The pyrrhotite is undergoing alteration to an amphibole (amp). (c) Pt-bismuthide and Pt-arsenide associated with pentlandite (ptl), quartz (qtz) and orthopyroxene, TN223\_40. (d) Very fine-grained Pt-arsenide particles on the pentlandite and amphibole grain boundary, TN205\_55. (e) Pd-Te-bismuthide (all bright particles) hosted in quartz and chlorite (chl), sample TN223\_25. (f) Pt-arsenide hosted in pentlandite (felsic fluid-affected pyroxenite), sample TN199\_3. The pentlandite is undergoing alteration by an amphibole and is affected by quartz which has an intrusive nature.

### 6.4.2. Felsic fluid-affected igneous lithologies

This category includes two samples closely associated with granitic veins and a number of samples, which have been affected by a felsic melt, particularly samples from TN199 where a breccia zone is present at the top Platreef contact. In both cases the mineralisation characteristics are similar and uncharacteristic of Platreef lithologies in general.

One of the granitic vein associated samples contains a ~40 cm thick granitic vein and feldspathic pyroxenite, whilst the other is a feldspathic pyroxenite sample situated ~2 m below a granitic vein. Both samples are dominated by Pd-Te-bismuthides and to a lesser extent Pt-arsenides and Pt-Bi-tellurides. One of the samples had a high Pt-arsenide content, attributed to two large particles. However, this intersection has a Pt/Pd ratio of <1 and hence the high Pt-arsenide content was considered to be a nugget effect. It is unclear if the granitic vein hosted any PGE grade as it was not sampled separately. The PGM grains are primarily associated with quartz and to a lesser extent magmatic and alteration silicates and BMS. Figure 6.6(e) is a BSE image from the sample containing a granitic vein showing numerous Pd-Te-bismuthide particles within quartz and chlorite. The quartz often displays an invasive texture, whereby the felsic fluid intruded into already crystallised or partially crystallised assemblages.

The samples affected by a felsic melt are dominated by Pt-arsenide and lesser Pd-Tebismuthides. These samples are from the upper Platreef in the central Tweefontein area and have relatively high Pt/Pd ratios. It's interesting to note that the Pt occurs as arsenides instead of the characteristic tellurides. The PGM grains are hosted in magmatic silicates, BMS and quartz, where the quartz again displays an invasive texture. Figure 6.6(f) highlights the invasive nature of quartz in these samples.

The average PGM grain size is relatively coarse in these intersections, but this is due to the increased amount of coarser-grained Pt-arsenide.

### 6.4.3. Metamorphic lithologies

Figure 6.7 graphically presents a typical PGM assemblage for recrystallised norite, parapyroxenite and the two calcsilicate and hornfels samples.

The two recrystallised norite samples, host to massive sulphide layers, have a PGM assemblage dominated by Pd-Te-bismuthides and lesser Pt-arsenides. The PGM are predominantly associated with BMS and to a lesser extent clinopyroxene. Figure 6.8(a) highlights the strong PGM-BMS association with Pd-bismuthide occurring on a grain



boundary between pentlandite and pyrrhotite. The recrystallised norite samples are host to similar sized PGM to those found in the igneous lithologies.

Figure 6.7. Typical PGM assemblages found in recrystallised norites, parapyroxenites, two calcsilicate interlayers from the top and base of the platreef, a hornfels interlayer and footwall hornfels. The metamorphic samples, except for the calcsilicate interlayers, are dominated by Pd-Te-bismuthides and lesser Pt-arsenides and Pt-Bi-tellurides. Pd-antimonides are significant in the calcsilicate interlayers where rare PGM such as Pd-Hg tellurides and Pd-selenides are present.

The parapyroxenite samples are dominated by Pd-bismuthides, which may contain tellurium. Pt-arsenide becomes significant in the four parapyroxenite samples from TN198 and from a highly serpentinised parapyroxenite sample. Generally Pd-Te-Sb-bismuthides, Pd-antimonides and PGE-sulpharsenides become significant in parapyroxenite samples from central Tweefontein and Tweefontein Hill although the parapyroxenite sample from borehole TN240 from Tweefontein North also contains significant Pd-Te-Sb-bismuthides. The PGM in the parapyroxenites are associated with BMS and clinopyroxene and lesser garnet and alteration silicates. The PGM-garnet association was significant in some samples.



Figure 6.8. BSE image of (a) Pd-bismuthide on a pentlandite (ptl) and pyrrhotite (pyrr) grain boundary, sample TN221\_204 (recrystallised norite). (b) Pt-arsenide found along a veinlet of pyrrhotite hosted in clinopyroxene, sample TN223\_161 (parapyroxenite). (c) Pd-bismuthide and Bi metal in clinopyroxene, sample TN198\_78 (parapyroxenite). (d) Fine Pt-Bi-telluride associated with garnet and serpentine in close proximity to pyrite particles, sample TN228\_65 (calcsilicate interlayer). (e) Pd-Te-bismuthide, which appears to have been re-mobilised by chlorite alteration, sample TN199\_60 (parapyroxenite). (f) Pd-Te-bismuthide hosted within serpentine, sample TN205\_160 (serpentinised parapyroxenite).

The PGM grain size for the parapyroxenites is between 5-64  $\mu$ m and 14  $\mu$ m on average. The larger grain sizes are again linked to increases in coarser-grained Pt-arsenide. Figures 6.8(b) and (c) are examples of PGM hosted in clinopyroxene. Note the presence of native bismuth in close proximity to the Pd-bismuthide in Figure 6.8(c). BSE images from parapyroxenite samples of PGM hosted in alteration minerals of chlorite and serpentine are observed in Figures 6.8(d) and (e) respectively. This highlights the redistribution of PGM by hydrothermal fluids.

The two serpentinised calcsilicate interlayers from Tweefontein North have different PGM assemblages and are host to the rare PGM found at Tweefontein. The first serpentinised calcsilicate interlayer was sampled from the upper part of the Platreef sequence. Its PGM assemblage comprises Pt-Pd-Bi-tellurides with lesser Pd-Hg-tellurides, unique to this sample, Pt-arsenide, Pt-Bi-tellurides, Pd-Te-bismuthides and Pd antimonides. A BSE image of fine Pt-Bi-telluride particles hosted in serpentine and garnet, in close proximity to pyrite is presented in Figure 6.8(f). The basal calcsilicate interlayer is composed of Pd-Te-bismuthides, Pd-antimonides and Pt-Bi-tellurides. One Pd-selenide particle was observed in this sample. The PGM from both calcsilicate samples are primarily associated with serpentinite, garnet and BMS, even though the upper calcsilicate interlayer only contains ~3 % BMS. A fine PGM grain size was observed in the calcsilicate interlayers at ~9  $\mu$ m on average.

The hornfels interlayer sampled from the upper part of the Platreef sequence is dominated by Pd-Te-bismuthides with lesser Pt-Bi-tellurides, Pt-arsenide and Pt-Pd-Bi-tellurides. The PGM are primarily associated with BMS (~2 % BMS in whole rock sample), and to a lesser extent cordierite. The footwall hornfels sample comprises Pd-Te-bismuthide and lesser PGE-sulpharsenides. The PGM are associated with BMS (~27 % BMS in whole rock sample) and cordierite in equal amounts. A very fine PGM grain size was observed in the hornfels samples at ~4  $\mu$ m on average.

### 6.5. DISCUSSION

The mineralogical results will be discussed in four categories namely igneous, metamorphic, felsic melt-affected and serpentinised lithologies.

### 6.5.1. Igneous lithologies

The majority of the igneous samples are unaltered. The BMS assemblages are similar along the strike of the Platreef at Tweefontein, but an increase in pyrrhotite content occurs with depth. The BMS primarily occur in the interstitial mineral assemblage, but net-textured and massive sulphide layers are developed usually near the base of the sequence.

The PGM assemblages in the Platreef igneous lithologies are dominated by Pt- and Pdbismuthides and -tellurides as well as Pt-arsenide. The Pt-bearing PGM are increased in samples from the upper Platreef in line with Pt/Pd ratios of above 1. The igneous lithologies have good PGM-BMS and PGM-magmatic silicate associations indicating a relatively primary magmatic origin, where the PGE were present in an immiscible sulphide liquid within the magma. Although only a few igneous samples were taken from each borehole, it must be highlighted that the PGM assemblage appears to be similar in the Platreef igneous lithologies with depth, but varies along strike. For this reason, the Platreef igneous lithologies are divided into three groups.

The first group includes areas from Tweefontein North where the typical chromitiferous package is developed. Although Pt- and Pd-bismuthides and -tellurides dominate, the first group is characterised by the presence of PGE-sulphides. This PGM assemblage is similar to that found in the igneous lithologies and the footwall gneisses at Overysel (Holwell and McDonald, 2007). The second group occurs in the central Tweefontein area and in Tweefontein North where the typical chromitiferous package is not developed. The PGM assemblage of the second group is dominated by Pt- and Pd-bismuthides and -tellurides and Pt-arsenide. It is devoid of PGE-sulphides. A similar assemblage is observed at Sandsloot to the north of Tweefontein Hill where the PGM assemblage is Pd-dominant and characterised by Sb- and As-bearing PGM. A similar Pd dominant and Sb- and As-bearing PGM assemblage is found to the south of Tweefontein on the farms Turfspruit and Macalacaskop (Hutchinson and Kinnaird, 2005).

Based on previous PGM studies on the central and northern sectors of the Platreef (Holwell *et al.*, 2006; Holwell and McDonald, 2007), Holwell (2011) identified a primary mineralisation style of Pt- and Pd-bismuthotellurides spatially associated with base metal sulphides. This is aligned with samples from group one and As-poor assemblages from group two at Tweefontein. The importance of identifying a more primary style of mineralisation in the Platreef was also emphasised by Holwell (2011) so that the role of secondary processes such as footwall contamination and hydrothermal fluids can be assessed. These secondary processes are believed to have influenced the PGM assemblage observed at Tweefontein Hill.

Along the strike of the Platreef, PGE-sulphides only occur where the relatively inert Archaean Granite basement forms the footwall in the north (Holwell and McDonald, 2006) and at Tweefontein North (Viljoen and Schürmann, 1998, Nichol and Kinnaird, 2008). In comparison, the Merensky Reef and UG-2 deposits are commonly PGE-sulphide-rich, but become alloy, telluride and arsenide dominant in areas of increased volatile activity such as potholes, faults and iron-replaced pegmatoids (Penberthy and Merkle, 1999; Cawthorn *et al.*, 2002). The presence of PGE-sulphides in areas of Tweefontein North where the chromitiferous package is developed may therefore indicate a less volatile and turbulent environment which is conducive to PGE sulphide development.

### 6.5.2. Metamorphic lithologies

In addition to an elevated BMS content, the footwall recrystallised norite samples contain abundant iron-rich orthopyroxene and minor iron-oxide and garnet when compared to primary norite. As suggested in previous chapters, the recrystallised norites may represent a set of sills which pre-date the Platreef. The reasons for the enrichment of Fe at the base of the Platreef was described in Chapter 5 and although unclear, may involve the original composition of these basal sill intrusions and/or a basal interaction zone (Nyama *et al.*, 2005; Latypov *et al.*, 2007).

Pyrrhotite is the main BMS mineral present in the metamorphic lithologies and net-textured and massive sulphide layers except for the calcsilicate xenoliths where pyrite, chalcopyrite and millerite dominate. Turfspruit and Macalacaskop further south also contain basal pyrrhotite-rich sub-massive ores, however, minor chalcopyrite- and pentlandite-rich layers were also reported (Hutchinson and Kinnaird, 2005), which are were not observed at Tweefontein. The BMS present in the parapyroxenites are hosted in clinopyroxene and feldspar, relative to the amount of feldspar present. The discrete BMS present in the serpentinised calcsilicate and hornfels lithologies are primarily hosted in the dominant silicate mineral present in each rock type.

The parapyroxenite, hornfels and recrystallised norite lithologies are generally Pd-dominant, primarily Pd-Te-bismuthides. Although the number of samples is relatively low, the parapyroxenites also revealed a variation in PGM assemblage along strike. A general increase in Sb and As-bearing PGM is observed from central Tweefontein southwards. This correlates to an increase in As-bearing PGM in the igneous lithologies from the central Tweefontein area to As- and Sb-bearing PGM at Tweefontein Hill. It is believed that the S, As and Sb were incorporated into the Platreef magma by the devolatilisation of the Duitchland

Formation calcsilicate and siliclastic floor rocks (Hutchinson and Kinnaird, 2005; Hutchinson and McDonald, 2008). An increased amount of assimilation and volatile activity is therefore likely to have resulted in the observed PGM assemblages from central Tweefontein and particularly at Tweefontein Hill.

The calcsilicate interlayers are host to PGM similar to those of the surrounding igneous lithologies as well as significant Pd-antimonides and a rare Pd-Hg-telluride and Pd-selenide species. A Pd-Hg-telluride was also observed in the middle of the Platreef package at Townlands in the south (Manyeruke, 2007) and in the GPNA member in the Rooipoort area (Smith *et al.*, 2011).

The metamorphic footwall and interlayer lithologies have relatively good PGM-BMS associations up to 40 %, despite some samples having only low amounts of BMS. This indicates that a downward migrating sulphide melt is likely to be the main mechanism responsible for the redistribution of PGE, predominantly Pd, into the footwall and metasedimentary xenoliths as suggested by Hutchinson and Kinnaird (2005) at Turfspruit. Hutchinson and McDonald (2008) offer an additional explanation for the enrichment of Pdbearing PGM in the footwall based on a laser ablation study conducted on sulphides associated with Pd dominant PGM assemblages from Turfspruit. Their results showed that the sulphides are uncharacteristically Pd-poor compared to the sulphides at Overysel, which helps explain why more discrete Pd-bearing PGM are present. They suggest that the addition of external semi-metals from the devolatilisation of the Duitschland footwall assisted the removal of Pd from the sulphide liquid. In addition, hydrothermal fluids are thought to play a role in the redistribution of PGE in the footwall lithologies, decoupling the BMS from the PGE mineralisation (Armitage et al., 2002; Holwell et al., 2006; Hutchinson and Kinnaird, 2005). Hydrothermal fluids are also likely to be responsible for the variability in the Pt/Pd ratio.

### 6.5.3. Felsic fluid-affected lithologies

Significantly different PGM assemblages and associations were observed in igneous lithologies affected by felsic fluids. The PGM assemblages are dominated by Pt-arsenide and Pd-bismuthides, except in one sample which contains a granitic vein, where the PGM assemblage is Pd-bismuthide dominant. It could not be established whether the granitic vein was host to PGE as it was not sampled separately. These samples all had a significant PGM-quartz association together with magmatic silicates, BMS and alteration silicates. The quartz displayed an invasive texture indicating that the melt was late-stage influencing the

PGM distribution and association. To the south of Tweefontein, pervasive felsic melt phases are believed to have infiltrated the Platreef soon after its partial or complete crystallisation (Hutchinson and Kinnaird, 2005).

### 6.5.4. Serpentinised lithologies

The PGM in the serpentinised igneous and metamorphic lithologies comprise Pt-arsenide and Pd-Te-bismuthides. Viljoen and Schürmann (1998) noted the dominance of Pt-arsenide in serpentinised lithologies. The rocks surrounding the serpentinised samples were not analysed making it difficult to assess if the serpentinisation changed the PGM assemblage. These samples have additional BMS- and PGM-serpentinite associations which are directly proportional to the amount of serpentinisation. This data implies a late-stage hydrothermal influence on the PGE mineralisation, which is aligned with previous studies along the strike of the Platreef (Armitage *et al.*, 2002; Hutchinson and Kinnaird, 2005; Holwell and McDonald, 2007).

### 6.6. CONCLUSIONS

The PGM assemblages at Tweefontein are dominated by Pt- and Pd-bismuthides and -tellurides and Pt-arsenides. The igneous lithologies have a relatively primary magmatic origin showing good PGM-BMS associations. A dense sulphide melt as well as metasomatic fluids are thought to be responsible for the redistribution of PGE into the footwall and metasedimentary interlayer lithologies.

The PGM assemblages appear to be rock-type dependant and display consistency within the same rock type with depth, but show significant differences along strike. The presence of PGE-sulphides in the Platreef package at Tweefontein North where the chromitiferous package is developed implies a relatively low amount of volatile activity and turbulence during crystallisation. An increased amount of volatile activity is thought to be involved in the PGE mineralisation in the central Tweefontein area and at Tweefontein Hill, evidenced by elevated amounts of As- and Sb-bearing PGM. Assimilation and associated metasomatism of country rock footwall and xenoliths/interlayers are therefore thought to play a role in the observed PGM assemblages along strike.

Igneous lithologies hosting a primary magmatic PGM assemblage may be modified by felsic and hydrothermal fluids to form a bismuthide-and arsenide-dominant assemblages with a significant amount hosted in quartz and serpentine respectively.

# CHAPTER 7 DISCUSSION AND CONCLUSIONS

### 7.1. INTRODUCTION

Previous detailed studies of the Platreef PGE mineralisation were conducted on the farms Macalacaskop and Turfspruit to the south of Tweefontein (Kinnaird *et al.*, 2005, Hutchinson and Kinnaird, 2005), Sandsloot to the north of Tweefontein (Armitage *et al.*, 2002; Holwell *et al.*, 2006) and Overysel in the far north (Holwell and McDonald, 2007). These studies highlighted that the PGE mineralisation is highly variable, involving magmatic processes as well as localised country rock contamination and syn and post-magmatic fluid activity. The data collected and presented in this study enables an evidence-based discussion for the first time on aspects of PGM mineralogy and mineralisation on the farm Tweefontein and to integrate these findings with previous work on the adjacent farms.

# 7.2. LITHOLOGICAL AND COMPOSITIONAL CHARACTERISTICS OF THE PLATREEF AT TWEEFONTEIN

Previous research has demonstrated the significant effect that the footwall variation along the Platreef strike has on the lithologies and mineralisation style observed (e.g. White, 1994; Harris and Chaumba, 2001; Armitage et al., 2002; Hutchinson and Kinnaird, 2005). This study investigates ten boreholes from Tweefontein North to Tweefontein Hill where the footwall lithologies along strike consist of shales and dolomitic rocks of the Duitschland Formation underlain by banded ironstone of the Penge Formation. Duitschland footwall rocks have been noted at Tweefontein Hill by Nex (2005), but the footwall at Tweefontein North is often indicated as banded ironstone based on work done by White (1994) and Viljoen and Schürmann (1998), but should in fact also be Duitschland Formation. To the north of Tweefontein at Sandsloot and Zwartfontein South, the footwall is Malmani dolomite (Harris and Chaumba, 2001; Armitage et al., 2002), with the Platreef resting on Archaean Granite basement at Zwartfontein North, Overysel and Drenthe (Gain and Mostert, 1982; Holwell and McDonald, 2006). The Platreef footwall to the south of Tweefontein at Turfspruit and northern Macalacaskop comprises a thicker succession of Duitschland lithologies, also including quartzites (Hutchinson and Kinnaird, 2005; Kinnaird et al., 2005). There is some debate surrounding what Transvaal sediments form the footwall further south of the Ysterberg-Planknek fault. The latest data was reported by van der Merwe (2008), who proposed that the shales of the Strubenskop and shales and limestone's of the Silverton Formations form the Platreef footwall in this area.

The contact metamorphism of the Duitschland lithologies at Tweefontein resulted in a metasedimentary footwall package, of variable thickness, comprising serpentinised calcsilicate, parapyroxenite and cordierite hornfels. Recrystallised, fine-grained noritic layers are also found within the immediate footwall and basal Platreef lithologies at Tweefontein North and Tweefontein Hill. Wagner (1929) first used the term parapyroxenite but it was Harris and Chaumba (2001) who described this rock type in detail due to its abundance at Sandsloot. They describe parapyroxenite as a recrystallised clinopyroxenite believed to be derived from the contact metamorphism of dolomitic rocks. Due to relatively low Cr and Na<sub>2</sub>O values, parapyroxenite is thought to have a non-igneous genesis (Harris and Chaumba, 2001). The parapyroxenites at Tweefontein have similar characteristics, except the majority contain variable but significant amounts of feldspar and can contain elevated Cr and Ti contents. These differences may be due to compositional differences between the dolomitic rocks from the Malmani Subgroup at Sandsloot and the Duitschland Formation at Tweefontein, but may indicate that the Tweefontein parapyroxenites may be more closely linked with an igneous genesis as the Cr and Ti contents closely resemble values commonly associated with igneous lithologies.

The thin recrystallised noritic layers found in the immediate footwall at Tweefontein may correlate to footwall pyroxene hornfels units noted by White (1994) at Tweefontein and 'Marginal Zone' norites reported at Sandsloot (Yudovskaya and Kinnaird, 2010), at Tweefontein (Buchanan et al. 1981; Nyama et al. 2005) and in the southern sector (Kinnaird et al., 2005; Manyeruke et al., 2005; Sharman-Harris et al., 2005; Mothetha, 2006; Kekana et al., 2011). Due to the recrystallised texture and location in the footwall at Tweefontein, these layers are thought to represent sills which intruded prior to the emplacement of the Platreef. The geochemistry and bulk mineralogy of this study has shown that these footwall noritic layers as well as some lower Platreef samples are relatively enriched in Fe, in the form of Ferich sulphide minerals and Fe-rich pyroxenes and/or Fe-oxides, and contain lower Na<sub>2</sub>O and higher TiO<sub>2</sub> values compared to Platreef lithologies. These attributes may reflect the original composition of the footwall sill intrusion or may represent a basal interaction zone. A geochemical study at Tweefontein Hill by Nyama et al. (2005) reports similar characteristics where a basal interaction zone was also proposed. On a global scale, the presence of more evolved chill margins at the base of mafic and ultramafic intrusive bodies is quite common. Latypov et al. (2007) looked at these 'marginal reversals' observed in many magmatic intrusions and although the mechanisms need further research, they suggest a gravitydependant and temperature gradient-driven process, which universally operates along cooling margins of magmatic intrusions.

In addition to significant differences in the footwall composition along the Platreef strike, the Platreef is affected by irregular footwall topography resulting in topographic footwall highs and depressions. These features have a significant impact on the Platreef thickness, stratigraphy and mineralisation and are particularly evident from Tweefontein southwards. (Hutchinson and Kinnaird, 2005; Kinnaird 2005; Kinnaird et al. 2005; Nex, 2005). This study showed the presence of topographic footwall depressions at Tweefontein North and Tweefontein Hill with a Platreef thickness of 170 m on average. These depressions are separated by a footwall high in the central Tweefontein area, where the Platreef has an average thickness of only ~70 m. The depression areas at Tweefontein are similar to that described further south, where the Platreef is more lithologically complex and contains basal massive and submassive sulphides, which do not necessarily carry significant PGE grade. A schematic longitudinal section of the Platreef, highlighting these features, was presented in Kinnaird et al. (2005) and is used in Figure 7.1. Irregular floor topography is believed to be a pre-Bushveld effect, but Nex (2005) highlighted the added effect that magma loading may have had on the topographic variation. At Tweefontein, hornfels forms part of the footwall in the depression areas but is absent in the topographic high area emphasising the pre-Bushveld structural control.

The Platreef lithologies at Tweefontein are composed of pyroxenites and norites with minor harzburgitic lithologies. In comparison, a higher proportion of ultramafic rocks characterise the Platreef to the south of Tweefontein (Kinnaird, 2005; Manyeruke *et al.*, 2005) with only minor ultramafic lithologies northward on Sandsloot (Holwell *et al.*, 2006), Overysel (Holwell and McDonald, 2006) and Drenthe (Gain and Mostert, 1982). Granitic veins randomly crosscut the stratigraphy at Tweefontein and are ubiquitous in the Platreef along strike. On Tweefontein, metasedimentary xenoliths/interlayers within the Platreef reflect the immediate footwall, indicating that they were not transported far from the source. Although these xenoliths/interlayers are primarily found near the base of the Platreef, they also occur in the middle and upper Platreef packages probably reflecting the incorporation of roof pendants. The majority of the Platreef lithologies are relatively unaltered, but localised serpentinisation and chloritisation, particularly at Tweefontein Hill, are associated with harzburgitic lithologies and metasedimentary interlayers. In contrast, significant alteration zones are noted at Sandsloot, particularly associated with the dolomitic footwall (Armitage *et al.*, 2002; Holwell *et al.*, 2006).

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Based on the stratigraphy and geochemical characteristics, the Platreef at Tweefontein can be subdivided into the upper and lower Platreef. The upper Platreef subdivision occurs in the top 20 to 40 m of the sequence and is defined by higher Mg#, Cr, Cr (ppm)/MgO and Pt/Pd values compared to the lower Platreef. In addition, the majority of the grade and base metal sulphide (BMS) content is enriched in the upper versus the lower Platreef, particularly for the northern and central parts of Tweefontein. The upper and lower Platreef may have been derived from different magma sources based on the "R Factor" concept proposed by Campbell and Naldrett (1979) whereby the abundance of the PGE relative to the BMS content is linked to the proportion of magma with which the sulphide ore equilibrated (Naldrett, 2005b). Previous detailed geochemical studies at Tweefontein Hill (Nyama et al., 2006) and to the south of Tweefontein (Hutchinson and Kinnaird, 2005; Kinnaird, 2005; Manyeruke et al., 2005) revealed compositional breaks in the Platreef sequence thought to represent distinct sill-like intrusions. They reported a more primitive sill at the top of the Platreef, which corresponds to the upper Platreef at Tweefontein. A relatively homogenous pyroxenitic package characterises the upper Platreef, although a more heterogeneous package is observed close to and at Tweefontein Hill. At Tweefontein North, the base of the upper Platreef is often marked by a chromitiferous package comprising a pegmatoidal feldspathic pyroxenite unit, up to 6 m thick, capped by a chromitite layer. This distinct horizon has been compared to the Merensky Reef found elsewhere in the Bushveld Complex (White, 1994; Viljoen and Schürmann, 1998). The lower Platreef is therefore likely to represent a different sill intrusion, but due to non-continuous sporadic sampling, it is difficult to establish if the lower Platreef has been derived from more than one sill intrusion.

### 7.3. SULPHIDE MINERALISATION

The predominant base metal sulphides (BMS) in the Platreef at Tweefontein are pyrrhotite, pentlandite, and chalcopyrite with minor pyrite as found elsewhere along the Platreef strike (e.g. White, 1994). In addition to differences in the BMS content between the upper and lower Platreef, there is a relative increase in BMS content, primarily pyrrhotite, towards the base of the Platreef with massive and submassive sulphide development near the base and in the footwall, particularly at Tweefontein Hill. The massive and sub-massive sulphide development along the Platreef has been attributed to gravitational settling of magmatic sulphides (White, 1994; Nex, 2005; Holwell and McDonald, 2006), but the additional influence of contamination on sulphide development at Turfspruit was highlighted by Sharman-Harris *et al.* (2005), Holwell *et al.* (2007) and Hutchinson and McDonald (2008). Holwell *et al.* (2007) showed that sulphur contamination from the dolomitic footwall at

Sandsloot occurred in areas of extensive hydrothermal activity, whilst the Archaean granite is not a significant contributor of sulphur to the Platreef. The Platreef sulphides at Turfspruit, however, were shown to be extensively contaminated with sulphur from the pyrite-bearing shales of the Duitschland Formation (Sharman-Harris et al., 2005). This led Hutchinson and McDonald (2008) to propose that at Turfspruit, the addition of S. As and Sb into the magma from the Duitschland footwall triggered the development of a PGE-poor sulphide liquid which was then able to mix, modify and dilute the magmatic sulphides. Due to the similarity in footwall between Turfspruit and Tweefontein, these proposed processes help to explain the increase in BMS towards the base and the development of massive and submassive sulphides, which are not necessarily associated with significant PGE grade. Similarly in the Stillwater Complex, an increased BMS content with massive and submassive sulphide development occurs near its base in areas where BMS are present in the country rocks (Zientek et al., 2002). Sulphide segregation however could have locally involved a number of different processes such as an increase in the oxygen fugacity due to the devolatilisation of the country rocks (De Waal, 1977), the presence of iron-rich fluids which have been experimentally shown to dissolve more sulphur than iron-poor fluids (Buchanan and Nolan, 1979) and silicic contamination from dolomite and granite (Buchanan and Rouse, 1984).

### 7.4. PGE MINERALISATION

This study not only provides the first detailed PGM data on the Tweefontein farm, but provides the most comprehensive PGM study along the Platreef to date including 49 Platreef and footwall samples, with over 9000 PGM analysed. This data reveals a distinct change in PGM mineralisation style between the depression at Tweefontein North compared to Tweefontein Hill, with a transitional zone in the central Tweefontein area defined by a footwall high.

Figure 7.1 illustrates the down hole PGE grade profiles, the Pt/Pd ratios and the available PGM assemblages along the Platreef strike from Turfspruit to Overysel. The PGE grade profiles are generally top-loaded from Overysel to Tweefontein North and more variable and bottom loaded from Tweefontein Hill southwards. A significant increase in PGE grade occurs in the upper part of the Platreef in the Tweefontein Hill borehole used in this study (Figure 7.1); however previous research by White (1994) and Nyama *et al.* (2005) report the PGE grade distribution at Tweefontein Hill to be primarily bottom-loaded. This data emphasizes the importance of the change in mineralisation style at Tweefontein in relation to the whole Platreef. From Tweefontein North to Turfspruit, the down hole Pt/Pd ratios demonstrate a systematic variation whereby the upper 20-40 m of the Platreef have higher Pt/Pd values

compared to the lower Platreef. This has been interpreted to represent an upper more primitive sill intrusion, described in Section 7.3. Although Figure 7.1 reports a Pt/Pd ratio for Sandsloot, Zwartfontein and Overysel, it must be emphasized that the downhole Pt/Pd values are highly variable in these areas. This implies that the primitive sill is developed or partially developed in some boreholes and absent in others. A study at Akanani, downdip of Sandsloot, has also shown an inconsistency in the development of the upper primitive sill (Judith Kinnaird pers. comm. – 19 January 2012). Yudovskaya and Kinnaird (2010) noted a chromitite layer at the top Platreef contact in some boreholes from Overysel, which may represent the base of an upper sill, similar to the chromitiferous horizon observed at Tweefontein North. These observations suggest that the Main Zone magma may have inconsistently incorporated portions of the upper Platreef, particularly from Sandsloot northwards, supporting research by Naldrett (2005a) at Drenthe.

### 7.4.1. Platreef PGM assemblages

The PGM assemblage at Tweefontein North is more Pt-dominated (Pt/Pd ~1 on average) compared to Tweefontein Hill (~0.8 on average). Please note that the Pt/Pd ratio does not necessarily explain the PGM assemblage as PGE may be present in solid solution in BMS or as discrete PGM. The PGM are primarily composed of Pt- and Pd-bismuthides and tellurides with minor PGE-sulphides and Pt-arsenides. PGE-sulphides occur in the Platreef where the chromitiferous layer is developed. Along the strike of the Platreef, PGE-sulphides only occur where the relatively inert Archaean Granite basement forms the footwall at Overysel and at Tweefontein North (see Figure 7.1). In comparison, the Merensky Reef and UG-2 deposits are commonly PGE-sulphide-rich, but become alloy, telluride and arsenide dominant in areas of increased volatile activity such as potholes, faults and iron-replaced pegmatoids (Penberthy and Merkle, 1999; Cawthorn et al., 2002). The presence of PGEsulphides in areas of Tweefontein North where the chromitiferous package is developed may therefore indicate a less volatile and less turbulent environment. It is possible that the topographic high in the central Tweefontein area played a role in isolating Tweefontein North, to a certain extent, from hydrothermal and contamination processes thought to have affected Tweefontein Hill.

Holwell (2011) stressed the importance of determining the most 'primary style' of mineralisation in the Platreef so as to assess the influence of secondary processes such as hydrothermal activity and contamination. Generally, PGM studies at Overysel and Sandsloot, although variable, are dominated by Pt and Pd bismuthotellurides as well as Pt-arsenide (see Figure 7.1), especially in the unaltered pyroxenites. This led Holwell (2011) to suggest that

this PGM assemblage forms part of the common initial mineralisation style for the Platreef, which has been locally modified by secondary processes. The general PGM assemblage at Tweefontein North is aligned with the 'primary' mineralisation style described by Holwell (2011). The igneous samples from one of the Tweefontein North boreholes did however show a dominance of As-bearing PGM, which may be a function of localised contamination.

The footwall lithologies at Tweefontein North are generally Pd-dominant, primarily bismuthides. It is probable that the enrichment of Bi-bearing PGM towards the base indicates the incorporation of Bi from the Duitschland footwall.

Contrary to the 'primary' mineralisation style at Tweefontein North, the Platreef and footwall lithologies at Tweefontein Hill are Pd-dominant characterised by Sb-, As- and Bi-bearing PGM. The presence of this PGM assemblage, which is very similar to that observed at Turfspruit (see Figure 7.1), provides further support for a greater amount of footwall assimilation, involving the addition of footwall S, As, Bi and Sb, in these areas compared to the Platreef further north. On a wider scale a similar PGM assemblage and association is observed in the massive sulphide ore of the Uitkomst Complex, Mpumalanga, South Africa (Theart and de Nooy, 2001).

It is generally accepted that the Platreef is an orthomagmatic sulphide deposit, where the PGE were present in an immiscible sulphide liquid within the Platreef magma (e.g. Campbell *et al.*, 1983, Armitage *et al.*, 2002). This process is supported by the PGM association data at Tweefontein as the PGM present in the igneous samples are mainly associated with magmatic silicates, which are usually in close proximity to sulphide grains, and on the grain boundary or included in BMS. The metamorphic footwall and interlayer lithologies also demonstrate good PGM-BMS associations up to 40 %, predominantly with pyrrhotite, despite some samples having small amounts of BMS. This indicates that a downward migrating sulphide melt is likely to be the main mechanism responsible for the PGE mineralisation, mainly Pd, in the footwall and metasedimentary xenoliths at Tweefontein.



#### Electrum

Figure 7.1. Variation in PGE mineralisation along the strike of the Platreef. (a) A schematic crosssection of the Platreef along strike by Kinnaird *et al.* (2005) showing the location of the various farms from south to north. (b) Downhole PGE grade profiles and Pt/Pd ratios along the Platreef strike. The PGE assay data from Overysel to Tweefontein Hill was supplied by the platinum division of Anglo American, whilst the data for Turfspruit was derived from Hutchinson and Kinnaird (2005). (c) PGM assemblages, for the Platreef, footwall and serpentinite lithologies, along the Platreef strike from Turfspruit to Overysel. The PGM assemblage sources: Overysel (Holwell and McDonald, 2007), Zwartfontein (Holwell, 2011), Sandsloot (Holwell *et al.*, 2006), Tweefontein (this study), Turfspruit (Hutchinson and Kinnaird, 2005). The enrichment of Pd-bearing PGM in the footwall at Tweefontein and Overysel (see Figure 7.1) is likely to be due to the mobility of Pd over Pt, which is known to occur in other PGE deposits (e.g. Wagner, 1929; Oberthür, 2002 – Great Dyke; Zientek *et al.*, 2002 – Stillwater Complex). Hutchinson and McDonald (2008) offer an additional explanation for the enrichment of Pd-bearing PGM in the footwall based on a laser ablation study conducted on sulphides associated with Pd dominant PGM assemblages from Turfspruit. Their results showed that the sulphides on Turfspruit are uncharacteristically Pd-poor compared to the sulphides at Overysel, which helps explain why more discrete Pd-bearing PGM are present. They suggest that the addition of external semi-metals from the devolatilisation of the Duitschland footwall assisted the removal of Pd from the sulphide liquid.

### 7.4.2. Hydrothermal and felsic fluid activity

At Tweefontein, hydrothermal and felsic fluid activity has altered the PGM type and association characteristics from the PGM deportment described for the Platreef. These are therefore classified as ore-modifying processes.

Hydrothermal fluids are thought to play an additional role in the redistribution of PGE, particularly in the footwall lithologies (Armitage *et al.*, 2002; Hutchinson and Kinnaird, 2005; Holwell *et al.*, 2006) and may be partly responsible for the variability in the Pt/Pd ratio observed in the footwall lithologies. In addition, the decoupling of Ni from Cu at Tweefontein may involve remobilisation of Cu, due to late-stage magmatic or hydrothermal processes (Armitage *et al.*, 2002). Further support for the mobility of Pd and Cu over Pt and Ni is in the Pd- and Cu-rich hydrothermal vein system in a crush-zone present in the BIF footwall lithologies at Tweefontein Hill (Nex *et al.*, 2008).

Hydrothermal serpentinisation is associated with calcsilicate footwall and xenolith units and harzburgitic lithologies observed along the Platreef strike (Hutchinson and Kinnaird, 2005; Holwell *et al.*, 2006; Holwell and McDonald, 2007). At Tweefontein, the PGM in serpentinised lithologies comprise Pt-arsenide and lesser Pd-Te-bismuthides and may contain Sb-bearing PGM (see Figure 7.1). The PGM association data highlights additional PGM-serpentinite associations, which are directly proportional to the amount of serpentinisation. The dominance of Pt-arsenide in serpentinised lithologies was also noted by Viljoen and Schürmann (1998) and Holwell and McDonald (2007).

Felsic fluids affected the mineralisation in some areas at Tweefontein, particularly in the central Tweefontein area. The PGM assemblages are very similar to those observed in

serpentinised zones, dominated by Pt-arsenide and Pd-bismuthides. One sample contained a granitic vein where the PGM assemblage is Pd-bismuthide dominant. It could not be established whether this granitic vein was host to PGE as it was not sampled separately. Whilst most granitic veins do not carry grade, Hutchinson and Kinnaird (2005) did record a PGE-rich granitic vein at Turfspruit. These samples all had a notable PGM-quartz association together with magmatic and alteration silicates. The quartz displayed an invasive texture indicating that the melt was late-stage, altering the association of the PGM and possibly the PGM assemblage. To the south of Tweefontein, pervasive felsic melt phases are believed to have infiltrated the Platreef soon after its partial or complete crystallisation (Hutchinson *et al.*, 2004; Hutchinson and Kinnaird, 2005). These felsic melts may be related to late-stage fractionates of the mafic magma or a product of the assimilation of footwall lithologies and/or xenoliths (Hutchinson and Kinnaird, 2005).

7.5. COMPARISON OF THE PLATREEF WITH THE UG-2 AND MERENSKY REEF Geochemical investigations of the Platreef and Merensky Reef have shown similar orthopyroxene compositions (Buchanan *et al.*, 1981) and initial <sup>87</sup>Sr/<sup>86</sup>Sr ratios (Barton *et al.*, 1986), leading researchers to propose that they were derived from the same magma. The chromitiferous horizon at Tweefontein North has also been linked to the Merensky Reef due to a similar stratigraphy and high PGE grades (e.g. White, 1994; Viljoen and Schürmann, 1998). At Tweefontein, most of the upper and some lower Platreef intersections have Cr/MgO values above 80, which is a cut off used by Seabrook *et al.* (2005) to characterise Critical Zone magmas in the eastern and western limbs. This suggests Critical Zone affinity for the Platreef at Tweefontein, where values below 80 near the base of the reef may be due to contamination of the Grasvally norite-pyroxenite-anorthosite (GPNA)-Platreef sequence, indicates that the Platreef formed from a separate magma or mix of magmas compared to the Critical Zone in the eastern and western limbs (McDonald *et al.*, 2005).

Other significant differences exist between the Platreef and the UG-2 and Merensky Reef of the eastern and western limbs. The Platreef shows significant variations in thickness and grade distribution along strike and down dip (e.g. White, 1994; Armitage *et al.*, 2002; Hutchinson and Kinnaird, 2005; Kinnaird *et al.*, 2011) with relatively minor variation observed in the Merensky Reef and UG-2 described by Cawthorn *et al.* (2002). In addition, base metal sulphides are more abundant in the Platreef together with lower and more variable PGE grades and more variable and complex PGM assemblages (Holwell *et al.*, 2006; Holwell *et al.*, 2005; Kinnaird, 2005; Kinnaird and Naldrett, 2011). A fundamental

footwall control resulting in variable Platreef thickness and varying degrees of country rock assimilation and associated volatile activity is believed to be the key factor in the observed differences.

The Merensky Reef and UG-2 deposits are commonly PGE-sulphide-rich, but become alloy, telluride and arsenide dominant in areas of increased volatile activity such as potholes, faults and iron-replaced pegmatoids (Penberthy and Merkle, 1999; Cawthorn *et al.*, 2002). In contrast, PGE-sulphides are rare on the Platreef and only occur where the relatively inert Archaean Granite basement forms the footwall in the north (Holwell and McDonald, 2007) and at Tweefontein North (Viljoen and Schürmann, 1998, Nichol and Kinnaird, 2008). This data provides support for an increased amount of country rock assimilation and volatile activity in the formation of the Platreef compared to the Merensky Reef or UG-2 deposits.

### 7.6. CONCLUSIONS

This study presents the first significant PGM data on the Tweefontein farm and forms one of the most comprehensive PGM studies on the Platreef to date. Significant insights into the understanding of the distinctly different PGE mineralisation styles at Tweefontein North and Tweefontein Hill are presented. Footwall composition and irregular floor topography, resulting in depression areas at Tweefontein North and Tweefontein Hill, are believed to play a key role in what processes become significant along the Tweefontein strike.

At Tweefontein North, the processes dominating the top-loaded PGE mineralisation were primarily magmatic. A semi-continuous chromitiferous horizon, unique in the Platreef, occurs in the upper part of the Platreef, thought to represent the base of an upper sill intrusion. The PGM assemblage, hosted by base metal sulphides and magmatic silicates, is dominated by Pt-and Pd-bismuthides and -tellurides with minor PGE-sulphides and Pt-arsenides. The presence of PGE-sulphides where the chromitiferous horizon is developed may indicate an environment low in volatile activity and one of the most primary mineralisation styles along the Platreef strike comparable to Overysel. The footwall high, which separates the depressions at Tweefontein North and Tweefontein Hill may have kept the Platreef at Tweefontein North relatively protected from additional processes affecting Tweefontein Hill.

In contrast, assimilation of the Duitschland footwall is thought to play a key role in the development of the variable but predominantly bottom-loaded PGE mineralisation at Tweefontein Hill. The PGM assemblage is Pd-dominant characterised by Sb-, As- and Bibearing PGM, reflecting the additional incorporation of Sb, As and Bi from the footwall. Similar to the processes previously suggested for Turfspruit to the south of Tweefontein, it is believed that the incorporation of sulphur from the Duitschland footwall increased the sulphide liquid content in the magma. This implies that the basal sulphide and PGE enrichment characterising Tweefontein Hill occurred due to the gravitational settling of a sulphide liquid containing a mix of sedimentary and PGE-hosting magmatic components.

Due to a good PGM-BMS association, a downward migrating sulphide melt is believed to be the main mechanism responsible for the redistribution of PGE, predominantly Pd, into the mineralised footwall and metasedimentary interlayers/xenoliths.

The Platreef and footwall lithologies may be modified by late-stage felsic and hydrothermal fluids to form bismuthide- and arsenide-dominant PGM assemblages, primarily hosted in quartz and serpentine respectively.

This study shows the PGM and sulphide mineralisation at Tweefontein to be multifaceted, involving magmatic processes, assimilation of the Duitchland footwall into the Platreef magma and late-stage hydrothermal and felsic fluid activity. It represents a significant contribution to the understanding of the distinctly different PGE mineralisation styles at Tweefontein and allows for a complete comparison of the Platreef PGE mineralisation from Overysel to Turfspruit.

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### **APPENDIX I: SAMPLE LIST AND DESCRIPTION**

The complete sample list is given in Tables I(a) and I(b), including the associated rock type.

The samples in each table are listed per borehole along strike, north to south.

Table I(a): Complete sample list, including the assigned rock type.

TN228_9	Pyroxenite
TN228_20	Serpentinised harzburgite
TN228_65	Calcsilicate
TN228_81	Hornfels
TN228_123	Feldspathic pyroxenite
TN228_149	Feldspathic pyroxenite
TN228_185	Parapyroxenite
TN228_201	Feldspathic pyroxenite
TN228_247	Recrystallised norite
TN228_253	Recrystallised norite
TN223_8	Pyroxenite
TN223_23	Feldspathic pyroxenite hosting a chromitite stringer
TN223_25	Pegmatoidal feldspathic pyroxenite and granitic vein (~40cm thick)
TN223_35	Norite
TN223_40	Norite
TN223_77	Feldspathic pyroxenite and pegmatoidal feldspathic pyroxenite
TN223_103	Pegmatoidal feldspathic pyroxenite
TN223_135	Norite
TN223_147	Norite
TN223_156	Melanorite
TN223_161	Parapyroxenite
TN221_11	Pyroxenite
TN221_25	Feldspathic pyroxenite
TN221_28	Feldspathic hazburgite
TN221_33	Feldspathic pyroxenite
TN221_65	Pegmatoidal feldspathic pyroxenite
TN221_73	Feldspathic pyroxenite and pegmatoidal feldspathic pyroxenite
TN221_185	Recrystallised norite
TN221_196	Recrystallised norite
TN221_204	Recrystallised norite
TN221_264	Parapyroxenite
TN240_6	Pyroxenite
TN240_22	Pyroxenite
TN240_25	Pegmatoidal feldspathic pyroxenite
TN240_46	Feldspathic pyroxenite
TN240_53	Melanorite
TN240_71	Pegmatoidal feldspathic pyroxenite
TN240_89	Melanorite
TN240_144	Parapyroxenite
TN240_214	Recrystallised norite and massive sulphide layer (~50cm thick)
TN240_231	Parapyroxenite

TN197_8	Pyroxenite
TN197_23	Harzburgite
TN197_32	Melanorite
TN197_47	Feldspathic pyroxenite and pegmatoidal feldspathic pyroxenite
TN197_54	Melanorite
TN197_70	Pegmatoidal feldspathic pyroxenite
TN197_88	Feldspathic pyroxenite and pegmatoidal feldspathic pyroxenite
TN197_145	Feldspathic pyroxenite
TN197_161	Calcsilicate
TN197_246	Parapyroxenite
TN198_32	Feldspathic pyroxenite hosting a chromitite stringer
TN198_34	Pegmatoidal feldspathic pyroxenite
TN198_46	Melanorite
TN198_55	Parapyroxenite
TN198_62	Parapyroxenite
TN198_69	Parapyroxenite
TN198_75	Parapyroxenite
TN198_78	Parapyroxenite
TN199_3	Feldspathic pyroxenite (directly after a breccia zone)
TN199_7	Feldspathic pyroxenite
TN199_19	Feldspathic pyroxenite
TN199_24	Feldspathic pyroxenite
TN199_30	Feldspathic pyroxenite
TN199_60	Parapyroxenite
TN201_11	Pyroxenite
TN201_32	Feldspathic pyroxenite. Situated ~2m below a granitic vein
TN201_47	Feldspathic pyroxenite
TN201_61	Pegmatoidal feldspathic pyroxenite
TN201_75	Pegmatoidal feldspathic pyroxenite
TN201_90	Parapyroxenite
TN201_99	Parapyroxenite
TN201_107	Parapyroxenite
TN203_33	Feldspathic pyroxenite
TN203_39	Serpentinised feldspathic harzburgite
TN203_44	Serpentinised feldspathic pyroxenite
TN203_55	Serpentinised melanorite
TN203_60	Melanorite
TN203_65	Melanorite
TN205_55	Pyroxenite
TN205_64	Feldspathic pyroxenite
TN205_115	Feldspathic pyroxenite
TN205_147	Serpentinised feldspathic harzburgite
TN205_152	Parapyroxenite
TN205_160	Serpentinised parapyroxenite
TN205_167	Parapyroxenite hosting a massive sulphide layer (~5cm thick)
TN205_177	Parapyroxenite
TN205 185	Hornfels

Table I(b): Complete sample list, including the assigned rock type.
## **APPENDIX II: GENERAL SAMPLE PREPARATION**

Between six and eight, ~1m quarter core intersections were sampled from the ten chosen boreholes, totalling eighty-nine samples. The samples were aligned with samples taken by Platinum for assay prior to this study. The selected samples were transported to Anglo American's Technical Solutions in Johannesburg. Approximately 5 cm quarter core pieces from each intersection were selected and submitted to SGS, Johannesburg for thin section preparation. The samples were then crushed to -3 mm in a jaw crusher. Subsequently, representative sample splits were obtained using an eight-way sample splitter/riffle. The jaw crusher and riffle were cleaned with compressed air between each sample to minimise contamination. A representative split was submitted to the University of the Witwatersrand for whole rock geochemical (X-ray fluorescence) analysis, whilst another was used to prepare polished blocks for automated SEM analysis on the QEMSCAN and Mineral Liberations Analyser (MLA).

# APPENDIX III WHOLE ROCK GEOCHEMISTRY - XRF

# Illa Sample preparation and methodology

### Major elements:

All samples are ignited at 1000°C for 40 minutes and the LOI is calculated. The ignited sample is mixed with a commercially available pre-ignited flux (with composition  $Li_2B_4O_7 = 47$  %,  $Li_2CO_3 = 36.7$  %,  $La_2O_3 = 16$  %) with a ratio of 1:5 and fired for 40 minutes at 1000°C. This is then poured and pressed by a mechanical press into a fused disk.

All data collection is performed on a PANalytical PW2404 WD XRF with a Rh tube, set at 50 kV and 50 mA. An analysis time is 40 sec per element and 20 sec per background (backgrounds are measured for Si, AI, Mg, Na and P only).

# Trace elements:

Approximately 6 g of sample is mixed with three drops of 4 % commercially purchased Mowiol (polyvinyl alcohol). This mixture is the pressed under 10 ton pressure into an AI cup using a 40 ton press. The pressed pellet is allowed to dry for 24 hours prior to analysis.

All data collection is performed on a PANalytical PW2404 WD XRF with a Rh tube, set at 50 kV and 50 mA. The instrument parameters for each element are as per the Protrace recommendation.

PANalytical software Protrace is used to process the raw data. The standards used for the calibration are the Protrace standards supplied by PANalytical. Protrace drift standards are run after every five analyses to compensate for instrument drift. Internal checks are performed by analysing known standards as unknowns and comparing to reported concentrations. The known standards used are AGV2, BHVO2, GSP2, NIM D and NIM S.

# IIIb: Whole rock geochemical data

The whole rock major and trace element geochemistry is given along strike from north to south in Tables IIIb(ii) to IIIb(xi) for samples from borehole TN228, TN223, TN221, TN240, TN197, TN198, TN199, TN201, TN203, TN205 respectively. The ratio of Fe<sub>2</sub>O<sub>3</sub>/FeO = 0.1 was used to calculate the FeO content from the Total Fe, initially given as Fe<sub>2</sub>O<sub>3</sub>. The Mg# was calculated using the formula (MgO/(MgO+FeO)). The rock type short codes used to describe the geochemical samples are given in table IIIb(i).

UP	Upper Platreef lithology
MP	Middle Platreef lithology
LP	Lower Platreef lithology
Hz	Harzburgite
RN	Recrystallised norite
Р	Parapyroxenite
С	Calcsilicate
Hn	Hornfels

Table IIIb(i): List of rock type short codes used to describe geochemical samples.

	TN228	TN228	TN228	TN228	TN228	TN228	TN228	TN228	TN228	TN228
	9	20	65	81	123	149	185	201	247	253
(Wt. %)	UP	Hz	С	Hn	MP	LP	Р	LP	RN	LP
SiO <sub>2</sub>	52.3	43.0	40.9	46.0	50.0	47.5	39.6	42.9	43.0	48.3
$AI_2O_3$	5.2	2.9	4.3	33.3	8.2	7.3	7.0	6.5	9.6	16.5
Fe <sub>2</sub> O <sub>3</sub>	1.4	1.8	1.2	1.0	1.5	1.2	1.4	2.1	3.6	1.7
FeO	11.7	14.5	9.7	8.0	11.8	9.4	11.5	17.0	28.9	14.0
Total Fe	13.1	16.3	10.9	9.0	13.2	10.5	12.9	19.1	32.5	15.8
MnO	0.2	0.2	0.3	0.1	0.3	0.2	0.4	0.3	0.4	0.2
MgO	22.6	32.4	28.0	9.9	20.1	18.4	25.5	23.1	7.0	11.1
CaO	4.2	3.0	15.0	0.3	6.5	14.8	13.8	6.7	5.5	5.9
Na₂O	0.5	0.1	0.0	0.4	0.8	0.3	0.0	0.2	0.4	1.2
K <sub>2</sub> O	0.1	0.2	0.0	0.8	0.1	0.2	0.0	0.1	0.1	0.6
TiO <sub>2</sub>	0.3	0.2	0.1	0.1	0.2	0.3	0.3	0.2	0.6	0.6
$P_2O_5$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Cr_2O_3$	0.4	0.6	0.0	0.3	0.2	0.2	0.0	0.2	0.0	0.1
NiO	1.0	0.9	0.2	0.1	0.1	0.1	0.4	0.4	0.1	0.1
TOTAL	99.9	99.8	99.8	100.3	99.7	99.9	100.0	99.7	99.2	100.4
LOI	2.8	7.1	9.6	3.4	1.6	2.4	6.7	4.1	-0.1	1.0
(ppm)										
Sc	21.7	28.8	34.8	26.0	31.9	32.0	37.1	38.9	30.2	37.2
Ti	3162.5	2824.8	4809.0	3857.2	1481.6	1761.2	2876.0	5580.6	3908.3	5476.2
V	49.6	129.9	425.2	115.1	89.3	97.2	125.1	164.8	152.6	166.2
Cr	292.3	2405.4	34402.5	2133.0	1442.0	1548.5	1686.3	1048.5	1460.3	1014.9
Со	5.4	154.6	175.7	106.8	88.4	89.5	147.7	86.4	109.1	89.6
Ni	823.4	5682.7	4984.6	3404.1	2090.8	1719.6	1933.2	1891.8	2063.9	1910.4
Cu	2970.2	2946.0	2582.7	1840.5	1475.4	1007.0	1238.4	1573.0	1332.4	1673.0
Zn	109.9	80.5	142.4	78.2	43.8	55.6	83.4	65.2	79.9	59.8
Ga	7.9	9.5	10.3	12.7	15.8	13.5	10.7	13.1	14.5	16.5
Ge	7.8	0.9	0.6	1.6	0.5	0.6	1.9	1.5	3.7	6.5
As	45.6	3.0	8.8	4.6	4.5	4.0	3.5	3.1	1.5	9.1
Se	13.3	11.3	14.3	11.4	11.1	6.9	7.4	8.6	9.3	9.5
Rb	4.7	8.2	6.4	27.6	19.1	9.9	5.4	11.6	7.2	12.7
Sr	26.7	70.7	37.7	114.3	200.7	146.8	111.4	172.6	249.3	174.1
Y	7.5	4.5	7.6	12.4	5.7	5.0	9.3	17.2	9.2	16.3
Zr	24.9	20.5	24.5	89.5	16.2	13.3	19.0	65.3	11.7	52.1
Nb	0.6	0.2	1.1	4.1	0.0	0.9	1.4	2.4	2.0	2.8
Мо	2.0	1.6	2.3	1.6	0.6	1.3	1.2	1.0	0.9	0.1
Ва	27.5	94.0	44.2	145.8	122.6	64.8	51.2	75.2	77.6	102.6
Pb	15.5	8.8	12.4	27.1	4.1	4.8	14.2	13.6	8.1	13.4
Bi	37.4	5.2	7.8	6.3	3.8	6.3	6.2	5.6	5.8	8.1
Th	3.9	2.1	5.5	14.8	5.2	10.0	4.6	5.0	6.8	7.0
U	1.2	0.6	5.0	3.6	2.7	2.6	3.0	4.1	3.0	4.6
Mg#	66.0	69.0	74.3	55.2	63.1	66.3	68.9	57.6	19.5	44.2
Cr(ppm)/MgO	12.9	74.2	1228.2	215.9	71.6	84.2	66.1	45.4	208.6	91.2
Cr/V	5.9	18.5	80.9	18.5	16.1	15.9	13.5	6.4	9.6	6.1

Table IIIb(ii): Whole rock and trace element geochemistry of samples from borehole TN228.

	TN223	TN223	TN223	TN223	TN223	TN223	TN223	TN223	TN223	TN223
	8	23	25	35	40	<u>//</u>	103	135	147	161
(VVI. %)	OP									P 20.0
	52.1	47.0	0.00	50.6	50.8	50.4	51.3	45.4	51.8	38.2
	0.0 1 4	0.2	9.9	17.0	12.1	8.3 1 E	12.5	12.3	12.7	10.1
	1.4	1.0	1.1 9 E	0.0	1.0	1.0	1.2	1.0	1.2	1.0
Tetol Fo	12.5	14.7	0.0	0.4	0.0	12.1	9.0	14.7	9.7	12.0
MnO	12.0	0.2	9.0	7.Z	9.0	13.0	10.0	10.5	10.9	0.1
MaQ	21.3	21.8	15.2	12.1	16.6	0.2 17 4	0.2 8.8	11 9	0.2 8.7	8.6
CaO	21.0	37	5.5	11.0	9.4	82	13.0	11.0	12.8	21.4
Na <sub>o</sub> O	 0 9	0.4	1.9	13	1.0	0.2	1 9	1 1	2.0	0.0
K <sub>2</sub> O	0.3	0.4	0.7	0.5	0.3	0.0	0.4	0.2	0.4	0.0
TiO	0.0	0.3	0.3	0.0	0.0	0.3	0.5	0.2	0.5	0.5
P₂Ω₅	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Cr_2O_2$	0.3	4.4	0.3	0.2	0.2	0.3	0.2	0.2	0.2	0.0
NiO	0.7	0.6	0.5	0.3	0.2	0.3	0.3	0.3	0.3	0.7
ΤΟΤΑΙ	99.5	99.5	99.8	100.4	99.9	99.9	99.8	99.7	100.4	99.9
	0.9	0.9	1 4	1 1	0.9	1.0	1.3	27	1.3	2.6
(ppm)	0.0	0.0			0.0					2.0
Sc	15.4	11.6	3.1	33.7	38.2	14.3	24.8	27.1	38.5	20.6
Ti	1531.6	1125.5	1131.6	2431.7	3716.3	2396.7	2469.1	6500.7	6852.3	6013.3
V	66.9	24.5	424.0	98.0	127.3	46.5	99.4	157.8	224.6	128.8
Cr	3001.5	50.7	1648.2	1554.2	1223.0	134.6	1298.2	189.8	881.2	931.5
Со	212.5	98.4	84.7	112.8	84.9	132.1	159.2	24.3	74.8	333.1
Ni	5908.1	1367.8	367.4	1051.6	947.3	2990.4	2757.2	1136.6	642.8	12912.7
Cu	2816.6	955.4	291.1	954.6	1318.3	4106.7	1143.4	734.3	930.9	20708.4
Zn	85.2	154.5	114.7	104.5	73.3	47.0	114.8	132.4	115.1	72.4
Ga	4.4	5.8	43.6	12.7	13.6	11.6	10.6	17.8	29.8	17.2
Ge	3.6	1.0	2.1	2.4	1.1	0.6	1.8	0.9	3.8	2.3
As	21.7	3.1	4.9	1.4	6.0	2.1	2.2	7.9	4.3	7.7
Se	12.7	2.1	3.4	2.5	4.6	11.8	8.3	17.4	5.6	38.6
Rb	9.6	1.9	50.8	2.3	9.0	1.4	6.4	8.6	29.9	5.8
Sr	26.3	9.1	37.2	103.0	51.2	21.4	74.1	126.2	218.5	77.5
Y	4.6	2.9	1.1	6.3	11.3	8.6	7.7	2.0	7.7	2.9
Zr	13.6	3.4	4.4	23.8	30.7	34.4	31.5	8.7	20.5	21.0
Nb	2.6	0.3	0.1	0.3	1.6	0.5	0.9	0.4	0.4	0.5
Мо	1.9	0.2	5.1	0.7	2.2	0.6	0.9	2.7	0.9	3.0
Ва	47.7	19.7	41.2	36.4	166.2	6.8	57.0	8.5	138.9	78.7
Pb	13.4	5.9	3.3	6.6	16.8	15.2	3.3	6.3	8.3	14.2
Bi	12.3	8.7	4.3	7.0	3.7	16.4	3.4	20.9	9.0	22.9
Th	4.9	2.1	4.7	3.5	1.8	1.6	3.0	7.8	3.3	5.6
U	7.8	2.1	5.5	1.0	0.9	1.6	1.6	3.2	3.2	0.2
Mg#	65.6	62.5	64.1	65.4	67.4	58.9	47.9	44.8	47.4	40.6
Cr(ppm)/MgO	140.8	2.3	108.5	128.7	73.7	7.7	147.5	15.9	101.2	108.9
Cr/V	44.9	2.1	3.9	15.9	9.6	2.9	13.1	1.2	3.9	7.2

Table IIIb(iii): Whole rock and trace element geochemistry of samples from borehole TN223. Please note that TN223\_156 was removed from the geochemistry data set due to invalid data.

	TN221	TN221	TN221	TN221	TN221	TN221	TN221	TN221	TN221	TN221
	11	25	28	33	65	73	185	196	204	264
(Wt. %)	UP	MP	Hz	MP	MP	MP	RN	LP	RN	Р
SiO <sub>2</sub>	52.4	49.5	50.4	50.6	51.2	50.9	35.8	45.8	34.0	46.7
$AI_2O_3$	5.1	7.4	3.5	13.3	10.1	12.6	11.8	9.6	9.0	2.3
Fe <sub>2</sub> O <sub>3</sub>	1.5	1.4	1.7	1.0	1.4	1.2	3.4	1.9	4.5	2.5
FeO	12.0	11.5	13.4	8.4	11.2	9.5	27.8	15.2	36.4	20.5
Total Fe	13.4	12.9	15.0	9.4	12.6	10.7	31.3	17.1	40.9	23.0
MnO	0.2	0.2	0.2	0.1	0.2	0.2	0.3	0.2	0.3	0.6
MgO	21.6	20.7	25.6	16.7	15.9	14.9	8.3	14.7	6.4	6.9
CaO	3.9	4.7	2.9	7.7	8.0	8.8	6.7	10.2	4.1	18.9
Na <sub>2</sub> O	0.6	0.6	0.3	0.9	1.0	1.2	1.1	1.1	1.1	0.1
K <sub>2</sub> O	0.2	0.2	0.1	0.2	0.2	0.1	0.2	0.1	0.1	0.1
TiO <sub>2</sub>	0.3	0.3	0.2	0.1	0.2	0.1	0.6	0.2	0.5	0.3
$P_2O_5$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Cr_2O_3$	0.3	2.7	0.4	0.2	0.3	0.2	0.1	0.2	0.1	0.0
NiO	0.9	0.7	1.0	0.5	0.4	0.1	1.2	0.7	1.6	0.1
TOTAL	99.2	99.9	99.6	99.9	100.0	99.9	97.3	99.8	98.1	98.9
LOI	0.9	0.3	2.8	0.7	1.3	0.2	4.1	2.9	5.6	0.2
(ppm)										
Sc	29.0	32.8	25.2	26.5	35.0	35.8	24.2	34.0	28.4	32.5
Ti	3424.1	3300.0	2033.8	1415.7	1950.3	1402.9	6765.5	2783.4	5827.2	2868.0
V	149.1	260.2	104.3	79.9	112.2	91.3	252.7	88.8	109.0	154.2
Cr	2478.7	19081.7	2611.2	1307.6	1947.8	1577.0	625.9	1104.9	156.8	2651.9
Co	188.7	173.1	225.3	135.4	138.8	87.2	296.3	187.0	198.5	173.1
Ni	7823.8	5844.3	7950.7	4218.0	3001.4	1032.3	10760.0	5065.2	5713.7	6936.9
Cu	3556.9	2789.3	4306.2	2372.5	1888.2	631.0	7351.7	2624.0	1907.7	3161.7
Zn	88.3	98.6	83.5	55.8	81.8	67.8	80.2	68.0	57.6	89.8
Ga	10.6	15.9	6.4	14.3	12.3	14.4	6.5	13.1	21.2	11.9
Ge	2.1	0.3	1.8	0.5	2.6	0.1	4.0	0.5	0.5	2.4
As	5.0	2.5	2.2	1.4	3.3	1.7	15.0	6.9	3.0	1.4
Se	16.8	13.4	14.9	7.1	10.1	4.0	32.5	12.0	12.2	14.2
Rb	8.0	6.6	4.9	8.6	8.0	6.1	8.6	7.0	8.9	6.4
Sr	50.1	65.9	19.3	140.1	155.3	192.4	179.9	188.0	74.4	39.5
Y	7.3	5.0	3.5	3.7	4.5	2.9	3.4	11.0	15.5	5.2
Zr	38.0	25.8	14.5	11.0	14.5	6.7	12.0	13.6	84.1	20.0
Nb	0.8	1.7	2.0	2.1	0.9	0.9	3.2	3.8	4.4	2.3
Мо	0.5	1.0	0.7	1.4	1.1	0.3	1.7	1.8	1.0	0.9
Ва	79.7	83.7	35.0	50.8	42.4	28.4	71.3	56.4	92.5	42.0
Pb	10.0	14.2	16.3	12.1	9.9	5.1	6.6	11.6	20.0	12.9
Bi	14.8	14.6	5.4	10.2	6.9	1.9	25.4	9.7	15.2	7.5
Th	0.0	2.9	0.9	4.3	2.2	3.4	10.6	8.6	8.3	4.2
U	5.5	5.4	6.3	4.0	4.9	5.9	6.7	6.9	7.8	4.2
Mg#	64.4	64.3	65.7	66.7	58.6	61.0	23.0	49.1	15.0	25.0
Cr(ppm)/MgO	114.6	922.3	102.2	78.1	122.7	106.1	75.1	75.4	24.5	387.1
Cr/V	16.6	73.3	25.0	16.4	17.4	17.3	2.5	12.4	1.4	17.2

Table IIIb(iv): Whole rock and trace element geochemistry of samples from borehole TN221.

	TN240	TN240								
	6	22	25	46	53	71	89	144	214	231
(Wt. %)	UP	MP	MP	MP	MP	LP	LP	Р	RN	Р
SiO <sub>2</sub>	52.8	53.4	51.8	50.5	49.5	49.9	48.9	46.7	27.7	42.9
$AI_2O_3$	5.6	5.7	8.6	9.8	18.3	9.4	13.9	12.9	9.7	9.0
Fe <sub>2</sub> O <sub>3</sub>	1.4	1.4	1.2	1.3	0.9	1.5	1.4	1.2	4.9	1.0
FeO	11.2	10.9	9.4	10.5	7.2	12.1	11.0	9.8	39.8	7.7
Total Fe	12.5	12.3	10.5	11.7	8.1	13.6	12.4	11.0	44.7	8.7
MnO	0.2	0.2	0.2	0.2	0.1	0.2	0.2	1.9	0.3	0.1
MgO	21.8	21.9	20.0	19.1	11.9	18.5	13.7	8.1	8.6	14.2
CaO	4.7	4.0	6.8	6.7	9.5	6.1	8.5	17.0	4.5	23.6
Na <sub>2</sub> O	0.7	0.6	0.8	0.9	1.6	1.0	1.3	0.5	0.8	0.7
K <sub>2</sub> O	0.4	0.4	0.2	0.2	0.3	0.2	0.3	0.7	0.2	0.1
TiO <sub>2</sub>	0.4	0.3	0.2	0.2	0.1	0.2	0.2	0.5	0.6	0.5
$P_2O_5$	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Cr_2O_3$	0.3	0.4	0.3	0.3	0.2	0.3	0.2	0.1	0.1	0.1
NiO	0.4	0.7	0.4	0.4	0.3	0.3	0.4	0.1	2.2	0.1
TOTAL	99.9	99.8	99.8	99.9	100.0	99.8	99.9	99.4	99.3	100.0
LOI	0.2	1.0	0.7	1.3	2.1	1.2	1.8	1.8	6.2	1.9
(ppm)										
Sc	30.1	35.2	37.1	30.4	29.8	36.6	28.7	37.6	23.5	52.5
Ti	4815.8	2856.4	2294.0	1910.9	1487.1	1973.9	1799.4	6367.6	6697.2	5371.1
V	180.8	122.3	109.8	94.0	64.4	97.1	86.5	215.1	261.7	85.2
Cr	2292.3	2805.9	2114.7	1769.6	1073.3	1786.7	1424.9	424.6	771.6	587.8
Со	119.6	138.1	118.2	156.6	106.3	155.3	142.0	67.3	570.4	48.4
Ni	2945.1	4490.1	2710.4	2541.6	2188.7	2392.4	2774.3	661.1	18236.3	1063.9
Cu	666.2	2624.1	1703.5	2192.3	1618.5	1595.2	1639.2	475.9	2942.7	1896.2
Zn	95.1	82.0	63.2	65.5	39.1	75.8	67.7	97.3	132.1	28.5
Ga	4.3	9.3	11.3	8.9	17.0	10.4	15.9	18.6	18.9	11.9
Ge	0.6	2.0	2.6	1.6	1.5	2.3	1.0	1.9	0.8	2.7
As	2.6	7.4	14.2	8.4	5.5	7.1	1.3	13.1	26.1	7.2
Se	10.0	14.5	10.7	9.5	6.8	7.2	8.1	4.6	40.8	12.3
Rb	13.7	16.7	8.8	6.5	12.9	7.1	12.5	47.2	10.1	3.1
Sr	67.5	51.3	88.9	93.9	207.3	117.9	188.4	38.9	85.8	51.7
Y	10.7	11.8	6.4	4.7	3.2	4.9	3.6	12.5	3.3	19.2
Zr	42.6	62.3	51.6	11.7	17.4	13.6	13.6	69.4	10.4	63.6
Nb	4.1	0.5	2.4	1.5	0.4	2.0	0.7	2.5	5.5	2.2
Мо	1.7	0.1	0.1	0.1	1.4	1.8	0.2	1.4	4.8	0.7
Ва	91.3	116.4	48.7	49.0	104.6	36.8	71.2	223.3	118.6	15.6
Pb	6.5	16.7	8.2	11.1	14.9	8.0	9.9	17.4	7.3	57.2
Bi	4.2	12.8	12.7	9.4	6.5	6.9	4.0	9.4	35.2	37.0
Th	7.2	6.5	3.4	5.3	3.8	6.1	1.8	5.6	8.2	5.6
U	3.7	4.8	3.7	2.0	5.2	1.8	4.3	0.4	5.7	2.7
Mg#	66.1	66.7	68.1	64.7	62.5	60.5	55.4	45.2	17.8	64.8
Cr(ppm)/MgO	105.4	128.2	105.8	92.6	89.9	96.4	103.9	52.5	89.7	41.3
Cr/V	12.7	22.9	19.3	18.8	16.7	18.4	16.5	2.0	2.9	6.9

Table IIIb(v): Whole rock and trace element geochemistry of samples from borehole TN240.

	TN197	TN197	TN197	TN197	TN197	TN197	TN197	TN197	TN197	TN197
	8	23	32	47	54	70	88	145	161	246
(Wt. %)	UP	Hz	MP	MP	MP	MP	MP	LP	С	Р
SiO <sub>2</sub>	53.0	49.4	50.2	51.0	51.2	51.0	49.7	50.1	41.0	62.8
$AI_2O_3$	5.4	3.5	15.4	13.3	12.9	9.6	14.7	14.8	5.2	1.0
Fe <sub>2</sub> O <sub>3</sub>	1.5	1.6	0.9	1.0	1.1	1.5	1.3	1.0	1.0	2.2
FeO	12.2	12.6	7.6	7.9	8.6	12.0	10.5	8.0	8.3	17.7
Total Fe	13.7	14.2	8.5	8.8	9.6	13.5	11.8	9.0	9.4	19.9
MnO	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.1	0.3	0.3
MgO	20.9	27.3	12.2	14.3	15.1	17.6	12.4	14.1	24.5	2.1
CaO	4.6	2.4	11.0	9.6	7.7	5.6	9.0	8.9	18.0	13.8
Na₂O	0.6	0.1	1.4	1.5	1.5	1.1	1.3	1.4	0.0	0.0
K₂Ō	0.2	0.2	0.3	0.2	0.2	0.1	0.1	0.2	0.0	0.0
TiO <sub>2</sub>	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.8	0.1
P₂Q₅	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$Cr_{2}O_{2}$	0.3	1.0	0.0	0.0	0.2	0.3	0.0	0.2	0.0	0.0
NiO	0.0	0.7	0.0	0.5	0.5	0.5	0.3	0.1	0.0	0.0
ΤΟΤΑΙ	99.9	99.3	100.0	99.8	99.2	99.7	99.9	99.2	99.7	99.9
	0.5	21	1 4	1.8	0.8	1 1	3.0	0.4	8.5	-0.8
(ppm)	0.0				0.0		0.0	011	0.0	0.0
Sc	34.2	27.2	33.2	34.4	30.9	28.9	31.0	27.6	20.9	17 7
Ti	3544 1	1890.2	1965.8	1815 3	1664.8	1858.2	1415.2	2298.6	5479.4	941.6
V	177.6	121.8	81.6	76.1	67.9	71.5	71.3	86.7	15.7	29.1
Cr	2374.3	6190.2	971.8	1391.0	1580 7	1894.9	692.7	991.3	84.8	86.5
Co	156 7	190.6	126.5	142.5	148 1	171.5	116 7	86.4	95.3	9.9
Ni	5247 5	5471 2	4397 7	3757.6	3695.2	3784 7	2012.2	1108.8	2629.0	521.1
Cu	2590.2	2330.6	2658.9	2141.3	2237.3	2859.3	3280 1	617 1	2867.3	446.6
Zn	93.0	112.2	42.5	40.7	51.0	75.8	79.5	64 1	50.9	31.2
Ga	8.8	87	16.6	13.1	15.5	13.0	15.9	16.2	10.8	3.9
Ge	0.6	1 4	2.0	03	5.6	1 7	0.6	43	0.4	5.7
Δς	3.5	0.6	2.0	0.0	2.0	0.0	4 5	4.0 1 0	0.4 4 5	7.4
AS Se	10.8	13.3	11.8	8.0	Q 7	0.0 Q ()	7.1	5.6	10.1	7. <del>4</del> 8.1
Ph	8.2	20.0	0.8	5.7	5.7 6.0	5.0	6.4	J.U	0.4	2.6
Sr	5/ 1	20.0	167.5	210.5	207.0	133.0	205.2	235.8	6.4	2.0
V	97.1	20.0 5 1	5.5	210.5	207.3	100.2	205.2	200.0	17.2	21.5 7 /
T Zr	3.7 35.7	12 /	15.5	J.Z 13 7	4.0	20.8	0.0	4.0	06.6	12.6
	1.2	2 /	2.0	20	2.4	20.0	0.9	12.5	30.0 16.0	12.0
Mo	4.2	0.5	1.0	0.0	0.4	2.9	1 1	1.2	10.0	2.0
Ro	0.1 69.6	0.5	1.0 96 5	0.0 56 5	50.0	0.7	1.1	07.0	1.4	2.9 10.2
Da	12.6	44.5	10.0	50.5	0.6	44.5	40.2	5.2	0.9	10.5
PU Di	13.0	10.9	10.0	0.9	9.0	0.9	0.J	5.3 4.0	03.0	2.1 10.6
	0.7	5.0	1.2	3.0	5.5 E 1	3.1 2.2	5.0 2.5	4.9	0.0 61.4	12.0
	4.1	5.Z	4.1	3.2	5.4	3.3	3.3	0.7	01.4	0.9
<u> </u>	1.4	0.7	5.3	1.4	5.8	4.0	4.7	1.7	ŏ.4	4.2
	63.2	08.5	01. <i>1</i>	07.5	03.8	59.4	54.1	53.7	/4.6	10.4
	113.6	226.4	/9.9	97.5	104.8	107.8	55.8	/0.2	3.5	42.2
Cr/V	13.4	50.8	11.9	18.3	23.3	26.5	9.7	11.4	5.4	3.0

Table IIIb(vi): Whole rock and trace element geochemistry of samples from borehole TN197.

	TN198							
	32	34	46	55	62	69	75	78
(Wt. %)	MP	MP	MP	Р	Р	Р	P	Р
SiO <sub>2</sub>	51.8	50.9	48.4	50.0	52.1	49.2	48.7	47.0
$AI_2O_3$	7.3	6.5	16.3	14.5	6.9	8.0	4.4	4.2
Fe <sub>2</sub> O <sub>3</sub>	1.2	1.4	0.9	0.8	1.0	1.0	1.3	1.4
FeO	10.0	11.1	7.1	6.4	7.9	8.3	10.2	11.7
Total Fe	11.3	12.5	8.0	7.2	8.9	9.4	11.4	13.1
MnO	0.2	0.2	0.1	0.2	0.2	0.3	0.3	0.4
MgO	21.3	23.2	10.5	9.3	13.1	11.4	11.5	13.6
CaO	5.6	4.7	13.1	15.6	15.8	19.5	21.5	20.7
Na <sub>2</sub> O	0.6	0.4	1.1	0.8	0.5	0.2	0.4	0.2
K <sub>2</sub> O	0.3	0.1	1.3	1.9	1.7	1.2	0.4	0.1
TiO <sub>2</sub>	0.2	0.1	0.1	0.2	0.3	0.4	0.4	0.3
$P_2O_5$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cr <sub>2</sub> O <sub>3</sub>	0.9	0.4	0.1	0.1	0.1	0.1	0.1	0.1
NiO	0.4	0.7	0.6	0.4	0.3	0.2	0.3	0.3
TOTAL	99.9	99.7	99.8	100.0	99.9	99.7	99.4	99.9
LOI	0.6	1.2	2.4	2.4	1.9	1.8	1.0	1.1
(ppm)								
Sc	31.9	31.1	31.2	40.9	58.7	51.9	58.0	50.0
Ti	2093.8	1567.8	1621.4	2627.6	3669.1	4105.3	4285.1	4047.0
V	144.1	102.5	82.9	141.9	169.7	162.2	188.1	149.7
Cr	5829.0	2489.9	869.7	602.8	717.7	766.9	554.4	474.4
Co	130.8	179.6	126.3	93.5	93.0	57.3	78.3	79.8
Ni	3321.4	5441.7	4040.7	2535.6	2098.3	1345.4	2144.8	1947.7
Cu	1854.6	2991.8	2681.2	1730.3	1449.4	918.5	1438.6	1355.1
Zn	88.1	84.8	50.0	58.1	58.4	43.6	47.6	57.7
Ga	12.8	7.2	15.2	15.8	12.8	11.9	7.0	7.6
Ge	0.8	0.3	2.0	3.7	1.5	4.2	0.3	4.5
As	1.0	7.7	1.0	15.7	0.4	5.7	17.4	6.4
Se	8.6	12.9	10.3	5.9	9.1	6.4	11.4	12.3
Rb	9.4	7.7	46.2	61.5	42.0	36.3	10.2	6.4
Sr	70.8	58.7	157.0	160.4	139.1	101.3	34.5	36.5
Y	4.5	2.1	5.5	8.8	17.3	8.6	12.7	12.7
Zr	18.0	8.4	11.6	29.3	43.9	42.7	42.5	34.2
Nb	1.2	0.8	0.8	2.0	3.4	2.7	1.3	1.2
Мо	0.5	1.2	0.4	2.9	2.3	2.6	2.5	2.6
Ba	67.0	54.9	90.1	116.9	211.8	92.6	57.8	17.5
Pb	9.6	11.7	10.3	9.3	12.5	10.8	16.2	16.4
Bi	7.6	4.5	5.3	6.1	7.2	5.7	10.9	7.1
Th	4.5	4.3	7.1	5.1	7.7	7.5	8.3	6.2
U	3.0	4.1	3.3	5.1	4.4	2.2	2.3	4.1
Mg#	67.9	67.5	59.7	59.4	62.3	57.8	53.0	53.8
Cr(ppm)/MgO	274.0	107.4	82.7	64.7	54.9	67.2	48.3	35.0
Cr/V	40.5	24.3	10.5	4.2	4.2	4.7	2.9	3.2

Table IIIb(vii): Whole rock and trace element geochemistry of samples from borehole TN198.

	TN199	TN199	TN199	TN199	TN199	TN199
	3	7	19	24	30	60
(Wt. %)	UP	UP	UP	UP	MP	Р
SiO <sub>2</sub>	53.8	54.7	53.6	53.4	52.8	44.5
$AI_2O_3$	6.1	6.6	5.9	6.6	6.9	8.8
Fe <sub>2</sub> O <sub>3</sub>	1.4	1.3	1.3	1.3	1.3	1.6
FeO	11.2	10.5	10.7	10.3	10.4	12.5
Total Fe	12.6	11.8	12.0	11.5	11.7	14.0
MnO	0.2	0.2	0.2	0.2	0.2	0.3
MgO	20.3	20.7	21.3	21.6	21.4	8.5
CaO	4.1	4.1	4.0	4.0	4.3	22.1
Na <sub>2</sub> O	0.5	0.7	0.8	0.7	0.8	0.2
K <sub>2</sub> O	0.5	0.5	0.5	0.5	0.5	0.0
TiO <sub>2</sub>	0.4	0.3	0.3	0.2	0.3	0.5
$P_2O_5$	0.1	0.0	0.0	0.0	0.1	0.0
$Cr_2O_3$	0.4	0.3	0.4	0.4	0.4	0.1
NiO	0.5	0.3	0.7	0.6	0.5	0.5
TOTAL	99.4	100.2	99.6	99.7	99.8	99.5
LOI	3.0	2.4	2.2	2.4	2.4	2.0
(ppm)						
Sc	32.8	32.9	26.4	29.7	29.2	61.1
Ti	4061.0	3144.6	3297.7	2589.9	3874.5	5831.2
V	172.8	146.1	128.9	113.3	126.7	190.9
Cr	2574.3	2373.6	2587.5	2561.7	2670.7	392.1
Co	129.4	107.6	157.3	133.7	134.6	146.3
Ni	3555.9	2246.0	5315.5	4102.3	3326.5	3603.6
Cu	1917.7	988.7	2617.1	2222.9	1979.0	2294.6
Zn	85.3	81.4	80.1	77.6	73.6	79.5
Ga	10.3	15.2	8.8	9.1	8.4	18.0
Ge	0.1	0.7	4.0	2.6	2.4	0.7
As	11.7	5.7	4.6	0.5	2.2	1.1
Se	9.9	8.7	13.2	10.7	8.5	11.2
Rb	23.2	21.4	21.7	20.4	18.0	3.5
Sr	41.9	57.0	53.3	56.0	63.4	97.2
Y	11.6	11.0	11.4	8.7	10.0	10.7
Zr	49.6	34.7	39.9	37.9	29.6	46.9
Nb	2.7	1.6	1.9	1.2	2.0	2.7
Мо	1.7	0.8	1.0	1.0	0.2	1.4
Ва	70.1	99.6	106.5	85.9	141.0	26.3
Pb	7.0	6.7	8.7	13.6	3.0	17.3
Bi	10.0	9.7	13.3	9.4	0.5	11.8
Th	11.3	7.3	7.9	6.5	4.0	10.8
U	1.0	1.4	2.2	2.4	0.0	3.8
Mg#	64.4	66.3	66.5	67.8	67.2	40.4
Cr(ppm)/MgO	126.6	114.9	121.8	118.5	125.0	46.3
Cr/V	14.9	16.2	20.1	22.6	21.1	2.1

Table IIIb(viii): Whole rock and trace element geochemistry of samples from borehole TN199.

	TN201	TN201	TN201	TN201	TN201	TN201	TN201	TN201
	11	32	47	61	75	90	99	107
(Wt. %)	UP	MP	MP	LP	LP	Р	P	Р
SiO <sub>2</sub>	52.1	49.6	51.5	45.9	50.1	47.0	39.2	47.4
$AI_2O_3$	7.3	13.9	14.5	18.1	15.7	19.1	10.7	6.9
Fe <sub>2</sub> O <sub>3</sub>	1.3	1.0	0.9	1.3	1.0	1.0	2.0	1.7
FeO	10.5	8.4	7.4	10.8	7.9	8.3	16.0	13.7
Total Fe	11.8	9.4	8.3	12.2	8.9	9.3	17.9	15.4
MnO	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4
MgO	20.8	15.4	13.3	14.3	10.7	6.9	8.3	10.5
CaO	4.9	8.6	9.4	7.0	11.2	13.2	22.3	17.1
Na <sub>2</sub> O	0.9	1.3	1.5	1.1	1.6	1.4	0.0	0.5
K <sub>2</sub> O	0.2	0.3	0.2	0.4	0.7	1.6	0.0	1.0
TiO <sub>2</sub>	0.2	0.2	0.2	0.2	0.2	0.2	0.5	0.3
$P_2O_5$	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
$Cr_2O_3$	0.3	0.3	0.2	0.1	0.1	0.1	0.0	0.0
NiO	0.5	0.3	0.3	0.3	0.3	0.4	0.6	0.2
TOTAL	99.2	99.4	99.6	99.7	99.7	99.5	99.9	99.7
LOI	0.4	1.0	1.5	1.8	2.0	3.8	4.0	1.2
(ppm)								
Sc	34.1	26.6	30.3	29.8	37.5	36.6	28.5	44.6
Ti	2390.7	1644.4	2040.7	2030.7	2356.9	2631.1	5367.4	4042.3
V	148.2	87.5	109.0	167.8	74.1	69.8	53.9	166.5
Cr	2268.8	1580.4	1171.6	738.1	448.3	444.2	131.1	213.5
Co	137.4	92.4	95.5	119.6	93.6	73.1	105.5	75.0
Ni	3799.5	1880.8	1877.5	1966.0	2409.0	2615.2	4411.2	1176.5
Cu	1999.3	1126.9	1225.4	1199.8	1496.5	5034.4	4898.1	821.2
Zn	86.7	59.7	49.4	90.3	49.2	33.4	24.1	51.0
Ga	9.2	14.9	12.0	27.6	15.3	14.6	16.3	11.5
Ge	3.3	2.3	2.6	0.1	2.6	1.5	2.1	3.2
As	6.2	7.2	4.3	1.4	3.8	5.4	1.4	6.2
Se	9.6	8.0	6.7 7 F	7.8 • • • •	6.2	8.2	19.3	4.9
RD Cr	9.1	14.6		14.4	25.0	63.Z	1.6	31.4
Sr	83.1	157.1	144.3	158.2	1/2./	224.0	19.1	89.5
ř Zr	1.3	4.9	0.7	2.4 17.0	0.7	5.9 16.0	10.1	8.4 20.9
	23.0	10.0	30.3 0 E	0.11	22.9	10.0	113.0	30.0 1 2
Mo	1.7	1.4	0.5	0.0	1.0	1.7	4.0	1.3
NO Bo	2.0 72.0	0.Z 71.2	1.0 56.0	1.U 59.5	2.0 107.6	250.9	1.4	00.2
Da Dh	10.5	10.1	50.9	50.5 7 1	107.0	200.0	9.0	90.Z
Ri	10.0	10.1 8 5	6.0	۱.۱ ۹.۹	7.3 5.1	9.0 7 7	9.0 18 5	۲.۷ ۲۵۹
Th	4.2 6 9	0.0 A A	6.5	0.0 3 A	5.4 6 /	65	10.0	70
U	3.5	5.0	0.0	0.0	0.4 2 4	34	53	7.9 4 3
 	66.4	64.8	64.3	56.9	57.3	45.7	34.2	43.4
Cr(ppm)/MaQ	109.7	102 4	88 0	51.8	<u> </u>	64 0	15.8	 20.3
Cr/V	15.3	18.1	10.7		<u>-+2.1</u> 6.0	6.4	<u>10.0</u> 2⊿	1 3
01/ v	10.0	10.1	10.7	7.4	0.0	0.4	∠.+	1.0

Table IIIb(ix): Whole rock and trace element geochemistry of samples from borehole TN201.

	TN203	TN203	TN203	TN203	TN203	TN203
	33	39	44	55	60	65
(Wt. %)	MP	Hz	MP	MP	MP	MP
SiO <sub>2</sub>	50.6	47.9	48.5	47.5	45.8	49.7
$AI_2O_3$	9.0	5.9	10.5	11.9	13.0	18.6
Fe <sub>2</sub> O <sub>3</sub>	1.2	1.4	1.3	1.1	1.2	0.8
FeO	9.9	11.1	10.4	8.7	9.8	6.5
Total Fe	11.2	12.5	11.6	9.7	11.0	7.3
MnO	0.2	0.2	0.2	0.2	0.2	0.1
MgO	17.1	27.6	20.8	20.1	19.1	8.6
CaO	9.0	4.1	5.6	8.7	9.2	12.5
Na <sub>2</sub> O	0.9	0.2	1.0	0.8	0.7	1.7
K <sub>2</sub> O	0.3	0.2	0.3	0.4	0.4	0.8
TiO <sub>2</sub>	0.4	0.2	0.3	0.2	0.2	0.2
$P_2O_5$	0.1	0.0	0.0	0.0	0.0	0.0
$Cr_2O_3$	0.3	0.3	0.2	0.1	0.1	0.1
NiO	0.6	0.7	0.3	0.3	0.3	0.3
TOTAL	99.8	99.8	99.3	100.0	100.0	99.8
LOI	1.7	5.7	3.7	4.4	4.9	2.0
(ppm)						
Sc	35.5	25.4	25.6	24.6	24.6	34.3
Ti	3923.8	2075.4	2796.2	2404.0	2237.0	2008.7
V	139.6	94.9	99.5	69.9	70.7	86.2
Cr	2232.5	2217.3	1322.7	549.6	809.8	626.8
Co	133.4	134.7	105.2	100.2	97.2	93.7
Ni	4516.2	4204.6	2209.6	2315.2	2371.0	1808.9
Cu	3501.2	2787.5	1136.0	1308.1	2002.1	1016.4
Zn	89.7	144.6	173.8	69.2	120.8	41.8
Ga	10.7	11.7	16.5	9.0	11.5	19.1
Ge	2.4	2.1	1.1	1.5	1.2	1.6
As	7.7	5.0	3.0	0.1	4.0	7.5
Se	10.7	8.5	4.2	9.1	7.6	7.6
Rb	14.6	11.8	10.2	14.7	15.4	37.5
Sr	95.8	16.7	97.1	148.9	137.1	197.7
Y	11.6	5.3	6.3	6.5	7.3	7.2
Zr	59.4	17.8	19.6	35.1	20.9	14.9
Nb	1.9	1.1	0.1	1.7	1.6	1.2
Мо	0.4	0.9	0.6	1.7	2.4	0.5
Ва	95.9	22.3	47.8	76.7	77.6	145.2
Pb	6.7	10.6	8.2	16.6	21.0	12.4
Bi	6.7	3.4	1.8	4.3	0.1	0.2
Th	4.6	1.8	0.6	7.6	1.4	0.7
U	0.1	2.8	1.5	0.9	0.3	0.4
Mg#	63.3	71.4	66.8	69.9	66.2	57.0
Cr(ppm)/MgO	130.4	80.3	63.5	27.3	42.4	73.0
Cr/V	16.0	23.4	13.3	7.9	11.5	7.3

Table IIIb(x): Whole rock and trace element geochemistry of samples from borehole TN203.

	TN205	TN205	TN205	TN205	TN205	TN205	TN205	TN205	TN205
	55	64	115	147	152	160	167	177	185
(Wt. %)	MP	MP	LP	Hz	Р	Р	Р	Р	Hn
SiO <sub>2</sub>	50.1	51.7	46.6	42.3	24.4	37.4	42.8	42.6	29.0
$AI_2O_3$	5.7	6.2	6.0	5.1	2.1	6.8	12.3	7.2	20.8
Fe <sub>2</sub> O <sub>3</sub>	1.6	1.4	2.7	1.9	5.6	1.9	1.7	1.7	3.7
FeO	12.7	11.2	21.6	15.6	45.0	15.6	13.8	14.1	30.2
Total Fe	14.3	12.6	24.3	17.5	50.6	17.5	15.5	15.8	33.9
MnO	0.2	0.3	0.4	0.3	0.2	0.3	0.2	0.2	0.3
MgO	21.6	22.7	17.1	28.8	14.3	33.2	7.7	8.0	9.2
CaO	5.5	4.9	3.1	4.2	3.9	3.3	18.4	24.5	1.7
Na <sub>2</sub> O	0.5	0.5	0.3	0.2	0.0	0.1	0.2	0.0	0.3
K <sub>2</sub> O	0.4	0.2	0.5	0.1	0.1	0.0	1.0	0.0	0.2
TiO <sub>2</sub>	0.2	0.2	0.2	0.1	0.1	0.2	0.3	0.7	0.9
$P_2O_5$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cr <sub>2</sub> O <sub>3</sub>	0.2	0.2	0.3	0.2	0.2	0.0	0.2	0.1	0.1
NiO	0.5	0.3	0.5	0.4	2.8	0.6	0.9	0.5	1.7
TOTAL	99.3	99.7	99.2	99.2	98.7	99.3	99.6	99.6	98.1
LOI	2.7	1.3	1.2	5.7	8.9	9.9	3.2	1.5	5.3
(ppm)									
Sc	24.1	29.6	31.2	16.2	17.1	11.4	38.7	60.5	35.1
Ti	2098.8	2168.1	2423.4	1197.3	1025.2	1993.5	3929.8	7903.5	10031.9
V	103.0	103.4	146.1	53.4	75.5	22.2	123.8	144.2	377.6
Cr	1346.5	1402.7	1885.1	1388.3	1484.3	75.5	1009.0	365.6	940.0
Со	150.4	123.8	170.8	139.6	518.9	120.5	181.7	95.5	255.1
NI	3769.5	2111.2	3675.3	2603.0	22530.5	3703.2	6520.8	3907.0	13655.4
	2537.9	1381.6	742.6	472.3	1282.3	1024.9	16/1.8	1360.1	3844.6
Zn Co	98.8	/9.5 E.C	79.6	82.2	69.4	244.9	34.8	29.9	357.0
Ga	1.2	0.0	9.4	0.3	13.0	10.0	19.0	20.7	49.0
Ge	12.0	0.3	12.4	0.3	5.8 5.2	1.5	2.0	2.4	3.4
AS So	1/ 0	2.0	11.0	0.7	5.Z	0.0	0.0	2.5 11.9	2.1 15 2
Se Rh	27.1	0.0	32.3	7.5 5.0	7.0	0.7	67.5	0.4	40.Z 21.3
Sr	45.5	67.2	57.3	56.7	19.7	10.7	168.3	51.8	42.6
Y	-0.0 6 4	5.2	67	4 4	2.0	8.2	9.5	14.4	1.5
7 7r	30.5	20.3	20.7	12.3	8.7	59.3	32.4	101 7	9.5
Nb	0.4	2.5	31	1.3	3.3	1 1	0.9	1.9	0.0
Mo	0.1	2.8	1.4	1.2	6.4	1.5	0.5	0.7	3.6
Ba	53.0	41.9	105.5	15.9	5.6	0.5	141.8	12.0	71.2
Pb	10.7	8.2	9.8	8.6	11.1	7.6	14.9	24.6	13.2
Bi	4.8	3.7	9.9	1.2	32.9	6.7	11.8	7.7	18.2
Th	3.1	5.2	6.8	1.5	1.7	4.2	1.3	2.8	4.3
U	0.2	0.2	2.9	0.4	10.2	5.8	1.5	7.1	8.3
Mg#	62.9	66.9	44.3	64.9	24.1	68.0	35.8	36.2	23.4
Cr(ppm)/MaO	62.5	61.8	110.0	48.2	104.0	2.3	131.0	45.8	101.7
Cr/V	13.1	13.6	12.9	26.0	19.7	3.4	8.2	2.5	2.5

Table IIIb(xi): Whole rock and trace element geochemistry of samples from borehole TN205.

### APPENDIX IV AUTOMATED MINERALOGY

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#### IVa Automated mineralogical sample list and descriptions

The samples selected for automated mineralogical analysis are divided into two groups, namely igneous and metamorphic samples. Tables IVa(i) and IVa(ii) give the igneous and metamorphic samples selected for automated SEM analysis respectively, including the assigned rock type. This grouping was used to assist data interpretation and will be used when presenting the bulk modal, base metal sulphide (BMS) and platinum-group mineral (PGM) datasets, in Appendix IVb, IVc and IVd. The samples in each table are listed along strike, north to south.

Sample ID	Rock type
TN228_9	Pyroxenite
TN228_20	Serpentinised harzburgite
TN223_23	Pyroxenite
TN223_25	Pyroxenite (granitic vein-associated)
TN223_40	Norite
TN223_135	Norite
TN223_156	Norite
TN221_11	Pyroxenite
TN221_25	Pyroxenite
TN221_65	Pyroxenite
TN240_22	Pyroxenite
TN240_89	Norite
TN197_8	Pyroxenite
TN197_32	Norite
TN197_54	Norite
TN198_32	Pyroxenite
TN199_3	Pyroxenite (felsic fluid-associated)
TN199_7	Pyroxenite (felsic fluid-associated)
TN199_19	Pyroxenite (felsic fluid-associated)
TN199_24	Pyroxenite (felsic fluid-associated)
TN199_30	Pyroxenite (felsic fluid-associated)
TN201_11	Pyroxenite
TN201_32	Pyroxenite (granitic vein-associated)
TN201_61	Norite
TN203_33	Pyroxenite
TN203_39	Serpentinised harzburgite
TN203_55	Serpentinised harzburgite
TN203_65	Norite
TN205_55	Pyroxenite

Table IVa(i). Igneous samples selected for automated SEM analysis, including the assigned rock type.

Table IVa(ii). Metamorphic samples selected for automated SEM analysis, including the assigned rock type.

Sample ID	Sample description
TN221_204	Recrystallised norite
TN240_214	Recrystallised norite
TN228_185	Parapyroxenite
TN223_161	Parapyroxenite
TN221_264	Parapyroxenite
TN240_144	Parapyroxenite
TN197_246	Parapyroxenite
TN198_55	Parapyroxenite
TN198_62	Parapyroxenite
TN198_75	Parapyroxenite
TN198_78	Parapyroxenite
TN199_60	Parapyroxenite
TN201_90	Parapyroxenite
TN201_99	Parapyroxenite
TN205_152	Parapyroxenite
TN205_160	Serpentinised parapyroxenite
TN228_65	Calcsilicate
TN197_161	Calcsilicate
TN228_81	Hornfels
TN205_185	Hornfels

# Appendix IVb Sample preparation

In the initial stage of the study, three boreholes namely TN197, TN221 and TN223 were crushed to -425 µm for the preparation of polished blocks for automated SEM analysis. After the analysis of these samples, a decision was made to prepare the remaining samples from the -3 mm material, without further crushing, to retain more association and textural information as some samples showed an undesirable amount of platinum-group mineral (PGM) liberation. The same set of polished blocks was used for QEMSCAN and MLA analysis.

Each sample was mixed with graphite using a graphite to sample ratio of 1:2. The sample was mixed with epoxy resin and placed in a 30mm diameter mould. The mould was placed in an epovac (10mins) followed by a pressure pot (6-8 hrs) to remove bubbles and maintain sample consistency. Once the mould was hardened, there were two grinding and two polishing stages in order to create a flat surface with an error of ~1 mm. The blocks were cleaned in an ultrasonic bath after each grinding and polishing stage. The polished blocks were then labelled, backfilled with resin and hardened in an oven at 50°C. A light microscope was used to manually check the polished blocks for inconsistencies. The polished blocks were finally carbon coated to 300 angstrom (angstrom unit= $10^{-8}$  of a centimetre).

Between 12-18 blocks were made for each sample based on the 3E+Au grade of each sample supplied by Platinum.

#### Appendix IVc The automated SEM technique

The QEMSCAN and MLA are both automated mineralogical SEM based systems owned by FEI. These systems were designed to support the mining industry via mineral processing applications (Sutherland and Gottlieb, 1991; Gu, 2003). Both instruments comprise a standard modern SEM fitted with energy dispersive spectrum (EDS) analysers together with specially developed software packages (Gu, 2003 and Pirrie *et al.*, 2004). The differences in hardware and software of both instruments create differences in application-suitability. The PGM analyses were conducted using the MLA whilst the QEMSCAN was used to analyse for basemetal sulphides (BMS) and bulk modal compositions. The MLA analyses were based on a FEI Quanta 600 M2 fitted with two Edax SDD detectors whilst the QEMSCAN analyses were based on a Carl Zeiss EVO-50 SEM fitted with two Bruker SDD detectors. The specially designed software packages for MLA and QEMSCAN are iDiscover and MLADataview respectively.

When a sample is analysed, backscattered electrons (BSE) are produced and are used to generate a BSE image displayed in varying grey levels based on mineral atomic number. The particles are located by automatically removing the backround (graphite and resin) and are analysed via a choice of measurement types, rapidly acquiring X-ray energy spectra. The measured spectra are then compared to a known database and each measurement point is assigned a mineral or phase name. The classified particles are called mineral maps, an example of which is given in Figure IVb(i). Data processing, to extract mineral distribution, grain size and association, is undertaken on classified mineral maps. Please note that there are stereological issues associated with measuring grainsize from 2-D polished blocks (Pirrie *et al.*, 2004).

The QEMSCAN measurement types used during this study include the Bulk Modal Analysis (BMA) and Trace Mineral Search (TMA), whilst the MLA used the Sparse Phase Liberation-lite (SPL-lite) measurement type. The BMA measurement analyses particles at a user-defined grid spacing and provides quantitative data on the bulk mineralogy. The TMS measurement selectively maps particles that contain mineral/s which have a BSE brightness above a user-defined threshold. Once the particle is located, it is analysed according to a user-defined grid spacing. This measurement allowed for the rapid analysis of BMS-containing particles. The SPL-lite measurement, used for PGM analysis, also uses BSE to locate particles that contain mineral/s above a certain BSE threshold. Once the particle is located, one analysis point is assigned to each grey level identified. In addition SPL-lite measures a user-defined area

around the mineral of interest instead of measuring the whole particle, ensuring efficiency whilst measuring coarse material.



Figure IVc(i). Example of a classified mineral map from the MLA instrument using the SPL-lite measurement type.

The quality of data produced from the automated SEM instruments is investigated and validated biannually by round robin standard sample analysis.

# Appendix IVd Bulk modal data (QEMSCAN)

The igneous samples are given in Tables IVd(i) to IVd(iii) and graphically presented in Figure IVd(i), whilst the metamorphic samples are reported in Tables IVd(iv) to IVd(v), graphically illustrated in Figure IVd(ii).

Table IVd(i). Quantitative bulk mineralogical analysis of the igneous samples from north to south along strike. The rock type of each sample is indicated. The results are given in mass %.

	TN228_9	TN228_20	TN223_23	TN223_25	TN223_40	TN223_135	TN223_156	TN221_11	TN221_25	TN221_65
Rock type*	Р	SH	Р	P-G	Ν	Ν	Ν	Р	Р	Р
Orthopyroxene	69.6	38.3	60.1	38.3	45.0	44.2	43.6	71.4	62.2	49.4
Clinopyroxene	8.2	3.7	5.9	7.9	15.1	10.6	14.8	6.4	7.0	16.7
Olivine	0.0	2.7	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Feldspar	8.4	2.0	5.9	35.2	33.3	29.9	26.0	12.5	15.8	22.2
Quartz	2.8	0.3	0.9	8.5	1.4	0.5	0.4	2.3	1.3	2.0
Serpentine	0.4	26.6	0.4	0.3	0.4	0.1	0.1	0.4	0.4	0.3
Chlorite	3.2	2.7	1.0	3.0	1.0	1.5	0.7	0.6	0.2	4.0
Amphibole	1.1	3.0	0.3	0.6	0.6	1.4	1.2	0.4	0.2	0.7
Talc	0.2	4.4	0.2	0.4	0.1	0.0	0.0	0.1	0.1	0.0
Mica	0.5	1.3	0.6	2.0	1.1	0.7	0.4	1.2	0.8	0.5
Garnet	0.4	0.4	0.1	0.4	0.2	0.9	0.5	0.1	0.1	0.4
Fe oxides	0.1	3.1	0.2	0.3	0.3	4.3	2.2	0.2	0.2	0.2
Chromite	0.1	2.3	21.2	0.3	0.0	1.0	0.3	0.1	7.4	0.5
Carbonates	0.4	2.1	0.1	0.2	0.1	0.2	0.0	0.1	0.1	0.2
Other Minerals	0.1	1.0	0.1	0.3	0.1	0.2	0.1	0.1	0.1	0.1
BMS	4.4	6.1	3.2	2.2	1.3	4.4	9.5	4.2	4.1	2.7
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

	TN240_22	TN240_89	TN197_8	TN197_32	TN197_54	TN198_32	TN199_3	TN199_7	TN199_19	TN199_24
Rock type*	Р	Ν	Р	Ν	Ν	Р	P-F	P-F	P-F	P-F
Orthopyroxene	64.2	47.1	65.8	31.3	51.0	58.3	52.1	56.0	61.1	57.0
Clinopyroxene	6.4	5.4	9.2	16.8	9.1	11.2	12.5	10.4	9.0	8.1
Olivine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feldspar	16.8	35.9	12.8	42.5	33.4	21.6	11.2	15.6	14.7	18.3
Quartz	3.0	0.2	2.8	1.1	0.9	0.6	6.5	5.1	4.6	4.0
Serpentine	0.1	0.1	0.3	0.2	0.3	0.2	0.6	0.6	0.6	0.9
Chlorite	2.1	2.8	0.6	1.3	0.9	0.9	10.2	7.6	4.6	6.4
Amphibole	0.5	1.2	0.6	1.0	0.4	0.5	1.5	0.9	1.0	0.9
Talc	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.2
Mica	1.1	0.7	1.1	0.7	0.5	1.1	2.4	1.5	1.1	1.3
Garnet	0.2	0.7	0.1	0.5	0.1	0.2	0.7	0.3	0.4	0.3
Fe oxides	0.3	0.0	0.4	0.1	0.2	0.1	0.1	0.0	0.1	0.0
Chromite	0.1	0.2	0.0	0.0	0.0	2.5	0.1	0.1	0.1	0.1
Carbonates	0.3	0.0	0.0	0.1	0.1	0.1	0.1	0.3	0.1	0.2
Other Minerals	0.1	0.0	0.1	0.1	0.1	0.1	0.2	0.1	0.3	0.1
BMS	4.5	5.6	6.0	4.3	3.0	2.6	1.5	1.0	2.3	2.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table IVd(ii). Quantitative bulk mineralogical analysis of the igneous samples from north to south along strike. The rock type of each sample is indicated. The results are given in mass %.

	TN199_30	TN201_11	TN201_32	TN201_61	TN203_33	TN203_39	TN203_55	TN203_65	TN205_55
Rock type*	P-F	Р	P-G	Ν	Р	SH	SH	Ν	Р
Orthopyroxene	62.6	60.9	46.8	46.2	50.2	46.4	29.9	17.4	54.5
Clinopyroxene	10.3	5.9	5.9	3.5	22.4	14.9	14.1	19.5	18.6
Olivine	0.0	0.0	0.0	0.1	0.0	0.4	0.9	0.0	0.0
Feldspar	16.2	27.0	41.9	36.0	17.7	3.3	26.2	49.9	6.9
Quartz	2.1	1.2	0.5	0.4	1.1	0.4	0.3	1.4	0.2
Serpentine	0.8	0.1	0.1	0.3	0.2	14.6	14.8	0.2	0.6
Chlorite	3.6	0.6	1.3	2.4	2.5	10.8	4.8	2.6	4.0
Amphibole	0.6	0.4	0.5	0.7	1.2	1.1	2.8	1.0	2.1
Talc	0.1	0.0	0.1	0.1	0.0	0.6	0.5	0.1	2.3
Mica	1.3	0.8	0.7	1.4	1.4	2.5	1.9	3.8	2.7
Garnet	0.1	0.1	0.3	0.7	0.6	0.4	0.9	0.7	0.5
Fe oxides	0.2	0.1	0.1	0.3	0.1	0.2	0.6	0.1	0.3
Chromite	0.1	0.1	0.0	0.0	0.1	0.5	0.0	0.0	0.1
Carbonates	0.0	0.0	0.1	0.1	0.1	0.3	0.4	0.2	0.2
Other Minerals	0.2	0.0	0.0	3.8	0.3	0.1	0.3	0.1	0.0
BMS	1.7	2.7	1.7	3.9	2.0	3.6	1.9	3.0	7.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table IVd(iii). Quantitative bulk mineralogical analysis of the igneous samples from north to south along strike. The rock type of each sample is indicated. The results are given in mass %.



Figure IVd(i). Graphical representation of the quantitative bulk mineralogical analysis of the igneous samples from north to south along strike. The rock type of each sample is indicated. The results are given in mass %.

	TN221_204	TN240_214	TN228_185	TN223_161	TN221_264	TN240_144	TN197_246	TN198_55	TN198_62	TN198_75
Rock type*	RN	RN	PA	PA	PA	PA	PA	PA	PA	PA
Orthopyroxene	19.9	18.3	3.6	0.5	8.3	2.6	2.9	2.7	3.4	1.2
Clinopyroxene	7.2	2.4	41.7	19.8	56.4	51.8	58.9	49.2	67.6	81.7
Olivine	0.0	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Feldspar	17.6	13.5	10.7	39.7	7.9	23.5	0.3	35.1	17.3	6.4
Quartz	4.2	0.0	0.5	0.4	1.7	0.4	31.5	0.4	1.0	1.1
Serpentine	0.0	0.0	19.1	0.1	0.0	0.0	0.0	0.1	0.2	0.1
Chlorite	2.7	5.0	3.6	1.3	0.9	6.0	0.1	0.7	3.2	0.8
Amphibole	0.7	1.1	5.7	16.3	3.5	1.9	3.9	1.2	1.7	2.0
Talc	0.0	0.0	0.6	0.0	0.0	0.1	0.0	0.1	0.0	0.0
Mica	0.3	0.6	0.2	0.6	0.3	2.8	0.1	6.4	2.0	0.6
Garnet	1.6	3.0	1.3	2.0	0.6	5.6	0.1	0.5	0.9	0.8
Cordierite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fe oxides	4.0	5.9	0.9	1.2	1.8	0.8	0.7	0.0	0.1	0.1
Chromite	0.2	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Al-oxides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Carbonates	0.4	0.0	0.6	1.1	0.5	1.0	0.2	0.6	0.7	0.5
Other Minerals	0.6	1.3	1.5	2.6	0.7	1.0	0.2	0.0	0.1	0.3
BMS	40.8	48.7	9.9	14.4	17.3	2.5	1.1	3.0	1.7	4.6
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table IVd(iv). Quantitative bulk mineralogical analysis of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated. The results are given in mass %.

\*RN=recrystallised norite, PA=parapyroxenite, SPA=serpentinised parapyroxenite, C=calcsilicate, HO=hornfels

	TN198_78	TN199_60	TN201_90	TN201_99	TN205_152	TN205_160	TN228_65	TN197_161	TN228_81	TN205_185
Rock type*	PA	PA	PA	PA	PA	SPA	С	С	НО	HO
Orthopyroxene	3.2	1.7	8.8	0.6	9.1	5.0	1.7	5.5	0.1	17.6
Clinopyroxene	76.5	57.3	24.7	21.1	12.4	9.9	32.2	37.9	0.2	0.3
Olivine	4.1	0.0	0.0	0.0	0.9	3.4	0.0	0.0	0.0	0.1
Feldspar	2.5	24.5	47.6	32.4	1.1	4.0	1.5	6.6	3.9	3.3
Quartz	0.5	1.0	0.2	0.1	0.0	0.0	0.3	1.8	0.1	0.0
Serpentine	0.2	0.1	0.0	0.0	6.8	49.2	37.9	23.4	0.3	0.0
Chlorite	1.1	1.5	4.1	1.7	1.5	11.8	1.2	1.2	0.3	2.3
Amphibole	4.1	3.7	1.9	17.1	0.6	2.9	1.9	6.4	0.1	0.5
Talc	0.0	0.0	0.1	0.0	1.2	0.1	0.1	0.3	0.4	0.1
Mica	0.6	0.1	5.1	0.1	0.4	0.4	0.2	0.2	4.0	1.7
Garnet	1.0	1.2	2.4	7.7	0.2	1.0	17.5	14.4	0.6	4.5
Cordierite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	82.8	27.3
Fe oxides	1.0	0.1	0.3	0.5	2.1	5.4	0.0	0.1	3.4	4.9
Chromite	0.0	0.2	0.0	0.0	0.6	0.0	0.0	0.1	0.0	0.0
Al-oxides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	7.7
Carbonates	0.6	0.9	0.1	1.2	0.5	0.2	2.3	0.2	0.1	0.0
Other Minerals	0.4	2.2	0.2	0.5	0.2	1.0	0.0	0.7	1.6	2.9
BMS	4.1	5.4	4.4	16.9	62.5	5.7	3.1	1.3	2.2	26.9
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table IVd(v). Quantitative bulk mineralogical analysis of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated. The results are given in mass %.

\*RN=recrystallised norite, PA=parapyroxenite, SPA=serpentinised parapyroxenite, C=calcsilicate, HO=hornfels



Figure IVd(ii). Graphical representation of the quantitative bulk mineralogical analysis of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated.

## Appendix IVe Base metal sulphide data (QEMSCAN)

The base metal sulphide distribution and association data for the igneous samples is given in Tables IVe(i) to IVe(ii) and graphically presented in Figures IVe(i) and IVe(ii), whilst the metamorphic samples are reported in Tables IVe(iv) and IVe(v), graphically illustrated in Figure IVe(iii) and IVe(iv).

Table IVe(i). BMS distribution and association data for the igneous samples from north to south along strike. The rock type of each sample is indicated. The quantitative BMS distribution results are given according to total BMS content. The BMS association results are qualitative.

	TN228_9	TN228_20	TN223_23	TN223_25	TN223_40	TN223_135	TN223_156	TN221_11	TN221_25	TN221_65
Rock type*	Р	SH	Р	P-G	Ν	Ν	Ν	Р	Р	Р
BMS distribution										
Pentlandite	1.4	2.1	1.0	0.7	0.3	0.5	1.2	1.5	1.3	0.6
Millerite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pyrite	2.0	0.1	0.7	0.2	0.2	0.9	0.3	1.0	0.5	0.4
Pyrrhotite	0.2	2.7	0.9	0.7	0.5	2.7	7.4	0.8	1.4	1.2
Chalcopyrite	0.8	1.1	0.6	0.5	0.3	0.4	0.6	0.9	0.9	0.5
Other Sulphides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total BMS	4.4	6.1	3.2	2.2	1.3	4.4	9.5	4.2	4.1	2.7
BMS association										
Liberated	0	13	58	63	73	54	72	70	87	69
Orthopyroxene	2	6	4	2	3	1	1	4	3	2
Clinopyroxene	0	0	4	2	2	4	3	2	1	2
Feldspar	88	0	33	2	14	41	24	22	9	22
Quartz	10	0	0	26	7	0	0	2	0	5
Serpentine	0	71	0	0	0	0	0	0	0	0
Fe-oxide	0	10	0	0	0	0	0	0	0	0
Chlorite	0	0	0	5	0	0	0	0	0	0
Total	100	100	100	100	100	100	100	100	100	100

	TN240_22	TN240_89	TN197_8	TN197_32	TN197_54	TN198_32	TN199_3	TN199_7	TN199_19	TN199_24
Rock type*	Р	Ν	Р	Ν	Ν	Р	P-F	P-F	P-F	P-F
BMS distribution										
Pentlandite	1.6	0.9	1.8	1.1	0.8	0.7	1.0	0.4	1.2	1.2
Millerite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pyrite	0.4	0.7	1.3	0.7	0.6	0.1	0.2	0.5	0.2	0.4
Pyrrhotite	1.4	3.1	1.7	1.7	0.9	1.0	0.1	0.2	1.0	1.3
Chalcopyrite	1.1	0.8	1.1	0.7	0.6	0.7	0.8	0.4	0.8	0.6
Other Sulphides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total BMS	4.5	5.6	6.0	4.3	3.0	2.6	2.1	1.5	3.3	3.4
BMS association										
Liberated	36	30	81	63	74	45	2	6	19	16
Orthopyroxene	9	3	9	8	11	27	31	31	10	13
Clinopyroxene	8	1	2	2	1	3	6	2	0	1
Feldspar	23	53	7	27	14	24	1	19	8	16
Quartz	23	13	2	1	1	1	43	40	61	54
Serpentine	0	0	0	0	0	0	0	0	0	0
Fe-oxide	0	0	0	0	0	0	0	0	0	0
Chlorite	1	0	0	0	0	0	17	1	2	0
Total	100	100	100	100	100	100	100	100	100	100

Table IVe(ii). BMS distribution and association data for the igneous samples from north to south along strike. The rock type of each sample is indicated. The quantitative BMS distribution results are given according to total BMS content. The BMS association results are qualitative.

	TN199 30	TN201 11	TN201 32	TN201 61	TN203 33	TN203 39	TN203 55	TN203 65	TN205 55
Rock type*	P-F	P	P-G	N	P	SH	SH	N	P
BMS distribution									
Pentlandite	0.6	0.8	0.4	0.4	0.5	1.2	0.3	0.5	1.1
Millerite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pyrite	0.3	0.1	0.4	0.6	0.2	0.3	0.4	0.7	1.0
Pyrrhotite	1.1	1.1	0.6	2.6	0.4	0.9	0.9	1.6	4.1
Chalcopyrite	0.5	0.6	0.3	0.3	0.9	1.1	0.3	0.2	0.8
Other Sulphides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total BMS	2.4	2.7	1.7	3.9	2.0	3.6	1.9	3.0	7.0
BMS association									
Liberated	7	43	54	46	24	15	3	30	8
Orthopyroxene	13	16	1	20	6	8	14	0	36
Clinopyroxene	19	2	2	0	10	8	6	12	39
Feldspar	22	21	33	33	40	24	33	55	16
Quartz	38	18	10	0	21	0	0	2	1
Serpentine	0	0	0	0	0	23	44	0	0
Fe-oxide	0	0	0	0	0	0	0	0	0
Chlorite	0	0	0	1	0	23	0	0	1
Total	100	100	100	100	100	100	100	100	100

Table IVe(iii). BMS distribution and association data for the igneous samples from north to south along strike. The rock type of each sample is indicated. The quantitative BMS distribution results are given according to total BMS content. The BMS association results are qualitative.



Figure IVe(i). Graphical representation of the quantitative BMS distribution of the igneous samples from north to south along strike. The rock type of each sample is indicated.



Figure IVe(ii). Graphical representation of the qualitative BMS association of the igneous samples from north to south along strike. The rock type of each sample is indicated.

	TN221_204	TN240_214	TN228_185	TN223_161	TN221_264	TN240_144	TN197_246	TN198_55	TN198_62	TN198_75
Rock type*	RN	RN	PA	PA	PA	PA	PA	PA	PA	PA
BMS distribution										
Pentlandite	2.9	5.3	1.0	1.9	1.0	0.1	0.1	0.7	0.4	0.7
Millerite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pyrite	1.2	0.3	0.3	0.7	0.5	1.8	0.1	0.3	0.2	0.9
Pyrrhotite	30.9	42.4	7.9	11.2	13.3	0.4	0.8	1.5	0.6	2.1
Chalcopyrite	5.8	0.7	0.7	0.6	2.5	0.2	0.1	0.4	0.5	0.8
Other Sulphides	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total BMS	40.8	48.7	9.9	14.4	17.3	2.5	1.1	3.0	1.7	4.6
BMS association										
Liberated	91	50	11	79	86	8	59	25	9	28
Orthopyroxene	1	22	0	0	0	0	0	0	0	0
Clinopyroxene	2	0	60	4	13	76	29	47	71	69
Feldspar	5	22	0	14	1	16	1	28	20	3
Quartz	1	0	0	0	0	0	8	0	0	0
Serpentine	0	0	29	0	0	0	0	0	0	0
Fe-oxide	0	3	0	0	0	0	4	0	0	0
Chlorite	0	3	0	0	0	0	0	0	0	0
Garnet	0	0	0	2	0	0	0	0	0	0
Cordierite	0	0	0	0	0	0	0	0	0	0
Al-oxide	0	0	0	0	0	0	0	0	0	0
Total	100	100	100	100	100	100	100	100	100	100

Table IVe(iv). BMS distribution and association data of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated. The quantitative BMS distribution results are given according to total BMS content. The BMS association results are qualitative.

\*RN=recrystallised norite, PA=parapyroxenite, SPA=serpentinised parapyroxenite, C=calcsilicate, HO=hornfels

	TN198_78	TN199_60	TN201_90	TN201_99	TN205_152	TN205_160	TN228_65	TN197_161	TN228_81	TN205_185
Rock type*	PA	PA	PA	PA	PA	SPA	С	С	HO	НО
BMS distribution										
Pentlandite	0.7	1.4	0.4	0.9	7.3	1.0	0.1	0.0	0.1	3.8
Millerite	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.3	0.0	0.0
Pyrite	0.5	1.5	2.5	12.4	0.4	0.4	2.7	0.4	0.1	0.4
Pyrrhotite	2.5	4.2	0.0	2.0	54.4	4.0	0.0	0.0	1.9	21.8
Chalcopyrite	0.4	0.9	1.4	1.6	0.4	0.2	0.3	0.6	0.1	0.7
Other Sulphides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total BMS	4.1	8.0	4.4	16.9	62.5	5.7	3.1	1.3	2.2	26.9
BMS association										
Liberated	9	30	20	41	77	5	8	47	14	13
Orthopyroxene	0	0	0	0	0	0	0	2	0	47
Clinopyroxene	91	42	3	8	7	15	0	1	0	0
Feldspar	0	28	76	26	0	1	0	0	0	7
Quartz	0	0	0	0	0	0	0	0	0	0
Serpentine	0	0	0	0	6	75	38	30	0	0
Fe-oxide	0	0	0	0	0	0	3	0	0	0
Chlorite	0	0	0	0	10	4	0	0	0	0
Garnet	0	0	0	25	0	0	51	20	0	0
Cordierite	0	0	0	0	0	0	0	0	86	16
Al-oxide	0	0	0	0	0	0	0	0	0	16
Total	100	100	100	100	100	100	100	100	100	100

Table IVe(v). BMS distribution and association data of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated. The quantitative BMS distribution results are given according to total BMS content. The BMS association results are qualitative.

\*RN=recrystallised norite, PA=parapyroxenite, SPA=serpentinised parapyroxenite, C=calcsilicate, HO=hornfels



Figure IVe(iii). Graphical representation of the quantitative BMS distribution of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated.



Figure IVe(iv). Graphical representation of the qualitative BMS association of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated.

## Appendix IVf Platinum-group mineral data (MLA)

The Platinum group mineral (PGM) distribution and grain size data for the igneous samples is given in Tables IVf(i) to IVf(iii) and graphically presented in Figure IVf(i), whilst the PGM association data for the igneous samples is given in Tables IVf(iv) to IVf(vi), graphically presented in Figure IVf(i).

The PGM distribution and grain size data for the metamorphic samples is reported in Tables IVf(vii) and IVd(Viii), graphically illustrated in Figure IV(iii), whilst the PGM association data is reported in Tables IVf(ix) and (x), graphically presented in Figure IVf(iv).

Table IVf(i). Quantitative PGM distribution and average PGM grain size of the igneous samples from north to south along strike. The number of PGM analysed per sample is included. The rock type of each sample is indicated. The results are given in area %.

	TN228_9	TN228_20	TN223_23	TN223_25	TN223_40	TN223_135	TN223_156	TN221_11	TN221_25	TN221_65
Rock type*	Р	SH	Р	P-G	Ν	Ν	Ν	Р	Р	Р
Pt-Bi-tellurides	0.6	64.8	47.8	7.2	49.3	26.1	62.2	57.6	42.2	31.4
Pt-antimonides	0.0	0.2	0.0	0.0	0.0	0.0	0.0	2.5	0.0	0.2
Pt-arsenides	0.3	12.0	9.4	15.1	3.5	8.9	1.5	1.4	0.0	9.3
PGE-sulphides	0.1	0.2	9.5	1.3	32.6	14.1	14.3	2.5	24.3	9.8
Pt-Pd-Bi-tellurides	93.9	0.5	6.2	0.6	1.4	3.0	1.6	4.4	20.2	0.0
Pd-Te-bismuthides	2.4	17.3	13.0	72.0	9.8	27.8	17.8	7.2	10.9	39.0
Pd-Te-Sb-bismuthides	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0
Pd-antimonides	0.0	0.6	6.3	1.4	0.0	8.6	0.4	1.1	0.2	0.2
Pd-Hg-tellurides	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pd-selenides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PGE-sulpharsenides	0.0	0.2	0.1	1.5	0.0	2.7	0.1	0.0	0.0	0.0
Electrum	2.5	4.2	7.7	0.8	3.5	8.7	1.9	23.3	2.3	10.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of PGM analysed	158	156	313	347	129	187	178	233	315	128
Average PGM grain size (µm)	29	23	7	21	11	7	8	10	10	26

	TN240_22	TN240_89	TN197_8	TN197_32	TN197_54	TN198_32	TN199_3	TN199_7	TN199_19	TN199_24
Rock type*	Р	Ν	Р	Ν	Ν	Р	P-F	P-F	P-F	P-F
Pt-Bi-tellurides	10.9	9.7	7.5	52.8	57.3	55.9	0.8	0.6	5.0	14.1
Pt-antimonides	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0
Pt-arsenides	77.5	60.3	37.8	2.8	0.3	0.7	75.4	15.5	33.3	37.0
PGE-sulphides	0.5	0.0	9.8	11.4	10.2	0.2	0.0	0.0	0.0	0.0
Pt-Pd-Bi-tellurides	0.0	0.1	0.2	2.6	1.1	24.0	3.6	51.0	31.6	4.3
Pd-Te-bismuthides	9.2	27.3	43.8	27.1	28.4	15.9	12.1	19.3	20.6	32.4
Pd-Te-Sb-bismuthides	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pd-antimonides	1.0	0.1	0.1	0.2	0.0	0.1	0.1	0.1	3.5	0.0
Pd-Hg-tellurides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pd-selenides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PGE-sulpharsenides	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.0	0.2	0.1
Electrum	0.9	2.2	0.6	3.0	2.7	3.1	7.6	12.3	5.8	12.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of PGM analysed	174	195	248	304	214	227	120	155	371	210
Average PGM grainsize (µm)	83	24	23	11	7	33	93	17	18	20

Table IVf(ii). Quantitative PGM distribution and average PGM grain size of the igneous samples from north to south along strike. The number of PGM analysed per sample is included. The rock type of each sample is indicated. The results are given in area %.
	TN199_30	TN201_11	TN201_32	TN201_61	TN203_33	TN203_39	TN203_55	TN203_65	TN205_55
Rock type*	P-F	Р	P_G	Ν	Р	SH	SH	Ν	Р
Pt-Bi-tellurides	50.6	44.1	0.2	31.3	6.1	0.1	31.8	7.6	2.9
Pt-antimonides	0.0	0.1	0.1	0.0	2.1	0.0	1.1	0.0	5.8
Pt-arsenides	17.4	3.3	88.2	3.3	36.2	48.1	5.0	53.3	14.6
PGE-sulphides	0.9	0.0	1.0	0.0	0.0	0.0	0.1	0.0	0.0
Pt-Pd-Bi-tellurides	0.5	33.8	1.1	18.2	17.5	0.9	4.2	3.0	0.0
Pd-Te-bismuthides	28.9	8.8	7.4	45.2	33.6	37.1	55.9	34.9	21.7
Pd-Te-Sb-bismuthides	0.0	0.0	0.0	0.0	0.0	1.7	0.3	0.0	46.9
Pd-antimonides	0.4	1.2	0.0	0.9	1.6	1.1	1.4	0.2	0.9
Pd-Hg-tellurides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pd-selenides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PGE-sulpharsenides	0.0	0.0	1.5	0.1	1.4	9.3	0.0	0.0	4.6
Electrum	1.3	8.7	0.5	1.0	1.5	1.7	0.2	1.0	2.7
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of PGM analysed	121	155	190	130	188	233	289	271	208
Average PGM grainsize (µm)	8	15	67	18	10	11	11	25	10

Table IVf(iii). Quantitative PGM distribution and average PGM grain size of the igneous samples from north to south along strike. The number of PGM analysed per sample is included. The rock type of each sample is indicated. The results are given in area %.



Figure IVf(i). Graphical representation of the quantitative PGM distribution of the igneous samples from north to south along strike. The rock type of each sample is indicated.

	TN228_9	TN228_20	TN223_23	TN223_25	TN223_40	TN223_135	TN223_156	TN221_11	TN221_25	TN221_65
Rock type*	Р	SH	Р	P-G	Ν	Ν	Ν	Р	Р	Р
BMS	4.0	39.5	11.6	16.8	16.0	38.8	22.2	14.0	41.4	19.3
Orthopyroxene	7.9	4.7	45.5	12.3	50.6	19.7	27.7	19.3	12.7	15.8
Clinopyroxene	0.6	0.0	3.4	0.0	1.5	1.4	17.7	4.6	1.2	0.1
Feldspar	1.5	0.3	7.9	22.8	8.3	21.9	16.5	7.1	16.1	12.1
Mica	0.0	0.1	0.3	0.1	0.0	0.1	0.0	0.0	1.1	0.0
Talc	1.3	2.5	0.0	9.0	0.0	0.0	0.0	0.1	0.3	0.3
Amphibole	1.3	0.5	1.8	0.7	0.3	2.3	3.4	1.3	0.1	0.2
Serpentine	0.0	8.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorite	3.5	0.5	8.1	9.7	0.6	6.0	4.0	0.3	0.8	1.1
Garnet	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cordierite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quartz	70.2	0.0	19.1	25.5	2.9	0.0	0.0	7.8	0.1	9.3
Fe-oxide	0.0	25.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other	0.3	3.6	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Liberated	9.4	13.8	0.0	3.0	19.7	9.7	8.5	45.5	26.1	41.9
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table IVf(iv). Semi-quantitative PGM association data of the igneous samples from north to south along strike. The rock type of each sample is indicated.

	TN240_22	TN240_89	TN197_8	TN197_32	TN197_54	TN198_32	TN199_3	TN199_7	TN199_19	TN199_24
Rock type*	Р	Ν	Р	Ν	Ν	Р	P-F	P-F	P-F	P-F
BMS	40.9	3.7	9.0	17.4	16.2	21.3	10.7	35.3	17.8	36.3
Orthopyroxene	4.3	2.4	24.2	8.3	16.7	60.0	53.2	44.9	45.1	43.2
Clinopyroxene	2.2	20.1	0.2	28.9	6.4	0.7	0.9	0.1	13.7	0.7
Feldspar	48.2	65.1	2.7	25.3	32.4	15.6	0.4	0.1	0.2	12.3
Mica	1.2	0.5	0.1	2.6	0.0	0.1	0.0	0.1	0.0	0.0
Talc	0.1	0.0	0.0	0.0	0.0	0.1	0.3	0.0	1.5	0.2
Amphibole	0.7	5.2	2.4	6.8	19.0	1.7	6.3	4.1	3.2	3.5
Serpentine	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorite	0.1	2.7	6.7	0.0	2.6	0.0	5.1	0.2	0.1	0.5
Garnet	0.0	0.0	0.0	0.6	0.0	0.1	0.0	0.0	0.0	0.0
Cordierite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quartz	2.0	0.0	1.1	1.2	1.3	0.0	15.9	11.8	16.0	3.4
Fe-oxide	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	1.5	0.0
Other	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Liberated	0.3	0.3	53.7	8.9	5.4	0.4	7.2	3.4	0.9	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table IVf(v). Semi-quantitative PGM association data of the igneous samples from north to south along strike. The rock type of each sample is indicated.

	TN199_30	TN201_11	TN201_32	TN201_61	TN203_33	TN203_39	TN203_55	TN203_65	TN205_55
Rock type*	P-F	Р	P-G	Ν	Р	SH	SH	Ν	Р
BMS	19.2	28.6	28.8	29.3	7.4	1.7	31.0	49.5	67.3
Orthopyroxene	64.3	41.9	3.3	44.5	57.3	61.0	34.5	1.2	5.5
Clinopyroxene	0.1	1.0	1.6	0.0	3.2	0.0	1.1	2.4	8.2
Feldspar	4.0	18.2	11.6	13.2	27.4	1.7	14.6	14.8	7.2
Mica	0.0	0.7	0.0	0.8	0.0	2.4	0.8	0.2	0.7
Talc	1.5	1.0	0.0	0.0	0.0	1.6	0.0	0.0	2.4
Amphibole	2.8	0.2	0.6	0.5	2.1	3.1	2.2	0.8	6.6
Serpentine	0.0	0.0	0.0	0.0	0.0	5.6	6.6	0.1	0.0
Chlorite	2.6	0.0	0.5	10.0	0.9	23.0	6.9	13.7	1.4
Garnet	2.3	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0
Cordierite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quartz	1.8	8.3	48.5	0.2	0.0	0.0	0.3	14.7	0.0
Fe-oxide	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.2
Other	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Liberated	0.9	0.0	5.0	0.5	1.7	0.0	1.7	2.7	0.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table IVf(vi). Semi-quantitative PGM association data of the igneous samples from north to south along strike. The rock type of each sample is indicated.



Figure IVf(ii). Graphical representation of the semi-quantitative PGM association of the Tweefontein igneous samples from north to south along strike. The rock type of each sample is indicated. This data was generated by the MLA instrument and is quantitative.

Table IVf(vii). Quantitative I	PGM distribution and aver	age PGM grain size of th	e metamorphic samples	s grouped into rock type	s and presented from
north to south along strike.	The number of PGM anal	lysed per sample is inclu	ded. The rock type of ea	ach sample is indicated.	The results are given
in area %.					

	TN221_204	TN240_214	TN228_185	TN223_161	TN221_264	TN240_144	TN197_246	TN198_55	TN198_62	TN198_75
Rock type*	RN	RN	PA	PA	PA	PA	PA	PA	PA	PA
Pt-Bi-tellurides	0.9	0.0	6.5	24.1	0.0	0.0	0.0	0.2	0.4	0.4
Pt-antimonides	0.0	0.1	0.2	0.0	0.2	0.0	0.0	0.0	0.5	0.0
Pt-arsenides	14.5	47.1	0.3	2.3	1.0	7.0	0.9	49.2	55.4	40.0
PGE-sulphides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pt-Pd-Bi-tellurides	0.0	0.1	0.0	6.7	0.0	0.0	0.0	0.1	0.0	6.7
Pd-Te-bismuthides	69.3	52.2	91.2	65.0	93.2	51.3	96.1	9.3	22.4	22.8
Pd-Te-Sb-bismuthides	0.0	0.2	1.7	0.1	0.9	19.3	0.8	32.6	3.6	7.8
Pd-antimonides	0.0	0.1	0.0	0.0	0.0	13.4	1.1	0.2	10.5	11.3
Pd-Hg-tellurides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pd-selenides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PGE-sulpharsenides	7.4	0.0	0.0	0.0	0.0	6.7	0.0	7.5	5.9	3.0
Electrum	7.9	0.1	0.1	1.8	4.7	2.2	1.1	0.9	1.3	8.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of PGM analysed	142	190	256	128	216	94	125	165	174	180
Average PGM grain size (µm)	8	30	6	17	5	9	5	64	8	11

Table IVf(viii).	Quantitative PGM	l distribution a	nd average PGM	grain size of the	metamorphic	samples group	ped into rock types	s and presented
from north to s	outh along strike.	The number of	f PGM analysed pe	r sample is inclu	ided. The rock	type of each s	ample is indicated	. The results are
given in area %	6.							

	TN198_78	TN199_60	TN201_90	TN201_99	TN205_152	TN205_160	TN228_65	TN197_161	TN228_81	TN205_185
Rock type*	PA	PA	PA	PA	PA	SPA	С	С	HO	HO
Pt-Bi-tellurides	0.0	0.0	9.7	1.4	0.2	0.0	11.1	25.4	12.5	0.4
Pt-antimonides	0.0	0.0	2.8	0.0	0.0	0.0	0.0	3.2	0.0	0.0
Pt-arsenides	27.5	4.5	14.5	1.0	0.3	56.0	14.9	0.3	6.1	0.0
PGE-sulphides	0.0	0.0	3.7	0.0	0.0	0.0	0.0	0.2	0.0	0.0
Pt-Pd-Bi-tellurides	0.0	0.2	5.1	9.3	0.0	0.0	37.2	1.3	8.0	0.0
Pd-Te-bismuthides	42.4	68.1	51.9	77.8	47.4	36.6	10.6	40.0	73.5	78.5
Pd-Te-Sb-bismuthides	22.8	26.0	0.0	0.0	27.7	0.7	0.0	0.2	0.0	1.3
Pd-antimonides	0.1	0.0	11.4	5.5	0.9	0.4	9.5	27.0	0.0	0.0
Pd-Hg-tellurides	0.0	0.0	0.0	0.0	0.0	0.0	15.9	0.0	0.0	0.0
Pd-selenides	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0
PGE-sulpharsenides	2.2	0.0	0.0	0.2	17.2	2.3	0.0	0.0	0.0	19.7
Electrum	5.0	1.2	0.9	4.8	6.2	4.0	0.8	1.8	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
No. of PGM analysed	129	105	201	219	136	208	112	138	41	183
Average PGM grain size (μm)	15	7	8	13	7	19	8	9	3	5



Figure IVf(iii). Graphical representation of the quantitative PGM distribution of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated.

	TN221_204	TN240_214	TN228_185	TN223_161	TN221_264	TN240_144	TN197_246	TN198_55	TN198_62	TN198_75
Rock type*	RN	RN	PA	PA	PA	PA	PA	PA	PA	PA
BMS	42.8	62.0	42.3	37.0	4.0	24.8	43.0	58.9	18.4	6.6
Orthopyroxene	21.6	1.3	0.6	1.8	0.0	7.9	45.3	23.5	45.0	0.0
Clinopyroxene	0.2	5.7	19.2	7.3	65.1	29.2	0.0	10.1	14.2	57.8
Feldspar	0.1	20.0	0.0	5.4	0.0	33.2	0.8	6.4	5.6	2.6
Mica	0.0	10.6	0.6	0.0	0.0	0.0	0.0	0.2	6.1	0.0
Talc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Amphibole	1.8	0.0	1.1	1.4	0.0	0.0	3.7	1.0	6.4	0.0
Serpentine	0.0	0.0	27.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorite	0.6	0.0	0.0	2.2	0.0	0.0	0.6	0.0	0.8	0.0
Garnet	0.0	0.0	4.4	0.0	0.0	4.9	0.0	0.0	0.0	33.0
Cordierite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Quartz	0.2	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.9	0.0
Fe-oxide	0.1	0.4	0.8	0.0	0.0	0.0	0.0	0.0	0.8	0.0
Other	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Liberated	32.7	0.0	0.0	44.8	30.9	0.0	4.8	0.0	1.7	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table IVf(ix). Semi-quantitative PGM association data of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated.

	TN198_78	TN199_60	TN201_90	TN201_99	TN205_152	TN205_160	TN228_65	TN197_161	TN228_81	TN205_185
Rock type*	PA	PA	PA	PA	PA	SPA	С	С	HO	HO
BMS	46.9	70.9	17.9	37.8	60.4	6.0	40.8	11.5	64.4	40.9
Orthopyroxene	24.8	0.6	2.9	0.0	6.3	1.8	0.0	0.0	0.0	12.3
Clinopyroxene	12.3	8.5	4.3	13.5	16.1	4.8	1.2	3.8	0.0	0.3
Feldspar	0.1	14.0	59.3	2.3	0.0	0.0	0.0	0.0	0.0	3.2
Mica	0.0	0.0	0.2	0.0	0.7	6.7	0.0	0.0	0.0	1.5
Talc	0.0	0.0	0.2	0.0	0.3	0.0	0.0	0.0	0.0	0.0
Amphibole	2.2	0.0	2.8	0.0	15.0	5.3	4.3	4.5	0.0	0.5
Serpentine	0.0	0.0	0.0	1.3	0.2	36.7	11.0	66.9	0.0	0.0
Chlorite	11.0	0.0	5.7	0.4	0.2	0.4	0.0	0.0	0.0	0.3
Garnet	0.0	5.1	6.8	35.8	0.2	0.0	40.4	4.8	2.3	0.0
Cordierite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.3	39.0
Quartz	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fe-oxide	2.4	0.0	0.0	0.0	0.8	38.0	0.0	0.0	0.0	2.0
Other	0.3	0.0	0.0	9.0	0.0	0.0	2.3	0.0	0.0	0.0
Liberated	0.0	0.9	0.0	0.0	0.0	0.3	0.0	8.5	0.0	0.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table IVf(x). Semi-quantitative PGM association data of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated.



IVf(iv). Graphical representation of the semi-quantitative PGM association of the metamorphic samples grouped into rock types and presented from north to south along strike. The rock type of each sample is indicated.